



Designation: G32 – 10

Standard Test Method for Cavitation Erosion Using Vibratory Apparatus¹

This standard is issued under the fixed designation G32; 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 reappraisal. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reappraisal.

1. Scope

1.1 This test method covers the production of cavitation damage on the face of a specimen vibrated at high frequency while immersed in a liquid. The vibration induces the formation and collapse of cavities in the liquid, and the collapsing cavities produce the damage to and erosion (material loss) of the specimen.

1.2 Although the mechanism for generating fluid cavitation in this method differs from that occurring in flowing systems and hydraulic machines (see 5.1), the nature of the material damage mechanism is believed to be basically similar. The method therefore offers a small-scale, relatively simple and controllable test that can be used to compare the cavitation erosion resistance of different materials, to study in detail the nature and progress of damage in a given material, or—by varying some of the test conditions—to study the effect of test variables on the damage produced.

1.3 This test method specifies standard test conditions covering the diameter, vibratory amplitude and frequency of the specimen, as well as the test liquid and its container. It permits deviations from some of these conditions if properly documented, that may be appropriate for some purposes. It gives guidance on setting up a suitable apparatus and covers test and reporting procedures and precautions to be taken. It also specifies standard reference materials that must be used to verify the operation of the facility and to define the normalized erosion resistance of other test materials.

1.4 A history of this test method is given in Appendix X4, followed by a comprehensive bibliography.

1.5 The values stated in SI units are to be regarded as standard. The inch-pound units given in parentheses are for information only.

1.6 *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 applica-*

bility of regulatory limitations prior to use. For specific safety warning information, see 6.1, 10.3, and 10.6.1.

2. Referenced Documents

2.1 ASTM Standards:²

- A276 Specification for Stainless Steel Bars and Shapes
- B160 Specification for Nickel Rod and Bar
- B211 Specification for Aluminum and Aluminum-Alloy Rolled or Cold Finished Bar, Rod, and Wire
- D1193 Specification for Reagent Water
- E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods
- E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method
- E960 Specification for Laboratory Glass Beakers
- G40 Terminology Relating to Wear and Erosion
- G73 Test Method for Liquid Impingement Erosion Using Rotating Apparatus
- G117 Guide for Calculating and Reporting Measures of Precision Using Data from Interlaboratory Wear or Erosion Tests
- G119 Guide for Determining Synergism Between Wear and Corrosion
- G134 Test Method for Erosion of Solid Materials by Cavitating Liquid Jet

3. Terminology

3.1 Definitions:

3.1.1 See Terminology G40 for definitions of terms relating to cavitation erosion. For convenience, important definitions for this standard are listed below; some are slightly modified from Terminology G40 or not contained therein.

3.1.2 *average erosion rate, n*—a less preferred term for cumulative erosion rate.

3.1.3 *cavitation, n*—the formation and subsequent collapse, within a liquid, of cavities or bubbles that contain vapor or a mixture of vapor and gas.

3.1.3.1 *Discussion*—In general, cavitation originates from a local decrease in hydrostatic pressure in the liquid, produced

¹ This test method is under the jurisdiction of ASTM Committee G02 on Wear and Erosion and is the direct responsibility of Subcommittee G02.10 on Erosion by Solids and Liquids.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

by motion of the liquid (see *flow cavitation*) or of a solid boundary (see *vibratory cavitation*). It is distinguished in this way from boiling, which originates from an increase in liquid temperature.

3.1.3.2 *Discussion*—The term cavitation, by itself, should not be used to denote the damage or erosion of a solid surface that can be caused by it; this effect of cavitation is termed *cavitation damage* or *cavitation erosion*. To erode a solid surface, bubbles or cavities must collapse on or near that surface.

3.1.4 *cavitation erosion, n*—progressive loss of original material from a solid surface due to continued exposure to cavitation.

3.1.5 *cumulative erosion, n*—the total amount of material lost from a solid surface during all exposure periods since it was first exposed to cavitation or impingement as a newly finished surface. (More specific terms that may be used are *cumulative mass loss*, *cumulative volume loss*, or *cumulative mean depth of erosion*. See also *cumulative erosion-time curve*.)

3.1.5.1 *Discussion*—Unless otherwise indicated by the context, it is implied that the conditions of cavitation or impingement have remained the same throughout all exposure periods, with no intermediate refinishing of the surface.

3.1.6 *cumulative erosion rate, n*—the cumulative erosion at a specified point in an erosion test divided by the corresponding cumulative exposure duration; that is, the slope of a line from the origin to the specified point on the cumulative erosion-time curve. (*Synonym: average erosion rate*)

3.1.7 *cumulative erosion-time curve*—a plot of cumulative erosion versus cumulative exposure duration, usually determined by periodic 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.

3.1.8 *erosion rate-time curve, n*—a plot of instantaneous erosion rate versus exposure duration, usually obtained by numerical or graphical differentiation of the cumulative erosion-time curve. (See also *erosion rate-time pattern*.)

3.1.9 *erosion rate-time pattern, n*—any qualitative description of the shape of the erosion rate-time curve in terms of the several stages of which it may be composed.

3.1.9.1 *Discussion*—In cavitation and liquid impingement erosion, a typical pattern may be composed of all or some of the following “periods” or “stages”: *incubation period*, *acceleration period*, *maximum-rate period*, *deceleration period*, *terminal period*, and occasionally *catastrophic period*. The generic term “period” is recommended when associated with quantitative measures of its duration, etc.; for purely qualitative descriptions the term “stage” is preferred.

3.1.10 *erosion threshold time, n*—the exposure time required to reach a mean depth of erosion of 1.0 μm .

3.1.10.1 *Discussion*—A mean depth of erosion of 1.0 μm is the least accurately measurable value considering the precision of the scale, specimen diameter, and density of the standard reference material.

3.1.11 *flow cavitation, n*—cavitation caused by a decrease in local pressure induced by changes in velocity of a flowing liquid, such as in flow around an obstacle or through a constriction.

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

3.1.12.1 *Discussion*—The incubation period is usually thought to represent the accumulation of plastic deformation and internal stresses under the surface, that precedes significant material loss. There is no exact measure of the duration of the incubation period. See related terms, *erosion threshold time* and *nominal incubation period*.

