Liquid Impingement Erosion

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Introduction

LIQUID IMPINGEMENT EROSION has been defined as "progressive loss of original material from a solid surface due to continued exposure to impacts by liquid drops or jets" (Ref 1). The operative words in this definition are "*impacts* by liquid drops or jets": liquid impingement erosion connotes repeated impacts or collisions between the surface being eroded and small discrete liquid bodies.

Excluded from this definition are erosion mechanisms due to the impingement of a continuous jet, due to the flow of a single-phase liquid over or against a surface, due to a cavitating flow, or due to a jet or flow containing solid particles--although all these can produce erosion (progressive loss of solid material) at least under some conditions. Some of these mechanisms will, however, be discussed briefly in order to distinguish them clearly from the primary subject.

The significance of the discrete impacts is that they generate impulsive contact pressures on the solid target, far higher than those produced by steady flows (see the discussion "Liquid/Solid Interaction--Impact Pressures" later in this article). Thus, the endurance limit and even the yield strength of the target material can easily be exceeded, thereby causing damage by purely mechanical interactions. In some circumstances the damage can also be accelerated by conjoint chemical action.

At sufficiently high impact velocities, solid material can be removed even by a single droplet (or other small liquid body). Much of what is currently known about the liquid/solid interactions in liquid impingement has been determined through laboratory experiments and analytical modeling involving single impacts.

Liquid impingement erosion in its advanced stages is characterized by a surface that appears jagged, composed of sharp peaks and pits (Fig. 1). A possible reason for this will be given later.

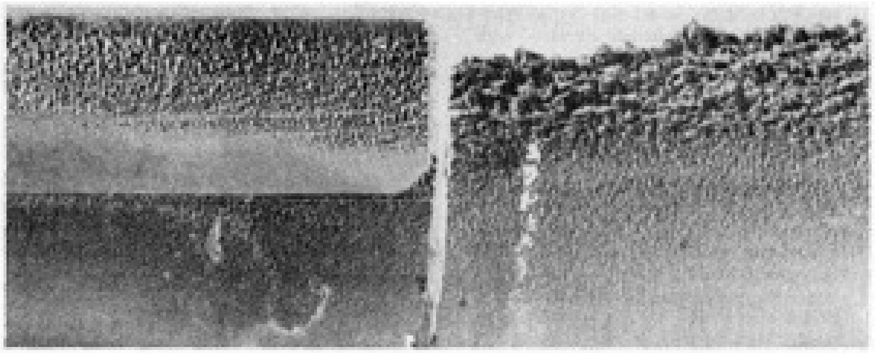

Fig. 1 Two portions of a steam turbine blade that has experienced liquid impingement erosion. The portion on the left was protected by a shield of rolled Stellite 6B brazed onto the leading edge of the blade; the portion on the right is unprotected type 403 stainless steel. Note the difference in degree of erosion. Normally such erosion does not impair the

blade's function. Both at 2.5×

A very comprehensive treatment and review of liquid impact erosion can be found in Ref 2; in particular the chapters therein by Adler (Ref 3) and by Brunton and Rochester (Ref 4). Reference 5 contains some now classic studies that provided the foundation for subsequent work. Many other contributions to this field are found in several ASTM symposium volumes (Ref 6, 7, 8, 9, 10) and in the proceedings of the international "Rain Erosion" and "Erosion by Liquid and Solid Impact" (or "ELSI") conferences (Ref 11, 12, 13, 14, 15, 16, 17). Individual papers from some will be cited in context.

Acknowledgements

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Occurrences in Practice

It is quite difficult to propel liquid droplets to high velocities without breaking them up, and liquid impingement erosion haas become a practical problem primarily where the target body moves at high speeds and collides with liquid drops that are moving much more slowly. Almost all the work done in this subject has been in connection with just two major problems: "moisture erosion" of low-pressure steam turbine blades operating with wet steam, and "rain erosion" of aircraft or missile surfaces and helicopter rotors.

Whenever vapor or gas flows carrying liquid droplets impinge upon solid surfaces--as in nuclear power plant pipes and heat exchangers, for example--erosion can also occur. However, the probable impact velocities and impact angles are such as to make "pure" liquid impingement erosion an unlikely mechanism. It is much more likely that an "erosion-corrosion" mechanism is then involved (see the discussion of "Impingement Attack and Erosion-Corrosion" later in this article).

Steam Turbine Blade Erosion. Moisture erosion of low-pressure blades has been a problem throughout steam turbine history, and remains a concern today. In the last stages of the low-pressure turbine, the steam expands to well below saturation conditions, and a portion of the vapor condenses into liquid. Although the condensation droplets are very small, some of them are deposited onto surfaces of the stationary blades (guide vanes), where they coalesce into films or rivulets and migrate to the trailing edge. Here they are torn off by the steam flow, in the form of much larger droplets.

These large droplets slowly accelerate under the forces of the steam acting on them, and when they are carried into the plane of rotation of the rotating blades, they have reached only a fraction of the steam velocity. As a result, the blades hit them with a velocity that is almost equal to the circumferential velocity (wheel speed) of the blades, which can be as high as 650 m/s (2100 ft/s) in a modern 3600 rpm turbine. References 18 and 19 describe these processes in detail. The same basic phenomenon can, of course, occur in wet vapor turbines operating with other working fluids, such as sodium or mercury.

The principal remedies in modern turbines include extracting moisture between blade rows, increasing axial spacing between stator and rotor to permit droplets to be accelerated and broken up, and making the leading edge of the blade more resistant to erosion. This last remedy has been accomplished by local flame hardening of the blade material, by brazed-on "shields" of Stellite (Fig. 1), or in some cases by shields of tool steel or weld-deposited hardfacing. Tests on many blade and shield materials are reported in Ref 20 and 21. The base material for present-day low-pressure blades is usually a 12% Cr martensitic stainless steel, a 17Cr-4Ni precipitation-hardening stainless steel, or, more rarely, a titanium alloy.

Recently, success has been claimed for new "self-shielding" blade alloys that harden under the action of the impacts. One such alloy is Jethete M152, a martensitic steel containing about 11% Cr, 2.9% Ni, 1.6% Mo, and 0.3% V. Other new approaches that have been investigated include plasma-deposited Stellite and an ion-plated chromium-tin multilayer coating; however, it is doubtful that relatively thin coatings can provide long-term protection.

The evaluation and prediction of steam turbine blade erosion is very complex; recent contributions include Ref 22 and 23.

