Designation: D2837 – 13$^{\varepsilon 1}$

Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products[1]

This standard is issued under the fixed designation D2837; 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.

ε^1 NOTE—Table 8 was editorially corrected in April 2014.

1. Scope*

1.1 This test method describes two essentially equivalent procedures: one for obtaining a long-term hydrostatic strength category based on stress, referred to herein as the hydrostatic design basis (HDB); and the other for obtaining a long-term hydrostatic strength category based on pressure, referred to herein as the pressure design basis (PDB). The HDB is based on the material's long-term hydrostatic strength (LTHS),and the PDB is based on the product's long-term hydrostatic pressure-strength ($LTHS_P$). The HDB is a material property and is obtained by evaluating stress rupture data derived from testing pipe made from the subject material. The PDB is a product specific property that reflects not only the properties of the material(s) from which the product is made, but also the influence on product strength by product design, geometry, and dimensions and by the specific method of manufacture. The PDB is obtained by evaluating pressure rupture data. The LTHS is determined by analyzing stress versus time-to-rupture (that is, stress-rupture) test data that cover a testing period of not less than 10 000 h and that are derived from sustained pressure testing of pipe made from the subject material. The data are analyzed by linear regression to yield a best-fit log-stress versus log time-to-fail straight-line equation. Using this equation, the material's mean strength at the 100 000-h intercept (LTHS) is determined by extrapolation. The resultant value of the LTHS determines the HDB strength category to which the material is assigned. The $LTHS_P$ is similarly determined except that the determination is based on pressure versus time data that are derived from a particular product. The categorized value of the $LTHS_P$ is the PDB. An HDB/PDB is one of a series of preferred long-term strength values. This test method is applicable to all known types of thermoplastic pipe materials and thermoplastic piping products. It is also applicable for any practical temperature and medium that yields stress-rupture data that exhibit an essentially straight-line relationship when plotted on log stress (pound-force per square inch) or log pressure (pound-force per square in. gage) versus log time-to-fail (hours) coordinates, and for which this straight-line relationship is expected to continue uninterrupted through at least 100 000 h.

1.2 Unless the experimentally obtained data approximate a straight line, when calculated using log-log coordinates, it is not possible to assign an HDB/PDB to the material. Data that exhibit high scatter or a "knee" (a downward shift, resulting in a subsequently steeper stress-rupture slope than indicated by the earlier data) but which meet the requirements of this test method tend to give a lower forecast of $LTHS/LTHS_P$. In the case of data that exhibit excessive scatter or a pronounced "knee," the lower confidence limit requirements of this test method are not met and the data are classified as unsuitable for analysis.

1.3 A fundamental premise of this test method is that when the experimental data define a straight-line relationship in accordance with this test method's requirements, this straight line may be assumed to continue beyond the experimental period, through at least 100 000 h (the time intercept at which the material's $LTHS/LTHS_P$ is determined). In the case of polyethylene piping materials, this test method includes a supplemental requirement for the "validating" of this assumption. No such validation requirements are included for other materials (see Note 1). Therefore, in all these other cases, it is up to the user of this test method to determine based on outside information whether this test method is satisfactory for the forecasting of a material's $LTHS/LTHS_P$ for each particular combination of internal/external environments and temperature.

NOTE 1—Extensive long-term data that have been obtained on commercial pressure pipe grades of polyvinyl chloride (PVC), polybutlene (PB), and cross linked polyethlene (PEX) materials have shown that this assumption is appropriate for the establishing of HDB's for these materials for water and for ambient temperatures. Refer to Note 2 and Appendix X1 for additional information.

*A Summary of Changes section appears at the end of this standard

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[1] This test method is under the jurisdiction of ASTM Committee F17 on Plastic Piping Systems and is the direct responsibility of Subcommittee F17.40 on Test Methods.

Current edition approved Nov. 15, 2013. Published December 2013. Originally approved in 1969. Last previous edition approved in 2011 as D2837 – 11. DOI: 10.1520/D2837-13.

1.4 The experimental procedure to obtain individual data points shall be as described in Test Method D1598, which forms a part of this test method. When any part of this test method is not in agreement with Test Method D1598, the provisions of this test method shall prevail.

1.5 General references are included at the end of this test method.

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.*

1.7 The values stated in inch-pound units are to be regarded as the standard. The values given in parentheses are for information only and are not considered the standard.

NOTE 2—Over 3000 sets of data, obtained with thermoplastic pipe and piping assemblies tested with water, natural gas, and compressed air, have been analyzed by the Plastic Pipe Institute's (PPI) Hydrostatic Stress Board[2]. None of the currently commercially offered compounds included in PPI TR-4, "PPI Listing of Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe" exhibit knee-type plots at the listed temperature, that is, deviate from a straight line in such a manner that a marked drop occurs in stress at some time when plotted on equiscalar log-log coordinates. Ambient temperature stress-rupture data that have been obtained on a number of the listed materials and that extend for test periods over 120 000 h give no indication of "knees." However, stress-rupture data which have been obtained on some thermoplastic compounds that are not suitable or recommended for piping compounds have been found to exhibit a downward trend at 23°C (73°F) in which the departure from linearity appears prior to this test method's minimum testing period of 10 000 h. In these cases, very low results are obtained or the data are found unsuitable for extrapolation when they are analyzed by this test method.

Extensive evaluation of stress-rupture data by PPI and others has also indicated that in the case of some materials and under certain test conditions, generally at higher test temperatures, a departure from linearity, or "down-turn", may occur beyond this test method's minimum required data collection period of 10 000 h. A PPI study has shown that in the case of polyethylene piping materials that are projected to exhibit a "down-turn" prior to 100 000 h at 73°F, the long-term field performance of these materials is prone to more problems than in the case of materials which have a projected "down-turn" that lies beyond the 100 000-h intercept. In response to these observations, a supplemental "validation" requirement for PE materials has been added to this test method in 1988. This requirement is designed to reject the use of this test method for the estimating of the long-term strength of any PE material for which supplemental elevated temperature testing fails to validate this test method's inherent assumption of continuing straight-line stress-rupture behavior through at least 100 000 h at 23°C (73°F).

