Standard Test Method for
Liquid Impingement Erosion Using Rotating Apparatus[1]

This standard is issued under the fixed designation G73; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (´) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers tests in which solid specimens are eroded or otherwise damaged by repeated discrete impacts of liquid drops or jets. Among the collateral forms of damage considered are degradation of optical properties of window materials, and penetration, separation, or destruction of coatings. The objective of the tests may be to determine the resistance to erosion or other damage of the materials or coatings under test, or to investigate the damage mechanisms and the effect of test variables. Because of the specialized nature of these tests and the desire in many cases to simulate to some degree the expected service environment, the specification of a standard apparatus is not deemed practicable. This test method gives guidance in setting up a test, and specifies test and analysis procedures and reporting requirements that can be followed even with quite widely differing materials, test facilities, and test conditions. It also provides a standardized scale of erosion resistance numbers applicable to metals and other structural materials. It serves, to some degree, as a tutorial on liquid impingement erosion.

1.2 The values stated in SI units are to be regarded as standard. The inch-pound units in parentheses are provided for information.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D1003 Test Method for Haze and Luminous Transmittance of Transparent Plastics
E92 Test Method for Vickers Hardness of Metallic Materials
E140 Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness
E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
E179 Guide for Selection of Geometric Conditions for Measurement of Reflection and Transmission Properties of Materials
G1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens
G32 Test Method for Cavitation Erosion Using Vibratory Apparatus
G40 Terminology Relating to Wear and Erosion
G134 Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet

2.2 *Military Standards:*[3]

MIL-C-83231 Coatings, Polyurethane, Rain Erosion Resistance for Exterior Aircraft and Missile Plastic Parts
MIL-P-8184 Plastic Sheet, Acrylic, Modified

3. Terminology

3.1 See Terminology G40 for definitions of terms that are not defined below in either 3.2 or 3.3. Definitions appear in 3.2 that are taken from Terminology G40 for important terms related to the title, Scope, or Summary of this test method. Definitions of Terms Specific to this Test Method are given in 3.3 that are not in Terminology G40.

3.2 *Definitions*—All definitions listed below are quoted from Terminology G40–05 (some modified).

3.2.1 *cumulative erosion-time curve*, *n—in cavitation and impingement erosion,* a plot of cumulative erosion versus cumulative exposure duration, usually determined by periodic

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interruption of the test and weighing of the specimen. This is the primary record of an erosion test. Most other characteristics, such as the incubation period, maximum erosion rate, terminal erosion rate, and erosion rate-time curve, are derived from it.

3.2.2 *damage*, *n—in cavitation or impingement*, any effect on a solid body resulting from its exposure to these phenomena. This may include loss of material, surface deformation, or any other changes in microstructure, properties, or appearance.

3.2.2.1 *Discussion*—This term as here defined should normally be used with the appropriate modifier, for example, "cavitation damage," "liquid impingement damage," "single-impact damage," and so forth.

3.2.3 *incubation period*, *n—in cavitation and impingement erosion*, the initial stage of the erosion rate-time pattern during which the erosion rate is zero or negligible compared to later stages.

3.2.3.1 *Discussion*—The incubation period is usually thought to represent the accumulation of plastic deformation and internal stresses under the surface hat precedes significant material loss. There is no exact measure of the duration of the incubation period. See related term, *nominal incubation period* in 3.3.9.

3.2.4 *liquid impingement erosion*, *n—*progressive loss of original material from a solid surface due to continued exposure to impacts by liquid drops or jets.

3.2.5 *maximum erosion rate*, *n—in cavitation and liquid impingement*, the maximum instantaneous erosion rate in a test that exhibits such a maximum followed by decreasing erosion rates. (See also *erosion rate–time pattern*.)

3.2.5.1 *Discussion*—Occurrence of such a maximum is typical of many cavitation and liquid impingement tests. In some instances it occurs as an instantaneous maximum, in others as a steady-state maximum which persists for some time.

3.2.6 *normalized erosion resistance,* N_e, *n—*a measure of the erosion resistance of a test material relative to that of a specified reference material, calculated by dividing the volume loss rate of the reference material by that of the test material when both are similarly tested and simliarly analyzed. By "similarly analyzed" is meant that the two erosion rates must be determined for corresponding portions of the erosion rate-time pattern; for instance, the maximum erosion rate or the terminal erosion rate.

3.2.6.1 *Discussion*—A recommended complete wording has the form, "The normalized erosion resistance of (test material) relative to (reference material) based on (criterion of data analysis) is (numerical value)."

3.2.7 *normalized incubation resistance,* N_0, *n—in cavitation and liquid impingement erosion*, the nominal incubation period of a test material, divided by the nominal incubation period of a specified reference material similarly tested and similarly analyzed. (See also *normalized erosion resistance*.)

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *apparatus severity factor, F*—an empirical factor that accounts for the systematic differences between rationalized erosion rates (or rationalized incubation periods) as determined for the same material and impact velocity in different facilities.

It reflects variations in test conditions not accounted for by the data reduction procedures of this test method.

3.3.2 *erosion resistance number,* NER—the normalized erosion resistance of a test material relative to a standardized scale, calculated from test results with one or more designated reference materials as described in this test method. See also *reference erosion resistance* (3.3.12).

3.3.3 *exposed surface (or area)*—that surface (or area) on the specimen nominally subjected to liquid impingement.

(1) For "distributed impact tests," it is generally to be taken as the projected area of the exposed surface of the specimen on a plane perpendicular to the direction of impingement. However, if a plane specimen surface is deliberately oriented so as to obtain impingement at an oblique angle, then the actual plane area is used.

(2) For "repetitive impact tests," it is to be taken as the projected area of the impinging liquid bodies on the specimen, the projection being taken in the direction of relative motion.

3.3.3.1 *Discussion*—In practice, it is usually found that the damaged area in repetitive impact tests is greater than the exposed area as defined above, but the above definition is adopted not only for simplicity but also for consistency between some of the other calculations for distributed and repetitive tests.

3.3.4 *impingement rate,* U_i $[LT^{-1}]$—the volume of liquid impinging per unit time on a unit area of exposed surface; for a plane target surface it is given by c *V* cos u.

3.3.5 *incubation impingement,* H_0 [L]—the mean cumulative impingement corresponding to the nominal incubation period; hence, impingement rate times nominal incubation time.

3.3.6 *incubation resistance number,* NOR—the normalized incubation resistance of a test material relative to a standardized scale, calculated from test results with one or more designated reference materials as described in this test method. See also reference incubation resistance (3.3.13).

3.3.7 *incubation specific impacts,* N_0—same as rationalized incubation period.

3.3.8 *mean cumulative impingement, H* [L]—the cumulative volume of liquid impinged per unit area of exposed surface; impingement rate times exposure time.

3.3.9 *nominal incubation period,* t_0—the intercept on the time or exposure axis of the straight-line extension of the maximum-slope portion of the cumulative erosion-time curve; while this is not a true measure of the incubation stage, it serves to locate the maximum erosion rate line on the cumulative erosion versus exposure coordinates.

3.3.10 *rationalized erosion rate,* R_e—volume of material lost per unit volume of liquid impinged, both calculated for the same area.

3.3.11 *rationalized incubation period,* N_0—the duration of the nominal incubation period expressed in dimensionless terms as the number of specific impacts; hence, the specific impact frequency times incubation time. (Also referred to as "incubation specific impacts.")

3.3.12 *reference erosion resistance,* S_{er}—a normalized erosion resistance, based on interlaboratory test results, assigned to a specified reference material in this test method so as to

constitute a benchmark in the "erosion resistance number" scale. The value of unity is assigned to 316 stainless steel of hardness 155 to 170 HV.

3.3.13 *reference incubation resistance, S_{or}*—a normalized incubation resistance, based on interlaboratory test results, assigned to a specific reference material in this test method so as to constitute a benchmark in the "incubation resistance number" scale. The value of unity is assigned to 316 stainless steel of hardness 155 to 170 HV.

3.3.14 *specific impacts, N*—the number of impact stress cycles of damaging magnitude experienced by a typical point on the exposed surface, or an approximation thereof as estimated on the basis of simplified assumptions as described in this test method. (This concept has sometimes been termed "impacts per site.")

3.3.15 *specific impact frequency, f_i* $[T^{-1}]$—the number of specific impacts experienced per unit time, given by $(a/b)\, U_i$.

3.3.16 *volume concentration, c*—the ratio of the volume of liquid to the total volume in the path traversed or swept out by the exposed area of the specimen.

3.3.17 *volume mean diameter* $[L]$—in a population of drops of different sizes, the diameter of a sphere whose volume equals the total volume of all drops divided by the total number of drops.

3.4 Symbols:

A = exposed area of specimen, m^2,
a = projected area of impinging drop or jet, m^2,
b = volume of impinging drop or jet, m^3,
d = diameter of impinging drop or jet, m,
F_0 = apparatus severity factor for incubation,
F_e = apparatus severity factor for erosion rate,
f_i = specific impact frequency, s^{-1},
H = mean cumulative impingement, m,
H_0 = incubation impingement, m,
N_0 = number of specific impacts for incubation, or "rationalized incubation period," dimensionless,
NER = erosion resistance number,
NOR = incubation resistance number,
n = number of jets or drops impacting on exposed surface of specimen in one revolution,
Q_e = volumetric erosion rate, m^3/s,
R_e = "rationalized erosion rate," (dY/dH), dimensionless,
S_e = normalized erosion resistance (relative to a specified reference material),
S_{er} = reference erosion resistance,
S_0 = normalized incubation resistance (relative to a specified reference material),
S_{or} = reference incubation resistance,
t = exposure time, s,
t_0 = nominal incubation time, s,
U_e = linear erosion rate (dY/dt), m/s = Q_e/A,
U_i = impingement rate (dH/dt), m/s,
U_r = rainfall rate, m/s,
U_t = terminal velocity of drops in falling rainfield, m/s,
V = impact velocity of drop or jet relative to specimen, m/s,
V_n = component of impact velocity normal to specimen surface, m/s,

Y = mean depth of erosion, m,
u = angle of incidence—the angle between the direction of impacting drops and the normal to the solid surface at point of impact,
c = volume concentration of liquid in rainfield or in space swept through by specimen, and
V = rotational speed of specimens, rev/s.

3.5 Except in equations where different units are expressly specified, the use of SI units listed in 3.4, or any other *coherent* system of units, will make equations correct without the need of additional numerical factors. When referring to quantities in text, tables, or figures, suitable multiples or submultiples of these units may, of course, be used.

