



Standard Test Method for Erosion of Solid Materials by a Cavitating Liquid Jet¹

This standard is issued under the fixed designation G 134; 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 covers a test that can be used to compare the cavitation erosion resistance of solid materials. A submerged cavitating jet, issuing from a nozzle, impinges on a test specimen placed in its path so that cavities collapse on it, thereby causing erosion. The test is carried out under specified conditions in a specified liquid, usually water. This test method can also be used to compare the cavitation erosion capability of various liquids.

1.2 This test method specifies the nozzle and nozzle holder shape and size, the specimen size and its method of mounting, and the minimum test chamber size. Procedures are described for selecting the standoff distance and one of several standard test conditions. Deviation from some of these conditions is permitted where appropriate and if properly documented. Guidance is given on setting up a suitable apparatus, test and reporting procedures, and the precautions to be taken. Standard reference materials are specified; these must be used to verify the operation of the facility and to define the normalized erosion resistance of other materials.

1.3 Two types of tests are encompassed, one using test liquids which can be run to waste, for example, tap water, and the other using liquids which must be recirculated, for example, reagent water or various oils. Slightly different test circuits are required for each type.

1.4 This test method provides an alternative to Test Method G 32. In that method, cavitation is induced by vibrating a submerged specimen at high frequency (20 kHz) with a specified amplitude. In the present method, cavitation is generated in a flowing system so that both the jet velocity and the downstream pressure (which causes the bubble collapse) can be varied independently.

1.5 The values stated in SI units are to be regarded as the standard. The values 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 applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:²

A 276 Specification for Stainless Steel Bars and Shapes

B 160 Specification for Nickel Rod and Bar

B 211 Specification for Aluminum and Aluminum-Alloy Bar, Rod, and Wire

D 1193 Specification for Reagent Water

E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

G 32 Test Method for Cavitation Erosion Using Vibratory Apparatus

G 40 Terminology Relating to Wear and Erosion

G 73 Practice for Liquid Impingement Erosion Testing

2.2 ASTM Adjuncts:

Manufacturing Drawings of the Apparatus³

3. Terminology

3.1 *Definitions*—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 – 90a.

3.1.1 *cavitation*—the formation and collapse, within a liquid, of cavities or bubbles that contain vapor or gas, or both.

3.1.1.1 *Discussion*—In general, cavitation originates from a decrease in static pressure in the liquid. It is distinguished in this way from boiling, which originates from an increase in liquid temperature. There are certain situations where it may be difficult to make a clear distinction between cavitation and boiling, and the more general definition that is given here is, therefore, preferred.

3.1.1.2 *Discussion*—In order to erode a solid surface by cavitation, it is necessary for the cavitation bubbles to collapse on or close to that surface.

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.

³ Available from ASTM International Headquarters. Order Adjunct No. ADJG0134.



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

3.1.3 *cumulative erosion*—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. 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.

3.1.4 *cumulative erosion rate*—the cumulative erosion divided by the corresponding cumulative exposure duration, that is, the slope of a line from the origin to a specified point on the cumulative erosion-time curve.

3.1.5 *cumulative erosion-time curve*—a plot of cumulative erosion versus cumulative exposure time, 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.

3.1.6 *flow cavitation*—cavitation caused by a decrease in static pressure induced by changes in velocity of a flowing liquid. Typically, this may be caused by flow around an obstacle or through a constriction, or relative to a blade or foil. A cavitation cloud or “cavitating wake” generally trails from some point adjacent to the obstacle or constriction to some distance downstream, the bubbles being formed at one place and collapsing at another.

3.1.7 *incubation period—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. 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).

3.1.8 *maximum erosion rate*—the maximum instantaneous erosion rate in a test that exhibits such a maximum followed by decreasing erosion rates. (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.)

3.1.9 *normalized erosion resistance, N_e* —the volume loss rate of a test material, divided into the rate of volume loss of a specified reference material similarly tested and similarly analyzed. *Similarly analyzed* means 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.

3.1.9.1 *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).”

3.1.10 *normalized incubation resistance, N_o* —the incubation period of a test material, divided by the incubation period of a specified reference material similarly tested and similarly analyzed.

3.1.11 *terminal erosion rate*—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. This occurs in some, but not all, cavitation and liquid impingement tests.

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *cavitating jet*—a continuous liquid jet (usually submerged) in which cavitation is induced by the nozzle design or sometimes by a center body. See also *jet cavitation*.

3.2.2 *cavitation number, σ* —a dimensionless number that measures the tendency for cavitation to occur in a flowing stream of liquid, and that, for the purpose of this test method, is defined by the following equation. All pressures are absolute.

$$\sigma = \frac{(p_d - p_v)}{\frac{1}{2} \rho V^2} \quad (1)$$

where:

p_v = vapor pressure,

p_d = static pressure in the downstream chamber,

V = jet velocity, and

ρ = liquid density.

3.2.2.1 For liquid flow through any orifice

$$\frac{1}{2} \rho V^2 = p_u - p_d \quad (2)$$

where:

p_u = upstream pressure.

3.2.2.2 For erosion testing by this test method, the cavitating flow in the nozzle is choked, so that the downstream pressure, as seen by the flow, is equal to the vapor pressure. The cavitation number thus reduces to

$$\sigma = \frac{p_d - p_v}{p_u - p_v} \quad (3)$$

which for many liquids and at many temperatures can be approximated by:

$$\sigma = \frac{p_d}{p_u} \quad (4)$$

since

$$p_u \gg p_d \gg p_v \quad (5)$$

3.2.3 *jet cavitation*—the cavitation generated in the vortices which travel in sequence singly or in clouds in the shear layer around a submerged jet. It can be amplified by the nozzle design so that vortices form in the vena contracta region inside the nozzle.

3.2.4 *stand-off distance*—in this test method, the distance between the *inlet* edge of the nozzle and the target face of the specimen. It is thus defined because the location and shape of the inlet edge determine the location of the vena contracta and the initiation of cavitation.

3.2.5 *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 the shape of that curve has the characteristic S-shape pattern that permits this. In such cases, the tangent erosion rate also represents the maximum cumulative erosion rate exhibited during the test.



3.2.6 *vena contracta*—the smallest locally occurring diameter of the main flow of a fluid after it enters into a nozzle or orifice from a larger conduit or a reservoir. At this point the main or primary flow is detached from the solid boundaries, and vortices or recirculating secondary flow patterns are formed in the intervening space.