When applying this test method to other materials, appropriate consideration should be given to the possibility that for the particular grade of material under evaluation and for the specific conditions of testing, particularly, when higher test temperatures and aggressive environments are involved, there may occur a substantial "down-turn" at some point beyond the data collection period. The ignoring of this possibility may lead to an overstatement by this test method of a material's actual LTHS/LTHS$_P$. To obtain sufficient assurance that this test method's inherent assumption of continuing linearity through at least 100 000 h is appropriate, the user should consult and consider information outside this test method, including very long-term testing or extensive field experience with similar materials. In cases for which there is insufficient assurance of the continuance of the straight-line behavior that is defined by the experimental data, the use of other test methods for the forecasting of long-term strength should be considered (see Appendix X1).

2. Referenced Documents

2.1 *ASTM Standards:*[3]

D1243 Test Method for Dilute Solution Viscosity of Vinyl Chloride Polymers

D1598 Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure

E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications

2.2 *ISO Standard:*

ISO 9080 Plastic Piping and Ducting Systems, Determination of Long-Term Hydrostatic Strength of Thermoplastics Materials in Pipe Form by Extrapolation[4]

2.3 *Plastics Pipe Institute:*[2]

PPI TR-3 Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Hydrostatic Design Stresses (HDS), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe

PPI TR-4 PPI Listing of Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe

3. Terminology

3.1 *Definitions:*

3.1.1 *failure*—bursting, cracking, splitting, or weeping (seepage of liquid) of the pipe during test.

3.1.2 *hoop stress*—the tensile stress in the wall of the pipe in the circumferential orientation due to internal hydrostatic pressure.

3.1.3 *hydrostatic design basis (HDB)*—one of a series of established stress values for a compound. It is obtained by categorizing the LTHS in accordance with Table 1.

3.1.4 *hydrostatic design stress (HDS)*—the estimated maximum tensile stress the material is capable of withstanding continuously with a high degree of certainty that failure of the pipe will not occur. This stress is circumferential when internal hydrostatic water pressure is applied.

3.1.5 *long-term hydrostatic strength (LTHS)*—the estimated tensile stress in the wall of the pipe in the circumferential orientation that when applied continuously will cause failure of the pipe at 100 000 h. This is the intercept of the stress regression line with the 100 000-h coordinate.

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[2] Available from Plastics Pipe Institute (PPI), 105 Decker Court, Suite 825, Irving, TX 75062, http://www.plasticpipe.org.

[3] 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.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org..

TABLE 1 Hydrostatic Design Basis Categories

NOTE 1—The LTHS is determined to the nearest 10 psi. Rounding procedures in Practice E29 should be followed.

Range of Calculated LTHS Values		Hydrostatic Design Basis	
psi	(MPa)	psi	(MPa)
190 to < 240	(1.31 to < 1.65)	200	(1.38)
240 to < 300	(1.65 to < 2.07)	250	(1.72)
300 to < 380	(2.07 to < 2.62)	315	(2.17)
380 to < 480	(2.62 to < 3.31)	400	(2.76)
480 to < 600	(3.31 to < 4.14)	500	(3.45)
600 to < 760	(4.14 to < 5.24)	630	(4.34)
760 to < 960	(5.24 to < 6.62)	800	(5.52)
960 to <1200	(6.62 to < 8.27)	1000	(6.89)
1200 to <1530	(8.27 to <10.55)	1250	(8.62)
1530 to <1730	(10.55 to <11.93)	1600	(11.03)
1730 to <1920	(11.93 to <13.24)	1800	(12.41)
1920 to <2160	(13.24 to <14.89)	2000	(13.79)
2160 to <2400	(14.89 to <16.55)	2250	(15.51)
2400 to <2690	(16.55 to <18.55)	2500	(17.24)
2690 to <3020	(18.55 to <20.82)	2800	(19.30)
3020 to <3410	(20.82 to <23.51)	3150	(21.72)
3410 to <3830	(23.51 to <26.41)	3550	(24.47)
3830 to <4320	(26.41 to <29.78)	4000	(27.58)
4320 to <4800	(29.78 to <33.09)	4500	(31.02)
4800 to <5380	(33.09 to <37.09)	5000	(34.47)
5380 to <6040	(37.09 to <41.62)	5600	(38.61)
6040 to <6810	(41.62 to <46.92)	6300	(43.41)
6810 to <7920	(46.92 to <54.62)	7100	(48.92)

3.1.6 *long-term hydrostatic pressure-strength ($LTHS_P$)*—the estimated internal pressure that when applied continuously will cause failure of the pipe at 100 000 h. This is the intercept of the pressure regression line with the 100 000-h interce

3.1.7 *pressure*—the force per unit area exerted by the medium in the pipe.

3.1.8 *pressure rating (PR)*—the estimated maximum water pressure the pipe is capable of withstanding continuously with a high degree of certainty that failure of the pipe will not occur.

3.1.8.1 The PR and HDS/HDB are related by the following equation.

$$PR = 2\,(HDB)\,(DF)/(SDR - 1) = 2\,(HDS)/(SDR - 1) \qquad (1)$$

3.1.8.2 The PR and PDB are related by the following equation:

$$PR = (PDB)\,(DF) \qquad (2)$$

3.1.9 *pressure design basis (PDB)*—one of a series of established pressure values for plastic piping components (multilayer pipe, fitting, valve, etc.) obtained by categorizing the $LTHS_P$ in accordance with Table 2.

3.1.10 *service (design) factor (DF)*—a number less than 1.00 (which takes into consideration all the variables and degree of safety involved in a thermoplastic pressure piping installation) which is multiplied by the HDB to give the HDS, or multiplied by the PDB to give the pressure rating.

3.1.11 The following equations shall be used for the relation between stress and pressure:

$$S = P(D - t)/2t \text{ for outside diameter controlled pipe} \qquad (3)$$

or

$$S = P(d + t)/2t \text{ for inside diameter controlled pipe} \qquad (4)$$

TABLE 2 Pressure Design Basis Categories

NOTE 1—The $LTHS_P$ is determined to the nearest 10 psi. Rounding procedures in Practice E29 should be followed.