4. Summary of Test Method

4.1 Liquid impingement tests are usually, but not always, conducted by attaching specimens to a rotating disk or arm, such that in their circular path they repeatedly pass through and impact against liquid sprays or jets (Sections 6 and 7). Standard reference materials (Section 8) should be used to calibrate the apparatus and included in all test programs.

4.2 Data analysis begins by establishing a cumulative erosion-time curve from measurements of mass loss (or other damage manifestation) periodically during the tests (Section 9). These curves are then characterized by specified attributes such as the nominal incubation time and the maximum erosion rate (Section 10).

4.3 For comparative materials evaluations, the results are normalized (Section 10) with respect to the standard reference materials included in the test program. A standardized scale of "erosion resistance numbers" is provided for structural bulk materials and coatings (10.4.3). For more in-depth analysis of the results, the incubation times or erosion rates are expressed in dimensionless "rationalized" forms that are based on more physically meaningful exposure duration variables than clock time as such (Section 11).

4.4 The information to be given in the report depends on the objectives of the test (Section 12).

5. Significance and Use

5.1 *Erosion Environments*—This test method may be used for evaluating the erosion resistance of materials for service environments where solid surfaces are subjected to repeated impacts by liquid drops or jets. Occasionally, liquid impact tests have also been used to evaluate materials exposed to a cavitating liquid environment. The test method is *not* intended nor applicable for evaluating or predicting the resistance of materials against erosion due to solid particle impingement, due to "impingement corrosion" in bubbly flows, due to liquids or slurries "washing" over a surface, or due to continuous high-velocity liquid jets aimed at a surface. For background on various forms of erosion and erosion tests, see Refs (1) through (7).[4] Ref (6) is an excellent comprehensive treatise.

5.2 *Discussion of Erosion Resistance*—Liquid impingement erosion and cavitation erosion are, broadly speaking, similar

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[4] The boldface numbers in parentheses refer to a list of references at the end of this standard.

processes and the relative resistance of materials to them is similar. In both, the damage is associated with repeated, small-scale, high-intensity pressure pulses acting on the solid surface. The precise failure mechanisms in the solid have been shown to differ depending on the material, and on the detailed nature, scale, and intensity of the fluid-solid interactions (Note 1). Thus, "erosion resistance" should not be regarded as one precisely-definable property of a material, but rather as a complex of properties whose relative importance may differ depending on the variables just mentioned. (It has not yet been possible to successfully correlate erosion resistance with any independently measurable material property.) For these reasons, the consistency between relative erosion resistance as measured in different facilities or under different conditions is not very good. Differences between two materials of say 20 % or less are probably not significant: another test might well show them ranked in reverse order. For bulk materials such as metals and structural plastics, the range of erosion resistances is much greater than that of typical strength properties: On a normalized scale on which Type 316 stainless steel is given a value of unity, the most resistant materials (some Stellites and tool steels) may have values greater than 10, and the least resistant (soft aluminum, some plastics) values less than 0.1 (see Refs (**7**) and (**8**)).

N$_{OTE}$ 1—On failure mechanisms in particular, see in Ref (**6**) under "The Mechanics of Liquid Impact" by W. F. Adler, "Erosion of Solid Surfaces by the Impact of Liquid Drops" by J. H. Brunton and M. C. Rochester, and "Cavitation Erosion" by C. M. Preece.

5.3 *Significance of the Variation of Erosion Rate with Time*:

5.3.1 The rate of erosion due to liquid impact or cavitation is not constant with time, but exhibits one of several "erosion rate-time patterns" discussed more fully in 10.3.3. The most common pattern consists of an "incubation period" during which material loss is slight or absent, followed by an acceleration of erosion rate to a maximum value, in turn followed by a declining erosion rate which may or may not tend to a "terminal" steady-state rate. The significance of the various stages in this history can differ according to the intended service applications of the materials being tested. In almost no case, however, are significant results obtained by simply testing all materials for the same length of time and comparing their cumulative mass loss.

5.3.2 The "incubation period" may be the most significant test result for window materials, coatings, and other applications for which the useful service life is terminated by initial surface damage even though mass loss is slight.

5.3.3 For bulk materials, this test method provides for determination of the "nominal incubation period" as well as the "maximum erosion rate," and material ratings based on each. Empirical relationships are given in Annex A2 by which the nominal incubation period and the maximum erosion rate can then be estimated for any liquid impingement conditions in which the principal impingement variables are known. It must be emphasized, however, that because of the previously described variation of erosion rate with exposure time, the above-mentioned parameters do not suffice to predict erosion for long exposure durations. Extrapolation based on the maximum erosion rate could overestimate the absolute magnitude of long-term cumulative erosion by a factor exceeding an order of magnitude. In addition, it could incorrectly predict the relative difference between long-term results for different materials.

5.3.4 Because of these considerations, some experimenters concerned with long-life components may wish to base material ratings not on the maximum erosion rate, but on the lower "terminal erosion rate" if such is exhibited in the tests. This can be done while still following this test method in many respects, but it should be recognized that the terminal erosion rate is probably more strongly affected by secondary variables such as test specimen shape, "repetitive" versus "distributed" impact conditions, drop size distributions, and so forth, than is the maximum erosion rate. Thus, between-laboratories variability may be even poorer for results based on terminal erosion rate, and the test time required will be much greater.

5.4 This test method is applicable for impact velocities ranging roughly from 60 m/s to 600 m/s; it should not be assumed that results obtained in that range are valid at much higher or lower velocities. At very low impact velocities, corrosion effects become increasingly important. At very high velocities the material removal processes can change markedly, and specimen temperature may also become a significant factor; testing should then be done at the velocities corresponding to the service environment.

5.5 *Related Test Methods*—Since the resistances of materials to liquid impingement erosion and to cavitation erosion have been considered related properties, cavitation erosion Test Methods G32 and G134 may be considered as alternative tests to this test method for some applications. For metals, the relative results from Test Method G32 or G134 should be similar but not necessarily identical to those from a liquid impact test (see 5.2). Either Test Method G32 or G134 may be less expensive than an impingement test, and provides for standardized specimens and test conditions, but may not match the characteristics of the impingement environment to be simulated. The advantages of a liquid impingement test are that droplet or jet sizes and impact velocities can be selected and it can simulate more closely a specific liquid impingement environment. A well-designed liquid impingement test is to be preferred for elastomers, coatings, and brittle materials, for which size effects may be quite important.

6. Apparatus

6.1 This test method is applicable principally to those erosion test devices in which one or more specimens are attached to the periphery of a rotating disk or arm, and their circular path passes through one or more liquid jets or sprays, causing discrete impacts between the specimen and the droplets or the cylindrical surface of the jets (Note 2). Fig. 1 and Fig. 2 show two representative devices of very different size and speed that participated in the interlaboratory study referred to in Section 13, though that in Fig. 2 is no longer in service. Considerations relating to the specimens and their attachment are covered in Section 7.

N$_{OTE}$ 2—Some representative rotating apparatus are described in Ref (**2**) by Ripken (pp. 3–21) and Hoff et al (pp. 42–69); in Ref. (**3**) by Elliott et al (pp. 127–161) and Thiruvengadam (pp. 249–287); and by A. A. Fyall in "Radome Engineering Handbook," J. D. Walton, editor, Marcel Dekker, Inc., New York, NY, 1970, pp. 461–572.
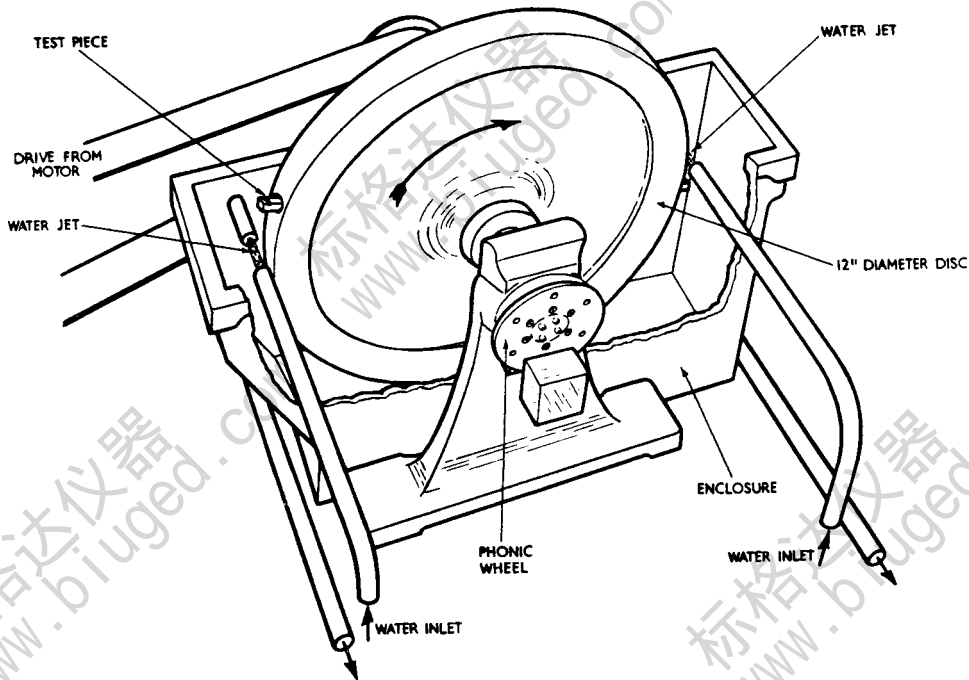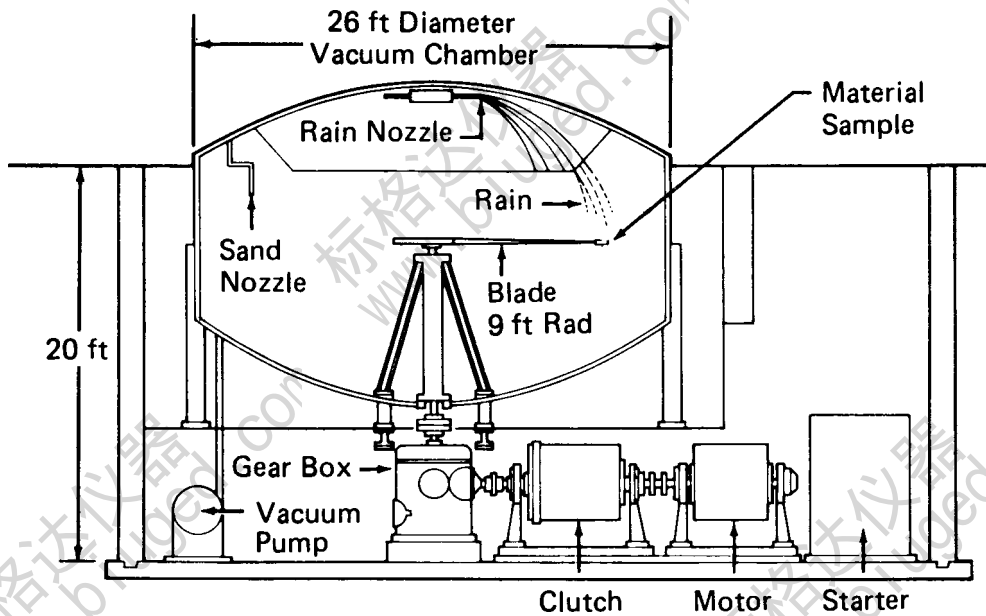
FIG. 1 Example of a Small, Relatively Low-Speed, Rotating Disk-and-Jet Repetitive Impact Apparatus (Courtesy of National Engineering Laboratory, East Kilbride, Scotland, UK)

NOTE—This specific apparatus is not longer in service.

