Designation: G 32 – 03

Standard Test Method for Cavitation Erosion Using Vibratory Apparatus[1]

This standard is issued under the fixed designation G 32; 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 (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method produces 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 The values stated in SI units are to be regarded as standard. The inch-pound units given in parentheses are for information only.

1.5 *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.* For specific safety precautionary information, see 6.1, 10.3, and 10.6.

2. Referenced Documents

2.1 *ASTM Standards:*

A 276 Specification for Stainless Steel Bars and Shapes[2]
B 160 Specification for Nickel Rod and Bar[3]
B 211 Specification for Aluminum and Aluminum-Alloy Bar, Rod, and Wire[4]
D 1193 Specification for Reagent Water[5]
E 177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods[6]
E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method[6]
E 960 Specification for Laboratory Glass Beakers[7]
G 40 Terminology Relating to Wear and Erosion[8]
G 73 Practice for Liquid Impingement Erosion Testing[8]
G 134 Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet[8]

3. Terminology

3.1 *Definitions:*

3.1.1 See Terminology G 40 for definitions of terms relating to cavitation erosion. For convenience, definitions of some important terms used in this test method are quoted below from Terminology G 40 – 98.

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 gas, or both.

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

[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 Liquids and Solids.

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[2] *Annual Book of ASTM Standards*, Vol 01.03.
[3] *Annual Book of ASTM Standards*, Vol 02.04.
[4] *Annual Book of ASTM Standards*, Vol 02.02.
[5] *Annual Book of ASTM Standards*, Vol 11.01.
[6] *Annual Book of ASTM Standards*, Vol 14.02.
[7] *Annual Book of ASTM Standards*, Vol 14.04.
[8] *Annual Book of ASTM Standards*, Vol 03.02.

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 *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. Also, the exposure duration associated with this stage. (Quantitatively it is sometimes defined as the intercept on the time or exposure axis, of a straight line extension of the maximum-slope portion of the cumulative erosion-time curve.)

3.1.11 *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*.)

3.1.11.1 *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.

3.1.12 *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.)

3.1.13 *normalized erosion resistance,* N_e, *n*—the volume loss rate of a test material, divided into the volume loss rate of a specified reference material 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.

3.1.13.1 *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)."

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

3.1.15 *tangent erosion rate*—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.

3.1.16 *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*.)

3.1.17 *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 G 134, which employs a cavitating liquit 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 5.7.

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. Practice G 73 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 X3.2.3), 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, X3.2).

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.

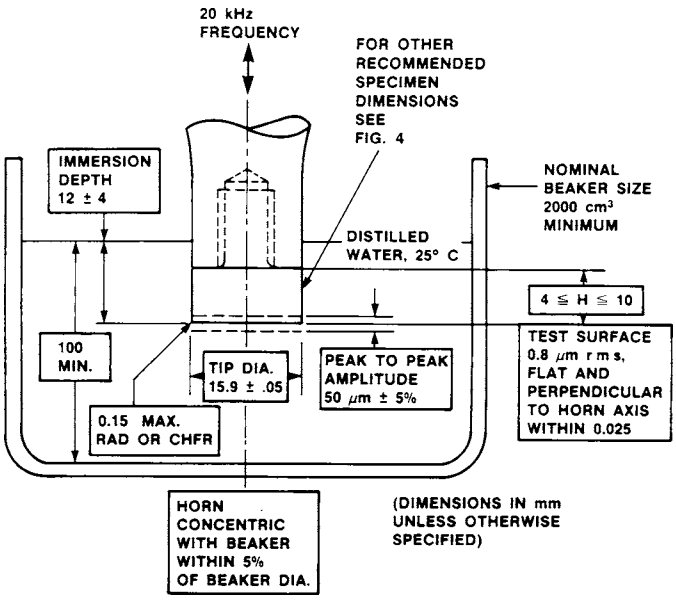


FIG. 1 Important Parameters of the Vibratory Cavitation Test

5.7 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.

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 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.[9] (**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.

[9] 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.