Range of Calculated $LTHS_P$ Values		Pressure Design Values	
psi	(MPa)	psi	(MPA)
96 to <120	(0.66 to <0.82)	100	(0.68)
120 to <153	(0.82 to <1.05)	125	(0.86)
153 to <190	(1.05 to <1.32)	160	(1.10)
190 to <240	(1.31 to <1.65)	200	(1.38)
240 to <300	(1.65 to <2.07)	250	(1.72)
300 to <380	(2.07 to <2.62)	315	(2.17)
380 to <480	(2.62 to <3.31)	400	(2.76)
480 to <600	(3.31 to <4.14)	500	(3.45)
600 to <760	(4.14 to <5.24)	630	(4.34)
760 to <960	(5.24 to <6.62)	800	(5.52)
960 to <1200	(6.62 to <8.27)	1000	(6.89)

where:

S = stress,
P = pressure,
D = average outside diameter,
d = average inside diameter, and
t = minimum wall thickness.

4. Significance and Use

4.1 The procedure for estimating long-term hydrostatic strength or pressure-strength is essentially an extrapolation with respect to time of a stress-time or pressure-time regression line based on data obtained in accordance with Test Method D1598. Stress or pressure-failure time plots are obtained for the selected temperature and environment: the extrapolation is made in such a manner that the long-term hydrostatic strength or pressure strengthis estimated for these conditions.

NOTE 3—Test temperatures should preferably be selected from the following: 40°C; 50°C; 60°C; 80°C; 100°C. It is strongly recommended that data also be generated at 23°C for comparative purposes.

4.2 The hydrostatic or pressure design basis is determined by considering the following items and evaluating them in accordance with 5.4.

4.2.1 Long-term hydrostatic strength or hydrostatic pressure-strength at 100 000 h,

4.2.2 Long-term hydrostatic strength or hydrostatic pressure-strength at 50 years, and

4.2.3 Stress that will give 5 % expansion at 100 000 h.

4.2.4 The intent is to make allowance for the basic stress-strain characteristics of the material, as they relate to time.

4.3 Results obtained at one temperature cannot, with any certainty, be used to estimate values for other temperatures. Therefore, it is essential that hydrostatic or pressure design bases be determined for each specific kind and type of plastic compound and each temperature. Estimates of long-term strengths of materials can be made for a specific temperature provided that calculated values, based on experimental data, are available for temperatures both above and below the temperature of interest.

4.4 Hydrostatic design stresses are obtained by multiplying the hydrostatic design basis values by a service (design) factor.

4.5 Pressure ratings for pipe may be calculated from the hydrostatic design stress (HDS) value for the specific material used to make the pipe, and its dimensions using the equations in 3.1.11.

4.5.1 Pressure ratings for multilayer pipe may be calculated by multiplying the pressure design basis (PDB) by the appropriate design factor (DF).

5. Procedure

5.1 *General*—Generated data in accordance with Test Method D1598.

5.2 *Stress Rupture*—Obtain the data required for 4.2.1 and 4.2.2 as follows:

5.2.1 Obtain a minimum of 18 failure stress/pressure-time points for each environment. Distribute these data points as follows:

Hours	Failure Points
<1000	At least 6
10 to 1000	At least 3
1000 to 6000	At least 3
After 6000	At least 3
After 10 000	At least 1

NOTE 4—When the long-term stress regression line of a compound is known, this method may be used, using fewer points and shorter times, to confirm material characteristics, or to evaluate minor process or formulation changes. See also PPI TR-3, "Policies and Procedures for Developing HDB, SDB, PDB, and MRS Ratings for Thermoplastic Piping Materials or Pipe."

5.2.2 Analyze the test results by using, for each specimen, the logarithm of the stress in psi or pressure in psig and the logarithm of the time-to-failure in hours as described in Appendix X2 (Note 5). Calculate the strength at 100 000 h. Include as failures at the conclusion of the test those specimens which have not failed after being under test for more than 10 000 h if they increase the value of the extrapolated strength. Accomplish this by first obtaining the linear log-log regression equation for only the specimens that failed, by the method of least squares as described in Appendix X2. Then use the stress in psi or pressure in psig for each specimen that has been under test for more than 10 000 h, and that has not failed, with this regression equation to calculate the time in hours. If this time is less than the hours the specimen has been under test, then use the point. Determine the final line for extrapolation by the method of least squares using the failure points along with those non-failure points selected by the method described above. Unless it can be demonstrated that they are part of the same regression line, do not use failure points for stresses or pressures that have failure times less than 10 h. Include failure points excluded from the calculation by this operation in the report, and identify them as being in this category. Refer also to Appendix 9.

NOTE 5—It should be noted that contrary to the custom in mathematics, it has been the practice of those testing plastics pipe to plot the independent variable (stress) on the vertical (y) axis and the dependent variable (time-to-failure) on the horizontal (x) axis. The procedure in Appendix X2 treats stress as an independent variable.

5.2.3 Determine the suitability of the data for use in determining the long-term hydrostatic strength or hydrostatic pressure-strength and hydrostatic or pressure design basis of plastic pipe as follows:

5.2.3.1 Extrapolate the data by the method given in Appendix X2, to 100 000 h and 50 years, and record the extrapolated stress or pressure values (4.2.1 and 4.2.2), and

5.2.3.2 Calculate, by the method given in Appendix X3, the lower confidence value of stress at 100 000 h.

5.2.3.3 If the lower confidence value at 100 000 h differs from the extrapolated LTHS/LTHS$_P$ value by more than 15 % of the latter, or M in Appendix X3 is zero or negative, or b in the equation $h = a + bf$ in Appendix X2 is positive, consider the data unsuitable.

5.3 *Circumferential Expansion*—Obtain the data required for 4.2.3 as follows:

5.3.1 Initially test at least three specimens at a stress of 50 % of the long-term hydrostatic strength determined in 5.2.3.1 until the circumferential expansion exceeds 5 % or for 2000 h, whichever occurs first. Measure the expansion of the circumference in the center of that section of the pipe specimen that is under test to the nearest 0.02 mm (0.001 in.) periodically (Note 6) during the test, unless the expansion at some other point is greater, in which case measure the section with the maximum expansion. Calculate the changes in circumference for each specimen as a percentage of the initial outside circumference. Calculate the expansion at 100 000 h for each specimen by the method given in Appendix X4 or by the plotting technique described in 5.3.3. If the calculated expansion for one or more of the specimens tested exceeds 5 %, then use the hydrostatic stress as determined from circumferential expansion measurements as the stress value to be categorized to establish the hydrostatic design basis.