3.1.13 *maximum erosion rate, n*—the maximum instantaneous erosion rate in a test that exhibits such a maximum followed by decreasing erosion rates. (See also *erosion rate-time pattern*.)

3.1.13.1 *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.

3.1.14 *mean depth of erosion (MDE), n*—the average thickness of material eroded from a specified surface area, usually calculated by dividing the measured mass loss by the density of the material to obtain the volume loss and dividing that by the area of the specified surface. (Also known as *mean depth of penetration* or *MDP*. Since that might be taken to denote the average value of the depths of individual pits, it is a less preferred term.)

3.1.15 *nominal incubation time, n*—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 time coordinates.

3.1.16 *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 similarly 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.

3.1.16.1 *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).”

3.1.17 *normalized incubation resistance N_o, n* —the nominal incubation time of a test material, divided by the nominal incubation time of a specified reference material similarly tested and similarly analyzed. (See also *normalized erosion resistance*.)

3.1.18 *tangent erosion rate, n*—the slope of a straight line drawn through the origin and tangent to the knee of the

cumulative erosion-time curve, when that curve has the characteristic S-shaped pattern that permits this. In such cases, the tangent erosion rate also represents the maximum cumulative erosion rate exhibited during the test.

3.1.19 *terminal erosion rate, n*—the final steady-state erosion rate that is reached (or appears to be approached asymptotically) after the erosion rate has declined from its maximum value. (See also *terminal period* and *erosion rate-time pattern*.)

3.1.20 *vibratory cavitation, n*—cavitation caused by the pressure fluctuations within a liquid, induced by the vibration of a solid surface immersed in the liquid.

4. Summary of Test Method

4.1 This test method generally utilizes a commercially obtained 20-kHz ultrasonic transducer to which is attached a suitably designed “horn” or velocity transformer. A specimen button of proper mass is attached by threading into the tip of the horn.

4.2 The specimen is immersed into a container of the test liquid (generally distilled water) that must be maintained at a specified temperature during test operation, while the specimen is vibrated at a specified amplitude. The amplitude and frequency of vibration of the test specimen must be accurately controlled and monitored.

4.3 The test specimen is weighed accurately before testing begins and again during periodic interruptions of the test, in order to obtain a history of mass loss versus time (which is not linear). Appropriate interpretation of this cumulative erosion-versus-time curve permits comparison of results between different materials or between different test fluids or other conditions.

5. Significance and Use

5.1 This test method may be used to estimate the relative resistance of materials to cavitation erosion as may be encountered, for instance, in pumps, hydraulic turbines, hydraulic dynamometers, valves, bearings, diesel engine cylinder liners, ship propellers, hydrofoils, and in internal flow passages with obstructions. An alternative method for similar purposes is Test Method **G134**, which employs a cavitating liquid jet to produce erosion on a stationary specimen. The latter may be more suitable for materials not readily formed into a precisely shaped specimen. The results of either, or *any*, cavitation erosion test should be used with caution; see **5.8**.

5.2 Some investigators have also used this test method as a screening test for materials subjected to liquid impingement erosion as encountered, for instance, in low-pressure steam turbines and in aircraft, missiles or spacecraft flying through rainstorms. Test Method **G73** describes another testing approach specifically intended for that type of environment.

5.3 This test method is not recommended for evaluating elastomeric or compliant coatings, some of which have been successfully used for protection against cavitation or liquid impingement of moderate intensity. This is because the compliance of the coating on the specimen may reduce the severity of the liquid cavitation induced by its vibratory motion. The

result would not be representative of a field application, where the hydrodynamic generation of cavitation is independent of the coating.

NOTE 1—An alternative approach that uses the same basic apparatus, and is deemed suitable for compliant coatings, is the “stationary specimen” method. In that method, the specimen is fixed within the liquid container, and the vibrating tip of the horn is placed in close proximity to it. The cavitation “bubbles” induced by the horn (usually fitted with a highly resistant replaceable tip) act on the specimen. While several investigators have used this approach (see **X4.2.3**), they have differed with regard to standoff distances and other arrangements. The stationary specimen approach can also be used for brittle materials which can not be formed into a threaded specimen nor into a disc that can be cemented to a threaded specimen, as required for this test method (see **7.6**).

5.4 This test method should not be directly used to rank materials for applications where electrochemical corrosion or solid particle impingement plays a major role. However, adaptations of the basic method and apparatus have been used for such purposes (see **9.2.5**, **9.2.6**, and **X4.2**). Guide **G119** may be followed in order to determine the synergism between the mechanical and electrochemical effects.

5.5 Those who are engaged in basic research, or concerned with very specialized applications, may need to vary some of the test parameters to suit their purposes. However, adherence to this test method in all other respects will permit a better understanding and correlation between the results of different investigators.

5.6 Because of the nonlinear nature of the erosion-versus-time curve in cavitation and liquid impingement erosion, the shape of that curve must be considered in making comparisons and drawing conclusions. See Section **11**.

5.7 The results of this test may be significantly affected by the specimen’s surface preparation. This must be considered in planning, conducting and reporting a test program. See also **7.4** and **12.2**.

5.8 The mechanisms of cavitation erosion and liquid impingement erosion are not fully understood and may differ, depending on the detailed nature, scale, and intensity of the liquid/solid interactions. “Erosion resistance” may, therefore, represent a mix of properties rather than a single property, and has not yet been successfully correlated with other independently measurable material properties. For this reason, the consistency of results between different test methods or under different field conditions is not very good. Small differences between two materials are probably not significant, and their relative ranking could well be reversed in another test.

5.9 If a test program must deviate from the standard specifications for apparatus, test specimens, or test conditions, the reasons shall be explained, and the results characterized as obtained by “ASTM Test Method G32 modified.” See also **5.4**, **5.5**, and **12.1**.