4. Summary of Test Method

4.1 This test method produces a submerged cavitating jet which impinges upon a stationary specimen, also submerged, causing cavitation bubbles to collapse on that specimen and thereby to erode it. This test method generally utilizes a commercially available positive displacement pump fitted with a hydraulic accumulator to damp out pulsations. The pump delivers test liquid through a small sharp-entry cylindrical-bore nozzle, which discharges a jet of liquid into a chamber at a controlled pressure. Cavitation starts in the *vena contracta* region of the jet within the length of the nozzle; it is stabilized by the cylindrical bore and it emerges, appearing to the eye as a cloud which is visible around the submerged liquid jet. A button type specimen is placed in the path of the jet at a specified stand-off distance from the entry edge of the nozzle. Cavitation bubbles collapse on the specimen, thus causing erosion. Both the upstream and the downstream chamber pressures and the temperature of the discharging liquid must be controlled and monitored. 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 the cumulative erosion-time curve derived from these measurements permits comparisons to be drawn between different materials, different test conditions, or between different liquids. A typical test rig can be built using a 2.5-kW pump capable of producing 21-MPa pressure. The standard nozzle bore diameter is 0.4 mm, but this may be changed if required for specialized tests.

5. Significance and Use

5.1 This test method may be used to estimate the relative resistances of materials to cavitation erosion, as may be encountered for instance in pumps, hydraulic turbines, valves, hydraulic dynamometers and couplings, bearings, diesel engine cylinder liners, ship propellers, hydrofoils, internal flow passages, and various components of fluid power systems or fuel systems of diesel engines. It can also be used to compare erosion produced by different liquids under the conditions simulated by the test. Its general applications are similar to those of Test Method G 32.

5.2 In this test method cavitation is generated in a flowing system. Both the velocity of flow which causes the formation of cavities and the chamber pressure in which they collapse can be changed easily and independently, so it is possible to study the effects of various parameters separately. Cavitation conditions can be controlled easily and precisely. Furthermore, if tests are performed at constant cavitation number (σ), it is possible, by suitably altering the pressures, to accelerate or slow down the testing process (see 11.2 and Fig. A2.2).

5.3 This test method with *standard conditions* should not be used to rank materials for applications where electrochemical

corrosion or solid particle impingement plays a major role. However, it could be adapted to evaluate erosion-corrosion effects if the appropriate liquid and cavitation number, for the service conditions of interest, are used (see 11.1).

5.4 For metallic materials, this test method could also be used as a screening test for applications subjected to highspeed liquid drop impingement, if the use of Practice G 73 is not feasible. However, this is not recommended for elastomeric coatings, composites, or other nonmetallic aerospace materials.

5.5 The mechanisms of cavitation erosion and liquid impingement erosion are not fully understood and may vary, depending on the detailed nature, scale, and intensity of the liquid/solid interactions. Erosion resistance may, therefore, arise from 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 (for example, vibratory, rotating disk, or cavitating jet) or under different experimental 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.

5.6 Because of the nonlinear nature of the erosion-time curve in cavitation erosion, the shape of that curve must be considered in making comparisons and drawing conclusions. Simply comparing the cumulative mass loss at the same cumulative test time for all materials will not give a reliable comparison.

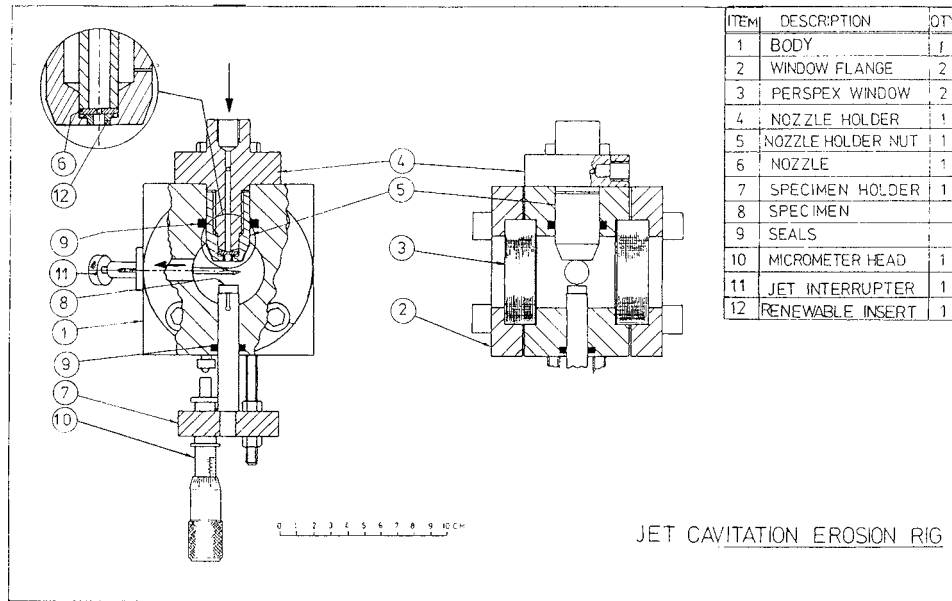
6. Apparatus

6.1 General Arrangement:

6.1.1 Fig. 1 shows an arrangement of the test chamber. A cavitating jet supplied from a constant pressure source (p_u) discharges, through a long-orifice nozzle (Fig. 2), into a chamber held at specified constant pressure (p_d). A flat-ended cylindrical specimen (Fig. 3) is mounted coaxially with the nozzle so that the stand-off distance between the nozzle inlet edge and the specimen face can be set at any required value. A movable jet deflector (Fig. 1, Item 11) may be provided to protect the specimen while test conditions are being set up. Windows may be provided at both sides of the chamber so that the erosion process can be observed. Unless the complete test chamber assembly can withstand maximum operating pressures that could occur under any conceivable circumstances, a pressure relief valve must be fitted.

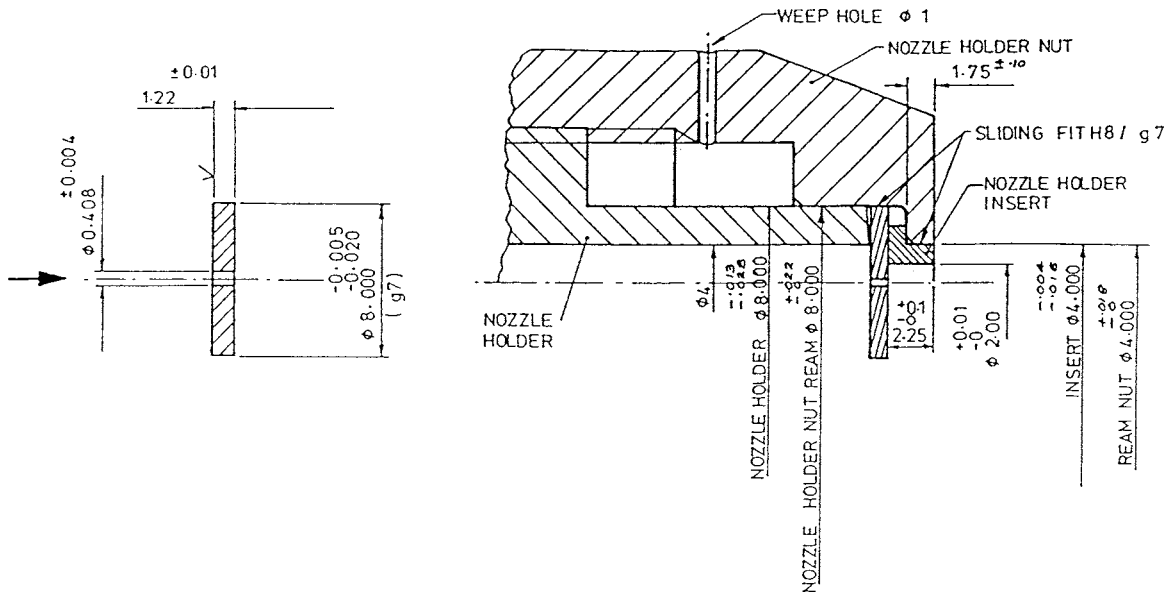
6.1.2 Manufacturing drawings of the apparatus giving pertinent dimensions are given in an Adjunct.³ For special applications; for example, where the nature of the test specimen material is granular with granules comparable to the nozzle size, a larger apparatus is required. All linear dimensions must then be increased proportionately; for example, by a factor of two to five for rock or concrete specimens.