NOTE 6—It is suggested that these measurements be made once every 24 h during the first 5 days, once every 3 days during the next 6 days, and once a week thereafter. The periods shall be selected on the basis of past experience with the type of pipe so that they will be reasonably distributed to obtain a good plot.

5.3.2 The stresses and distribution of specimens used to determine hydrostatic stress from circumferential expansion measurements shall be as follows:

Approximate Percent of Long-Term Hydrostatic Strength (see 5.2)	Minimum Number of Specimens
20	3
30	3
40	3
50	3
60	3

Subject the specimens to test until the circumferential expansion exceeds 5 % or for 2000 h, whichever occurs first.

5.3.3 The results may be calculated by the methods given in Appendix X4 and Appendix X5 or plotted by the following procedures. Plot the percent changes in circumference against time in hours on log-log graph paper. Draw a straight line by the method of least squares, with time as the independent variable as described in Appendix X4. Calculate the expansion of the circumference in percent at 100 000 h for each specimen by the equation from Appendix X4:

$$c = a' + 5.00\, b' \qquad (5)$$

Do not use extrapolations of curves for specimens that expand more than 5 % in less than 1000 h. Plot the corresponding expansion-stress points from the 100 000 h intercept on log-log graph paper and draw a line representative of these points by the method of least squares with stress as the independent variable as described in Appendix X5.

5.3.4 Calculate the stress corresponding to a circumferential expansion of 5.00 % in accordance with 5.3.3 and Appendix X5. The stress is the antilog of r in the equation $c = a'' + b'' r$ in Appendix X5. Use the values for a'' and b'' as calculated in Appendix X5 and 0.6990 for c . This stress may be obtained by calculation or read from the circumferential expansion-stress plot obtained in 5.3.3. In cases of disagreement, use the calculation procedure.

5.4 *Hydrostatic Design Basis*—The procedure for determining the HDB shall be as follows (see also Appendix X8):

5.4.1 Calculate the hydrostatic strength at 100 000 h (LTHS) in accordance with 5.2.

5.4.2 Calculate the hydrostatic strength at 50 years in accordance with 5.2.3.1.

5.4.3 Estimate the long-term hydrostatic strength using expansion test data and in accordance with 5.3.

NOTE 7—For all the presently used stress rated thermoplastic pipe materials in North America, the 5 % expansion strengths are not the limiting factor. Therefore, this measurement is not required for such materials.

5.4.4 Determine the hydrostatic design basis (HDB) by categorizing, in accordance with Table 1, the applicable hydrostatic strength value as specified below:

5.4.4.1 Use the LTHS value (5.4.1) if it is less than 125 % of the 50-year value (5.4.2), and less than the expansion strength value (5.4.3).

5.4.4.2 Use the 50-year value if it is less than 80 % of the LTHS value, and less than the expansion strength value.

5.4.4.3 Use the expansion strength value if it is less than the LTHS and 50-year values.

5.5 *Hydrostatic Design Stress*—Obtain the hydrostatic design stress by multiplying the hydrostatic design basis by a service (design) factor selected for the application on the basis of two general groups of conditions. The first group considers the manufacturing and testing variables, specifically normal variations in the material, manufacture, dimensions, good handling techniques, and in the evaluation procedures in this test method and in Test Method D1598 (Note 8). The second group considers the application or use, specifically installation, environment, temperature, hazard involved, life expectancy desired, and the degree of reliability selected (Note 9). Select the service factor so that the hydrostatic design stress obtained provides a service life for an indefinite period beyond the actual test period.

NOTE 8—Experience to date, based on data submitted to PPI, indicates that variation due to this group of conditions are usually within ±10 %, for any specific compound.

NOTE 9—It is not the intent of this standard to give service (design) factors. The service (design) factor should be selected by the design engineer after evaluating fully the service conditions and the engineering properties of the specific plastics under consideration. Alternatively, it may be specified by the authority having jurisdiction.

It is recommended that numbers selected from ANSI Standard Z17.1-1973 for Preferred Numbers, in the R10 series (25 % increments) be used, namely, 0.80, 0.63, 0.50, 0.40, 0.32, 0.25, 0.20, 0.16, 0.12, or 0.10. If smaller steps seem necessary it is recommended that the R20 series (12 % increments) be used, namely, 0.90, 0.80, 0.71, 0.63, 0.56, 0.50, 0.45, 0.40, 0.36, 0.32, 0.28, 0.25, 0.22, 0.20, 0.18, 0.16, 0.14, 0.12, 0.112, or 0.10.

5.6 *Determination or Validation of the HDB for Polyethylene Materials, or Both*—Apply any of the following procedures to PE material to validate its HDB at any temperature. When an elevated temperature HDB is validated, all lower temperature HDB's are considered validated for that material. If a brittle failure occurs before 10 000 h when testing in accordance with 5.2, the Alternate Method (Procedure I) shall be used. Procedure I may also be used to determine the HDB at elevated temperatures for some PE materials.

5.6.1 *Alternate Method Procedure I:*

5.6.1.1 Develop stress rupture data in accordance with 5.2 for the temperature at which an HDB is desired. Using only the ductile failures, determine the linear regression equation. The failure point data must be spread over at least two log decades. The stress intercept at 100 000-h using this equation is the "ductile" LTHS.

5.6.1.2 To determine the brittle failure performance, solve for the three coefficients of the rate process method equation as follows:

(1) Select an elevated temperature appropriate for the polyethylene material. The maximum temperature chosen should not be greater than 95°C (203°F).

(2) Select a stress at this temperature at which all failures occur in the brittle mode (a crack through the pipe wall with no visible evidence of material deformation). This set of temperature and stress is called Condition I. Test at least six pipe specimens at this Condition I until failure.

(3) At the same temperature, select another stress about 75 to 150 psi lower than for Condition I. Test at least six pipe specimens at this Condition II until failure.

(4) Select a temperature 10°C (18°F) to 20°C (36°F) lower than the one in Condition I and use the same stress as Condition I. This is Condition III. Test at least six pipe specimens at this Condition III until failure.

(5) Using all these brittle failure data points from Conditions I, II, and III, calculate the A, B, and C coefficients for the following three-coefficient rate process method equation:

$$\log t = A + \frac{B}{T} + \frac{C \log S}{T} \qquad (6)$$

where:

t = time, h,
T = absolute temperature, °K (K = C + 273),
S = hoop stress, psi, and
A, B, C = constants.