6. Apparatus

6.1 The vibratory apparatus used for this test method produces axial oscillations of a test specimen inserted to a specified depth in the test liquid. The vibrations are generated by a magnetostrictive or piezoelectric transducer, driven by a suitable electronic oscillator and power amplifier. The power of

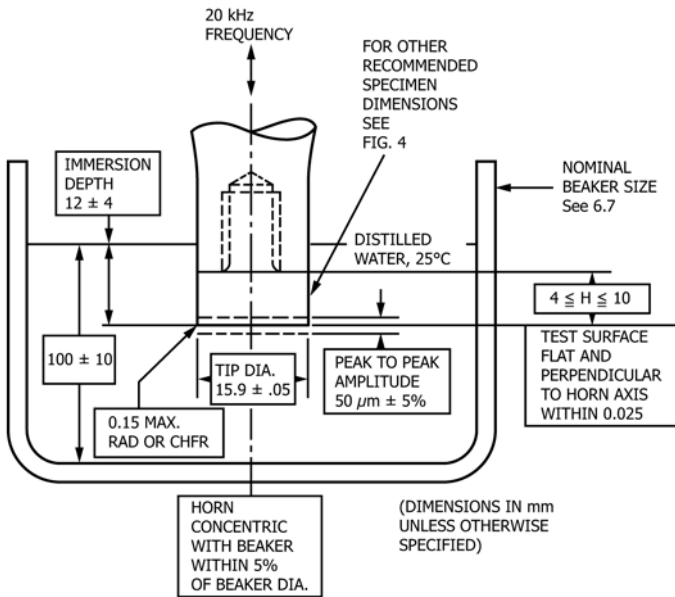


FIG. 1 Important Parameters of the Vibratory Cavitation Test

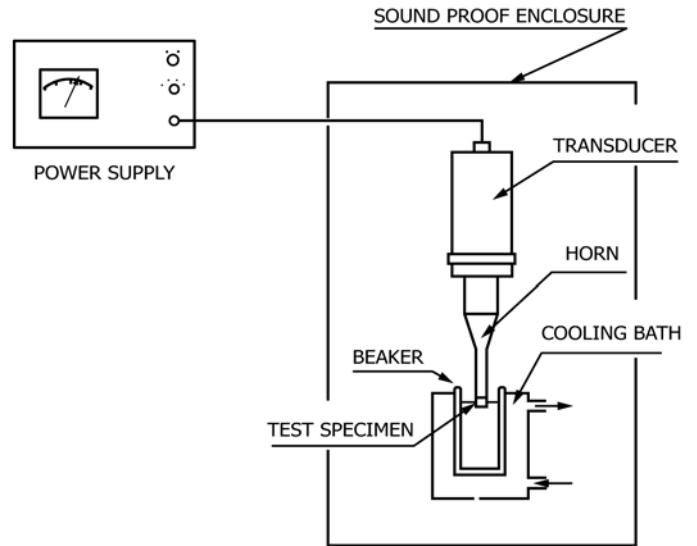


FIG. 2 Schematic of Vibratory Cavitation Erosion Apparatus

the system should be sufficient to permit constant amplitude of the specimen in air as well as submerged. An acoustic power output of 250 to 1000 W has been found suitable. Such systems are commercially available, intended for ultrasonic welding, emulsifying, and so forth.³ (**Warning**—This apparatus may generate high sound levels. The use of ear protection may be necessary. Provision of an acoustical enclosure is recommended.)

6.1.1 The basic parameters involved in this test method are pictorially shown in Fig. 1. Schematic and photographic views of representative equipment are shown in Figs. 2 and 3 respectively.

6.2 To obtain a higher vibratory amplitude at the specimen than at the transducer, a suitably shaped tapered cylindrical member, generally termed the “horn” or “velocity transformer,” is required. Catenoidal, exponential and stepped horn profiles have been used for this application. The diameter of the horn at its tip shall conform to that specified for the specimen (see 7.1).

6.3 The test specimen (see also Section 7 and Fig. 4) is shaped as a button with the same outer diameter as the horn tip, and has a smaller diameter threaded shank, which is screwed into a threaded hole at the end of the horn. The depth of the hole in the horn shall be the minimum consistent with the required length of engagement of the specimen shank.

6.4 The transducer and horn assembly shall be supported in a manner that does not interfere with, and receives no force input from, the vibratory motion. This can be accomplished, for example, by attaching the support structure to a stationary housing of the transducer, or to a flange located at a nodal plane



FIG. 3 Photograph of a Typical Apparatus

³ Several manufacturers of ultrasonic processing or plastics welding equipment offer apparatus off-the-shelf, or specially modified, to meet the specifications given in this standard. A list of those known to the subcommittee having jurisdiction is available from its chairman. Inclusion in this list does not imply such equipment has been qualified in a test program.

of the vibrating assembly. It is also necessary to prevent any misalignment of the horn due to forces caused by the electrical cable, cooling system, or transducer enclosure.

6.5 Frequency Control:

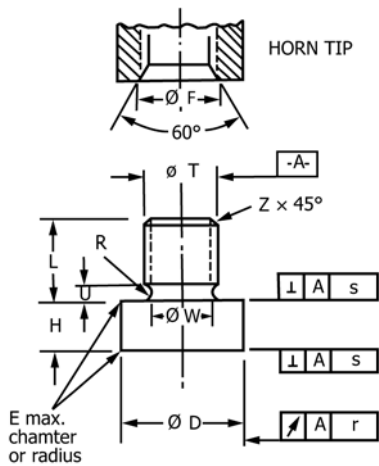


TABLE OF VALUES

	mm	inch
D*	15.9 ± 0.05	0.624 ± 0.002
E*	0.15	0.006
F	(W + 2.2) ± 0.25	(W + 0.09) ± 0.01
H	See 7.2	
L	10.0 ± 0.5	0.394 ± 0.02
R	0.8 ± 0.15	0.031 ± 0.006
T	Thread, see X2.2.1	
U	2.0 ± 0.5	0.08 ± 0.02
W	Thread minor dia, see Table X2.2	
Z	0.8 ± 0.15	0.031 ± 0.006
r*	0.050	0.002
s*	0.025	0.001

NOTE 1—Asterisk (*) indicates mandatory; others recommended.