6.2 The long-orifice nozzle (Fig. 2) is simply a cylindrical bore hole of length equal to 3.0 ± 0.1 bore diameters. It is important that the inlet edge is sharp and free from manufacturing defects and burrs. The nozzle must be made from a



NOTE 1—Reprinted by permission of the University of Nottingham.

FIG. 1 Test Chamber Assembly



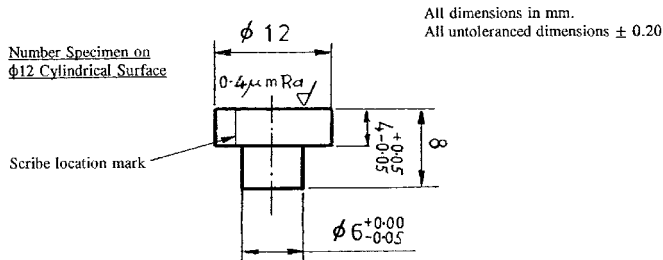
NOTE 1—Material is Nitronic 60.

NOTE 2—It is important that the inlet corner is sharp. It must not reflect light.

NOTE 3—Before drilling small hole, polish both sides with 1200 paper. Drill first, 0.35 and follow with, 0.40.

NOTE 4—All dimensions are in mm.

FIG. 2 Nozzle and Nozzle Holder



Machining at one third of the speed and one third of the feed recommended for the material to minimise work hardening.

Heat treatment _____

Material _____

(See Section 8 for additional information.)

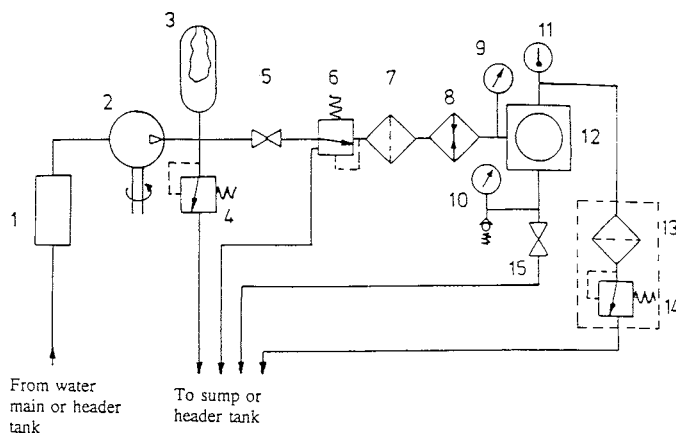
FIG. 3 Test Specimen

highly erosion- and corrosion-resistant alloy.⁴ The shape of the nozzle holder affects the nozzle performance so it is also specified in Fig. 2.

6.3 The specimen is held in place in a two-jaw collet. A line shall be scribed on the top of the holder so that it can be aligned with a corresponding line on the specimen to ensure that the specimen is fitted always in the same angular position. Similar provision shall be made so that the holder fits only one way into the chamber block.

6.4 The complete test circuit is shown in Fig. 4, and further

⁴ Nitronic-60 has been found satisfactory for this application. Other materials that could be considered include 17-4 PH stainless steel, Inconel 718, and Stellite 6.



NOTE 1—Key:

- | | |
|--|--|
| 1. Pulsation damper | 8. Heater |
| 2. Pump | 9. Upstream pressure gage 0 to 25 MPa |
| 3. Hydraulic accumulator pulsation damper | 10. Downstream pressure gage with protector 0 to 0.6 MPa |
| 4. Pressure-relief valve | 11. Thermometer |
| 5. On-Off valve | 12. Test chamber |
| 6. Pressure-regulating valve or by-pass throttle valve | 13. Downstream filter |
| 7. H.P. filter | 14. Pressure regulator |
| | 15. Drain valve |

NOTE 2—If closed system with header tank is used, cooling is essential.

FIG. 4 Test Circuit

described in Annex A1. The test chamber (12) can be used with either open or recirculating systems. The open system uses a tap water supply with the discharge running to waste, while in the closed system the test liquid is recirculated. (**Warning**—If tests with corrosive liquids are contemplated, all system components including the pump should be of stainless steel or other materials capable of handling such liquids.)

6.5 A pump capable of producing a pressure of 21 MPa and a flow of 4.5 L/min is required.

6.6 For measurement of upstream and chamber pressures, either standard test gages (0.25 % accuracy) or pressure transducers of at least equal precision and stability, having appropriate pressure ranges, shall be provided. It is strongly recommended that the low-pressure gage used for the downstream pressure measurement be protected by an appropriate pressure relief valve.

6.7 For measurement of the liquid temperature, a thermometer well or thermocouple shall be provided in the outlet pipe just downstream of the test chamber.

6.8 A suitable heater shall be provided in the system so that the desired test temperature can be maintained.

6.9 It is useful and makes testing easier if pressure regulators are fitted to control upstream and downstream pressures.

6.10 As the nozzle and regulating valve openings are small and solid particles must not reach the specimen, filters (40 μ m or finer) shall be fitted in both upstream and downstream lines. Alternatively a settling tank can be fitted on the downstream side.

6.11 If a recirculating system is used, a sump large enough to ensure adequate cooling shall be provided. A sump capacity of not less than 100 L is recommended; cooling is essential in such a system.

6.12 A very useful addition to the facility is an automatic timer which switches the pump off after a preset test time has elapsed.

7. Precautions

7.1 **Caution**—When testing relatively weak or brittle materials, ensure that they will not be damaged by merely the stagnation pressure developed by the jet and that, therefore, the erosion is attributable solely to cavitation. This can be done most easily by a preliminary test during which cavitation is suppressed while the jet velocity is kept constant; this is achieved by increasing both the downstream pressure and the upstream pressure by the same amount. Sometimes it may be advisable to check on the margin of safety by increasing the upstream pressure (but not exceeding the safe pressure limits for the apparatus) in this preliminary test until damage to the specimen does occur.