(6) Using this model, calculate the stress intercept value at 100 000 h for the temperature at which the HDB is desired. This resulting stress intercept is the "brittle" LTHS.

TABLE 3 Validation of 73°F (23°C) HDB

HDB to be Validated (psi)	193°F (90°C) Test Temperature /		176°F (80°C) Test Temperature	
	Stress (psi)	Time (h)	Stress (psi)	Time (h)
1600	735	70	825	200
1250	575	70	645	200
1000	460	70	515	200
800	365	70	415	200
630	290	70	325	200
500	230	70	260	200

TABLE 4 Validation of 100°F (38°C) HDB

HDB to be Validated (psi)	193°F (90°C) Test Temperature / 176°F (80°C) Test Temperature			
	Stress (psi)	Time (h)	Stress (psi)	Time (h)
1600	850	300	960	1000
1250	670	300	750	1000
1000	600	300	600	1000
800	535	300	480	1000
630	340	300	380	1000
500	265	300	300	1000

TABLE 5 Validation of 120°F (49°C) HDB

HDB to be Validated (psi)	193°F(90°C) Test Temperature / 176°F(80°C) Test Temperature			
	Stress (psi)	Time (h)	Stress (psi)	Time (h)
1600	970	1100	1090	3400
1250	760	1100	850	3400
1000	610	1100	685	3400
800	490	1100	545	3400
630	385	1100	430	3400
500	305	1100	345	3400

TABLE 6 Validation of 140°F (60°C) HDB

HDB to be Validated (psi)	193°F(90°C) Test Temperature / 176°F(80°C) Test Temperature			
	Stress (psi)	Time (h)	Stress (psi)	Time (h)
1250	860	3800	970	11300
1000	690	3800	775	11300
800	550	3800	620	11300
630	435	3800	490	11300
500	345	3800	390	11300
400	275	3800	310	11300

TABLE 7 Validation of 160°F (71°C) HDB

HDB to be Validated (psi)	193°F(90°C) Test Temperature / 176°F(80°C) Test Temperature			
	Stress (psi)	Time (h)	Stress (psi)	Time (h)
1250	975	12600	1100	37500
1000	780	12600	885	37500
800	625	12600	705	37500
630	495	12600	550	37500
500	390	12600	440	37500
400	315	12600	350	37500

NOTE 10—The ISO 9080[5] four coefficient model may be used if it has a better statistical fit to the data.

5.6.1.3 Use the lower value of the ductile failure LTHS (see 5.6.1.1) or the brittle failure LTHS (see 5.6.1.2) to determine the HDB category per Table 1 for this PE material. The HDB determined by this procedure is considered validated.

5.6.2 *Standard Method (Procedure II)*—The HDB for a PE material at a desired temperature is validated when the following criterion is met:

5.6.2.1 Develop stress rupture data in accordance with 5.2 for the temperature at which an HDB is desired. Analyze the data to determine the linear regression equation. Extrapolate this equation to 100 000 h to determine the LTHS. Use Table 1 to determine the HDB category at this temperature.

5.6.2.2 Use Tables 3-7 to define the time and stress requirements needed to validate this HDB. Test at least six specimens at the stress level determined by the tables. These specimens must have a minimum log average time exceeding the value shown in the table to validate the HDB. For example, to validate an HDB of 1000 psi at 140°F, this required time is 3800 h at 193°F (90°C)/690 psi or 11 300 h at 176°F (80°C)/775 psi.

5.6.2.3 If a temperature/stress condition in the tables results in a premature ductile failure for a particular PE material, the stress at that temperature may be lowered by 15 %. The corresponding required time for this lowered stress is then six times the value in the table. For example, when validating an HDB of 1600 psi at 73°F, if testing at 80°C/825 psi results in ductile failures, lower the stress to 700 psi and retest. The required time to validate using this condition is now 1200 h. If ductile failures still occur, the stress may be lowered to 595 psi and the corresponding time is increased to 7200 h.

5.6.3 *Rate Process Method (Procedure III)*—If there are no brittle failures before 10 000 h when developing the data according to 5.2, this rate process method may be used to validate the HDB.

5.6.3.1 Develop data for the brittle failure performance as described in 5.6.1.2, except use the data from Condition I, Condition II, and the LTHS value at 100 000 h determined from the linear regression model to calculate the A, B, and C coefficients for the rate process model.

5.6.3.2 Using this model, calculate the mean estimated failure time for the temperature and stress used in Condition III. When the average time (log basis) for the six specimens tested at Condition III has reached this time, the extrapolation to 100 000 h to obtain the LTHS has been validated. (Examples are shown in Appendix X9.)

5.6.4 *ISO 9080 Based Method for Validation of 140°F (60°C) HDB (Procedure IV)*—With some PE compounds the rate process method may result in very long test times to generate brittle failures. This method may also be used to validate a HDB at 140°F. It can not be used if there are brittle failures before 10 000 h when developing the data according to 5.2 to establish the HDB at 140°F.

5.6.4.1 Develop a linear regression according to 5.2 based on *ductile* stress-rupture data at either 80°C or 90°C. Use Table 8 to determine the appropriate data level for the temperature to be validated. The regression data must satisfy the following requirements:

(1) The 97.5% LCL ratio for these data must be greater than 90%.

(2) Non-failed specimens at the longest running times may be included in the regression provided their inclusion does not decrease the LTHS (see 5.2.2).

5.6.4.2 The log average of the five longest running times (used in the regression) must exceed the minimum time t_{max}

TABLE 8 Validation of HDB at 140°F

Temperature to be validated °F	193°F (90°C) Regression		176°F† (80°C) Regression	
	Data Level[A]	Min . t_{max}[B]	Data Level[A]	Min. t_{max}[B]
140°F (60°C)	E-6	5500	E-10+	17 000

[A] Per data interval requirements in PPI TR-3.

[B] t_{max}= log average of 5 longest test times (included in regression)

† Editorially corrected in April 2014.

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[5] For additional information contact the Plastics Pipe Institute Hydrostatic Stress Board Chairman, 105 Decker Court, Suite 825, Irving, TX 75062, http://www.plasticpipe.org

indicated in Table 8 to validate the HDB at 140°F (Example shown in Appendix X9).