Aircraft Rain Erosion. Rain erosion became a major problem in the 1950s, when military aircraft reached transonic and supersonic speeds. The impact of rain drops, 2 mm (0.08 in.) or more in size, on unprotected aluminum alloy surfaces, optical and infrared windows, and radomes caused severe erosion which seriously limited operational time in rain storms. This resulted in many government-funded research projects into erosion mechanisms as well as development and evaluation of protective coatings. Reference 24 gives an overview of the rain erosion problem, with special reference to radomes. The current status concerning remedies has been summarized as follows by Schmitt (Ref 25):

> Protection of aircraft radomes and composite surfaces is accomplished with two classes of elastomeric coatings--polyurethanes for widespread lower temperature applications, and fluorocarbons where elevated temperatures (above 177 °C, 350 °F) or special requirements (camouflage colors, thermal flash protection) are involved.
>
> For applications where supersonic rain erosion is a concern, the inherent erosion resistance of the base materials combined with streamline geometry to reduce impact angles is the most often used approach. Another aerodynamic technique is to utilize the shock waves to shatter and fragment the raindrops into very small pieces that produce less damage. For hemispherical domes where impact angles must be large (near normal), protective coatings of boron phosphide, germanium carbon and diamond are being pursued, but they are restricted to velocities less than Mach 2. At extremely high velocities, protection at high impact angles may require metal tips or sacrificial layers even though a performance penalty must be paid. In many cases, lack of adequate materials and potential catastrophic failure simply precludes operation at high supersonic speed in rainy environments.

References 8, 9, 10, 11, 12, 13, 14, 15, 16, and 17 contain numerous papers on evaluation of materials and coatings for rain erosion applications. Among the most recent are investigations of infrared window materials, slip-cast fused silica, and hard carbon-coated germanium in Ref 17; polyurethane and fluoroelastomer coated composite constructions, composite materials for radomes, new materials for radomes, and infrared windows (including polyethersulfone, polyetherimide, polyetherketone, and germanium) in Ref 16; and slip-cast fused silica, boron-aluminum composites, composite and honeycomb structures, polytetrafluoroethylene (PTFE) and polymethylmethacrylate (PMM) in Ref 15.

As mentioned earlier, rain erosion also poses a threat to missile surfaces and helicopter rotors.

Figure 2 shows the catastrophic failure of a missile dome due to rain erosion effects.

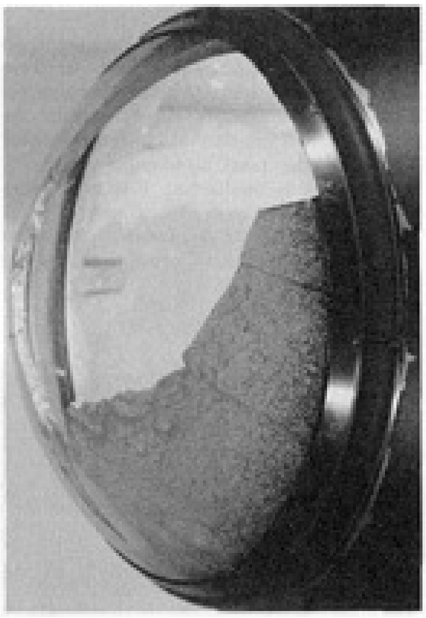

Fig. 2 Rain erosion effects on a Maverick missile dome made of coated zinc sulfide that was exposed for 10 s at a speed of about 210 m/s (690 ft/s). The dome itself suffered catastrophic damage, and erosion is also seen on the filled elastomeric mounting ring. Courtesy of G.F. Schmitt, Jr., Materials Laboratory, Wright Research and Development Center, Department of the Air Force

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Relationship to Other Erosion Processes

Continuous Jet Impingement. Impingement of a high-velocity continuous jet can cause material removal, and that fact has led to the development of jet-cutting technology used in quarrying, mining, and material cutting. While there is some overlapping with erosion research, much of the literature is found in the "American Water Jet Conferences" and the "International Conferences on Jet Cutting Technology."

Steady continuous jet impingement produces only stagnation pressure on the target, whereas discrete impacts produce much higher shock-wave or "water-hammer" pressures. Thus, high supply pressures are needed to achieve material removal with truly continuous jets. This has led jet-cutting research to develop techniques for producing moving and oscillating jets, pulsating jets, and cavitating jets, all of which serve to introduce something akin to discrete impact conditions (also, jets laden with abrasive particles are used). References 26 and 27 describe these techniques.

Rough comparisons of test data suggest that the erosion rate due to a continuous jet can be from one to five orders of magnitude lower than that due to the same quantity of liquid impinging at the same velocity but in the form of droplets.

Cavitation Erosion. Whereas liquid impingement connotes a continuous vaporous or gaseous phase containing discrete liquid droplets, cavitation connotes a continuous liquid phase containing discrete vaporous or gaseous bubbles or cavities. Despite this seeming antithesis, the nature of cavitation damage and liquid impingement damage has many similarities. Both, in fact, are due to small-scale liquid/solid impacts. In cavitation, micro-jet impacts have been shown to occur in the asymmetrical collapse of cavitation bubbles adjacent to a solid surface, although shock waves generated by collapsing cavity clusters may also contribute to damage.

The relative resistance of materials to the two types of erosion is much the same, the damage appearance is similar, the complicated time dependence of the erosion rate is similar (see the section "Time Dependence of Erosion Rate" in this article), and historically cavitation tests have been used to screen materials for service in liquid impingement environments, and vice versa. In some practical cases, it is not clear whether the mechanism causing erosion was impingement or cavitation erosion. One such example is the heavily eroded dynamometer stator shown in Fig. 3. Erosion in such machines has often been characterized as cavitation erosion; however, the author believes it to be liquid impact erosion caused by the discrete streams of water issuing from the rotor pockets and sweeping across the stator vanes. This is supported by dynamic pressure transducer spectra which were dominated by discrete spikes at the rotor vane passing frequency, but did not show the characteristic signature of cavitation. In addition, injection of air bubbles, which can inhibit cavitation, had no influence on the signals or on the erosion.