7.2 **Caution**—This apparatus can generate high sound levels, so the use of ear protection may be necessary.

8. Test Specimen

8.1 The test specimen is shown in Fig. 3. The test surface shall be plane, and normal to the specimen axis within an indicator reading of 0.02 mm.

8.2 Unless otherwise required, the test surface shall be lightly machined, then optionally ground or polished to a maximum surface roughness of 0.4 μ m (16 μ in.), in such a way

as to minimize surface damage or alteration. (For some materials, machining at one third the speed and one third the feed normally recommended has been found satisfactory.) While extremely fine finish is not required, there shall be no visible pits or scratch marks that would serve as sites for accelerated cavitation damage. For final finishing, 600-grit emery cloth may be used.

8.3 Some materials may require heat treatment to remove effects caused by machining and to ensure uniform hardness. The treatment must not alter the desired state of the material.

8.4 For materials available in sheet form, it is permissible to fix a disk of material by an appropriate adhesive to a suitably modified carrier. Ensure that the test material thickness is sufficient to accommodate erosion without weakening the specimen. A thickness of 3 mm would generally be sufficient.

8.5 A number of additional specimens may be required for setting up test conditions; for example, pressures, temperatures.

8.6 Ensure that a sufficient number of test specimens are prepared from the same stock.

9. Calibration

9.1 A pressure/flow test as described in A2.1, to determine its discharge coefficient, shall be carried out on a new nozzle and thereafter at regular intervals, initially after 40 h of use, to check that the nozzle has not deteriorated. If there develops any change in discharge coefficient greater than 1 %, take corrective action. An increase in the discharge coefficient indicates wear of the inlet edge; a decrease indicates blockage. Also examine the nozzle holder exit for erosion.

9.2 Perform a complete test on a standard reference material (see 12.9 and Table 1) at standard test conditions (see 10.1) from time to time to verify the consistency of performance of the apparatus. Conduct this calibration at standard test conditions even if the apparatus is usually operated at optional test conditions.

9.3 As a brief check, a sample of previously tested material can be inserted for an interval of time appropriate to the

material, say half an hour for steel. The result can then be compared with the previously obtained data.

10. Standard Test Conditions

10.1 If this test method is cited without additional test parameters, it shall be understood that the test conditions selected conform to the following:

10.1.1 The test liquid shall be tap water or reagent water conforming to Type IV of Specification D 1193.

10.1.2 The water temperature at nozzle inlet shall be $35 \pm 1^\circ\text{C}$.

10.1.3 Preliminary tests shall be carried out at two cavitation numbers on two different specimens, to enable assessment at various cavitation conditions and to determine appropriate testing times. These two values and the corresponding pressures are prescribed in Table 1.

10.1.4 The major tests shall be carried out at one constant cavitation number (selected on the basis of 10.1.3) so that cavitation conditions remain constant. One of the pressures must be specified and the other can be calculated from definition of cavitation number, σ (see 3.2.2). The value will depend on the materials tested and should be chosen so that the test durations are acceptable.

10.1.5 The tests shall be carried out at the stand-off distance at which maximum cumulative erosion rate occurs. This value of stand-off distance depends on cavitation number σ . As a guide for establishing this optimum stand-off distance, Fig. 5 may be used. The exact value for the apparatus used shall be determined experimentally; see A2.3. If the value of the cavitation number is to be changed, a new optimum stand-off distance must be established.

11. Optional Test Conditions

11.1 The standard test conditions conforming to Section 10 satisfy a large number of cases in which the relative resistance of materials under ordinary environmental conditions is to be determined. However, there are cases in which other temperatures, other pressures, and other liquids must be used. In these

TABLE 1 Standard Test Conditions and Reference Materials

NOTE 1—Test liquid: Water (tap or deionized)

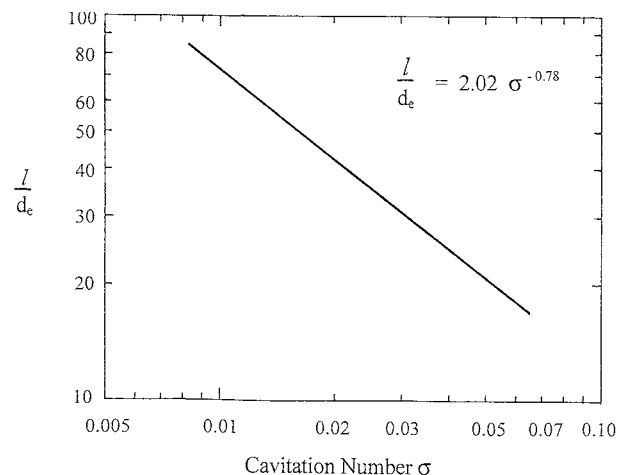
Test temperature: $T = 35 (\pm 1)^\circ\text{C}$

Corresponding vapor pressure: $p_v = 0.00563 \text{ MPa}$

NOTE 2—Upstream pressure (p_u) and downstream pressure (p_d) given in MPa absolute, for different cavitation numbers (σ) and reference materials.

NOTE 3—If two materials are to be used as references, nickel is to be tested at the lower pressure if the other material is aluminum, or at the higher pressure if the other material is steel.

Material	$\sigma = 0.014$		$\sigma = 0.025$	
	p_u	p_d	p_u	p_d
Soft aluminum 1100, UNS A91100, Specification B 211. (Heat for 2 h at 400°C , air cool.)	12.5	0.18	12.5	0.32
Annealed wrought Nickel 200, UNS N02200, Specification B 160. (See Note 3)	12.5	0.18	12.5	0.32
	17.5	0.25	17.4	0.44
Austenitic stainless steel Type 316, UNS S31600, Specification A 276, Hardness 150 to 175 HV.	17.5	0.25	17.4	0.44



l = stand-off distance, $d_c = d\sqrt{C_d}$, C_d = discharge coefficient, d = nozzle diameter

FIG. 5 Variation of Stand-Off Distance With Cavitation Number

cases reference to or citation of this test method shall clearly refer to and specify all deviations from the provisions of Section 10.

11.2 Testing at higher or lower upstream pressures but still at the same value of cavitation number must sometimes be done. Testing at high pressure increases erosion rate since maximum erosion rate is proportional to $(p_u)^n$ where $n \approx 4$. (The actual value of n will be influenced by the details of the apparatus used and by the cavitation number.) Thus highly resistant materials can be tested at higher pressure to speed up testing. Conversely, less-resistant materials can be tested at lower pressures. Also tests can be made at other values of cavitation number. In such cases a new optimum stand-off distance will have to be established (Fig. 5; also A2.3).

11.3 Tests so far specified use air-saturated liquid. The apparatus is suitable for testing using liquids with various dissolved gas content provided that an appropriate sump is fitted.

12. Procedure

12.1 Before the test, clean the specimen carefully and weigh on a balance having accuracy and sensitivity of 0.1 mg or better.