FIG. 2 Example of a Large, High-Speed, Rotating Arm-and-Spray Distributed Impact Apparatus (Courtesy of Bell Aerospace TEXTRON, Buffalo, NY)

6.2 A distinction is made between "distributed impact tests" and "repetitive impact tests." Devices using sprays or simulated rainfields fall into the first category, and most using jets into the second.

NOTE 3—Repetitive impact tests, as compared to distributed impact tests, generally provide much higher specific impact frequencies and have higher severity factors (see 6.5), thus producing erosion more rapidly at equal impact velocities. However, because the damage is localized at a line or point on the specimen, the topography and progress of damage differs somewhat from that in distributed impact tests or under most typical service conditions.

6.3 Test devices of the types described above have been built for peripheral velocities (and hence impact velocities) from about 50 m/s to as high as 1000 m/s. The higher velocities pose considerable difficulties relating to power requirements,

aerodynamic heating and noise, and balancing. Partial evacuation of the test chamber may be required. At the intended operating speeds it should be possible to maintain the speed steady within 0.5 %, and to measure it within 0.1 %.

6.4 Droplet or jet diameters have ranged from around 0.1 mm to about 5 mm. Droplets may be generated by spray nozzles, vibrating hollow needles, or rotating disks with water fed onto their surface. The typical droplet or jet diameter, and the volume of liquid actually impacting the specimen per unit time, should be determined within 10 %. For jets, the diameter can usually be assumed to equal the nozzle diameter. However, photographic verification is desirable since jets may exhibit instabilities under some conditions. With drops, there will usually be a size distribution, and in most cases it will be necessary to determine that distribution by photography and analysis of the photographs. Some drop-generating techniques, such as vibrating needles, provide more uniform drop sizes than sprays. For a single-number characterization, the volume mean diameter should be used, so as to obtain the correct relationship between total volume and total number of drops. Ideally, the apparatus should be characterized by the drop population per unit volume in the path traversed by the specimen, and the repeatability thereof, as a function of test settings. From this, the impingement rate and specific impact frequency, needed for Section 11, can then be readily determined.

6.5 Even when erosion test results are "rationalized" (see Section 11) by taking into account the amount of liquid impacting the specimen, there will still be systematic differences from one apparatus to another. These are represented by the "apparatus severity factors," which can be calculated from test results by equations given in 11.5, and can be estimated in the design stage as shown in Annex A2. This can help in planning an apparatus suitable for the type of materials to be tested and in predicting the required test times.

6.6 For repetitive impact tests using jets and plane specimens, care should be taken to ensure that the erosion track is of uniform width and depth, and that undue erosion is not occurring at a specimen edge. This may require appropriate angular alignment of the specimen.

6.7 For both repetitive and distributed impact tests, care should be taken to ensure that the jet or spray can reconstitute itself between successive passages of a specimen. Otherwise the actual amount and shape of liquid impinging may be considerably different from that assumed.

6.8 There are other types of liquid impact erosion-test devices besides those described above. Some research investigations have been made with "liquid gun" devices, in which a short discrete slug of liquid is projected out of a nozzle against a target specimen. Both single-shot and repetitive-shot versions of this type exist. For tests at very high impact velocities, specimen-carrying rocket sleds passing through an artificial rain field have been used (Note 4). On the laboratory scale, there are linear test devices in which a specimen carrier is projected against a stationary suspended droplet or other liquid body. Some of the provisions of this test method may be applied to these tests and their reports also.

Note 4—Typical "liquid gun" apparatus are described in Ref (1) by

deCorso and Kothmann (pp. 32–45) and Brunton (pp. 83–98); in Ref (4) by Rochester and Brunton (pp. 128–151); and in Ref (5) by Field et al (pp. 298–319). Rocket sled tests are described by Schmitt in Ref (3) (pp. 323–352) and in Ref (5) (pp. 376–405).

Note 5—It is *not* feasible to accelerate droplets to adequately high velocities by entrainment in a fast-moving stream of gas or vapor, because the droplets are likely to be broken up into such smaller sizes that their damage potential is slight.

7. Test Specimens

7.1 Specimens may present a curved (airfoil or cylindrical) or a flat surface to the impinging liquid. The shape chosen may depend on the test objectives, such as whether a particular prototype geometry is to be simulated. It should be recognized, however, that a curved profile will result in a variation of the normal component of impact velocities, impact angles, and impingement rates over the exposed surface, and a variation in the extent of damaged area as the test proceeds.

7.2 Specimens may be machined from solid bar, cut from sheet, or consist of a coating applied to a standardized substrate, any of which may be attached over a supporting structure. Specimens and their attachment provisions should be designed to facilitate the repeated removal, cleaning, and weighing of the specimens. The specimen should fit only one way and be located by positive stops, or other provisions for repeatable alignment shall be used. (**Warning**—Specimen holders or attachment methods should be designed to minimize localized stressing of the specimen due to centrifugal or clamping forces, especially when weak or brittle materials are to be tested.)

7.3 If specimens are machined from bulk or bar material, the final cuts should be light to avoid work-hardening of the surface, which may have a significant effect on the incubation period. Surface roughness should be in the range from 0.4 to 1.6 µm (16 to 63 µin.) rms, as obtained by fine machining or medium grinding, unless there is a specific reason for choosing another value. In that case, it should be reported.

7.4 If the specimen is formed from sheet material, or is a coating, it should be recognized that wave reflection from the interface with the backup or base material may affect results. Care should be taken that sheet materials are properly supported. Deposited coatings should have the thickness to be used in service, or the thickness must be considered a test variable.

7.5 The performance of elastomeric coatings will depend on the application technique and on the substrate. Unless the effect of technique is being investigated, each coating should be applied using its manufacturer's recommended technique, including whatever surface preparation, curing method, and post-application conditioning are specified. Two types of substrates are recommended: (*1*) a substrate identical in construction to that of the end use item on which the coating is to be used (this type of specimen will enable investigation of coating/substrate interactions under liquid impact), and (*2*) a standardized substrate (such as a glass-epoxy laminate, a graphite-epoxy composite, or an aluminum alloy) so that relative ranking and resistance of the coating may be determined.

8. Reference Materials; Apparatus Calibration

8.1 In any test whose objective is the determination of the erosion resistance properties of test materials, at least *two* of the reference materials listed in 8.3 shall be included in the test program. This serves the dual purpose of providing a reference for calculating relative or normalized resistance values of the test materials, and for calculating the "severity factors" of the facility. For the second purpose, metallic reference materials are always used. Annex A1 gives some of the properties of the metallic reference materials and their nominal "reference erosion resistance" values to be used in these calculations. The data analysis procedures for determining normalized erosion resistance are specified in Section 10. Optional procedures for determining "Apparatus Severity Factors" are given in Section 11.

8.2 The choice of the reference materials should be based on the expected erosion resistance of the materials to be evaluated. The greater the difference between test material and reference material, the poorer is the consistency of the normalized results among different laboratories.

8.3 *Reference Materials*:

8.3.1 *For Metals and Other High-Resistance Materials*:

8.3.1.1 Aluminum 1100-0.

8.3.1.2 Aluminum 6061-T6.

8.3.1.3 Nickel, 99.98 % pure, annealed.[5]

8.3.1.4 Stainless Steel Type AISI 316, of hardness 155-170 HV.

8.3.1.5 (See Annex A1 for properties from interlaboratory test.)

8.3.2 *For Plastics, Ceramics, and Window Materials*—One of the metals specified, plus:

8.3.2.1 Poly (methyl methacrylate)—(*PMMA*), conforming to MIL-P-8184, Type II, Class 2 (as cast).[6]

8.3.3 *For Reinforced Plastic and Composite Materials*—One of the metals specified, plus one of the following:

8.3.3.1 Glass-Epoxy Laminate (E-Glass, Style 181 fabric Epon 828 epoxy resin), without gel coating.

8.3.3.2 Poly (methyl methacrylate) (*PMMA*), conforming to MIL-P-8184,[6] as cast.

8.3.4 *For Elastomers* (*as coatings*)—One of the metals specified, plus:

8.3.4.1 Polyurethane, sprayed, in accordance with MIL-C-83231.

8.3.4.2 Uncoated Substrate (glass-epoxy laminate, aluminum, or other materials as above).

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[5] Nickel 270 was used in the interlaboratory test for this test method, as well as for the first (1967–68) interlaboratory test for Test Method G32, but it may no longer be available. Nickel 200 (containing 99 % Ni) was substituted for the second (1990–91) interlaboratory test for Test Method G32. It proved to have an erosion resistance about 40 % higher, and incubation resistance about 65 % higher, than Ni 270.

[6] Plexiglas 55, conforming to MIL-P-8184, obtained from Rohm and Haas Co., was used widely as a reference material at the time this test method was first developed, but it may no longer be available and is not on the Qualified Product List for MIL-P-8184. The sole source of supply known to the committee at this time is Acrivue 352, available from Swedlow, Inc., 12122 Western Ave., Garden Grove, CA 92641. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

9. Test Procedures

9.1 *Introduction*:

9.1.1 Since the test procedures for different types of material differ to some extent, separate sections are provided below for structural materials and coatings (9.2), elastomeric coatings (9.3), window materials (9.4), and transparent thin-film coatings on window materials (9.5). A generalized cleaning and drying procedure is given in 9.6 for eroded specimens where retained moisture may be a problem.

9.1.2 Unless otherwise specified, at least three specimens shall be tested for each test variation (that is, for a given material at a given test condition).

9.1.3 A common requirement in most of these test procedures is that the test must be interrupted periodically for the specimen to be removed for cleaning, drying, and weighing or other damage evaluation. In those cases where the time required for these steps is much greater than the time of actual testing (as may be true for elastomeric coatings and other nonmetallic specimens), an acceptable alternative procedure is to test a series of identical specimens, each for a different length of uninterrupted exposure, to obtain one synthesized test record. This option is to be taken as implied in the subsequent sections.