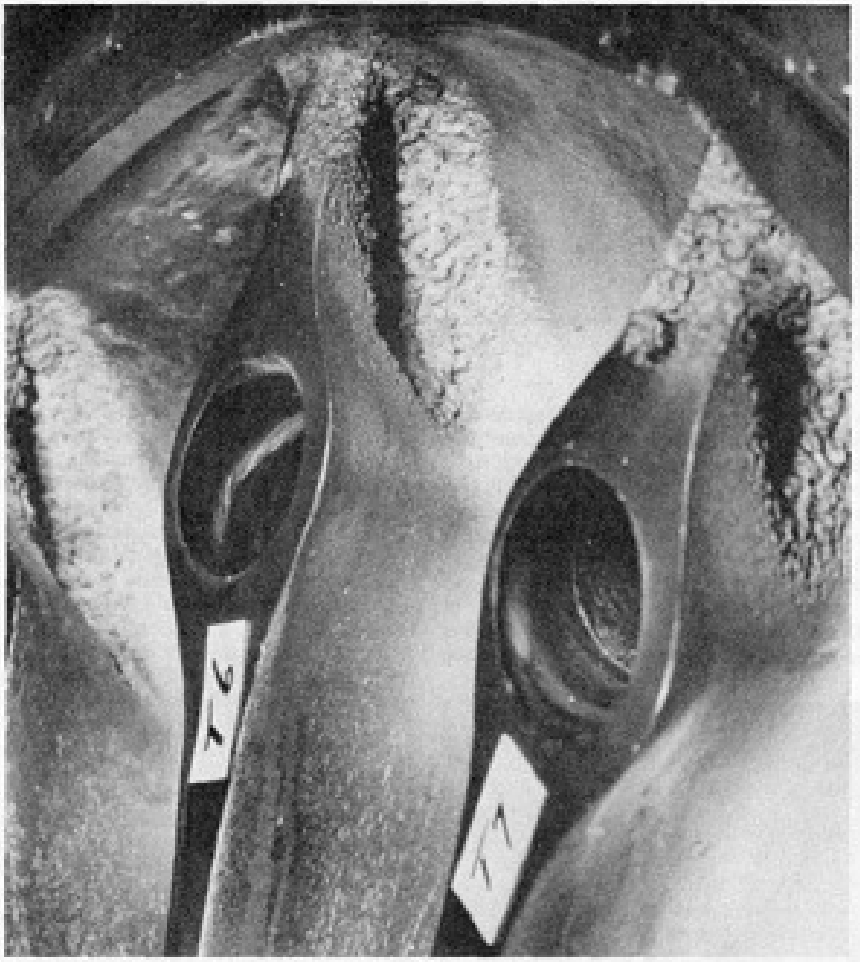

Fig. 3 Severe erosion of copper-manganese-aluminum stator vanes in a hydraulic dynamometer. Each vane has lost about 10 cm^3 (0.6 $in.^3$) of material. See text for a discussion of the erosion mechanism.

For additional information on cavitation damage, see the article "Cavitation Erosion" in this Volume.

Solid Particle Erosion. It might easily be assumed that solid particle erosion would have many similarities to liquid impingement erosion, since both involve the impact of small discrete bodies. This is not the case, however, because the damage mechanisms, the effects of impact variables, and the response of materials are all quite different.

For example, the resistance of common engineering alloys to liquid impingement ranges over several orders of magnitude, whereas most common ductile alloys have about the same resistance to solid impingement; liquid impingement erosion rates vary with about the 5th power of impact velocity, whereas solid particle erosion varies with about the 2.5th power; liquid impingement erosion is greatest with normal (perpendicular) impacts, whereas solid particle erosion in ductile alloys peaks with impacts some 60 to 70° away from perpendicular; and finally, liquid impingement erosion exhibits a complicated time dependence, whereas the erosion rate due to solid particle impingement is essentially linear. See the article "Solid Particle Erosion" in this Volume for further details.

Impingement Attack and Erosion-Corrosion. There are many practical situations where material loss occurs in the presence of flowing fluids but cannot be fully explained by purely mechanical action such as liquid impingement, solid particle impingement, or cavitation. Only recently has a substantial amount of scientifically oriented work on these phenomena been reported in the literature.

"Impingement attack" is a term sometimes used for material loss in tube bends and heat exchanger tube entrances, where the forces of unsteady, turbulent, or bubbly flows are believed to remove protective oxide layers and thus permit continuing and accelerated corrosion. "Wire drawing" is a term used for a grooving type of erosion produced in small gaps such as valve seats and component joints with a high pressure drop across them. This type of erosion could be due to localized cavitation or to erosion-corrosion.

"Erosion-corrosion" can refer to any conjoint (synergistic) action between corrosive and erosive processes, such that the resulting material loss rates are greater than the sum of the individual processes taken by themselves. Corrosive actions in the presence of solid particles, slurries, and sliding wear are covered in detail in the articles "Solid Particle Erosion," "Slurry Erosion," and "Corrosive Wear" in this Volume.

For purely fluid systems, some recent work on "corrosive-erosion" has emphasized a mechanism in which impulsive mechanical interactions play little or no role. For example, the flow of liquid or droplets along a carbon or low-alloy steel surface prevents equilibrium in the corrosive process and results in continuing chemical dissolution of the protective oxide (magnetite) layer (Ref 28). This is more accurately called "flow-assisted corrosion."

Only a few references can be cited here. Keck and Griffith (Ref 29) propose models for both convection-assisted oxide dissolution and for oxide fatigue by liquid droplet impacts. Coulon (Ref 30) distinguishes mechanisms by the flow velocity causing them: corrosion, 0 to 10 m/s (0 to 35 ft/s); corrosion-erosion, 10 to 50 m/s (35 to 165 ft/s); erosion-corrosion, 50 to 200 m/s (165 to 655 ft/s); and erosion, >200 m/s (>655 ft/s). Henzel *et al.* (Ref 31) give an update on experience and remedies. Both Ref 30 and 31 provide empirical schemes for estimating material loss due to erosion-corrosion, including factors relating to material, flow velocity, and temperature, as well as geometry factors borrowed from another empirical model by Keller (Ref 32).

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Mechanisms of Liquid Impact Erosion

Liquid/Solid Interactions--Impact Pressures. The high-velocity impact of a liquid drop against a plane solid surface produces two effects that result in damage to that surface: high contact pressure, which is generated in the area of the impact, and subsequent liquid "jetting" flow along the surface, radiating out from the impact area (Ref 33). A first approximation of the average impact pressure, before radial outflow initiates, is the one-dimensional water-hammer pressure; that is, pressure generated in the impact of an infinite flat liquid surface against an infinite flat rigid surface. In this case a plane shock wave is formed at the instant of impact and travels into the liquid, bringing to rest one "layer" after another.

This impact or shock pressure, *P,* can be defined as:

$$P = \rho C V$$

where ρ is the liquid density, C is the shock wave velocity in the liquid, and V is the impact velocity. For practical impact velocities, this can be approximated by:

$$P = \rho C_0 V\,(1 + kV/C_0)$$

where C_0 is the acoustic velocity of the liquid, and $k = 2$ for water. For example, for water impacting at 500 m/s (1640 ft/s), this pressure is about 1250 MPa (180 ksi)--considerably above the yield strength of many alloys. The stagnation pressure of a continuous jet ($\rho V^2/2$) at that speed is about one-tenth of the former.

The real situation is much more complicated, because of the roundness of the impacting droplet and the elastic and plastic deformations of the solid surface. Although much work has been done on this topic in recent years (for example, Ref 34, 35, 36, 37), a complete understanding has not yet been achieved. However, the following salient features (see Fig. 4) are now widely accepted for the impact of a round drop on a rigid surface:

- At the initial instant of impact, contact is made at a point. Because the droplet radius of curvature is initially infinite compared to the contact radius, quasi-one-dimensional conditions prevail and a shock wave of the one-dimensional impact pressure is formed at that instant and begins to travel up into the drop (Fig. 4a)
- As the contact area spreads out, its perimeter at first is moving radially outward at a speed greater than the shock velocity; consequently an obliquely attached bulbous shock front is formed enclosing the compressed liquid and no free outflow can take place (Fig. 4b). During this stage, the highest impact pressure is found at the growing contact perimeter, where its value gradually increases up to about $3\rho C_0 V$, while that at the impact center decreases
- At some point, defined by a critical contact angle, ϕ_c, the conditions for an attached shock are no longer met; the shock front then detaches from the solid surface and moves up along the surface of the droplet. The compressed liquid is now free to spread or "jet" out laterally and relieve the contact pressures (Fig. 4c). In experiments, however, actual jetting is not observed until the contact angle ϕ has reached a value significantly greater

than the theoretical critical value ϕ_c; the reasons for this behavior are not yet fully understood. The maximum lateral jetting velocity is many times greater than the impact velocity, but theoretical prediction of its value is still uncertain.