5.7 *Substantiation of the HDB for Polyethylene Materials*—When it is desired to show that a PE material has additional ductile performance capacity than is required by validation of the 73°F (23°C) time/stress curve to 100 000 hours, one of the following three procedures may be used to further substantiate that the stress regression curve is linear to the 50 year (438 000 hour) intercept.

5.7.1 If the HDB at 140°F or higher temperature has been validated by 5.6.2 or 5.6.4, then linear extrapolation of the 73°F (23°C) stress regression curve to 50 years (438 000 hours) is substantiated.

5.7.2 If the HDB at 73°F has been validated by 5.6.3, use the twelve data points from Condition I and II, along with the 50 year (438,000 hour) intercept value, to solve for the three-coefficient rate process extrapolation equation. Then using this new model, calculate the mean estimated failure time for Condition III. When the log average time for six specimens tested at Condition III has reached this time, linear extrapolation of the 73°F (23°C) stress regression curve to 50 years (438 000 hours) is substantiated.

5.7.3 If the HDB at 73°F has been validated by 5.6.2, linear extrapolation of the stress regression curve to 50 years (438 000 hours) is substantiated when the log average failure time of six test specimens at 176°F (80°C) surpasses 6000 hours, or at 193°F (90°C) surpasses 2400 hours at a stress of no more than 100 psi below where all failures are ductile. A ductile failure reference stress shall be established by 3 specimens all failing in the ductile mode at the same temperature.

NOTE 11—The Long-Term Hydrostatic Strength at 50 years (LTHS50) is not to be used for pressure rating calculations. The maximum stress is still calculated using the HDB (with the appropriate design service factors) obtained from the LTHS at 100,000 hours. PE materials meeting this additional substantiation of the 73°F (23°C) extrapolation shall be denoted by an asterisk (*) in PPI TR-4.

5.8 *Pressure Rating*—Calculate the pressure rating for each diameter and wall thickness of pipe from the hydrostatic design stress (hydrostatic design basis × service factor) for the specific material in the pipe by means of the equations in 3.1.11.

5.9 *Pressure Design Basis*—The procedure for determining the PDB shall be as follows:

5.9.1 Calculate the hydrostatic pressure-strength at 100 000 h ($LTHS_P$) in accordance with 5.2.

5.9.2 Calculate the hydrostatic pressure-strength at 50 years in accordance with 5.2.3.1.

5.9.3 Determine the pressure design basis (PDB) by categorizing, in accordance with Table 2, the applicable hydrostatic pressure-strength value as specified below:

5.9.4 Use the $LTHS_P$ value (5.9.1) if it is less than 125 % of the 50-year value (5.9.2).

5.9.4.1 Use the 50-year value if it is less than 80 % of the LTHSP value.

6. Report

6.1 The report shall include the following:

6.1.1 Complete identification of the sample, including material type, source, manufacturer's name and code number, and previous significant history, if any,

6.1.2 Pipe dimensions including nominal size, average and minimum wall thickness, and average outside diameter,

6.1.3 Test temperature,

6.1.4 Test environment inside and outside of the pipe,

6.1.5 A table of the stresses in pounds-force per square inch or pressures in pounds-force per square inch gage and the time-to-failure in hours for all the specimens tested (specimens that are designated as failures after they have been under stress or pressure for more than 10 000 h shall be indicated),

6.1.6 The estimated long-term hydrostatic strength or pressure-strength (Note 12),

6.1.7 The estimated stress at 50 years,

6.1.8 A table of the percent circumferential expansion versus time data and the estimated stress at 5.00 % expansion. This item need not be reported if previous test results show that the stress calculated for 5 % expansion is significantly greater than that reported in 6.1.6 or 6.1.7, or for PDB values.

6.1.9 The hydrostatic design basis or pressure design basis,

6.1.10 The nature of the failures in accordance with 3.4,

6.1.11 Any unusual behavior observed in the tests,

6.1.12 If the material is polyethylene, the results of the validation in accordance with 5.6,

6.1.13 Dates of test, and

6.1.14 Name of laboratory and supervisor of the tests.

NOTE 12—The outside environment of the pipe test specimen shall be placed after the values reported.

7. Precision and Bias

7.1 No statement is made about either the precision or the bias of Test Method D2837 for measuring the hydrostatic design basis since the result merely states whether there is conformance to the criteria for success specified in the procedure.

APPENDIXES

(Nonmandatory Information)

X1. METHODOLOGY FOR THE FORECASTING OF THE LONGER-TERM HYDROSTATIC STRENGTH OF THERMOPLASTIC PIPING MATERIALS IN CONSIDERATION OF THE NATURE OF THEIR STRESS-RUPTURE BEHAVIOR

X1.1 Similar to what has been observed for metals at higher temperatures, the stress-rupture data obtained on thermoplastics piping materials generally yields a relatively straight line when plotted on log stress versus log time-to-fail coordinates. By means of regression analysis, such straight-line behavior can readily be represented by a mathematical equation. Using this equation, the long-term strength of a material for a time under load much beyond the longest time over which the data were obtained can be determined by extrapolation. This straight-line behavior has been observed to hold true for nearly all plastic piping materials, provided failures always occur by the same mechanism. However, it has also been observed that when the cause of failure transitions from one mechanism to another, that is, from failure caused by excessive ductile deformation to a failure resulting by the initiation and growth of a crack, this may result in a significant downward shift (that is a gradual "downturn," or a relatively sharp "knee") in the slope of the initially defined stress-rupture line. In such cases, the stress-rupture data can best be characterized by means of two straight lines: an initial line of fairly flat slope; followed by a second line of steeper slope. The change in slope from the first to the second line can be minimal, in which case the stress rupture behavior is generally sufficiently well-characterized by a single average line; or, the change can be significant, in which case, it is more accurately represented by two straight lines, each with a different slope (see Fig. X1.1). Should there occur a significant downward trend in slope, the extrapolation of the trend solely defined by the earlier stage of stress-rupture behavior may result in an excessive overestimation of a material's actual LTHS. For a more accurate forecast, it should be made based on the trend exhibited by the second straight line, a trend that may not always be evidenced by the data collected during the minimum testing period of 10 000 h, as required by this test method.