9.1.4 When damage is determined by mass loss measurements, repeat the cleaning, drying, and weighing operations until two successive weighings yield identical (or acceptably similar) readings, unless prior qualification of the cleaning procedure has proved such repetition unnecessary.

9.2 *Test Procedure for Structural Bulk Materials and Coatings*:

9.2.1 This section applies to specimens representative of structural materials and systems for which the loss of material and consequent change of shape and size is of primary concern. This includes metals, structural plastics, structural composites, metals with metallic or ceramic coatings, and so forth. The applicable portions of this section may be followed for the other classes of materials if mass loss is also of interest.

9.2.2 The primary test result to be obtained for each specimen is a cumulative erosion-versus-time curve, generated by periodically halting the test, removing and weighing the specimen, and recording the cumulative mass loss and the corresponding volume loss versus cumulative exposure time. All other characterizations relating to erosion rates and erosion resistance properties are derived analytically from these curves. The following paragraphs detail the procedure. In addition, photographs, or topographic and metallographic observations of the eroded surface, as well as hardness measurements, and so forth., may be taken, when more detailed information is desired on development of the damage.

9.2.3 Begin with a specimen newly machined and prepared in accordance with Section 7. Conduct a hardness test, preferably at a location near but not on the surface actually exposed to erosion. For metallic materials, to facilitate comparisons, the (equivalent) Vickers hardness number should be determined. Test Method E92 or Tables E140 may be applicable. Clean and dry the specimen carefully, and determine its mass on a balance with precision and accuracy of 1 mg or less. For the initial cleaning of metallic specimens, scrubbing with a bristle brush

or nonabrasive cloth and a suitable volatile solvent is recommended. For nonmetallic specimens, consult the manufacturer for preferred cleaning methods.

9.2.4 Install the specimen in the test apparatus. Bring the apparatus up to stable operating speed first, set any other environmental conditions, then turn on the water flow and record the time.

9.2.5 After a predetermined time interval, turn off the water flow, record the time, and bring the apparatus to rest. Remove the specimen carefully, clean and dry it, and determine its new mass on a balance as before. For cleaning eroded metallic specimens, use the procedure suggested in 9.2.3, unless there is evidence of corrosion also being present, in which case an

applicable procedure from Practice G1 is recommended. If retained water or water deposits may pose a problem, follow 9.6.

9.2.6 Calculate the cumulative exposure time, the cumulative mass loss, divide by the material density to obtain the corresponding cumulative volume loss, tabulate these values and plot the cumulative volume loss versus exposure time on a test record chart.

9.2.7 Repeat steps 9.2.4 through 9.2.6 at least until the incubation period and maximum erosion rate have been clearly established and the erosion rate has begun to decline. It is recommended that the test be continued until a straight line can be drawn through the origin and tangent to the cumulative
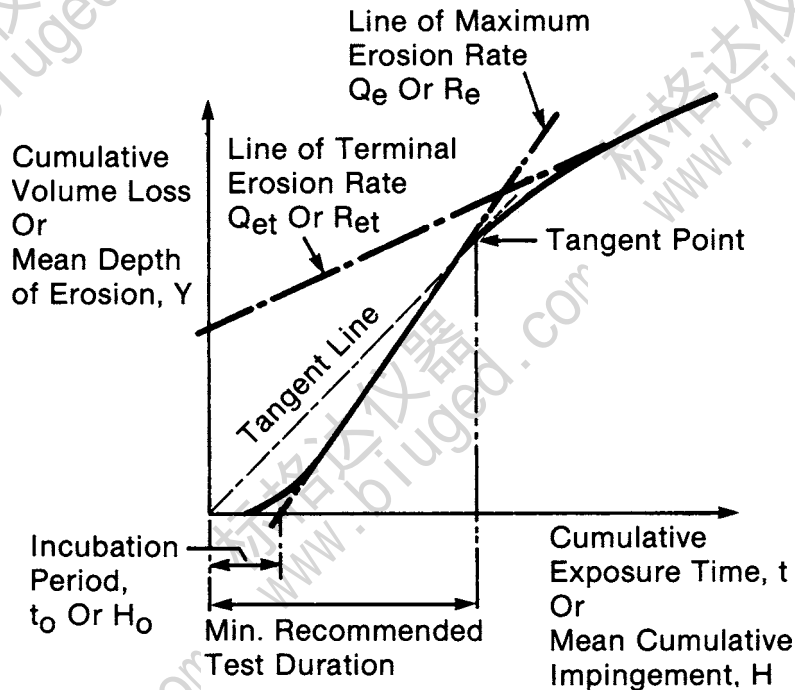
(a) Cumulative Erosion-Time Curve
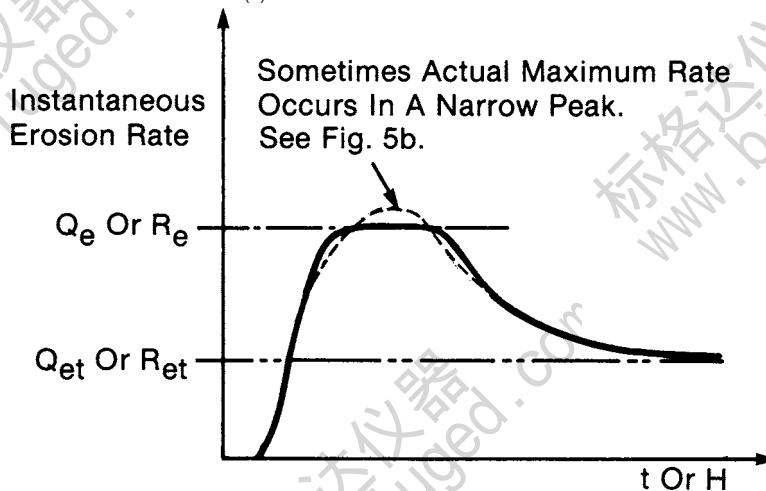
(b) Erosion Rate–Time Curve (Derivative of Cumulative Erosion–Time Curve)

FIG. 3 Typical Erosion–Time Pattern and Parameters Used to Quantify It

erosion-time curve (see Fig. 3). Optionally, the test may be continued longer in order to investigate long-term erosion behavior and to determine whether a terminal erosion rate is established. (Comparative material evaluations may be based on the terminal erosion rate; see 10.3.5.) (**Warning**—Erosion should not be allowed to progress beyond a maximum depth exceeding the width of the actual area of damage; this applies particularly to repetitive impact tests.)

9.2.8 The time intervals between successive mass determinations should be short enough so that the erosion rate-time pattern can be discerned, and the nominal incubation period and the maximum erosion rate graphically established to an accuracy of 10 %. Trial and error may be required. For metals, the following equation may be used as an initial guideline; it corresponds to one third of the estimated incubation time based on (Eq A2.1):

$$Dt = 10 \sim H_v!^2 K_m / [f_i \sim V/100!^{4.9}\# \tag{1}$$

where:
Dt = estimated time interval, s,
H_v = Vickers hardness of material, HV,
V = impact velocity, m/s,
f_i = specific impact frequency, s^{-1}, and
K_m = factor ranging from 0.3 for materials of poor resistance in relation to hardness to 3.0 for materials of superior resistance in relation to hardness.

9.2.9 At the conclusion of the test determine the actual area over which significant erosion has occurred. Since this may require some subjective judgment, sketches or photographs may be used to clarify and to document that determination.

9.3 *Test Procedure for Elastomeric Coatings*:

9.3.1 The primary test result to be obtained for each specimen is exposure time to failure. These results are obtained *either* by continuously monitoring the condition of the coatings during the exposure by a viewing system (such as a stroboscopic light and closed-circuit television or periscope arrangement) or by periodically stopping the test and examining the condition of the coating. Failure shall be defined as penetration of the coating to the substrate either by general erosion of the coating surface until the substrate is exposed, pinpoint holes through the coating, or adhesion loss of the elastomeric layer from the substrate. Mass loss measurements may be desired for certain bulk elastomer materials or even very thick coatings where rapid failure to the substrate is unlikely. Follow applicable portions of 9.2.

9.3.2 Begin with a new specimen prepared in accordance with 7.5. Inspect the specimen to assure that the coating surface is free of defects that would accelerate its failure.

9.3.3 Install the specimen in the test apparatus. Bring the apparatus up to stable operating speed first, set any other environmental conditions, then turn on the water flow and record the time.

9.3.4 After continuous exposure (desirable with elastomers, although not absolutely essential) during which the specimen is observed, terminate the test when the substrate is exposed by erosion of the coating, adhesion loss, or other damage. If observation capability is not available, the test should be run for a predetermined time and then shut down to inspect the coating for failure. In either case, turn off the water flow, record

the time, and bring the apparatus to rest. Remove the specimen carefully, and determine whether failure to the substrate has indeed occurred. If mass loss measurements are to be made, clean and dry it in accordance with 9.6.

9.3.5 For tests of laminate and composite substrate materials, it is necessary to inspect the specimens after test to determine if damage has occurred to the substrate even though the coating has remained intact. Examples of substrate damage include pulverization of the resin matrix or reinforcing fibers, delamination between layers of cloth fabric reinforcement in laminates, or crushing of thin-wall constructions.

9.3.6 Repeat steps 9.3.3 through 9.3.5 if necessary until the failure point has been established. The time intervals between successive determinations should be short enough so that the erosion failure time can be established to an accuracy of 20 % or better. Trial and error may be required.

9.3.7 At the conclusion of the test, determine the actual area over which significant erosion or damage has occurred.

9.3.8 At least four and preferably six coated specimens shall be tested for each test variation.

9.4 *Test Procedure for Window Materials*:

9.4.1 The primary test results to be obtained for each specimen are cumulative transmission curves over the wavelength region appropriate for the end-use application, as a function of exposure time. These curves are generated by periodically halting the test, removing and drying the specimen, making transmission measurements limited to the exposed area by an appropriate method (for example, Test Method D1003) over the wavelength region of interest, and recording the transmission-versus-cumulative exposure time. It is important that successive transmission measurements are made through the same portion of the specimen. Care should be taken to avoid transmission measurements through areas containing large cracks which may be associated with mounting of the specimen in the apparatus (that is, edge or corner cracks). Concurrent mass loss measurements are recommended as a way of further characterizing the damage of the material. Follow applicable portions of 9.2 for mass loss determinations.

9.4.2 It has been found that some materials exhibit considerable transmission loss during the incubation period (before significant mass loss) while others will begin to lose mass and still retain transmissive properties. A combination of the transmission curves and erosion curves provides a required characterization of the erosion resistance of these materials.