Figure 5 shows high-speed photographs at various stages of the impact between a solid projectile and a gelatine droplet in a laboratory apparatus. In this case the impact velocity was 110 m/s (360 ft/s) and the maximum jetting velocity 1170 m/s (3840 ft/s).

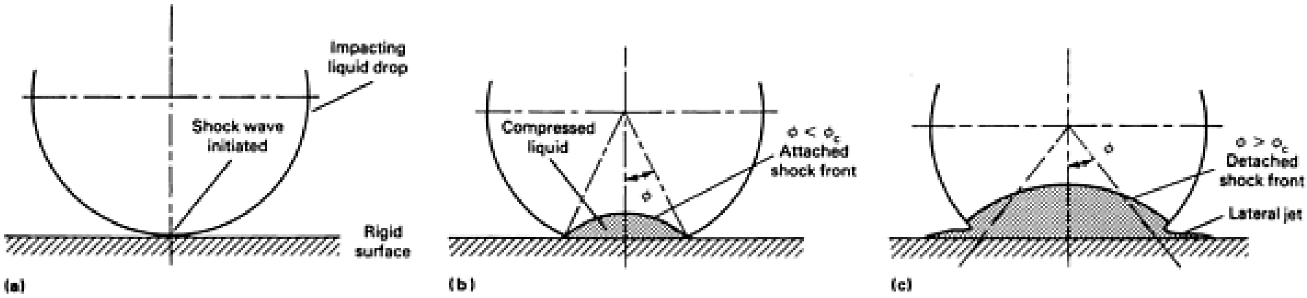

Fig. 4 Idealized diagram of the early stages of liquid drop impact. (a) Initial contact. (b) Compressible stage with attached shock front. (c) Detached shock and jetting stage. See text for detailed discussion of these three stages.

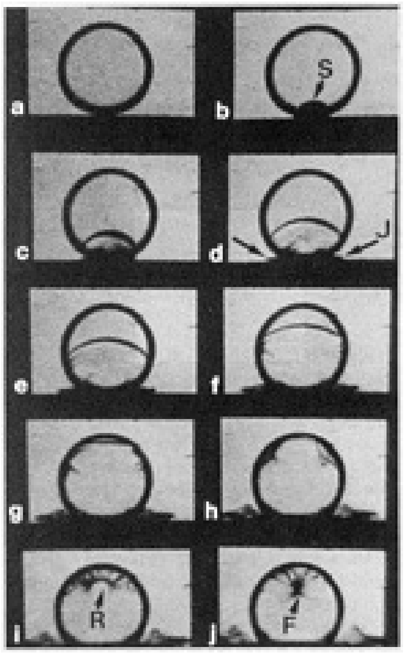

Fig. 5 High-speed photographs of the impact between a 10 mm (0.4 in.) diam two-dimensional droplet of gelatin and a metal slider moving at 110 m/s (360 ft/s) at intervals of 1 μs. S denotes the shock front, first seen in frame b. Jetting is just visible in frame c and is labeled J in frame d. Note the reflection of the shock as a rarefaction wave R in frames h through j, causing a region of cavitation indicated by F. In these photos, there has not yet been time for any gross spreading out of the droplet to occur. Courtesy of J.E. Field, Cavendish Laboratory, University of Cambridge, United Kingdom

The liquid/solid interaction is further complicated when the solid surface becomes deformed from erosion, usually exhibiting jagged peaks and craters. Then both the pressures and jetting patterns will be affected by where the initial contact takes place, and by the size of the droplet in relation to topographic features. For example, a drop falling on a peak or slope may not develop full impact pressure; one falling in a crater may produce increased pressures due to shock wave collisions or "shaped charge" effects. This may explain the characteristic pitted appearance because if even shallow pits are formed, subsequent material loss occurs preferentially in the pits and continues to deepen them.

Material Response--Development of Damage. As described above, the solid surface is subjected to a multitude of sharp pressure pulses and jetting outflows, each of very short time duration and acting on a very small area. What then happens to the solid material is hard to generalize because it will depend on whether the solid is ductile or brittle, on its microstructure, and on whether the impacts are severe enough to produce single-impact damage. Adler (Ref 3) lists the primary causes of damage as direct deformation, stress wave propagation, lateral outflow jetting, and hydraulic penetration. At impact, the formation of the shock front in the liquid is accompanied by corresponding stress waves propagating into the solid; the solid response is therefore also impulsive and governed by its dynamic rather than static mechanical properties.

In ductile materials, a single intense impact may produce a central depression, with a ring of plastic deformation around it where the jetting outflow may remove material by a tearing action (Fig. 6). With less intense but repeated impacts, there is no immediate material loss, but randomly disposed dimples gradually develop, and the surface undergoes gradual deformation (often characterized by twinning) and work hardening. Metallographic and x-ray diffraction studies have shown that during this "incubation stage," these effects eventually extend to 30 to 50 μm below the surface, thereafter remaining about the same as actual erosion (material loss) then begins and progresses. The material loss may occur through propagation of fatiguelike cracks that eventually intersect to release erosion fragments. The fractures have often been described as transgranular. This process can be assisted by tearing that is due to increased liquid forces on irregular surface steps and fissures. In materials with pronounced nonuniform structure, damage will initiate at weak spots or in the weaker components. Figures 7 and 8 illustrate the character of erosion damage in a martensitic stainless steel (AISI type 403) and Stellite 6B, respectively.

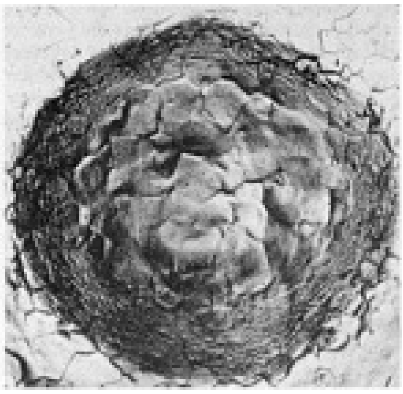

Fig. 6 Deformation due to a single impact on aluminum impacted by a short discrete jet of water at 750 m/s (2460 ft/s). Note the central depression, which is of similar diameter to the impacting jet, and the circumferential surface ripples surrounding it. Courtesy of J.E. Field, Cavendish Laboratory, University of Cambridge, United Kingdom