X1.2 Studies[6] conducted on polyolefin pipes indicate that, exclusive of potential effects of polymer chemical degradation, or aging, that may occur in consequence of the effects of environments that are aggressive to the polymer, stress-rupture failures can occur over two stages. In the first stage, failures are of a ductile nature, but, in the second, they are the consequence of the initiation and slow growth of small cracks or faults. The schematic in Fig. X1.1 depicts this two-stage behavior. Other materials have also been found to exhibit such two-stage

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[6] M. Ifwarson and H. Leijstrom, What Controls The Lifetime of Plastic Pipes and How Can the Lifetime be Extrapolated, a paper presented at Plastic Pipes VIII, Koningshof, The Netherlands.

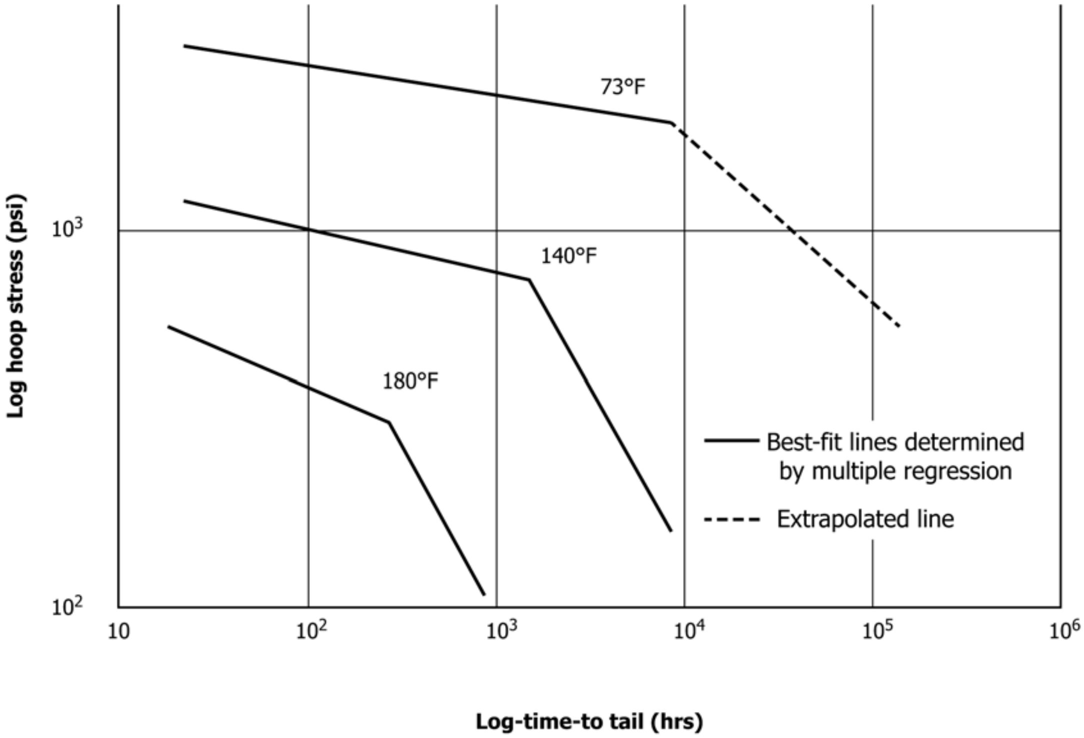

FIG. X1.1 Schematic of the Stress-Rupture Characteristics of a Material Which Exhibits Two Stages in Stress-Rupture Properties, and of the Shift in the Stress-Rupture Lines that Results by Increasing the Test Temperature.

failure behavior; however, different failure mechanisms may be involved. As is also illustrated by Fig. X1.1, increasing the test temperature decidedly shifts to earlier times the point at which there occurs a transition in failure mechanism. Studies show that the shift, or accelerating effect, caused by increasing temperature follows established chemical and physical rate-process principles[7,8]. The significance of this finding is that shorter-time observations of stress-rupture behavior at higher temperatures may be used as a predictor of longer-time behavior at lower temperatures. The "validation" requirements for PE piping materials that is included in this test method has been established based on the well-documented time/temperature shift observed in these materials.

X1.3 As explained in the scope, the inherent assumption of this test method is that the straight-line behavior between log stress and log time-to-fail that is described by the experimental data shall continue uninterrupted through at least the time for which the forecast for the LTHS is being made. Should there occur a significant downturn (that is, a downward shift in the stress-rupture slope) prior to the 100 000-h intercept, an extrapolation based on a trend defined by 10 000 h of data may produce an overstated LTHS. While this test method includes lower confidence requirements that work to exclude its application to data that exhibit a significant downward trend, such requirements have no effect on predicting whether such a trend may take place beyond the longest time of data collection. For the latter purpose, other information needs to be considered, such as stress-rupture performance at temperatures that are higher than that for which the LTHS is being established. While for polyethylene materials this test method does include a separate protocol by which one can validate the assumption that for ambient temperature there will be no downturn before the 100 000-h intercept, there is no such requirement for other materials. In the later case, the suitability of this test method should be determined upon consideration of outside information.

X1.4 One kind of outside information is the results of very long-term stress-rupture studies which have been conducted on thermoplastic piping materials that are chemically and physically similar to the material of interest. Another kind is very extensive field experience with specific kinds and grades of materials. For example, as previously mentioned, it is well-established both through testing and very extensive experience that rigid PVC piping materials which have been formulated using PVC resins of certain minimum molecular weight exhibit no "downturn" at ambient temperatures through at least 100 000 h when tested using water or air as the pressure medium. In recognition of this, PPI requires in its policies governing PVC formulations[9] that PVC resins used for pressure piping have an inherent viscosity range from 0.88 to 0.96, when measured in accordance with Test Method D1243. Other materials, including the following, have also been shown to be free of "downturns" for similar test conditions: PE materials which have been cross-linked to a certain minimum extent as specified by ASTM product specifications: polybutylene (PB) piping materials of the grade specified by ASTM piping standards; and most pipe grade fluoropolymers.