9.4.3 Begin with a specimen newly machined, polished, and prepared in accordance with Section 7. Conduct a pretest transmission coefficient measurement at the appropriate wavelengths through the portion of the specimen to be exposed to the erosive environment. The precision and accuracy of this measurement should be within 61 %.

9.4.4 Install the specimen in the test apparatus. Bring the apparatus up to stable operating speed first, set any other environmental conditions, then turn on the water flow and record the time.

9.4.5 After a predetermined time interval, turn off the water flow, record the time, and bring the apparatus to rest. Remove the specimen carefully, clean and dry it in accordance with 9.6, and measure its new transmission coefficient. Tabulate, and

plot either transmission coefficient or transmission loss, and volume loss (see 9.2.6), versus exposure time on a test record chart.

9.4.6 Repeat steps 9.4.4 and 9.4.5 at least until the material has lost its transmission properties completely or to a specified nonfunctional level. If the material retains its transmission characteristics and erosion mass loss governs its performance, follow 9.2.7.

9.4.7 The time intervals between successive transmission or mass determinations should be short enough so that the transmission loss-versus-time curve, the erosion rate-time pattern, the incubation period and the maximum erosion rate can be graphically established to an accuracy of 10 % or better. Trial and error may be required.

9.5 *Test Procedures for Transparent Thin Film Coatings on Window Materials*:

9.5.1 This section applies to transparent thin film coatings such as anti-reflection coatings, conductive coatings, and abrasion-resistant or other protective coatings. The damage measurements to be made may comprise transmission loss for anti-reflection coatings, loss of conductivity for conductive coatings, and visual determination of the extent of removal of protective coatings (for example, abrasion-resistant coatings on polycarbonate). Test Method D1003 or Guide E179 may be applicable.

9.5.2 Begin with a fully coated specimen machined, polished, and prepared so that the coating has no obvious areas of adhesion loss to the substrate and otherwise in accordance with Section 7. Conduct pretest transmission, conductivity, or visual inspection measurements on the exposed surface of the specimen. The precision and accuracy of transmission and conductivity measurements should be within 61 %.

9.5.3 Install the specimen in the test apparatus, taking care not to scratch through the coating. Bring the apparatus up to stable-operating speed first, set any other environmental conditions, then turn on the water flow and record the time.

9.5.4 After a predetermined time interval, turn off the water flow, record the time, and bring the apparatus to rest. Remove the specimen carefully, clean and dry it by 9.6 or an appropriate method, and repeat the appropriate measurements to determine damage. Tabulate these results (or the change from original measurements, if preferred) and plot versus exposure time on a test record chart. The observation of protective coating removal should be done microscopically to determine the size of areas of removed coating, percentage of total surface area where coating has been removed, and manner of coating removal (total removal of the substrate or removal by layers). Overlaying a grid can assist in size and percentage removal determination, but this should be done only after any transmission or conductivity measurements.

9.5.5 Repeat steps 9.5.3 and 9.5.4, at least until the material has lost its transmission, or conductivity, properties completely or to a predetermined nonfunctional level, or some other specified criterion of failure has been met.

9.5.6 The time intervals between successive transmission, conductivity, or removal determinations should be short enough so that the transmission loss-versus-time curve, conductivity change-versus-time curve, and coating removal pattern, can be graphically established to an accuracy of 20 % or better. Trial and error may be required. In some cases, coating removal may be very rapid and because of the thinness of these coatings, difficult to observe.

9.6 *General Cleaning and Drying Procedure for Eroded Specimens*:

9.6.1 Measurements of mass loss and of transmission or reflectivity properties of an eroded specimen may be affected both by deposited minerals from the impinging drops and by retained liquid in the erosion pits. It is important, therefore, to remove these, particularly for specimens of relatively low density. Composite materials and certain plastics have been found especially susceptible to water retention. This section specifies a general procedure recommended for such materials; some laboratories apply such a procedure routinely for all types of specimens.

9.6.2 After the specimen is removed from the apparatus, it should be cleaned of any water-deposited residue by gentle scrubbing or by immersion in a low-intensity ultrasonic cleaning bath, provided this can be done without disturbing or further damaging the eroded surface, and then dried in a forced-air oven. A relatively low temperature of 50°C (125°F) is recommended for those materials (such as plastics, organic resin composites, and elastomeric coatings) that might be adversely affected by higher temperatures. It is essential that the drying be long enough to drive off all accumulated moisture in the eroded surface. An appropriate drying time may be determined by measurements on a balance until there is no change in mass between successive measurements. Also, equilibrium moisture condition is indicated by absence of either mass gain or mass loss while specimen is resting on a balance of high sensitivity (0.01 mg). Overnight drying for 16 h has been found satisfactory for most specimens.

9.6.3 For dried small specimens, handling with plastic gloves, metal tweezers, or tongs is recommended. Manual handling of specimens during installation and removal in the test apparatus is unavoidable but care should be taken to minimize handling as much as possible. After drying as described in 9.6.2, some materials, specimens may need to be desiccated as they cool for a period of time (typically 1 h) to ensure no pickup of water during cooling. Calcium carbonate is a suggested desiccant.

10. Calculation of Erosion Resistance

10.1 *Introduction*:

10.1.1 With the present state of the art, it is not possible to define "absolute" erosion resistance parameters, or even to identify the dimensions of such a parameter or the units in which it should be expressed. This comes from the lack of any accepted complete physical model for relating erosion performance to material parameters and major variables describing the impingement conditions. Therefore, most investigators resort to comparative evaluations of different materials. The purpose of this section is to specify standardized approaches for calculating and presenting relative or normalized measures of erosion resistance for the different classes of materials considered.

10.1.2 Since damage due to liquid impingement does not progress linearly with time, it is first necessary to provide

standardized approaches for quantitative representation of the time-dependent test data. One generalized approach is given in 10.2. More specific approaches for material loss characteristics are given in 10.3 through 10.4, and for other types of damage in 10.5 through 10.7.

10.1.3 Almost all quantities associated with erosion—for example, erosion rates and incubation periods of different materials, or at different velocities, or in different facilities—range over many orders of magnitude and exhibit a high variability. For this reason, all calculations of means and of standard deviations, and other statistical evaluations, should be performed on the *logarithms* of the physical quantities, rather than on the quantities themselves. (If this were not done, it would often be found that the standard deviation is of similar magnitude to the mean, leading to the logically absurd inference that the physical quantities in question range from positive to negative.) Note that this procedure yields the *geometric means* of the physical quantities. Also note that the standard deviation on the logarithmic scale is by its very nature a *relative* measure of variability, and therein resembles the "coefficient of variation" on the physical scale.

10.2 *Evaluation Based on Time-To-Failure*:

10.2.1 In some investigations it may be possible to test each specimen until a condition is reached that corresponds to the end of useful life in the intended service application. A suitable criterion of this condition might be a specified mean depth of erosion, a specified maximum penetration, any penetration of a coating, or a specified limiting value of transmission coefficient. In such cases, the test results are characterized by the cumulative exposure time to reach the failure condition. Normalized erosion resistance values, relative to a specified reference material, are expressed simply as the ratio of the time-to-failure of the test material to the time-to-failure of the

reference material. For this approach, the test conditions—impact velocities and drop sizes—should be as close as possible to those expected in service. While in principle this approach could be used for all kinds of erosion tests, in practice it may not always be feasible and not as informative as alternative approaches described below.

10.2.2 If this approach is chosen, the test report shall clearly so state and shall specify the criterion of failure used. The results should not be used to evaluate the materials with respect to any other criterion of failure.

10.3 *Quantitative Representation of Test Results for Material Loss*:

10.3.1 This section describes the minimum steps required to represent test results of material loss, for the purpose of comparing or ranking the performance of different materials. Additional data analysis required to put the results into "rationalized" form for more basic investigations is described in Section 11.

10.3.2 For each test material, including the reference materials, plot the cumulative volumetric erosion versus time, showing the original data points. Replicate tests should be plotted on the same sheet, using different symbols. For the purposes of this section it does not matter what units are used to represent material volume loss and exposure duration, so long as the same are used for all materials. It is not necessary to draw a complete curve through the points.

10.3.3 *Erosion Rate–Time Patterns*—As previously noted, the rate of erosion does not normally remain constant during a test. It is likely that each specimen will exhibit an erosion "rate–time pattern" somewhat like one of the cumulative erosion–time curves of Fig. 4. Curve A represents the most common or "well-behaved" erosion rate–time pattern, and most of the data analysis procedures given in this test method
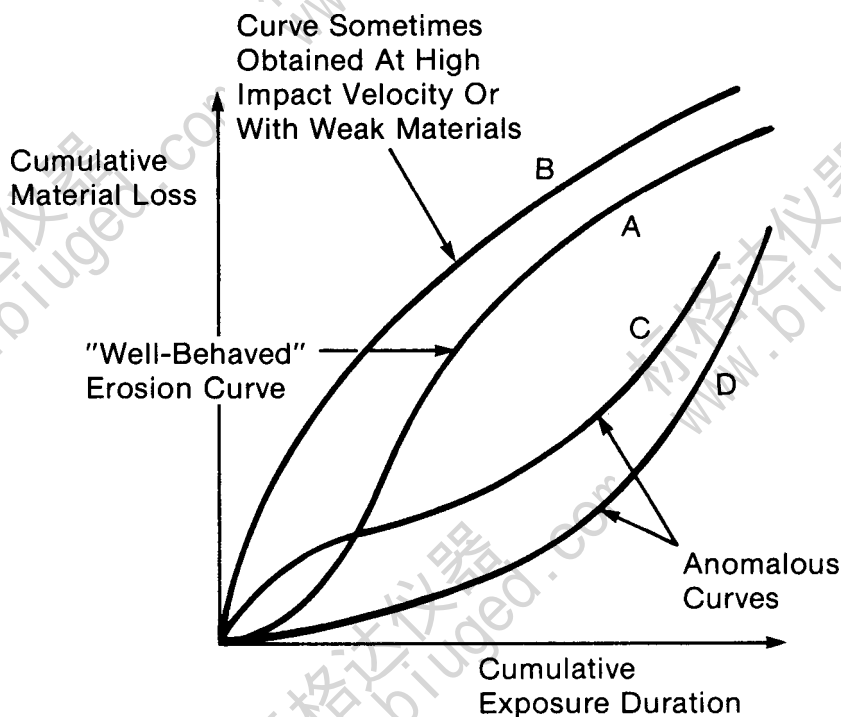

FIG. 4 Well-Behaved and Anomalous Cumulative Erosion–Time Curves

apply to this type of curve. Some erosion tests—particularly at high impact velocities—do not appear to have an incubation stage, and look like curve B in Fig. 4. This may be because of excessive time intervals between test points; or because the impact velocity is high enough so that each single impact removes material and no incubation period exists. It is recommended that the absence of an incubation stage be verified by testing at least one specimen with shorter time intervals between mass determinations. If indeed there is no incubation period, results of such tests can be represented by the maximum erosion rate (see 10.3.4) or terminal erosion rate (see 10.3.5). Occasionally anomalous behavior such as curves C or D may be obtained. This may indicate a brittle material with poor erosion behavior, or a problem with the apparatus. Only the method of 10.2 can be used with such results.