FIG. 4 Dimensions and Tolerances of the Test Specimen

6.5.1 The frequency of oscillation of the test specimen shall be 20 ± 0.5 kHz.

6.5.2 The whole transducer-horn-specimen system shall be designed for longitudinal resonance at this frequency.

NOTE 2—If both light and heavy alloys are to be tested, then two horns of different length may be needed in order to permit use of similarly sized specimens. One horn might be used for specimens having densities 5 g/cm³ or more and tuned for a button mass of about 10 g (0.022 lb), and the other for densities less than 5 g/cm³, tuned for a button mass of about 5 g (0.011 lb). See also 7.2 and Table X2.2.

6.5.3 A means for monitoring or checking frequency shall be provided; this could be a signal from the power supply or a transducer, feeding into a frequency counter.

6.6 Amplitude Control:

6.6.1 Means shall be provided to measure and control vibration amplitude of the horn tip within the tolerances specified in 9.1.1.7 or 9.1.2.

6.6.2 If the ultrasonic system has automatic control to maintain resonance and constant amplitude, amplitude calibration may be done with the specimen in the air and will still apply when the specimen is submerged. This may be done with a filar microscope, dial indicator, eddy-current displacement sensor, or other suitable means (see also Appendix X1).

6.6.3 If the apparatus does not have automatic amplitude control, it may be necessary to provide a strain gage or accelerometer on some part of the vibrating assembly for continuous monitoring.

6.7 Liquid Vessel:

6.7.1 The size of the vessel containing the test liquid is a compromise. It must be small enough to permit satisfactory temperature control, and large enough to avoid possible effects of wave reflections from its boundaries, and of erosion debris.

6.7.2 The vessel shall be cylindrical in cross-section, and the depth of liquid in it shall be 100 ± 10 mm, unless otherwise required.

6.7.3 The vessel's inside diameter will depend on whether the cooling method (see 6.8) is an external cooling bath into which the vessel is immersed, or a cooling coil immersed within the vessel. In either case, it is recommended that the unobstructed diameter (that is, the internal diameter of the vessel or of the cooling coil within it if used) be 100 ± 15 mm.

6.7.4 A standard commercially available low-form glass beaker (for example, Type I or II of Specification E960) may be suitable. A 600-mL beaker may be suitable when a cooling bath is used, and a 1000-mL to 1500-mL beaker when a cooling coil is used.

6.8 Means shall be provided to maintain the temperature of the test liquid near the specimen at a specified temperature (see 9.1.1.5). This is commonly achieved by means of a cooling bath around the liquid-containing vessel or a cooling coil immersed within it, with suitable thermostatic control. The temperature sensor should be located as close as practicable to the specimen, but at a point where it does not interfere with the cavitation process and is not damaged by it. A suggested location is approximately 3 mm radially from the specimen periphery, and at a depth of immersion approximately 3 mm below that of the specimen face.

6.9 Optionally, a heating system may be provided, for two purposes: (1) to achieve degassing of the liquid, and (2) to bring the liquid temperature to the desired value before the test begins. Such a system may consist of a separate heating coil, or combined with the cooling system, with suitable thermostatic control. A comprehensive thermal control system that includes cooling, heating, and magnetic stirring provisions has been used by at least one investigator.

6.10 A timer should be provided to measure the test duration or to switch off the test automatically after a preset time.

7. Test Specimens

7.1 The specimen button diameter (see also 6.3) shall be 15.9 ± 0.05 mm (0.626 ± 0.002 in.). The test surface shall be plane and square to the transducer axis within an indicator reading of 0.025 mm (0.001 in.). No rim on or around the specimen test surface shall be used. The circular edges of the specimen button shall be smooth, but any chamfer or radius shall not exceed 0.15 mm (0.006 in.).

7.2 The button thickness of the specimen (Dimension H in Figs. 1 and 4) shall be not less than 4 mm (0.157 in.) and not more than 10 mm (0.394 in.). See Table X2.2 for relationships between button thickness and mass.

7.3 Specimens of different materials to be tested with the same horn should have approximately the same button mass, within the dimensional limits of 7.2. See also 6.5.2.

TABLE 1 Material Used in Interlaboratory Study

Designation: Nickel 200, UNS N02200, ASTM B160	
Composition (limit values): Ni 99 min; max others: 0.25 Cu, 0.40 Fe, 0.35 Mn, 0.15 C, 0.35 Si, 0.01 S	
Specific gravity (nominal): 8.89	
Form: 0.75-in. (19 mm) rod, cold drawn and annealed	
Properties:	
Yield strength (nominal) ^A :	103 to 207 MPa (15 to 30 ksi)
(measured) ^B :	284 MPa (41.2 ksi)
Tensile strength (nominal):	379 to 517 MPa (55 to 75 ksi)
(measured):	586 MPa (85 ksi)
Elongation (nominal):	40 to 55 %
(measured):	58 %
Reduction of area (nominal):	N/A
(measured):	76 %
Hardness (nominal):	45 to 70 HRB, 90 to 120 HB
(measured):	49 HRB

^A “Nominal” properties are from “Huntington Alloys” data sheets. (Strength properties were listed in ksi; SI values in this table are conversions.)

^B “Measured” properties reported from tests on sample from same rod as used for erosion test specimens. (Strength properties were reported in ksi; SI values in this table are conversions.)

7.4 Specimens should be prepared in a manner consistent with the purposes of the test. Three options are given in **7.4.1 – 7.4.3**.

7.4.1 Unless otherwise required, the test surface shall be lightly machined, then ground and polished to a maximum surface roughness of 0.8 μm (32 $\mu\text{in.}$), in such a way as to minimize surface damage or alteration. While an extremely fine finish is not required, there shall be no visible pits or scratch marks that would serve as sites for accelerated cavitation damage. Final finishing with 600 grit emery cloth has been found satisfactory.

7.4.2 For screening of materials for their erosion resistance in a particular application, the surface preparation method should be as close as possible to that used in the end application. For example, rolled sheet material would be tested in the as-rolled condition and weld-deposited hard facings would be tested in the as-deposited and final machined or polished condition, or both.

7.4.3 In tests where any possible effects of surface preparation (for example, subsurface alterations, or work hardening) on the results are to be minimized, the following procedure is recommended: Prepare machined surfaces for testing by successively finer polishing down to 600 grit, with at least 50 strokes of each grade of paper. This method provides a surface finish on the order of 0.1 to 0.2 μm (4 to 8 $\mu\text{in.}$) rms, with a depth to the plastic/elastic boundary on the order of 20 μm . Should the experiment require the complete removal of any altered layer, an additional 25 μm of material should be removed via electropolishing.