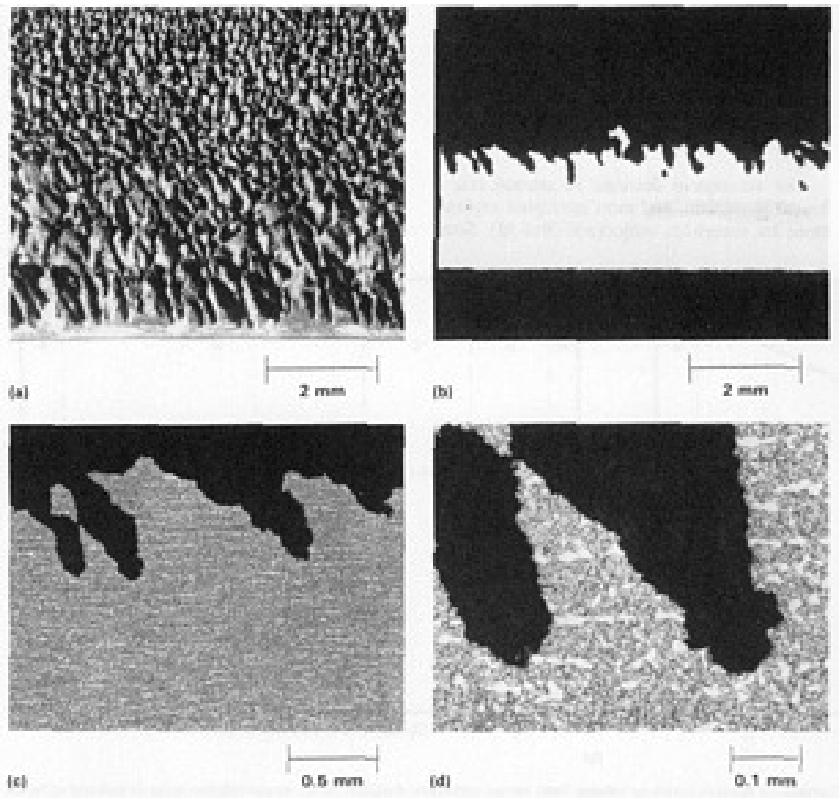

Fig. 7 Character of erosion in type 403 martensitic stainless steel. (a) Macrograph of eroded area. 10×. (b) Unetched section. 10×. (c) Section through several pits. GRARD II etch. 50×. (d) Enlarged portion of (c). 200×. Courtesy of Westinghouse Electric Corporation

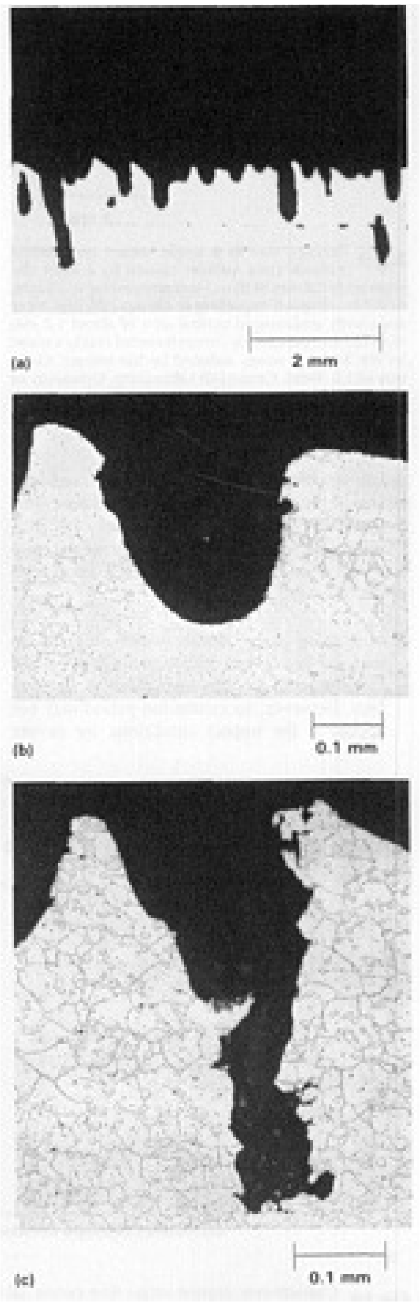

Fig. 8 Character of erosion in Stellite 6B alloy. (a) Unetched section. 10×. (b) and (c) Etched sections through specific pits. Both at 200×

In brittle materials, circumferential cracks may form around the impact site that are caused by tensile stress waves propagating outward along the surface (Fig. 9). In thin sheets subjected to impacts, material can spall off the inside surface due to the compressive stress wave from the impact reflecting there as a tensile wave.

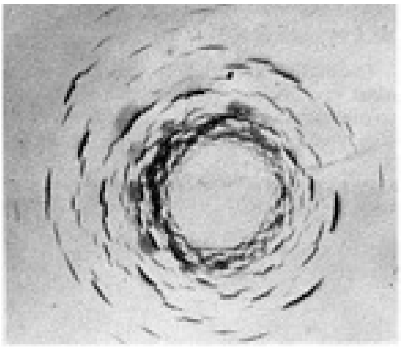

Fig. 9 Damage due to a single impact on a brittle material (zinc sulfide) caused by a short discrete jet of 0.8 mm (0.03 in.) (corresponding to a 5 mm, or 0.2 in., droplet) impacting at 300 m/s (985 ft/s). Note apparently undamaged central area of about 1.2 mm (0.05 in.) surrounded by circumferential cracks caused by the Rayleigh waves induced by the impact. Courtesy of J.E. Field, Cavendish Laboratory, University of Cambridge, United Kingdom, from Ph.D. thesis by D. Townsend

For materials and composite structures used in aerospace applications, it is difficult to generalize damage mechanisms. For example, in thermosetting polymers or chopped fiber-reinforced composites, the damage takes the form of chunking (removal of large-size lumps of material) from the surface (Ref 25). Furthermore, the initial measure of damage for radome and infrared window materials is not gross material removal, but impairment of electromagnetic transmission characteristics, which leads to loss of function. In the extreme, however, damage can be catastrophic, as shown in Fig. 2.

Corrosion Interactions. More research on corrosion interactions has been done for cavitation than for liquid impingement, but the general observations described below can apply to both.

In the early days before high impact pressures were understood, it was often supposed that liquid impingement as well as cavitation damage had to be largely or significantly corrosive in nature. It is now recognized, and has been proven experimentally, that such erosion can occur without any corrosive component. Moreover, under impingement of high intensity, material loss can occur so rapidly that corrosion--even if otherwise possible--does not have time to play a role. Nevertheless, at intermediate mechanical intensities there is opportunity for corrosion to weaken the material and facilitate its removal by the mechanical impact forces. Several investigators have shown some parallels between erosion and corrosion fatigue behavior.