10.3.4 *Representation by Nominal Incubation Period and Maximum Erosion Rate*—This is the preferred evaluation method for this test method, and applies primarily to results similar to Curve A of Fig. 4. Results similar to Curve B can also be included as special cases, characterized by only their maximum erosion rate. For each specimen, draw a straight line that best represents the maximum rate stage of the test. In some cases, the test points will very nearly fall along or scatter about a straight line (Fig. 5a). In other cases, the points may suggest an S-shaped curve, such that a maximum slope is exhibited only at one point or very fleetingly (Fig. 5b). In the latter case, the extreme maximum slope may not be a good representation of the results, and a recommended procedure is to draw a straight "effective line" through the maximum slope point, such that the maximum deviation between that line and the actual curve does not exceed 1/10th of the ordinate of the upper intercept of the "effective line" and the actual curve. The results for each specimen are then described by two parameters: *(1)* the maximum volumetric erosion rate (Q_e), given by
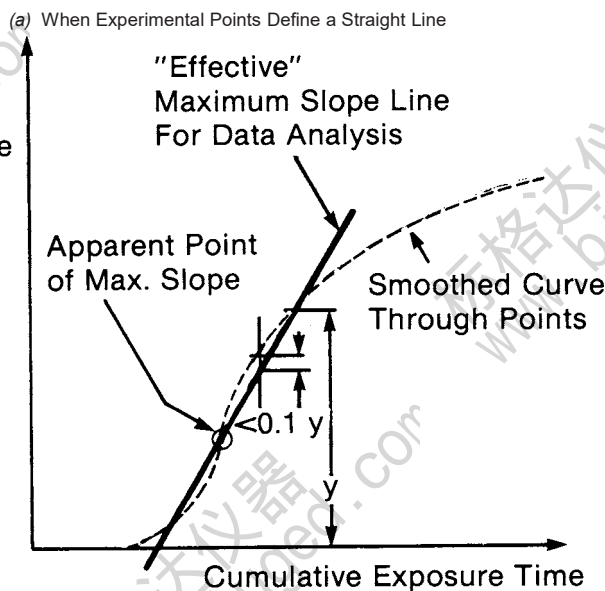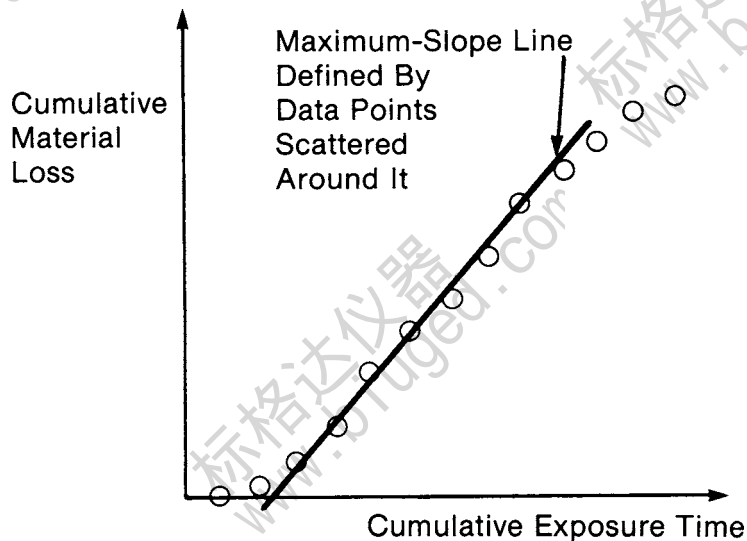
(a) When Experimental Points Define a Straight Line

(b) When Experimental Points Define An S-Shaped Curve

FIG. 5 Procedures for Drawing Maximum-Slope Lines

the slope of the actual or effective straight line defined above, and *(2)* the nominal incubation period (t_0), given by the intercept of that line on the horizontal or exposure axis.

10.3.5 *Representation by Terminal Erosion Rate*—For applications in which the expected useful life extends well beyond the maximum erosion rate period, into the deceleration period and terminal period, comparative evaluations may be based on the "terminal erosion rate" if the tests are continued for a sufficiently long exposure time and a steady-state terminal erosion rate is exhibited. Draw a straight line passing through the test points representative of the terminal stage, or a straight line in which the test points appear to approach asymptotically.

Designate the slope of this line by Q_{et}. Calculate normalized erosion resistance values by (Eq 2), using Q_{et} instead of Q_e for both test material and reference material.

Note 6—Material comparisons based on this assume that the early erosion history, including maximum erosion rate period, is insignificant compared to the later stages. For a more complete representation, the intercept of the terminal-rate line on the *Y*-axis, or its intersection with the maximum-rate line, would also have to be characterized. This test method at present offers no recommended approach for quantitative representation of the complete erosion–time pattern or its prediction under service operation from test results under different impingement conditions. See also comments in 5.3.4.

10.3.6 For replicate tests, calculate the geometric mean of the above defined parameters. (If the ratio of the maximum to minimum values is less than 1.5, the arithmetic rather than geometric means may be used; the difference between them will be less than 2 %.)

10.4 *Normalization of Test Results*:

10.4.1 The results for different materials may be normalized in one of two ways: either by direct comparisons relative to one of the designated reference materials similarly tested (see 10.4.2), or by indirect comparisons relative to a standardized reference scale (see 10.4.3).

10.4.2 *Direct Normalization*—Assume that *r* represents one of the designated reference materials from 8.3 included in the test program, and that its results at given test conditions are Q_{er} and t_{0r}. Let the corresponding results for test material *x* at the same test conditions be Q_{ex} and t_{0x}. Then the following relationships apply.

Normalized erosion resistance of *x* relative to *r*:

$$S_{ex/r} = Q_{er}/Q_{ex} \qquad (2)$$

Normalized incubation resistance of *x* relative to *r*:

$$S_{0x/r} = t_{0x}/t_{0r} \qquad (3)$$

10.4.3 *Standardized Scale for Erosion Resistance Numbers*:

10.4.3.1 The purpose of the standardized scale is twofold: firstly, to provide one generalized numerical scale for erosion resistance properties, and secondly, to help average out some of the variabilities and inconsistencies in erosion testing by using more than one reference material to normalize test results. The scale is based on the "reference values" of erosion and incubation resistance for the designated reference materials, given in Annex A1. The relative magnitudes were established by regression analysis of the results of an interlaboratory test involving ten laboratories (see Ref 9), and were given an absolute level by assigning the value of unity to stainless steel Type 316.

10.4.3.2 Assume that, in a given test program, *k* of these reference materials were included, and that the results, all at the same test conditions, for test material *x* and reference materials *i* (*i* = 1, 2, ... *k*) are:

Q_{ex} = maximum erosion rate for test material *x,*
Q_{ei} = maximum erosion rate for reference material *I,*
t_{0x} = nominal incubation period for test material *x,*
t_{0i} = nominal incubation period for reference material *I,*
S_{eri} = reference erosion resistance for reference material *i,*
S_{0ri} = and reference incubation resistance for reference material *i.*

where the S_{eri} and S_{0ri} values are obtained from Annex A1. Then the "erosion resistance number" NER and the "incubation resistance number" NOR of material *x* are calculated as follows:

$$\log (NER) = \left[\sum_{i=1}^{k} (\log Q_{ei} + \log S_{eri}) \right]/k - \log Q_{ex} \qquad (4)$$

$$\log (NOR) = \left[\sum_{i=1}^{k} (\log S_{0ri} - \log t_{0i}) \right]/k + \log t_{0x} \qquad (5)$$

10.4.3.3 This procedure yields a geometric mean of the several values that would be obtained by use of only one reference material at a time. Such averaging is desirable because the relative erosion resistances of the reference materials, as tested in a particular laboratory, probably will not coincide with their relative resistances from Annex A1. Experience shows that no two erosion tests will in general give identical relative results among different materials. The above procedure is intended to minimize the resulting discrepancy.

10.4.4 If comparative sets of tests are conducted at more than one operating condition (for example, impact velocity), normalized erosion properties according to 10.4.2 or 10.4.3 should be calculated individually for each condition. Combined normalized properties may then be calculated by taking the geometric means of the individual normalized properties for all conditions, providing the same stage of erosion (usually maximum erosion rate) has been reached by all materials.

10.5 *Elastomeric Coatings*—For elastomeric coatings, the performance in time-to-failure (or mass loss where appropriate) is gaged relative to a baseline-coating material (typically MIL-C-83231 polyurethane). Presentation of the data can take the form of bar charts which compare the relative erosion resistance of various coatings. If the failure times are determined as a function of coating thickness or of the exposure parameters, then performance envelopes can be established for these coatings. Typically variations in time to failure will be about 10 to 15 % within any particular coating substrate combination exposed to any particular environmental condition.

10.6 *Window Materials*—For window materials where transmission change is a key description of response to the erosive environment, the transmission of the unexposed material is taken as a baseline. This may also be expressed as a relative percentage transmission at a particular wavelength compared to air (no window material) or to another reference material at the same wavelength. The transmission change as

an absolute value (as measured in a spectrophotometer) or as a ratio of material transmission to reference material transmission is then plotted versus exposure time. If determinations are made as a function of different exposure parameters (velocity, drop size, impingement angle, and rain intensity), then sets of transmission performance curves can be developed to establish performance envelopes. For example, percent transmission loss at a given wavelength per unit time exposure with other variables as parametric variations could be obtained.

10.7 *Thin-Film Coatings on Window Materials*—For thin-film coatings on window materials, the transmission or conductivity of the unexposed coated material is taken as baseline. The change in transmission or conductivity or the areal removal percentage as an absolute value or as a ratio of eroded material to reference material is then plotted versus exposure time. Performance envelopes could be developed as a function of exposure parameters.