NOTE 3—Information on subsurface alterations due to machining and grinding can be found in Refs (**1 and 2**).⁴

7.5 The threaded connection between specimen and horn must be carefully designed, and sufficiently prestressed on assembly, to avoid the possibility of excessive vibratory stresses, fatigue failures, and leakage of fluid into the threads. There must be no sharp corners in the thread roots or at the junction between threaded shank and button. A smooth radius or undercut shall be provided at that junction. Other recommendations are given in **Fig. 4** and **Appendix X2**.

7.6 For test materials that are very light, or weak, or brittle, or that cannot be readily machined into a homogeneous specimen, it may be desirable to use a threaded stud made of the same material as the horn (or some other suitable material) and to attach a flat disk of the test material by means of brazing, adhesives, or other suitable process. Such a disk shall be at least 3 mm (0.12 in.) in thickness, unless it is the purpose of the specimen to test an overlay or surface layer system. In that case, the test report shall describe the overlay material, its thickness, the substrate material, and the deposition or attachment process. For such nonhomogeneous specimens, the button weight recommendation given in **7.3** still applies.

7.7 No flats shall be machined into the cylindrical surface of the specimen or horn tip. Tightening of the specimen should be accomplished by a tool that depends on frictional clamping but

does not mar the cylindrical surface, such as a collet or specially designed clamp-on wrench, preferably one that can be used in conjunction with a torque wrench. (See **10.3** and **Appendix X2** for tightening requirements and guidelines.)

8. Calibration

8.1 Calibration and Qualification of Apparatus:

8.1.1 Perform a frequency and amplitude calibration of the assembled system at least with the first sample of each group of specimens of same button mass and length. Also calibrate the temperature measurement system by an appropriate method.

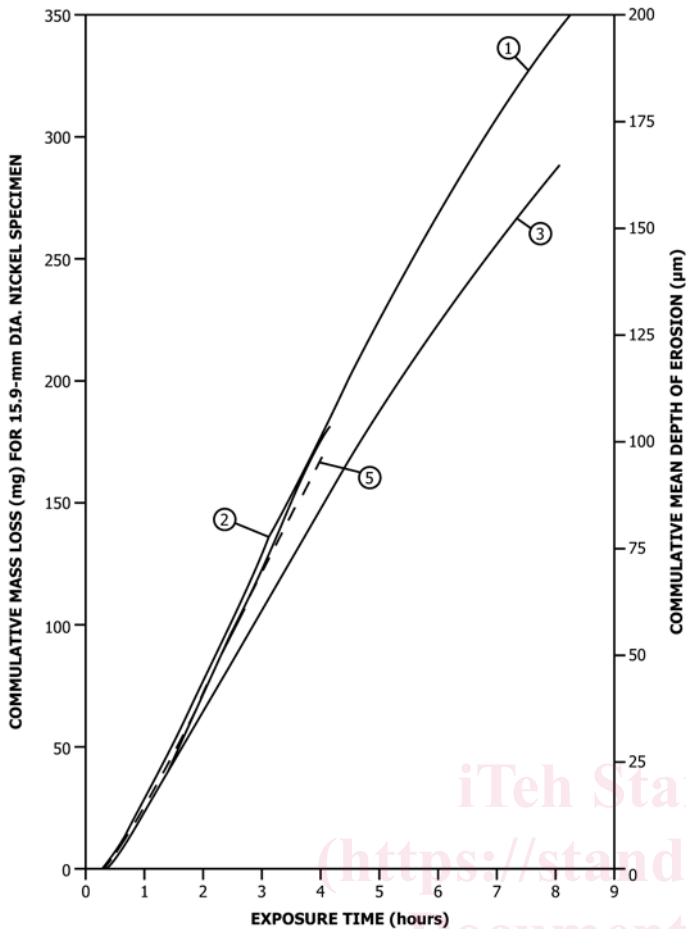
8.1.2 To qualify the apparatus initially, and to verify its performance from time to time, perform tests with the preferred reference material specified in **8.1.3** (annealed Nickel 200) or, if a laboratory cannot obtain Ni 200, one of the supplementary reference materials specified in **8.1.4**. Do this at standard test conditions (see **9.1**) even if the apparatus is normally operated at optional conditions. Detailed guidelines and criteria for qualification are given in **Appendix X3**.

8.1.3 The preferred reference material is annealed wrought Nickel 200 (UNS N02200), conforming to Specification **B160**. This is a commercially pure (99.5 %) nickel product; see **Table 1** for its properties. Test curves from a “provisional” interlaboratory study are shown in **Fig. 5**, and statistical results from that study are shown in **Table 2**. The appearance of a test specimen at various stages is shown in **Fig. 6**.

8.1.4 A supplementary reference material of greater erosion resistance is annealed austenitic stainless steel Type 316, of hardness 150 to 175 HV (UNS S31600, Specification **A276**). A supplementary reference material of lesser erosion resistance is Aluminum Alloy 6061-T6 (UNS A96061, Specification **B211**). Their properties are shown in **Table 3**. A comparative test study with these materials was conducted for the original development of this Test Method; see Refs (**3 and 4**). Curves and limited statistical results from four laboratories are presented in **X3.2**.

8.2 Normalization of Test Results:

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



NOTE 1—The curves for Laboratories 1 through 3 represent averages from three replicate tests; that for Laboratory 5 is based on two replicate tests.

FIG. 5 Cumulative Erosion-Time Curves for Nickel 200 from Four Laboratories (see 13.1.2)

8.2.1 In each major program include among the materials tested one or more reference materials, tested at the same condition to facilitate calculation of “normalized erosion resistance” of the other materials.

8.2.2 If possible include the preferred reference material, annealed Ni 200, as specified in 8.1.3.

8.2.3 Alternatively, or in addition, include one of the supplementary reference materials (see 8.1.4). The choice may be based on the range of expected erosion resistance of the group of materials being tested.