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Time Dependence of Erosion Rate

Qualitative Description. Liquid impingement erosion shares with cavitation erosion a unique characteristic that makes accurate long-term predictions or extrapolations of erosion nearly impossible. This is the very nonlinear nature of the progress of erosion with time, under constant impingement conditions (Ref 38). Qualitatively, the so-called "erosion-time pattern" depicted in Fig. 10 is generally composed of the following stages:

- *Incubation stage,* during which little or no material loss occurs, although roughening and metallurgical changes take place in the surface. However, an incubation period may not appear if the impact conditions are severe enough for each single impact to cause material loss
- *Acceleration stage,* during which the erosion rate increases rapidly to a maximum
- *Maximum rate stages,* during which the erosion rate remains constant or nearly so. The erosion rate for this stage is most commonly quoted as a single-number result of an erosion test. However, some tests show only a fleeting peak in the erosion rate-versus-time curve, with no prolonged steady rate
- *Deceleration (or attenuation) stage,* during which the erosion rate declines to some fraction (often from $\frac{1}{4}$ to $\frac{1}{2}$) of the maximum rate
- *Terminal (or final steady-state) stage,* during which the rate remains constant once again indefinitely. However, some tests do not show this stage, and the erosion rate either continues to decline or goes into a series of fluctuations. With some brittle materials or coatings, the rate can increase in what is called a "catastrophic stage"

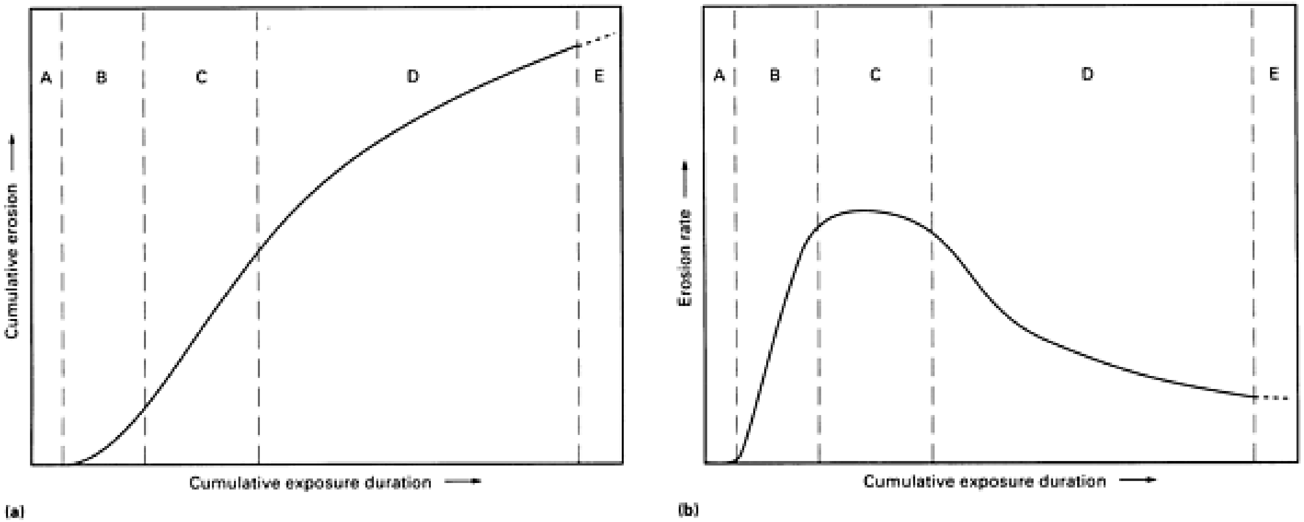

Fig. 10 Characteristic erosion versus time curves. (a) Cumulative erosion (mass or volume loss) versus exposure duration (time, or cumulative mass or volume of liquid impinged). (b) Corresponding instantaneous erosion rate versus exposure duration obtained by differentiating curve (a). The following stages have been identified thereon: A, incubation stage; B, acceleration

stage; C, maximum rate stage (sometimes called first steady-state stage); D, deceleration stage; and E, terminal or final steady-state stage, if assumed to exist.

Figure 11 shows some nontypical curves that are sometimes encountered. All of the curves in Fig. 10 and 11 have been derived from actual test curves in the literature.

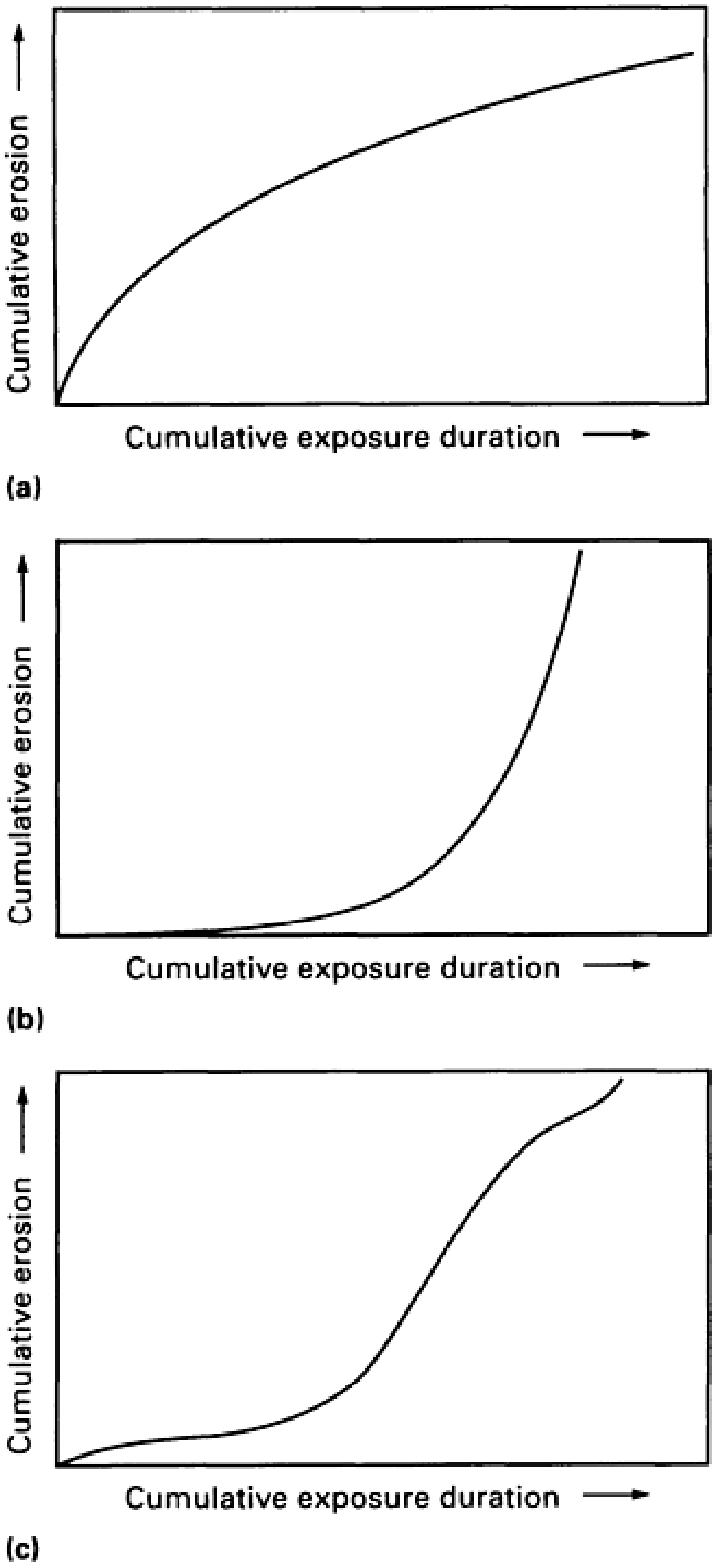

Fig. 11 Less common types of cumulative erosion versus time curves sometimes obtained. (a) Curve without incubation or acceleration stages, with continuously decreasing rate (obtained in this case with very small droplets and very high impact velocity). (b) Curve with continuously increasing erosion rate, resulting in catastrophic damage (obtained in this case on

titanium carbide). (c) Curve with fluctuations in erosion rate (obtained in this case on a titanium alloy)

Reasons for Time Dependence. The incubation and acceleration stages are easy to explain in qualitative terms if one postulates that the removal of erosion fragments results from a fatiguelike failure mechanism. Then many impacts must occur in one area for a fragment to be loosened from the surface. The statistical nature of the process then results in a gradual transition--the acceleration period--from the incubation stage to the steady-state (maximum rate) stage.