11. Expressing Test Results in Rationalized Terms, and Determining Apparatus Severity Factors

11.1 *Purpose*—If the only purpose of the tests is to determine the relative erosion resistance of the materials tested, then the normalized results calculated according to Section 10 may suffice. However, if it is desired to make quantitative comparisons between results from different impingement conditions, or to develop empirical models, or to verify theoretical predictions, then individual test results (incubation time and maximum erosion rate) must be expressed in terms of rational physically meaningful variables. The variables proposed in this method are therefore termed rationalized incubation period (see 11.4) and rationalized erosion rate (see 11.3). Both are dimensionless, so that their magnitude is a pure number independent of the measurement units chosen. In order to compute both, it is necessary to plot the cumulative erosion–time curve on coordinates of mean depth of erosion versus mean cumulative impingement, or to make suitable conversions from results plotted differently (see 11.2). The paragraphs below discuss how these variables should be determined. Finally, these results can also be used to assign severity factors to the test facility (see 11.5).

11.2 *Preliminary Calculations*:

11.2.1 *Mean depth of erosion (Y)* is calculated by dividing the cumulative volume loss from 9.2.6 by the exposed area as defined in 3.3.

11.2.2 *Mean cumulative impingement (H)* is calculated by multiplying the cumulative exposure time by the impingement rate (U_i) as defined in 3.3 and calculated according to 11.2.3 or in some other appropriate manner.

11.2.3 *Impingement rate* (U_i) is basically defined by:

$$U_i = V \, n \, b/A \qquad (6)$$

where symbols are defined in 3.4. For repetitive jet impact tests, b is the volume of that portion of the jet which impacts upon the exposed surface of the specimen and has a projected area equal to *A*. For distributed impact tests, impingement rate is often more conveniently calculated by (Eq 7) below:

$$U_i = c \, V \cos u \qquad (7)$$

Volume concentration (c) may be determined by photographic or sampling methods, or calculated from the spray

characteristics, or from rainfall rate as shown in 11.2.4. If the specimen is cylindrical or airfoil–shaped, U_i as calculated above will of course vary over its surface. For a single-number nominal value, the angle variation is ignored and cos u assumed equal to unity.

11.2.4 If the rainfall rate U_r is known, and if the drops can be assumed to have reached terminal velocity U_t, the volume concentration c is given by:

$$c = U_r/U_t \qquad (8)$$

The terminal velocity U_t can be measured photographically, or calculated theoretically. Fyall **(10)** gives a curve of U_t versus *d,* for normal atmospheric conditions. In the range of *d* from 0.1 to 3 mm, it may be approximated by:

$$U_t = 4.0 \, d^{0.56} \qquad (9)$$

where *d* is the drop diameter in mm and U_t the velocity in m/s. From this we obtain:

$$c = \frac{U_r}{1.44 \times 10^7 \, d^{0.56}} \qquad (10)$$

with U_r in mm/h and *d* in mm.

11.3 *Rationalized Erosion Rate (R_e)*—This corresponds simply to the slope of the maximum rate line (as described in 10.3.4) on the coordinates as described in 11.1. Alternatively, it can be calculated as follows:

$$R_e = U_e/U_i = Q_e/~U_iA! \qquad (11)$$

where symbols are defined in 3.4.

11.4 *Rationalized Incubation Period (N_0)*:

11.4.1 The rationalized incubation period represents the nominal number of "specific impacts," or stress cycles "felt" by any typical point on the exposed surface, during the nominal incubation time.

11.4.2 For repetitive impact tests, the number of impacts is, by definition, the same on all points of the exposed surface as defined in 3.3, and is directly countable or calculable from the time duration, the rotational speed, and the number of impacts per revolution. However, the definitions of relevant variables are so chosen that the same value should be obtained by application of the relationships given for distributed impact tests below.

11.4.3 For distributed impact tests, it is assumed that impacts are uniformly distributed over the exposed surface. Then the number of "specific impacts" felt by a typical point on a surface is equal to the total number of impacts occurring on the surface, multiplied by the area of influence of each impact, and divided by the surface area. For the purposes of this test method, we define the nominal area of influence of an impact as the projected area of the impacting liquid body. The following relationships then hold:

$$N_0 = f_i t_0 = ~a/b! \, U_i t_0 = ~a/b! \, H_0 \qquad (12)$$

where *(a/b)* = (projected area divided by volume) of impacting drops or jets. (For drops, *a/b* = 3/2d; for jets, *a/b* = 4/p*d*.) Other symbols are defined in 3.4.

NOTE 7—In reality, the area directly subjected to high impact pressures is considerably smaller than the projected area of the impacting liquid bodies and is a function of impact velocity. However, stress waves radiate out from the impact zone both along the surface and into the material, and

in addition damaging effects are believed to occur as a result of lateral outflow of liquid from the impact zone. Since all of these phenomena are extremely complicated and not fully understood, the definition adopted is believed to be a practical approximation. Furthermore, since for repetitive impact the nominal area of influence of impacts and the nominal exposed area of the specimen are then identical, the number of "specific impacts" thus reduces to the actual number of impacts on the specimen, as it logically should.

11.5 *Apparatus Severity Factors*:

11.5.1 The concept of apparatus severity factors is based on the findings from Ref **(9)** that, for a given test material and impact velocity, even the "rationalized" results differed widely between different test facilities, but that these differences (expressed as ratios) were relatively consistent and therefore presumably reflect system variables not accounted for in the simple rationalized results. (Such variables can include whether drops or jets are impacting, the drop or jet size, the specimen shape, radius arm to the specimen and hence centrifugal acceleration at the impact point, the impact frequency, ambient pressure, and others. These variables will help to determine, for instance, if any or how much water is retained on the specimen surface from one impact to the next.) In the interlaboratory test results, facility severity factors ranged approximately from 0.3 to 3.0 for erosion rate, and from 0.5 to 2.0 for incubation period. Regression analysis resulted in empirical prediction equations involving severity factors (see Annex A2), which can be used to infer apparatus severity factors from test results on reference materials as described below. Annex A2 also gives empirical expressions for estimating severity factors from some of the variables stated in this section.

11.5.2 *Apparatus Severity Factor for Incubation Period (F_0)*—A single measure of F_0 is obtained from the relation:

$$\log F_0 \; 5 \; \log S_{0r} \; 2 \; \log N_0 \; 2 \; 4.90 \; \log V \; 1 \; 16.24 \qquad (13)$$

where S_{0r} = "Reference Incubation Resistance" of the reference material tested, from Annex A1. An averaged measure is determined from several test results (different reference materials and different impact velocities) by calculating individual values of $(\log F_0)$ from the above equation, taking their arithmetic mean, and then taking the antilog of that.

11.5.3 *Apparatus Severity Factor for Erosion Rate (F_e)*—A single measure of F_e is obtained from the relation:

$$\log F_e \; 5 \; \log S_{er} \; 1 \; \log R_e \; 2 \; 4.80 \; \log V \; 1 \; 16.31 \qquad (14)$$

where S_{er} = "Reference Erosion Resistance" of the reference material tested, from Annex A1. An averaged measure is determined in the same way as described in 11.5.2 for F_0.

12. Report

12.1 The amount of information to be reported depends, of course, on the objectives of the test and on whether the results are presented in a technical paper, a research report, or a material evaluation report. The minimum requirements for the last-mentioned will be indicated in the lists below by an asterisk.

12.2 *Information on Apparatus, Specimen, and Method*:

12.2.1 General description; shape of specimen carrier,*

12.2.2 Number of specimens carried,*

12.2.3 Radius of specimen attachment,*

12.2.4 Method of attachment of specimen,

12.2.5 Shape and size of specimen (including whether exposed surface is flat or rounded),*

12.2.6 Exposed area of specimen,*

12.2.7 Form of impinging liquid (whether jets, droplets, or sprays),*

12.2.8 Method of generation of liquid,

12.2.9 Distance from origin of liquid particles to point of impact with specimen, and

12.2.10 Cleaning and drying procedure used before each weighing.

12.3 *Information on Test Conditions*:

12.3.1 Normal impact velocity,*

12.3.2 Nominal angle of incidence (angle between normal to the specimen surface and its direction of motion),*

12.3.3 Absolute velocities of specimen and of liquid, respectively,

12.3.4 Mean diameter of the impacting liquid jets or droplets,*

12.3.5 Size distribution curve of droplets,

12.3.6 Volume concentration of liquid in the path of the specimen,

12.3.7 Specific impact frequency (based on volume mean drop diameter for sprays or rainfields),

12.3.8 Ambient pressure and temperature in test chamber,*

12.3.9 Temperature of the liquid, and of target if important,

12.3.10 If the liquid is not water, its identification, density, acoustic velocity, and viscosity,* and

12.3.11 Observation, if possible, of whether the specimen retains liquid on its surface between successive impacts.

12.4 *Information on Test and Reference Materials*:

12.4.1 Designation or identification,*

12.4.2 Composition,*

12.4.3 Density or specific gravity,*

12.4.4 Type of material stock used and method of specimen manufacture and preparation,*

12.4.5 Heat treatment, if any, before and after specimen preparation,*

12.4.6 Hardness,*

12.4.7 Engineering ultimate tensile strength,

12.4.8 True ultimate tensile strength,

12.4.9 Elongation and reduction of area in tension test, and

12.4.10 Surface roughness on exposed surface (* if outside of range specified in 7.3).

12.5 *Information on Test Results*:

12.5.1 Tabulation of mean values of nominal incubation period, maximum erosion rate (and if applicable the terminal erosion rate) for each test variation (material and operating condition) in original units.*

12.5.2 The above data converted into rationalized form according to Section 11.

12.5.3 Either the individual results for each specimen of replicate tests, or number of replicate specimens tested and the standard deviation of results for each test variation.*

12.5.4 The cumulative erosion-versus-time curve for each test variation, on coordinates of original units.

12.5.5 The same as above, but on rationalized coordinates (mean depth of erosion versus mean height of impingement).

12.5.6 Normalized erosion properties as calculated in accordance with Section 10. Each tabulation of normalized results shall state clearly whether based on time-to-failure, on incubation period, on maximum erosion rate, or on terminal erosion rate.*

12.5.7 Facility severity factors calculated according to Section 11.

12.5.8 Erosion rate-time curves.

12.5.9 Qualitative description of erosion rate-time pattern. See 10.3.3; also, definition in Terminology G40.*

12.6 *Statement of Compliance*—A statement, if correct in all essentials, that this test method was followed; or, in case of partial compliance, a statement describing the deviations from this test method or listing the sections that were followed.

13. Precision and Bias

13.1 *Introduction*—Some statistics relating to precision were obtained from the interlaboratory test described in Ref **(9)** and Appendix X1. Because of the wide variations in capability and conditions among the different laboratories, it was not possible to design the test program or to analyze the results from a rigorous statistical viewpoint as described in Practice E177. (Even the materials tested were not identical, because some laboratories required bar stock and others sheet stock, which had different properties.) Thus, the results given below should be considered as approximate and tentative. A different set of test data might well yield different results.