9. Test Conditions

9.1 Standard Test Conditions:

9.1.1 If this test method is cited without additional test parameters, it shall be understood that the following test conditions apply:

9.1.1.1 The test liquid shall be distilled or deionized water, meeting specifications for Type III reagent water given by Specification D1193.

9.1.1.2 The depth of the liquid in its container shall be 100 ± 10 mm (3.94 ± 0.39 in.), with cooling coils (if any) in place.

9.1.1.3 The immersion depth of the specimen test surface shall be 12 ± 4 mm (0.47 ± 0.16 in.).

9.1.1.4 The specimen (horn tip) shall be concentric with the cylindrical axis of the container, within ± 5 % of the container diameter.

9.1.1.5 Maintain the temperature of the test liquid at $25 \pm 2^\circ\text{C}$ ($77 \pm 3.6^\circ\text{F}$). **Caution**—Failure to maintain specified temperature can significantly affect the results; see 9.2.2.

9.1.1.6 The gas over the test liquid shall be air, at a pressure differing less than 6 % from one standard atmosphere (101.3 kPa; 760 mm (29.92 in.) Hg). If the pressure is outside this range, for example, because of altitude, this must be noted in the report as a deviation from standard conditions.

9.1.1.7 The peak-to-peak displacement amplitude of the test surface of the specimen shall be $50 \mu\text{m}$ (0.002 in.) ± 5 % throughout the test.

9.1.2 An alternative peak-to-peak displacement amplitude of $25 \mu\text{m}$ (0.001 in.) may be used for weak, brittle, or nonmetallic materials that would be damaged too rapidly or could not withstand the inertial vibratory stresses with the standard amplitude of 9.1.1.7. See Appendix X2 for guidance. This amplitude may also be appropriate for erosion-corrosion studies. If this amplitude is used, this must be clearly stated in conjunction with any statement that this test method (Test Method G32) was followed.

9.2 Optional Test Conditions:

9.2.1 The standard test conditions of 9.1.1 satisfy a large number of applications in which the relative resistance of materials under ordinary environmental conditions is to be determined. However, there can be applications for which other temperatures, other pressures, and other liquids must be used. When such is the case, any presentation of results shall clearly refer to and specify all deviations from the test conditions of 9.1.1. (See also 12.1.) Deviations from standard test conditions should not be used unless essential for purposes of the test.

9.2.2 Investigations of the effect of liquid temperature on cavitation erosion (see X4.2.2) have shown that the erosion rate peaks strongly at a temperature about halfway between freezing and boiling point, for example, for water under atmospheric pressure at about 50°C (122°F). Near the standard temperature of 25°C , each increase of 1°C probably increases the erosion rate by 1 to 2 %. Thus, there may be economic incentive to conduct water tests with especially resistant materials (for example, tool steels, stellites) at a temperature higher than that specified in 9.1.1.5. This can generally be done simply by adjusting the temperature control, since without any cooling the liquid temperature may rise even beyond the optimum.

9.2.3 To conduct specialized tests at elevated temperature or pressure, or with difficult or hazardous liquids, the liquid-containing vessel must be appropriately designed. Usually, a seal must be provided between the vessel and the horn assembly. While bellows seals can be used, it is preferable to design the supporting features (see 6.4) to incorporate the sealing function.

9.2.4 The procedures specified in Section 10 still apply. Opening and disassembling the test vessel should be

TABLE 2 Statistical Results^A of Provisional Interlaboratory Study using Ni 200

Test Result: Statistic	Maximum erosion rate ($\mu\text{m}/\text{h}$)	Nominal Incubation time (min)	Time to 50 μm MDE (min)	Time to 100 μm MDE (min)
Individual Laboratory Results ^B				
Laboratory 1 average:	29.6	29.7	131	234
standard deviation:	0.88	6.8	4.7	4.6
coefficient of variation %:	3.0	22.9	3.6	2.0
Laboratory 2 average:	27.6	19.0	128	236
standard deviation:	0.66	2.7	2.9	4.5
coefficient of variation %:	2.4	14.2	2.3	1.9
Laboratory 3 average:	23.5	18.3	147	275
standard deviation:	0.14	2.5	3.1	4.5
coefficient of variation %:	0.6	13.7	2.1	1.6
Laboratory 5 average:	26.0	19.7	133	248
standard deviation:	1.90	3.5	14.9	24.7
coefficient of variation %:	7.3	17.8	11.2	10.0
Average of laboratory averages:	26.6	21.7	135	248
Pooled Variabilities—Absolute Values				
“Repeatability” standard deviation:	1.12	4.24	8.07	13.0
“Reproducibility” standard deviation:	2.74	6.40	10.6	21.7
“95 % Repeatability Limit” ^C :	3.13	11.9	22.6	36.4
“95 % Reproducibility Limit” ^C :	7.67	17.9	29.8	60.8
Pooled Variabilities—Normalized Values ^D				
“Repeatability” coefficient of variation, %:	4.2	19.6	6.0	5.2
“Reproducibility” coefficient of variation, %:	10.3	29.5	7.9	8.7
“95 % Repeatability Limit” coefficient, %:	12	55	17	14
“95 % Reproducibility Limit” coefficient, %:	29	83	22	25

^A This table is revised from that in the research report⁵ in that values for Laboratory 4, and pooled values including Laboratory 4, have been omitted.

^B All laboratory results are based on three replications, except time to 50 μm and 100 μm for Laboratory 5 (two replications).

^C A “95 % limit” represents the difference between two random test results that would not be exceeded in 95 % of such pairs (see Practice E177).

^D Normalized variabilities: coefficients of variation are corresponding standard deviations, and “95 % limit” coefficients are corresponding limits, expressed as percent of the “average of laboratory averages.”

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minimized, as this may distort the erosion results by causing extraneous oxidation, etc., through additional exposure to air.

9.2.5 When testing with liquids that may be corrosive (for example, seawater) Guide G119 may be followed in order to determine the synergism between the mechanical and electrochemical effects. See, for example, Ref (5).

9.2.6 For tests intended to simulate cavitation erosion-corrosion conditions, it may be appropriate to operate the equipment in a pulsed or cyclic manner. A 60-s-on/60-s-off cycle is recommended as a basic duty cycle for such tests. If the nature of the interactions between erosion and corrosion is to be studied, then varying duty cycles may be required.