12.2 Set the stand-off distance at the required value (see 10.1.5).

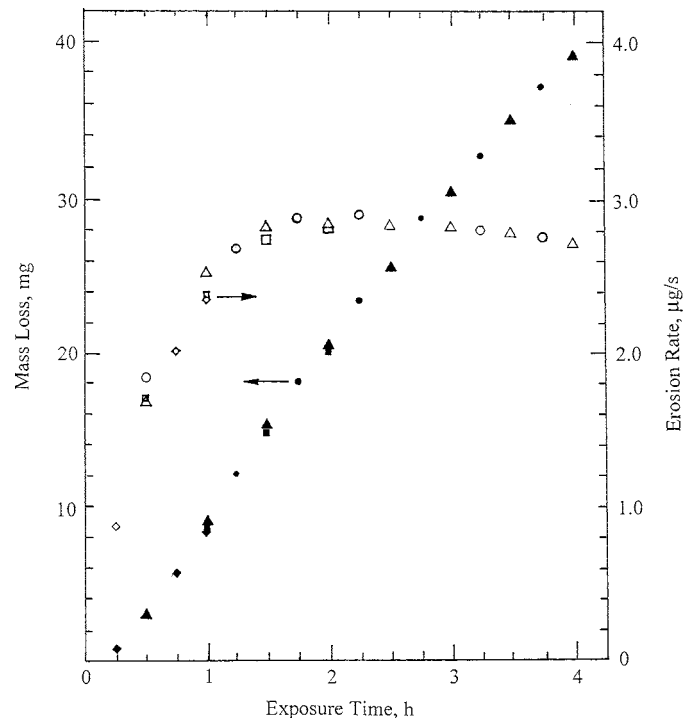
12.3 Insert a dummy specimen, fill the system with liquid, start the pump, adjust the upstream and downstream pressure, and run the system for about 20 min to allow the temperature to stabilize at the required value. Stop and remove the dummy specimen.

12.4 Insert the test specimen, making sure it is aligned correctly. Refill the test chamber with liquid and make sure that all the air is bled from the system. Start the pump and as soon as the pressures have reached the set values start the timer preset to the required test interval. Monitor pressures and temperatures. (**Warning**—A technique for using the apparatus must be developed so that the starting and stopping periods are of small duration in comparison to the test incremental time.)

12.5 Periodically stop the pump, and remove the specimen. Carefully clean and dry the specimen, and determine its mass loss by reweighing. These procedures should be repeated several times until identical successive balance readings are obtained. Continue the test by repeating the procedure described in 12.4. (**Warning**—Careful cleaning, to remove debris and deposits, and drying is essential. For cleaning, an ultrasonic bath (such as may be bought for cleaning dentures) may be used with a solvent such as acetone or ethyl alcohol. For general drying, a hair dryer may be used. For porous materials, drying in a vacuum desiccator is recommended.)

12.6 It is well known that 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. Time intervals for stainless steel can be inferred from the sample results given in Fig. 6.

12.7 Continue the test of each specimen at least until the cumulative erosion rate has reached a maximum and has



NOTE 1—Material—17/4 precipitation-hardened stainless steel; Test Conditions: $p_u = 19.6$ MPa, $p_d = 0.4$ MPa, $\sigma = 0.020$, $T = 30$ to 31°C .

NOTE 2—Filled-in symbols represent cumulative mass loss; open symbols represent mass loss rate.

FIG. 6 Example of a Plot of Results for One Material

started to diminish, that is, until a tangent can be drawn from the origin to the knee of the cumulative erosion-time curve. If long-term behavior is important, some specimens should be tested, if possible, until the terminal erosion rate (if any) is reached. If several materials are to be compared, all materials should be tested until they reach about the same volumetric amount of erosion, if feasible within time constraints.

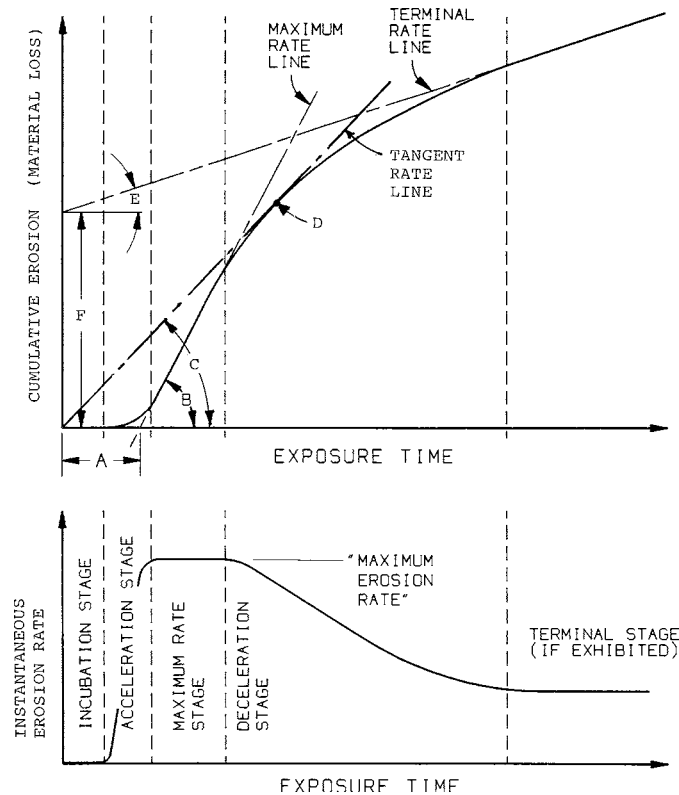
12.8 Plot the mass loss against time as the test proceeds; this may help to identify any errors.

12.9 In each major test program, include among the materials tested at least one of the reference materials listed in Table 1, tested under the same conditions to facilitate calculation of normalized erosion resistance of the other materials.

13. Calculation and Interpretation of Results

13.1 Interpretation and reporting of cavitation erosion test data is made difficult by two factors. The first is that the rate of erosion (material loss) is not constant with time (see Figs. 6 and 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 second is that there is no independent or absolute definition of “erosion resistance,” nor can units of measurement be ascribed to it. Paragraphs 13.2-13.7 describe required, as well as optional, data interpretation steps.

13.2 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 volume loss versus time curve. That



NOTE 1—A = Incubation Time; $\tan B$ = Maximum (Instantaneous) Erosion Rate; $\tan C$ = Tangent Erosion Rate; D = Tangent Point; $\tan E$ = Terminal Erosion Rate; F = Terminal Line Intercept.

NOTE 2—A terminal stage is not always reached.

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

is because the volume loss is the more significant when materials of different densities are compared.

13.3 Because of the shape of the cumulative erosion-time curve, it is *not* meaningful to compare the mass or volume loss 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, for a crude single-number comparison one *may* compare the cumulative exposure times to reach the *same cumulative volume loss*.