13.2 *Repeatability*—Among replicate tests (same laboratory, same impact velocity, same test material) in the interlaboratory test program, the standard deviation on the logarithmic scale was typically about 0.05, which corresponds approximately to a coefficient of variation of 12 % on the arithmetic scale.

13.3 *Reproducibility*—An approximate measure of reproducibility was obtained in this study by calculating the standard deviations of the normalized results (expressed on the logarithmic scale) for each material relative to Nickel 270. Nickel 270

was chosen as the reference material because it provided the greatest number of direct comparisons for normalization. Ideally, the variabilities for different impact velocities at the same laboratory and for different laboratories at the same impact velocity might be determined separately, but there were not enough data for that. Therefore, each direct comparison between Nickel 270 and another material (both tested in the same laboratory at the same velocity) was considered as one observation. The results are tabulated as follows:

Material	Number of Observations	Standard Deviation on Log Scale	
		for S_e	for S_o
Aluminum 1100-0	4	0.319	0.275
Aluminum 6061-T6	11	0.115	0.157
Stainless steel type 316	8	0.135	0.099
"Pooled" estimate for all materials		0.168	0.165

Note that the variability tends to increase as the resistance of the test material deviates more from that of the reference material. The "pooled" estimate for all three materials, a standard deviation s of 0.165 on the logarithmic scale, corresponds to a "scatter ratio" on the arithmetic scale (defined by 10^{2s}) of 2.14. *That is, about 60 % of normalized results for the same test material agree within a factor of 2.* This demonstrates that erosion resistance is not an accurately-determinable property. (Note that absolute results, even when "rationalized," will vary even more between laboratories because of different severity factors.)

13.4 *Bias*—No statement can be made regarding bias, because there is no absolute definition or measurement of erosion resistance. Erosion tests measure only relative results between different materials, and these can differ according to the test method or test conditions employed.

14. Keywords

14.1 droplet impact; erosion; erosion by liquids; erosion resistance; erosion test; liquid impact; liquid impingement; rain erosion; rotating arm apparatus

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ANNEXES

(Mandatory Information)

A1. PROPERTIES OF REFERENCE MATERIALS

A1.1 Table A1.1 presents the measured properties of the materials used in the interlaboratory test program described in Appendix X1.

TABLE A1.1 Properties of Reference Materials[A]

Material	Aluminum 110 0-0	Aluminum 6061-T6	Nickel[B] 99.98 %	Stainless Steel AISI 316
Hardness, HV	24–29	95–115	68–82	155–175
Ultimate tensile strength, MPa (ksi)	90 (13)	310–330 (45–48)	340–370 (49–53)	550–600 (80–87)
Elongation, %	39–46	12–20	50–62	49–63
Reduction of area, %	50–80	27–35	60–90	56–77
Specific gravity	2.7	2.7	8.9	7.8
"Reference Erosion Resistance" (S_{er})	0.04	0.08	0.5	1.0[C]
"Reference Incubation Resistance" (S_{or})	0.005	0.05	0.2	1.0[C]

[A] These are the measured properties of the materials used in the interlaboratory test program described in Appendix X1.
[B] INCO "Nickel 270" was used in the interlaboratory test.
[C] Arbitrarily assigned reference base.

A2. GENERALIZED PREDICTION EQUATIONS FOR SEVERITY FACTORS, NOMINAL INCUBATION PERIOD AND MAXIMUM EROSION RATE, ADAPTED FROM REF (9):

A2.1   The following equation have been adapted from **(9)**:

$$\log N_0 = \log NOR - 4.90 \log V + 16.24 - 2 \log F_0 \quad (A2.1)$$

$$\log R_e = 4.80 \log V - 2 \log NER - 16.31 + \log F_e \quad (A2.2)$$

In the above, F_0 and F_e represent "severity factors" for the environment or the apparatus for which the prediction is made. Their values can be *estimated* by:

$$\log F_0 = 0.40 J - 0.16 \quad (A2.3)$$

$$\log F_e = 0.67 \log d + 0.57 J - 0.22 K - 0.34 \quad (A2.4)$$

A2.2 Other symbols are defined below:

N_0 = rationalized incubation period,
R_e = rationalized maximum erosion rate,
NER = " erosion resistance number" of material,
  NOR = "incubation resistance number" of material,
V = impact velocity, m/s,
d = diameter of drops or jets, mm,
J = 0 for droplets, = 1 for jets,
K = 0 for flat specimens at normal impact,
K = 1 for curved or cylindrical specimens, and
log = logarithm to base 10.

See Appendix X1 for further discussion of these equations and their origin.

APPENDIX

(Nonmandatory Information)

X1. SUMMARY OF INTERLABORATORY TEST RESULTS

X1.1 The ASTM liquid impingement interlaboratory test program involved ten laboratories in the United States, United Kingdom, France, Germany (Federal Republic), and Sweden. Nominal impact velocities specified were 140, 210, and 400 m/s, although some laboratories deviated from this. Test materials offered included a neoprene coating, poly(methyl-methacrylate) ("Plexiglas 55"), "Stellite 6B," and the four metallic reference materials listed in 8.3.1. A test plan was devised that reflected the velocity capabilities and material interests of the various laboratories, but even that plan could not be fully adhered to.

X1.2 The results were first expressed in several alternative "rationalized forms," and preliminary statistical studies verified that those described in Section 11 provided the most consistent results between different laboratories. These results were then subjected to multiple linear regression analysis in two stages. In the first stage, the mathematical model used expressed the rationalized test results in terms of velocity raised to a power, material erosion resistance values, and apparatus severity factors. The technique by which the last two

were evaluated is described in Ref **(9)**. The results of this effort, slightly modified, are Eq A2.1 and Eq A2.2, the "reference resistance" values listed in Annex A1, and the apparatus severity factors, which are listed in Table X1.1 along with other major attributes of the apparatus.

X1.3 In the second stage of regression analysis, several different mathematical models were explored that omitted apparatus severity factors, but instead included some of the" secondary" variables that conceivably could influence the severity factors. (These included jet or drop size, specimen shape, volume concentration, and others.) From among the various prediction equations so obtained, a pair were chosen that provided reasonable fits to the data and had reasonably similar velocity exponents to those from the first-stage equations.

X1.4 Finally, both sets of equations were slightly modified to have the *same* velocity exponents for corresponding equations, and direct comparison between these then yielded the approximate "prediction equations" for the severity factors in terms of secondary variables, given here as Eq A2.3 and Eq

TABLE X1.1 Apparatus Characteristics

Laboratory	Specimen	K	J	d	R_A	c	F_0	F_e
A	S	0	0	2.0	1.450	1.2 (−6)	0.87	0.81
B	B	0	1	1.6	0.160	2.5 (−3)	1.95	2.00
C	B	0	1	0.8	0.150	1.3 (−3)	1.82	1.90
D	S	0	0	2.0	2.190	1.2 (−6)	1.15	1.23
E	B	1	0	1.8	2.740	2.3 (−6)	0.66	0.59
F	B	0	0	1.2	1.200	1.2 (−5)	0.55	0.52
G	B	0	1	1.5	0.096	2.0 (−3)	1.51	1.70
H	S	1	0	1.8	1.170	6.2 (−7)	0.51	0.50
J	B	1	1	5.0	0.308	2.0 (−3)	1.74	3.40
K	S	1	0	1.3	1.520	1.4 (−6)	0.58	0.30

where:
S = specimen of sheet material,
B = specimen of bar (rod) material,
K = 0 if exposed surface is flat,
K = 1 if exposed surface is curved,
J = 0 if droplets impinge,
J = 1 if jets impinge laterally,
d = jet or drop mean diameter, mm,
R_A = radius of rotation of specimen, m,
c = volume concentration (floating decimal notation),
F_0 = incubation severity, from regression analysis, and
F_e = erosion severity, from regression analysis.

A2.4. (Substitution of these in Eq A2.1 and Eq A2.2, of course, reconstructs very nearly the equations obtained in the second regression effort.)

X1.5 It may be noted that although Eq A2.3 and Eq A2.4 are different, the actual values for incubation severity (F_0) and for erosion rate severity (F_e) are very nearly equal to each other for most, but not all facilities. It remains for future studies to determine whether indeed the same equation should be used for both.

X1.6 In order to show the variability of normalized material resistance values, Table X1.2 presents all available determinations of incubation resistance and erosion resistance relative to Nickel 270, based on direct normalization as described in 10.4.2. The standard deviations computed from this tabulation are those listed in 13.3.

X1.7 The mean values computed from this tabulation may be compared to the normalized resistance values obtained from the first stage of regression analysis, using all test data. These are listed on the lowest line on Table X1.2. In most cases there is reasonable agreement, except for the normalized incubation resistance for aluminum 6061-T6. This discrepancy is at present unexplained. The "reference resistance" values given in Annex A1 are rounded off from the average of values obtained by several different analyses of the round-robin test data. They are arithmetic, not logarithmic, values and have been normalized to Type 316 stainless steel instead of to Nickel 270 as in Table X1.2.

TABLE X1.2 Results of Direct Normalization to Nickel 270 (Based on all Available Pair-Wise Comparisons)

Laboratory	Impact Velocity, m/s	Log (Normalized Incubation Resistance)			Log (Normalized Erosion Resistance)		
		Al 1100-0	Al 6061-T6	S.S. 316	Al 1100-0	Al 6061-T6	S.S. 316
A	210	−1.69	−0.50		−1.12	−0.61	
B	134		−0.30	0.81		−0.95	0.43
B	201	−1.49	−0.42	0.80	−1.09	−0.62	0.30
C	140		−0.22	0.90		−0.85	0.34
C	210		−0.54	0.86		−0.83	0.36
D	307		−0.34			−0.84	
E[A]	400		−1.32	0.86		−1.90	−0.24
F	265		−0.40	0.91		−0.75	0.33
F	400		−0.39	0.86		−0.63	0.41
G	140	−1.23	−0.56	0.74	−0.75	−0.69	0.01
J	94		−0.60	0.61		−0.86	0.21
K	217	−1.87	−0.78		−1.53	−0.81	
Mean Values		−1.57	−0.46	0.81	−1.12	−0.77	0.30
Standard Deviation		0.27	0.16	0.10	0.32	0.12	0.14
Values from regression analysis[B]		−1.65	−0.78	0.65	−1.27	−0.78	0.28

[A] Results from Laboratory E were considered anomalous and not included in above statistics.

[B] For comparison, these are the normalized values obtained by regression analysis of *all* data, not only those allowing direct paired comparisons.

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