10. Procedure

10.1 For each new test specimen, clean the liquid vessel and fill it with fresh liquid.

NOTE 4—Early versions of this test method called for stabilizing the gas content of the liquid before beginning a test on a new specimen, by first running a “dummy specimen” of high erosion resistance for 30 min. However, there is no convincing evidence that this makes any significant difference to the results, and it may be supposed that operating with the test specimen for the first 30 min produces the same effect. However, this procedure may be suitable when very early stages of the test are to be investigated.

10.2 Clean the test specimen carefully and weigh it on an accurate and sensitive balance (0.1-mg accuracy and sensitivity) before the test.

10.3 After making sure that the threads and contact surfaces of the horn and the specimen are perfectly free of debris, thread the specimen into the horn until finger tight, then tighten to a

suitable torque. The resulting prestressing of the threaded shank must be sufficient to ensure that contact is not lost between horn and specimen shoulder as a result of vibratory inertial loads. See guidelines given in Appendix X2. (Warning—Fatigue failure of the threaded portion of the specimens may become a problem under some circumstances. The specimen must be tightly secured to the horn to ensure good energy transmission and avoid any separation between specimen button and horn tip. A very thin (virtually invisible) layer of liquid or solid boundary lubricant may be used to ensure effective preloading and to prevent galling between specimen and horn. However, excessive amounts of liquid or grease lubricants can result in damage to mating surfaces in the joint, due to cavitation of the lubricant. See also Appendix X2.) (Warning—Heating of the horn and unusual noise are indications of either fatigue failure or improper tightening of the specimen, or presence of dirt or excessive amount of lubricant.)

10.4 Insert the specimen into the liquid to a depth as specified in 9.1.1.3, and concentric with the container as specified in 9.1.1.4.

10.5 Start the apparatus and the timer, and bring the amplitude as quickly as possible to the specified value. On apparatus with automatic amplitude control this is usually accomplished simply by repeating the control settings or dial readings determined in a previous calibration (see 6.6 and 8.1.1). Also make sure that the temperature is stabilized at the desired value as soon as possible. Monitor these conditions from time to time.

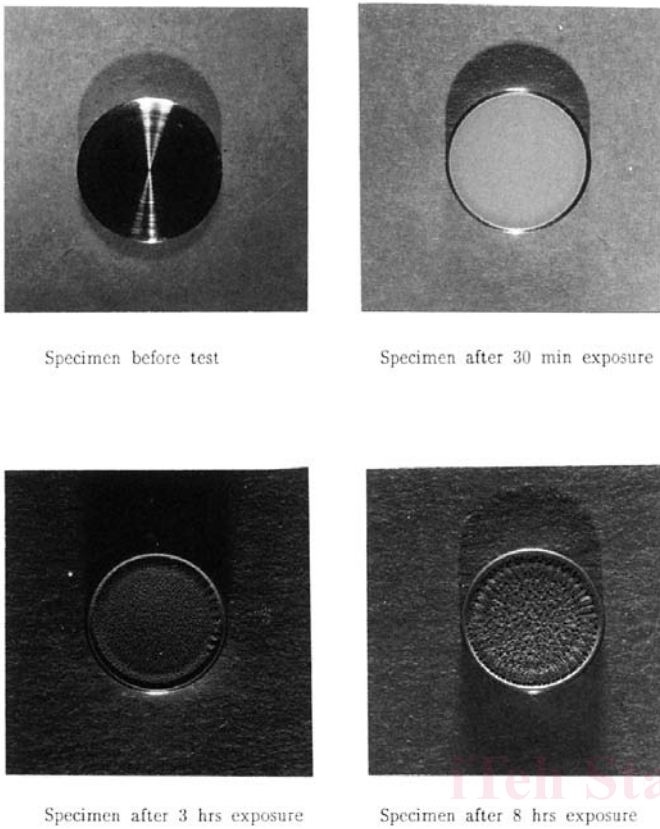


FIG. 6 Photographs of a Nickel 200 Specimen Taken at Several Cumulative Exposure Times

TABLE 3 Properties of Supplementary Reference Materials (from tables in Ref (4))

Property	Aluminum Alloy 6061-T6	Stainless Steel AISI 316
Hardness, HRB	60.1	74.8
Tensile strength, MPA (ksi)	328 (40.7)	560 (81.3)
Elongation, %	21.5	69.0
Reduction of area, %	44	76.9
Density, g/cm ³	2.71	7.91

10.6 At the end of the test interval, stop the apparatus, remove the specimen, and carefully clean, dry and weigh it to determine its new mass and hence the mass loss. See 10.6.1 for cleaning and drying recommendations. 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.

10.6.1 Very carefully clean and dry the specimen before each weighing. Rinsing with ethyl alcohol or other suitable solvent may be sufficient. An ultrasonic cleaning bath (such as for cleaning dentures), has also been found satisfactory. (**Warning**—This should NOT be used with solvents.) Dry with a stream of hot, dry air, as from a hair dryer. For porous (for example, cast) materials a vacuum desiccator may be used. Do not dry with cloth or paper products that may leave lint on the specimen.)

10.7 Repeat 10.3 – 10.6 for the next test interval, and so on until the criteria of 10.10 or 10.11 have been met. It is recommended that a running plot of cumulative mass loss versus cumulative exposure time be maintained.

10.8 After 8 to 12 h of testing with the same liquid, strain out the debris, or discard and refill with fresh liquid.

10.9 As shown in Fig. 7, the rate of mass loss varies with exposure time. The intervals between measurements must be such that a curve of cumulative mass loss versus cumulative exposure time can be established with reasonable accuracy. The duration of these intervals, therefore, depends upon the test material and its erosion resistance and cannot be rigorously specified in advance. Suitable intervals may be approximately 15 min for aluminum alloys, 30 min for pure nickel, 1 to 2 h for stainless steel, and 4 to 8 h for stellite. Intervals near the beginning of a test may need to be shorter if the shape of the erosion-time curve during the “incubation” and “acceleration” periods, and the erosion threshold time, are to be accurately established.