13.4 For a more complete description of the test result, use the following parameters (see Fig. 7):

13.4.1 The maximum (instantaneous) erosion rate, that is, the slope of the straight line that best approximates the linear (or nearly linear) steepest portion of the cumulative erosion-time curve (B in Fig. 7). This is the most commonly used single-number result found in the literature, and its reporting is *required* in this test method.

13.4.2 The nominal incubation time, that is, the intercept of the maximum erosion rate line on the time axis (A in Fig. 7). This also is *required*.

13.4.3 The tangent erosion rate (C in Fig. 7), or the maximum cumulative erosion rate. This is strongly recommended.

13.4.4 The exposure time or the volume loss corresponding to the tangent point (D in Fig. 7), which defines the “knee” of the cumulative erosion-time curve.

13.5 The use of other carefully defined test result representations, *in addition to those specified above*, is optional. Some that have been used include the terminal erosion rate (E in Fig. 7), its intercept (F in Fig. 7), or the volume loss at its intersection with the maximum rate line, and curves of instantaneous erosion rate versus time or of cumulative erosion rate versus time.

13.6 To represent the results for one material from tests on several specimens, *either* determine the above-specified parameters for each specimen individually and then calculate and report their averages and standard deviations, *or* plot the points from all specimens on one cumulative erosion-time graph, draw the best-fit curve through the scatter band, and determine the parameters for that curve. In the second method, the standard deviation of all points from the curve could be calculated.



13.7 To facilitate comparisons between results from different types of cavitation erosion tests, it is also necessary to present results in *normalized* form, relative to one or more standard reference materials included in the test program (see Table 1). Specific parameters used include normalized erosion resistance and normalized incubation resistance (see Section 3).

14. Report

14.1 Report the following information:

14.1.1 The purpose of the test.

14.1.2 A clear statement of whether or not the test conditions conformed to Section 10. Describe any deviations.

14.1.3 Identification and properties of each test material, including not only its standard designation, but also (when applicable) its composition, density, and the actual hardness, tensile strength, yield (or proof) stress, elongation and reduction in area, measured in a tensile test of a sample from the same lot as the specimens. If possible, also give surface roughness measurements taken on a finished specimen face, and hardness on a finished specimen surface other than the face exposed to cavitation.

14.1.4 A description of the test specimen and the method of preparing the test surface, if different from the specifications of 8.1 and 8.2. Also, details of post-machining heat treatment, if any.

14.1.5 The number of specimens tested.

14.1.6 Identification of the liquid used. If different from 10.1.1, give its specifications including its name and composition, and its density and vapor pressure at the test temperature or at several temperatures bracketing the test temperature. For heavy oils or other viscous liquids, also give the viscosity and surface tension, if known.

14.1.7 Full specification of test conditions, including measured test temperature, cavitation number, upstream and downstream pressures, and stand-off distance.

14.1.8 A tabulation giving the following information on each specimen tested:

14.1.8.1 Total cumulative time of exposure,

14.1.8.2 Total cumulative mass loss (mg),

14.1.8.3 Total cumulative volume loss (mm³), calculated from mass loss and material density,

14.1.8.4 Maximum instantaneous rate of erosion (see 13.4.1),

14.1.8.5 Nominal incubation time (see 13.4.2), and

14.1.8.6 The tangent erosion rate (see 13.4.3).

14.1.9 A tabulation giving the normalized erosion resistance and normalized incubation resistance for each material tested (see 13.6), relative to the reference material included in the test.

14.1.10 In a full report, also include the following for each specimen tested:

14.1.10.1 Tabulation of cumulative exposure times and corresponding cumulative mass losses and other selected parameters for each specimen. An example is shown in Table 2.

TABLE 2 Example of Test Results for One Specimen

NOTE 1—Material—Armco Iron E04, density 7.858 g/cm³

Liquid—Tap water

Test Conditions— $p_u = 12.5$ MPa; $p_d/p_u = 0.0144$; $T = 30^\circ\text{C}$

Exposure Time, h	Specimen Mass, g	Cumulative Material Loss		Cumulative Erosion Rate	
		mg	mm ³	mg/h	mm ³ /h
0.0	4.41519	0.0	0.0	0.0	0.0
0.667	4.41367	1.52	0.193	2.28	0.290
1.333	4.41056	4.63	0.589	3.47	0.442
2.333	4.40262	12.57	1.600	5.39	0.686
3.0	4.39606	19.13	2.434	6.38	0.811
4.0	4.38636	28.83	3.669	7.21	0.917
5.0	4.37770	37.49	4.771	7.50	0.954
6.0	4.36988	45.31	5.766	7.55	0.961
7.333	4.36117	54.02	6.875	7.37	0.938

14.1.10.2 Plot of cumulative mass loss or cumulative volume loss, or both, versus exposure time for each specimen; a cumulative erosion rate plot is optional. As an example, see Fig. 6.

14.1.11 Any special occurrences or observations.

15. Precision and Bias

15.1 Precision:

15.1.1 Tests—No formal interlaboratory test has yet been conducted; thus no information can be given on reproducibility (between-laboratory variability). However, results from a single laboratory have been provided from which repeatability (within-laboratory variability) estimates can be calculated. These results were derived from tests on three different materials all at the same operating conditions, and on a fourth material at two different operating conditions. In each of these variations (or cells), replicate tests were done on three specimens.

15.1.2 Test Results—A smooth curve was drawn through the test points for each specimen and then characterized by three parameters, in accordance with 13.4: the maximum instantaneous erosion rate (see 13.4.1), the incubation time (see 13.4.2), and the maximum cumulative erosion rate, which in all cases but one was the tangent erosion rate (see 13.4.3). (In the one anomalous test, the cumulative erosion-versus-time plot curved upward at the end, and no tangent line could be drawn.) These results are tabulated in Table 3.

15.1.3 Statistical Analysis—In order to obtain pooled estimates of repeatability, the method prescribed in Practice E 691 had to be modified slightly because none of the cell results is directly comparable to any other, involving as they do different materials and operating conditions, and widely varying magnitudes of results. Therefore, we cannot simply pool variances (or squares of cell standard deviations) to obtain repeatability standard deviation as shown in Practice E 691. Instead we must work immediately with normalized values; that is, coefficients of variation, as follows:

$$C_{vr} = \sqrt{\frac{1}{p} \sum C_v^2} \quad (6)$$



TABLE 3 Summary of Test Results for Repeatability Study

NOTE 1—Each average and standard deviation shown is derived from three replicate tests.