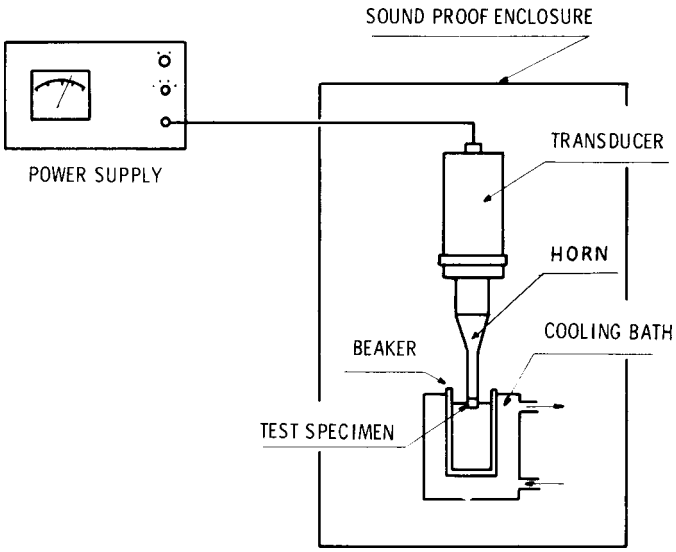


FIG. 2 Schematic of Vibratory Cavitation Erosion Apparatus

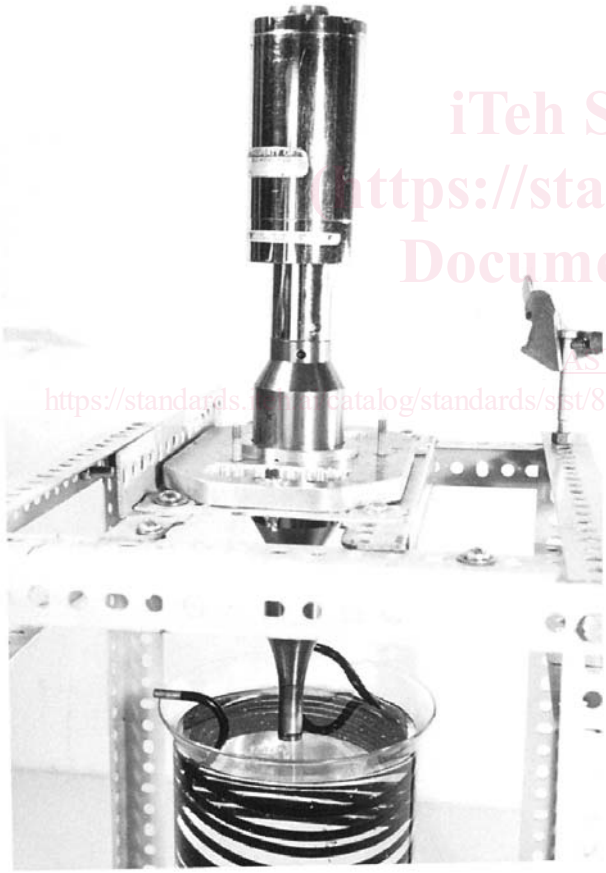


FIG. 3 Photograph of a Typical Apparatus

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).

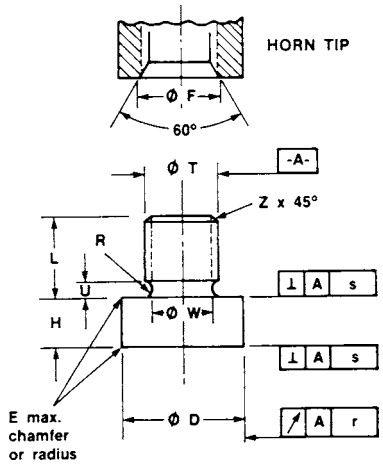


TABLE OF VALUES

	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 Paragraph 7.2	
L	10.0 ± 0.5	0.394 ± 0.02
R	0.8 ± 0.15	0.031± 0.006
T	Thread, see Paragraph 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

6.3 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 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*:

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/cm^3 or more and tuned for a button mass of about 10 g (0.022 lb), and

the other for densities less than 5 g/cm^3, 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 capacity of the vessel containing the test liquid shall be at least 2 L. Standard commercially available 2- to 4-L low-form glass beakers (for example; Type II of Specification E 960) are suitable vessels for most applications. If other containers are used they shall have a cylindrical cross section.

6.7.2 The height of the vessel shall be at least 140 mm (5.51 in.).

6.8 Means shall be provided to maintain the temperature of the test liquid 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.

6.9 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.

7.4 Unless otherwise required, the test surface shall be lightly machined, then optionally ground and polished, to a maximum surface roughness of 0.8 µm (32 µin.), 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.

7.5 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 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.

8.1.2 Perform tests with specimens of the standard reference material specified in 8.3 from time to time to verify the performance of the apparatus. Do this at standard test conditions (see 8.1.3) even if the apparatus is normally operated at optional conditions.

8.1.3 The standard reference material is annealed wrought Nickel 200 (UNS N02200), conforming to Specification B 160. This is a commercially pure (99.5 %) nickel product; see Table 1 for its properties.

8.1.4 The approximate range of test results to be expected for this material, under the standard test conditions specified in Section 9, is shown in Fig. 5 (based on results reported in an interlaboratory study). The appearance of a test specimen at several stages in a test is shown in Fig. 6.

8.2 *Calibrating the Test Program*:

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 In all cases include annealed Nickel 200 as specified in 8.1.3.