10.10 It is recommended that the testing of each specimen be continued at least until the average rate of erosion (also termed cumulative erosion rate) has reached a maximum and begins to diminish, that is, until the “tangent erosion rate” line (see 3.1) can be drawn.

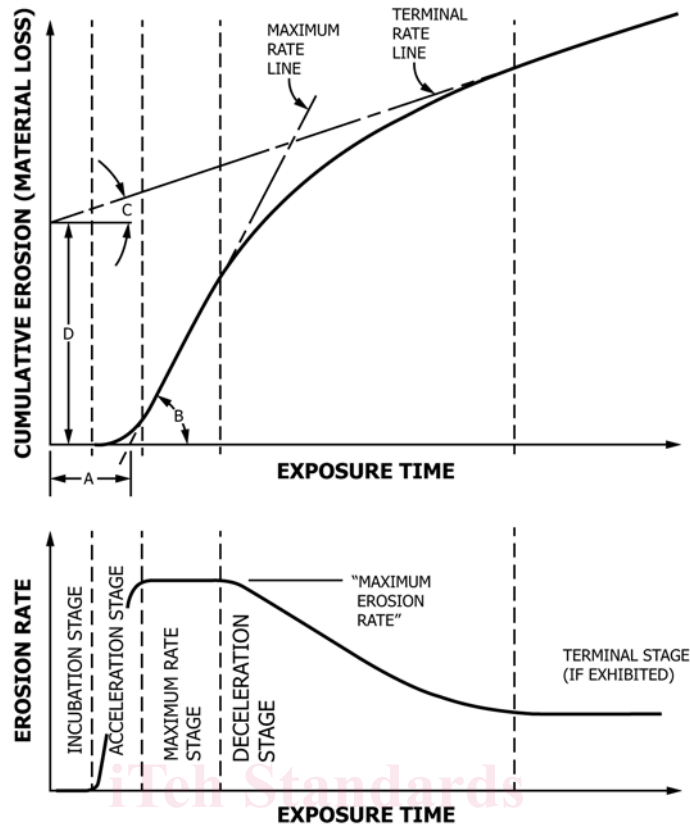
NOTE 5—This recommendation assumes that either the “maximum erosion rate” or the “tangent erosion rate” is considered a significant measure of the resistance of the material, and ensures that both can be determined. However, there is another school of thought that holds the maximum rate is a transient phenomenon, and a truer measure is the eventual “terminal erosion rate” if that can be established. Thus, the desirable total duration of the test may depend on the test objectives, the school of thought to which the investigator adheres, and the practical limitations. For stainless steel, it can take 40 h to get beyond the maximum rate stage, see Ref (6); for stellite probably more than 100.

10.11 It is recommended that when several materials are to be compared, all materials be tested until they reach comparable mean depths of erosion.

11. Calculation or Interpretation of Results

11.1 Interpretation and reporting of cavitation erosion test data is made difficult by the fact that the rate of erosion (material loss) is not constant with time, but goes through several stages (see Fig. 7). This makes it impossible to represent the test result fully by a single number, or to predict long-term behavior from a short-term test. The following paragraphs describe required as well as optional data interpretation steps.

11.2 The primary result of an erosion test is the cumulative erosion-time curve. Although the raw data will be in terms of mass loss versus time, for analysis and reporting purposes this should be converted to a “mean depth of erosion” (MDE) versus time curve, since a volumetric loss is more significant than a mass loss when materials of different densities are compared. Calculate the mean depth of erosion, for the purpose of this test method, on the basis of the full area of the test surface of the specimen, even though generally a narrow annular region at the periphery of the test surface remains virtually undamaged. For the button diameter specified in 7.1, this area is 1.986 cm² (0.308 in.²).



NOTE 1—A = nominal incubation time; tan B = maximum erosion rate; tan C = terminal erosion rate; and D = terminal line intercept.

FIG. 7 Characteristic Stages of the Erosion Rate-Time Pattern, and Parameters for Representation of the Cumulative Erosion-Time Curve

11.3 Because of the shape of the cumulative erosion-time curve, it is not meaningful to compare the mass loss or MDE for different materials after the same cumulative exposure time. (The reason is that a selected time may still be within the incubation or acceleration stage for a very resistant material, whereas for a weak material the same time may be within the maximum rate or deceleration stage.) However, one may compare the cumulative exposure times to reach the same cumulative MDE. For that purpose, the following values shall be reported: (1) Time to 50 μm , designated t_{50} ; (2) time to 100 μm , designated t_{100} ; and (3) optionally, if practicable, time to 200 μm , designated t_{200} .

11.4 For a more complete description of the test result, use the following parameters (refer to Fig. 7):

11.4.1 The “maximum rate of erosion,” that is, slope of the straight line that best approximates the linear (or nearly linear) steepest portion of the cumulative erosion-time curve, expressed in micrometres per hour. This is the most commonly used single-number result found in the literature, and its use is *required* in this test method.

11.4.2 The “nominal incubation time,” that is, intercept of the maximum erosion rate line on the time axis. This also is *required*. However, this is *not* a measure of the incubation period, whose duration remains undefined. See also 11.4.3 below.

11.4.3 The “erosion threshold time” (ETT) or time required to reach a mean depth of erosion (MDE) of 1.0 μm . This is an indication of when measurable mass loss begins. Reporting of this is optional.

11.4.4 The “terminal erosion rate” if exhibited in a test that is continued for a sufficiently long time. This is optional.

11.4.5 If the terminal erosion rate is reported, then the MDE corresponding to the intersection of the terminal-rate line with the maximum-rate line, or alternatively its intercept on the MDE axis, must also be reported.

11.5 The use of other carefully defined test result representations, in addition to those required above, is optional. Some that have been used include the “tangent erosion rate” (the slope of a straight line drawn through the origin and tangent to the knee of the cumulative erosion-time curve), the MDE of that tangency point, and curves of “instantaneous erosion rate” versus time or of “average erosion rate” versus time. A recent proposal is to plot the results on Weibull Cumulative Distribution Function coordinates, and determine several parameters from the resulting straight line(s); see Ref (7) and others by the same author.

11.6 This test method is sufficiently well specified that direct comparisons between results obtained in different laboratories are meaningful, provided that the standard test