Group Number	Test ^A Conditions	Material ^B	Tangent Rate		Maximum Rate		Incubation Time	
			Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
			mg/h		mg/h		h	
1	I	A	7.65	0.192	10.11	1.127	1.103	0.1021
1	I	B	10.76	0.392	14.47	0.681	0.780	0.0520
1	I	C	37.97	0.833	53.37	4.366	0.084	0.0101
2	II	D	11.56	0.225	15.43	1.201	0.377	0.0252
2	III	D	4.31 ^C	0.046	5.30	0.281	0.617	0.0451

^A Test conditions (pressures are absolute):I: $p_u = 12.5$ MPa; $p_d/p_u = 0.0144$; $T = 30^\circ\text{C}$; tap water.II: $p_u = 19.6$ MPa; $p_d/p_u = 0.0204$; $T = 50^\circ\text{C}$; acidic water.III: $p_u = 15.3$ MPa; $p_d/p_u = 0.0261$; $T = 50^\circ\text{C}$; acidic water.^B Materials:

A = Armco Iron E04; B = Single-phase Brass M63;

C = Aluminum Alloy PA2; D = 17-4 PH stainless steel.

^C One of these three tests did not exhibit a tangent rate and the maximum cumulative erosion rate was used instead.

where:

 C_{vr} = repeatability coefficient of variation, C_v = s/x = cell coefficient of variation, s = cell standard deviation, x = cell average, and p = number of cell results pooled.

15.1.4 *Repeatability*—The statistical results for each of the test characteristics are shown in Table 4. Pooled results are shown for each group of tests separately, and for all data combined. It will be seen that the repeatability within Group 2 was better than that within Group 1; no explanation is offered for this. But the most significant result is that the repeatability

TABLE 4 Repeatability Coefficients of Variation, %

Group Number	Tangent Rate	Maximum Rate	Incubation Time
1 only	2.85	8.43	9.56
2 only	1.57	6.67	7.00
1 and 2 pooled	2.42	7.77	8.63

coefficient of variation for the tangent erosion rate (about 2.4 %) was far better than those for the maximum erosion rate and the incubation time (around 8 %). This was true even though the shape of individual test curves in the same cell sometimes varied considerably. This reinforces the desirability of continuing tests until the knee of the cumulative erosion-time curve has been passed, and the tangent erosion rate can be established.

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

16. Keywords

16.1 cavitating jet; cavitation; cavitation erosion; erosion by liquids; erosion of solids; erosion test; flow cavitation

ANNEXES

(Mandatory Information)

A1. APPARATUS AND HYDRAULIC SYSTEM

A1.1 Test Cell:

A1.1.1 Fig. 1 shows the arrangement of the test cell. Manufacturing drawings of the Nottingham University apparatus are available as an adjunct.

A1.1.2 For the nozzle, the sharpness of the inlet edge is very important as it affects the contraction of the jet and hence strongly influences the cavitation intensity. It is important, therefore, to adhere to the manufacturing instructions given in Fig. 2. Another sensitive element is the nozzle holder insert; as it will erode with time, it must be replaced occasionally. It is very important that its concentricity with the nozzle is maintained.

A1.1.3 The test chamber itself shall be provided with an air bleeding and drainage system.

A1.2 Upstream Pressure Control:

A1.2.1 A hydraulic accumulator to damp out pump pulsation and a pressure relief valve must be provided. Flow control is achieved by returning some of the flow through throttle valves to the sump or by a pressure-regulating valve if fitted.

A1.2.2 Both a pressure control valve and a by-pass control have been used on different sets of apparatus. A pressureregulating system is slightly easier to operate, but it requires a more expensive valve, especially if a stainless steel version is



necessary. In the by-pass system, two stainless steel final metering valves are used. They must be trimmed so that the pressure difference is divided between them to minimize cavitation. With a little practice it is a simple operation. Once set and when conditions are unaltered there is often no need to readjust valves when the specimen has been changed.

A1.3 Downstream Pressure Control—Downstream pressure must be controlled accurately at low pressure levels so it is difficult to obtain a suitable control valve. To overcome this problem, a small pressure container (76.2 mm in diameter, 400 mm high) was made from unplasticized PVC water piping. The vessel is pressurized by compressed air controlled by an easily obtainable precision pneumatic regulator. The inlet pipe from the test cell is connected near the top of the pressure container. Inside, some distance above the bottom, is a needle float valve which releases water when the level in the container becomes too high. The space below the needle valve is a trap for debris. The float must be sufficiently strong so as not to be crushed by the downstream pressure.

A1.4 Hydraulic System:

A1.4.1 The system is described briefly in Section 6; more details of the system currently used at one laboratory (University of Nottingham, U.K.) are given here. The numbers in parentheses refer to corresponding numbers in Fig. 4.

A1.4.2 A small positive-displacement pump (2) (maximum pressure 21 MPa, flow 4.5 L/min) is supplied either from water mains or from a header tank which also serves as a sump. Pulsations produced by the pump in the inlet pipe are damped out by a flexible tube pulsation damper (1) and on the downstream side of the pump by a hydraulic accumulator (3). A pressure relief valve (4) is also provided. An isolating valve (5) is required when changing specimens and nozzles.

A1.4.3 A pressure regulating valve (6) is used to control working pressure, the dumped flow being returned to sump. (This valve can be replaced by two throttle valves in series in

the by-pass line leading to the sump). Two valves are required to divide the pressure drop as otherwise cavitation will soon erode one of them. The valves should be trimmed so that cavitation is minimized. The flow to the test chamber then passes through a filter and an electric heater system fitted with automatic temperature control.

A1.4.4 The bore of the straight passage leading to the nozzle should be not less than ten nozzle bore diameters so that the dynamic pressure can be neglected. The length of this passage, including a section of the inlet pipe, should be not less than 100 nozzle bore diameters to provide good approach conditions.

A1.4.5 Upstream and downstream pressures are measured by pressure gages (9) and (10); the latter must be protected by a pressure relief valve. Liquid temperature is measured by a thermometer (11) placed in a well just downstream of the test chamber.

A1.4.6 Because of erosion debris flowing out of the test cell, a downstream filter (13) or a settling chamber must be provided upstream of the downstream pressure regulator (14). (Small eroded pieces would quickly block the pressure regulating valve.) The test liquid in an open system is run to waste; in a closed system it is returned through a cooler (if necessary) to the header (sump) tank.

A1.5 Component Identification:

A1.5.1 The following components, used in the University of Nottingham test rig, have been found satisfactory. Other components with comparable characteristics can be used:

A1.5.2 Pump from CAT Pumps, P.O. Box 885, Minneapolis, MN 55440, Model 551, maximum pressure of 21.0 MPa. (The pump is run at about 380 rpm as rated flow is too large).

A1.5.3 Inlet pipe pulsation damper from CAT Pumps.

A1.5.4 All pipe fittings and valves from Swagelock & Whitey Co., OH.

A1.5.5 Pressure relief valve Model C-5375 A/2, from Marshalsea Hydraulics Ltd, Taunton, Somerset, TA1 4DZ, UK.