The subsequent decrease in erosion rate is harder to explain, and most attempted explanations are somewhat conjectural (Ref 38). Some have also been based on the statistics of the damage mechanisms, combined with changes in the surface properties brought on by erosion itself. Some are based on the topographical changes in the surface: as the surface is roughened, the surface area is increased, and more energy is needed to continue erosion. Also, liquid drops will now tend to impact on the peaks or the slopes of the roughened surface; in both cases the impact pressures may be reduced. Finally, the liquid retained in erosion craters has been supposed to cushion and protect the surface.

Implications for Testing and Prediction. Clearly, this complicated time dependence of erosion, and the variations thereof, make it very difficult to define a single meaningful test result of an erosion test, or assign from that an erosion resistance of a material, or predict long-term erosion behavior from a short test. Many authors in the literature have proposed mathematical formulations for the erosion-time curve (or portions of it). Some of these have been essentially empirical, some have been based on proposed analytical models for the erosion process; however none so far has achieved general acceptance. See the discussion of "Comprehensive Prediction Methods and Erosion Theories" later in this article for additional information.

For the purpose of reporting test results, ASTM Standard Practice G 73 for Liquid Impingement Erosion Testing (Ref 39), as well as ASTM Standard Method G 32 for Vibratory Cavitation Erosion Testing (Ref 40) recommend that curves of cumulative mass loss versus time be shown in a test report, since any other parameters (for example, erosion rates) must be derived from that. For tabular data and comparisons (between materials or test conditions), ASTM G 73 prescribes tabulating the maximum erosion rate and a nominal incubation period, which is simply the intercept on the time axis of the maximum erosion rate line. In order to describe the longer-term behavior, some authors also use the terminal (final steady-state) erosion rate and some parameter that defines the intersection of that line with the maximum-rate line or the erosion axis (Fig. 12). Note that even this simplified model of the erosion-time pattern, consisting of three straight-line segments, requires four experimentally or analytically derived parameters to define it.

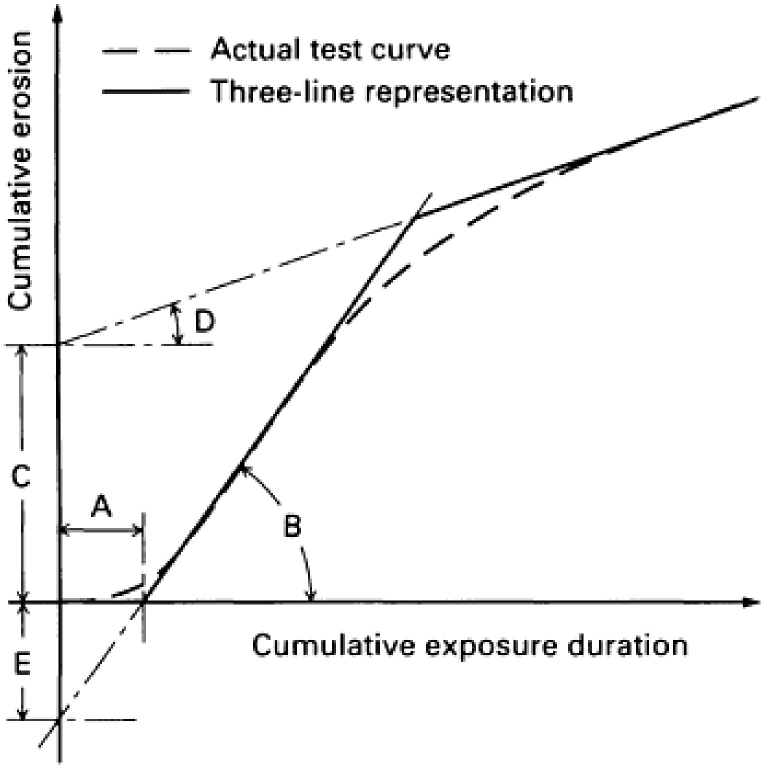

Fig. 12 The erosion versus time curve from Fig. 10, showing some numerical parameters that may be recorded to characterize the test results. A, nominal incubation period; B, slope representing maximum erosion rate; C, *y*-axis intercept of terminal erosion rate line; D, slope representing terminal erosion rate. ASTM G 73 (Ref 39) specifies that at least A and B be tabulated in any test report. Some authors have used E (*y*-axis intercept of maximum erosion rate line) in place of A; it tends to be constant when some parameters (for example, impact velocity) are varied.

The author's experience, in attempting to correlate test data from various sources, has been that the maximum erosion rate is the most predictable by empirical relationships. However, this parameter alone cannot be used to predict long-term erosion in the absolute sense, and there are indications that it does not predict it well even in the relative sense. Thus, more work is certainly needed in reaching a generalized method for long-term erosion prediction.

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Test Methods for Erosion Studies

Erosion tests are conducted to evaluate materials as well as to study the effects of other variables on erosion. Basic studies of single impacts have been conducted with "liquid gun" devices, in which a small quantity of liquid is ejected through a carefully designed nozzle and impacts a stationary specimen (Ref 33), or by projecting a solid target against a stationary liquid or gelatine body (Ref 37).

However, for multiple-impact studies and for evaluating the resistance of materials, the usual approach is to attach the specimen(s) to the periphery of a rotating disc or arm, such that in their circular path they repeatedly pass through and impact against liquid jets, sprays, or simulated rain drops (Ref 20, 21, 39, 41, 42). The velocity of the specimen then determines the impact velocity. Such test facilities range from small laboratory apparatus with specimen velocities of up to about 200 m/s (655 ft/s) to large self-contained facilities (some with vacuum-controlled test chambers); some of the latter are capable of impact velocities up to 1000 m/s (Mach 3, or 3300 ft/s). ASTM G 73 (Ref 39) gives comprehensive guidelines for conducting this type of test and for analyzing the data.

The successful selection and development of improved materials and coatings for rain erosion have been largely based on rotating arm tests. Service experience and in-flight tests have confirmed that the laboratory tests predict the correct relative erosion resistance as well as the failure modes. For high supersonic rain erosion studies, however, specimens have been attached to rocket sleds propelled at speeds up to 1700 m/s (5580 ft/s) through an artificial rain field (Ref 45). Wind tunnels have also been adapted for rain erosion tests.

As noted earlier, cavitation erosion test methods such as the vibratory method (Ref 40), the cavitating jet method, and the submerged rotating disk method have also been used to screen materials for service under liquid impingement conditions.