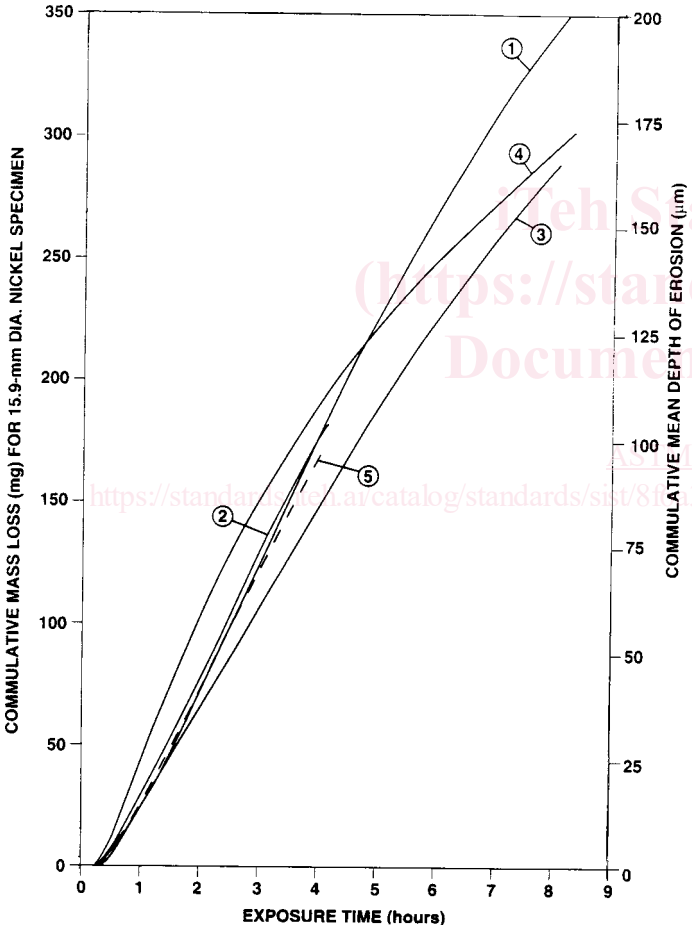
8.2.3 A reference material of lesser erosion resistance is Aluminum Alloy 6061-T6 (UNS A96061, Specification B 211).

TABLE 1 Material Used in Interlaboratory Study

Designation: Nickel 200, UNS N02200, ASTM B 160	
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.)



NOTE 1—Each curve represents an average of two or three replicate tests.

FIG. 5 Cumulative Erosion-Time Curves for Nickel 200 From Five Laboratories

8.2.4 A reference material of greater erosion resistance is annealed austenitic stainless steel Type 316, of hardness 150 to 175 HV (UNS S31600, Specification A 276).

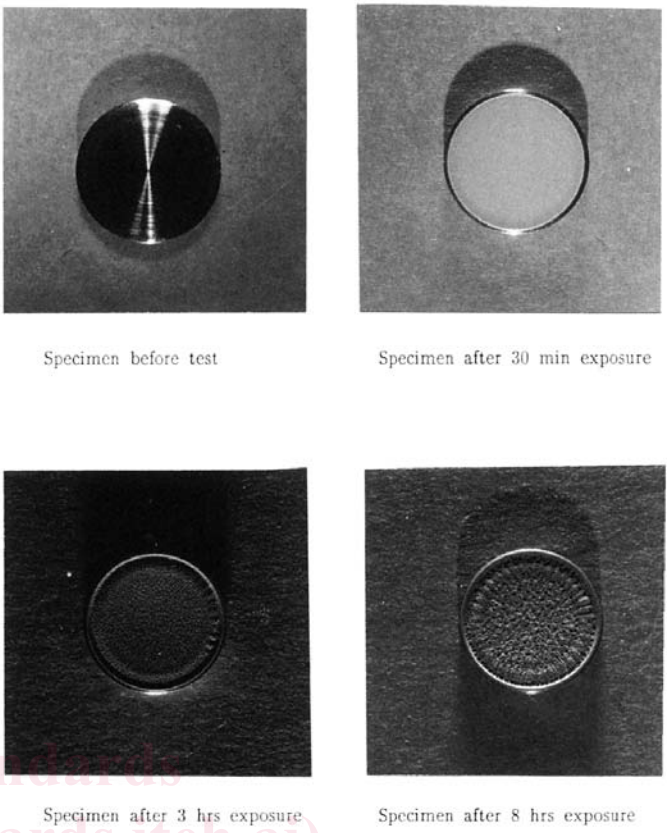


FIG. 6 Photographs of a Nickel 200 Specimen Taken at Several Cumulative Exposure Times

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 D 1193.

9.1.1.2 The depth of the liquid in its container shall be at least 100 mm (3.94 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 ± 2°C (77± 3.6°F).

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 μm (0.002 in.) ±5 % throughout the test.