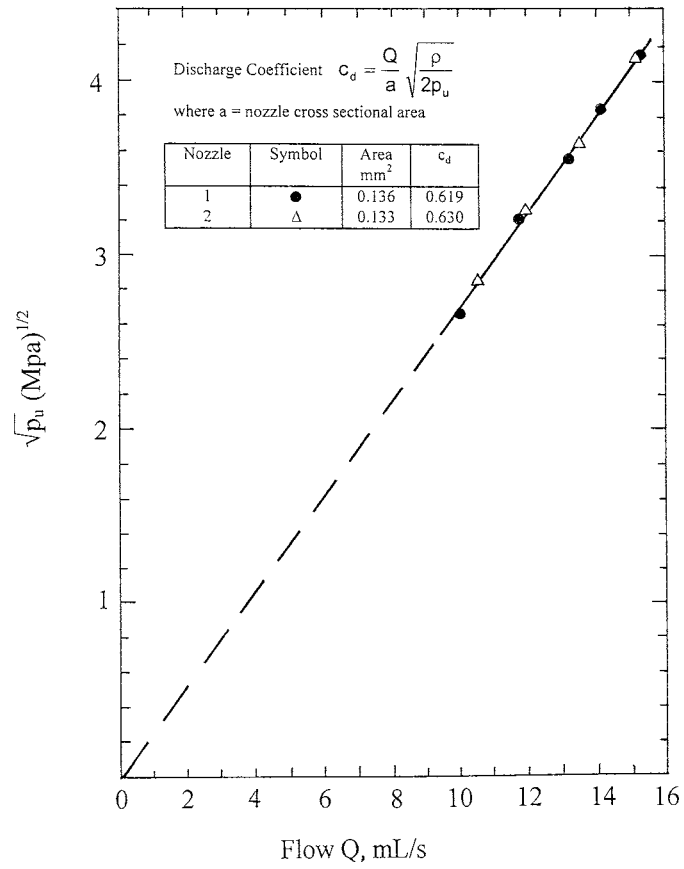
A2. AUXILIARY OPERATIONS

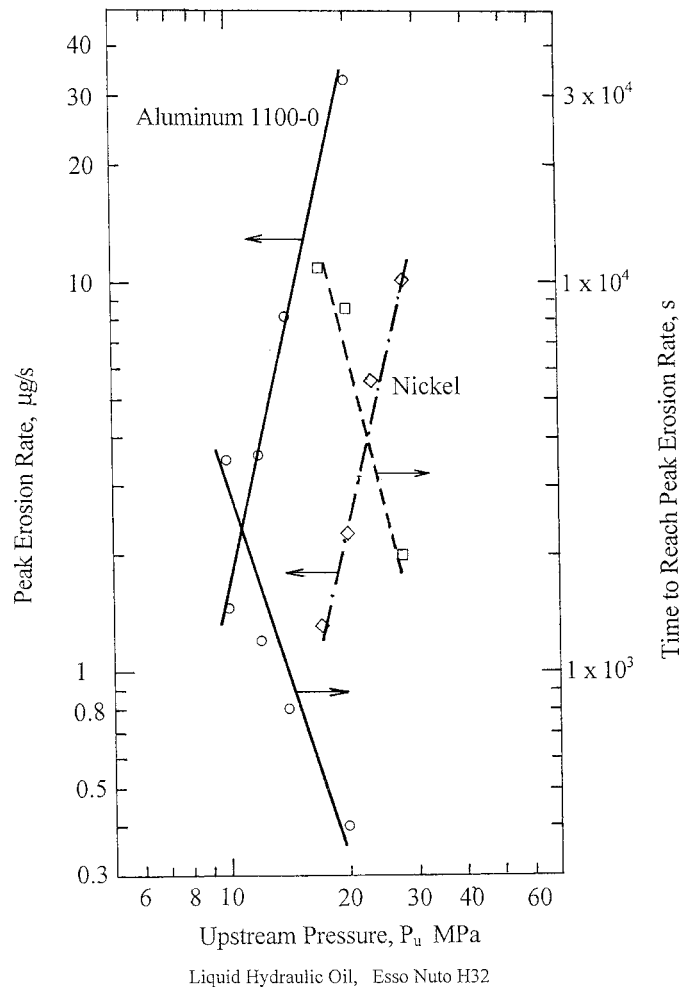
A2.1 Nozzle Calibration—The nozzle is mounted in the test cell and the discharge is redirected to a measuring cylinder. The apparatus is run at a number of different upstream pressures in the range from 8 to 15 MPa absolute and the pressure, the flow rate, and the temperature are measured. A graph of the square root of the difference between the upstream pressure and the vapor pressure of the test liquid is plotted against flow rate, and the discharge coefficient calculated, as shown in Fig. A2.1. Note that under these test conditions the nozzle will be cavitating, the flow will be choked, and the downstream pressure as seen by the nozzle will be the vapor pressure, p_v .

A2.2 Testing at Different Pressures—When the cavitation number is kept constant and both pressures are changed, the relationships between the maximum erosion rate, time to reach

that rate, and the pressure are shown in Fig. A2.2.

A2.3 Experimental Determination of Optimum Stand-Off Distance—To determine the optimum stand-off distance, conduct a series of abbreviated erosion tests on different specimens of the same material, at a number of different stand-off distances but at the same specified conditions of cavitation number and p_u . Follow the test procedures of Section 12, but run each test for only two or three time intervals; with Nickel 200 or brass, for instance, mass loss measurements after 10 and 20 min of exposure would suffice. Plots of the cumulative mass loss versus stand-off distance, for constant exposure duration, will show peaks at the optimum stand-off. If the exposure durations for different stand-off distances are not *exactly* the same, then plot the corresponding cumulative erosion rates versus stand-off distance.





NOTE 1—The cavitation number in these tests was 0.0143.

FIG. A2.2 Variation of Peak Erosion Rate and Time to Reach Peak with Nozzle Pressure

APPENDIX

(Nonmandatory Information)

X1. BACKGROUND OF METHOD

X1.1 A cavitating jet produces erosion on a surface placed in its path. This erosion can be considerably increased by suitable design of the nozzle (see Sections 4 and 6 of this test method). This was first proposed by Lichtarowicz (1)⁵ and later used for erosion testing by Lichtarowicz (2), Kleinbreuer (3), and Yamaguchi and Shimizu (4). Since then, a number of laboratories over the world have built and are using cavitating jet apparatus based mainly on the design described in (2), which is the basis for this test method.

X1.2 More information on this test method can be found in

⁵ The boldface numbers in parentheses refer to the list of references at the end of this standard.

(5), (6), and (7). A different type of cavitating jet configuration is described in (8) and (9). The present test method, however, is intended to provide a relatively low-cost, simple to implement, design that can be readily duplicated in different laboratories.

X1.3 One of the important features in this test method is the nozzle holder (Fig. 2), which influences the intensity of cavitation emerging from the nozzle assembly. Testing times can be decreased and erosion increased by changing the dimensions and shape of the holder. The present standard design, based on several years of testing, presents a reasonable optimization between cavitation intensity produced and nozzle assembly life.



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