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Means for Combatting Erosion

Modification of Impingement Conditions. If possible, the geometry and/or fluid dynamics should be modified to reduce the amount of liquid impacting the exposed surfaces, to reduce the impact velocity of the droplets (or change the impact angle to reduce the normal component of impact velocity), to reduce the droplet size, or to reduce time of operation under the most severe conditions. Efforts in all of these directions are made in steam turbines as well as in aircraft and missiles, but details are beyond the scope of this discussion.

Material Selection and Protective Shielding. Some of the material aspects have already been covered in earlier sections of this article. Figure 13 provides an overview of relative erosion resistance of metallic alloys, based primarily on a series of results (from both impingement and cavitation tests) examined in Ref 44. Some items from recent investigations (Ref 52, 53, 59, 60) have been added; most of these were cavitation tests. Because of the inconsistencies inherent in erosion testing, this can be used only as a rough guide. Some investigators have found that the relative resistances of some materials depended on the impact velocity, implying significantly different velocity dependencies for them.

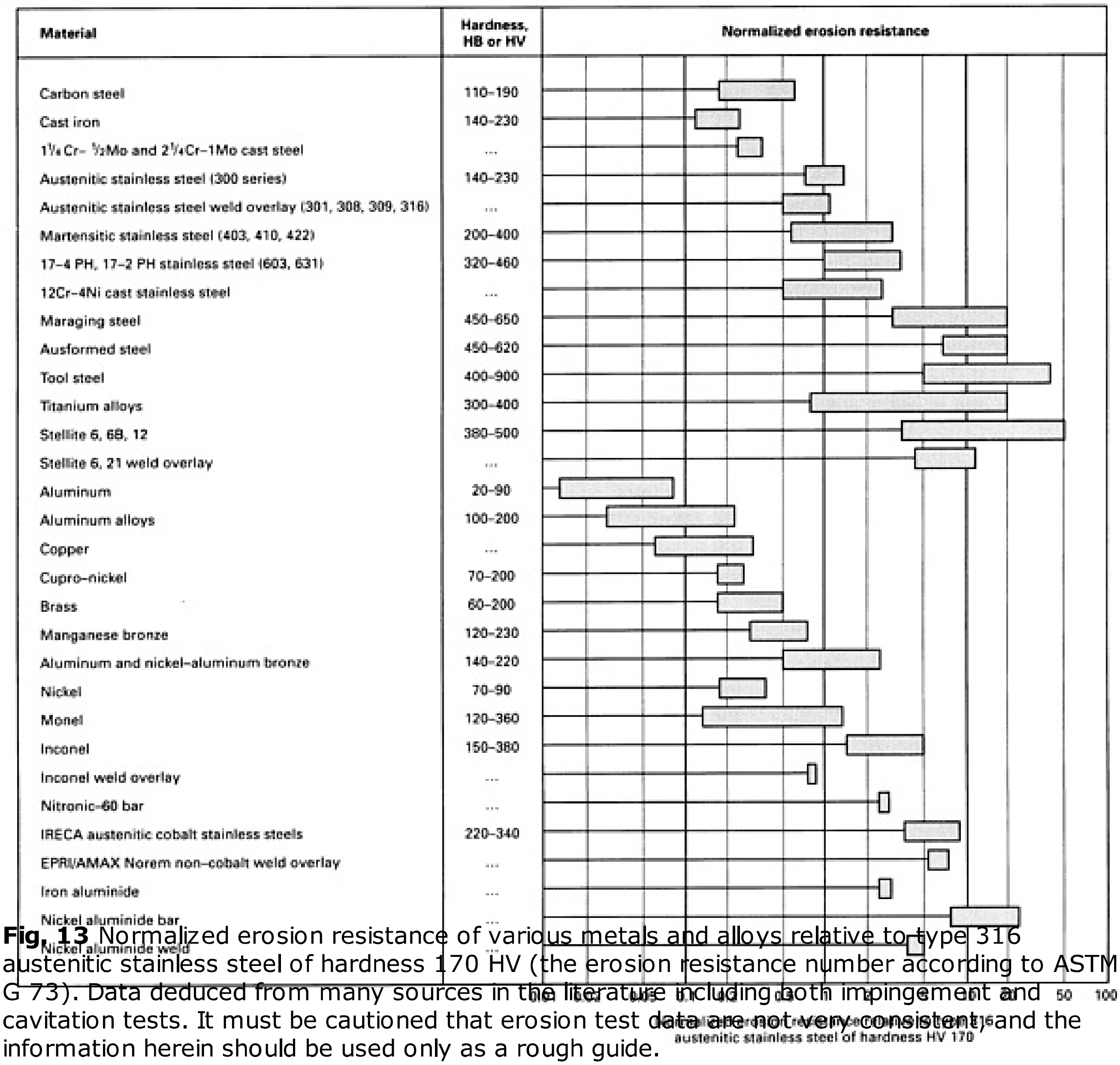

Fig. 13 Normalized erosion resistance of various metals and alloys relative to type 316 austenitic stainless steel of hardness 170 HV (the erosion resistance number according to ASTM G 73). Data deduced from many sources in the literature including both impingement and cavitation tests. It must be cautioned that erosion test data are not very consistent, and the information herein should be used only as a rough guide.

Shielding or cladding approaches for erosion protection have usually employed a harder layer than the base material, or one that by virtue of its composition or microstructure is more resistant to erosion (and corrosion). However, another approach that can be successful in low-intensity environments is the use of elastomeric coatings, which, by virtue of their elasticity, reduce the magnitude of the impact pressures; this approach is widely used against rain erosion at moderate speeds.

Table 1 lists some of the materials and coatings used for rain erosion applications, in order of preference as specified by Schmitt (Ref 25).

Table 1 Materials in use for rain erosion protection

"Recommended" as well as "not recommended" materials are listed in order of preference or resistance. "Not recommended" materials may have good erosion resistance but other undesirable properties such as poor shock resistance.

Materials for aircraft radomes	
Recommended	**Not recommended**
Elastomeric coatings:	
Polyurethane Fluorocarbon Neoprene	Silicone Acrylic Polyester
Bulk plastics:	
Modified polyphenylene oxide Polycarbonate Polyethylene Polyacetal Nylon Modified acrylic	Tetrafluoroethylene Polyimide Epoxy Acrylonitrile-butadiene-styrene (ABS)
Reinforced composites:	
Glass cloth reinforced epoxy Filament wound glass epoxy Quartz cloth reinforced epoxy	Chopped glass reinforced epoxy or polyester Kevlar-epoxy

Materials for missile radomes	
Recommended	**Not recommended**
Monolithic ceramics:	
Hot-pressed silicon nitride Alumina Beryllia Cordierite Reaction-sintered silicon nitride	Slipcast fused silica Boron nitride
Reinforced ceramics:	
1-D celcon polyacetal silica Alumina cloth-silica matrix 3-D reinforced silica-silica	. . .

Materials for optical and infrared domes	
Recommended	**Not recommended**
Glasses and ceramics:	
Sapphire Spinel Calcium aluminosilicate Calcium borosilicate Magnesium fluoride Clear fused silica	. . .
Chalcogenides:	
Germanium Zinc sulfide Gallium arsenide Zinc selenide	. . .

Source: Ref 25

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