X1.5 For materials and test conditions for which there exists no assurance that there will not occur a "knee" or "downturn" beyond the period of data collection, there is available an extrapolation test method that takes this possibility into consideration. The observation that increased test temperature results in a mathematically correlateable shift in stress-rupture plots has let to the development of international standard ISO 9080. By means of this method, a forecast of a material's LTHS may be made based on the results of multiple linear regression analysis of test data obtained at a number of different elevated test temperature, such as shown by Fig. X1.1. The objective of the testing at elevated temperature is to collect sufficient data for identifying and characterizing in shorter times downward shifts in stress-rupture plots that may not show up until after very lengthy testing at lower temperatures. To adequately define the transitions that may occur in stress-rupture behavior, this ISO method requires that data be collected for not only the base temperature, but also for certain specified elevated temperatures. And to establish the best-fit mathematical relationship that defines the observed results, including any observed changes in stress-rupture slopes at all test temperatures, this method offers a choice of certain mathematical models. The model that is found through multiple regression analysis to best fit all of the experimental data is then used to project an estimate of the material's LTHS. Obviously, this methodology requires considerably more data and more complex mathematical analysis than called-for by this test method. However, in cases for which it is known or suspected that a stress-rupture downturn may occur after some time beyond the period of data collection, the ISO method can yield more reliable estimates of LTHS; therefore, it may be more appropriate for that material than the simpler method that is defined by this test method.

NOTE X1.1—The level of strength and the point at which occurs the transition from a flatter to a steeper slope depends on the nature of the polymer (for example, the starting monomer, copolymer, molecular weight, and molecular weight distribution), the additives used in the plastic composition, the conditions under which the plastic material has been processed, and other variables. Fig. X1.1 illustrates a case where laboratory data obtained for the test temperature of 73°F yields a straight log-stress versus log time-to-fail straight line through 10 000 h, the minimum test period required by this test method, followed by a second line of steeper slope. If a forecast of the 73°F long-term strength of this material were to be made by the extrapolating to the 100 000-h intercept of the trend defined by the first line, this clearly will lead to an overstatement of this material's actual long-term strength. Since testing at

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[7] Bartenev, G.M., and Xuyev, V.S., "Strength and Failure of Viscoelastic Materials," 1st English Publication, 1968.

[8] Bragaw, C. G., "Service Rating of Polyethylene Piping Systems by The Rate Process Method," *Eighth Plastic Fuel Gas Pipe Symposium*, New Orleans, LA, Nov. 29–30–Dec. 1, 1983.

[9] PPI TR-3, "Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Hydrostatic Design Stresses (HDS), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe " issued by the Plastics Pipe Institute.

elevated test temperature shifts the stress-rupture lines to lower stresses and to significantly shorter failure times, and as this shift has been determined to be mathematically correlatable with test temperature, supplementary stress-rupture data obtained at elevated temperatures can be used to test the inherent assumption of Test Method D2837; namely, that a straight-line which is defined by data that covers a period of 10 000 h will continue through at least 100 000 h. This testing strategy is the basis for the "validation" procedure in Test Method D2837 that is applied to PE materials.

For cases in which the preceding assumption of continued linearity is either not validated through other work or information, or when it is suspected it may not apply, a more complete characterization of elevated temperature stress-rupture behavior, sufficient to adequately define both the shallower and steeper stages of the elevated temperature stress-rupture behavior, allows one to derive through multiple regression analysis a general mathematical relationship that covers both stages and therefore, can be used to more accurately forecast long-term strength for any temperature within the range of minimum and maximum test temperatures. A recognized method that employes this testing and multiple regression strategy is ISO 9080.

X2. LEAST SQUARES CALCULATIONS FOR LONG-TERM HYDROSTATIC STRENGTH

X2.1 The following symbols are used:

N = number of points on the time to failure versus stress plot,
f = logarithm of failure stress, psi,
F = arithmetic average of all f values,
h = logarithm of failure time, h, and
H = arithmetic average of all h values.

The equation of the straight line is:

$$h = a + bf \qquad (X2.1)$$

X2.1.1 Compute the three quantities:

$$U = \sum f^2 - \left[\left(\sum f\right)^2/N\right] \left(\text{or} \sum f^2 - NF^2\right) \qquad (X2.2)$$

$$V = \sum h^2 - \left[\left(\sum h\right)^2/N\right] \left(\text{or} \sum h^2 - NH^2\right) \qquad (X2.3)$$

$$W = \sum fh - \left[\left(\sum f\right)\left(\sum h\right)/N\right] \left(\text{or} \sum fh - NFH\right) \qquad (X2.4)$$

X2.1.2 Calculate a and b as follows:

$$b = W/U \qquad (X2.5)$$

and

$$a = H - bF \qquad (X2.6)$$

If b is positive, the data are unsuitable for evaluating the material.

X2.1.3 Substitute these values of a and b into the equation:

$$h = a + bf \qquad (X2.7)$$

X2.1.4 A sample calculation made in accordance with Appendix X2 is given in Appendix X7.

X3. CALCULATIONS OF LOWER CONFIDENCE LIMIT

X3.1 Let $f_{100\,000}$ represent the value of stress corresponding to 100 000 h failure-time. Then:

$$f_{100\,000} = (5 - a)/b \qquad (X3.1)$$

X3.2 The lower confidence value of stress at 100 000 h is given by the following calculations:

X3.2.1 Calculate $D = 5 - H$.

X3.2.2 Calculate the variance,

$$s^2 = [1/(N-2)][V - (W^2/U)] \qquad (X3.2)$$

and its square root, s, the standard deviation.

X3.2.3 Substitute the value, t, of Student's t distribution, from Appendix X5 corresponding to $N - 2$ degrees of freedom at the two-sided 5 % level of significance (Note X3.1). See also Table X3.1.

X3.2.4 Calculate the quantity:

$$M = b^2 - (t^2 s^2/U) \qquad (X3.3)$$

If M is negative or zero, the slope of log cycles versus stress is not significantly different from zero. In this case, the lower confidence limit cannot be calculated, and the data are unreliable for the evaluation of the material. The calculations below should be carried out only when the value of M is positive.

X3.2.5 Calculate the quantity:

$$L = \left[bD - ts\sqrt{(D^2/U) + (M/N)}\right]/M \qquad (X3.4)$$

(See Appendix X6.)

X3.2.6 The lower confidence limit of $f_{100\,000}$ is equal to $L + F$ (Note X3.2).

NOTE X3.1—For instance, Statistical Methods for Chemists by W. J. Youden, Page 119, Wiley, (1951) New York.

NOTE X3.2—The probability is 0.975 that the value of the regression line at 100 000 h exceeds this stress.

TABLE X3.1 Calculations

Degrees of Freedom, $N - 2$	Students "t"[A]	Degrees of Freedom, $N - 2$	Students "t"[A]	Degrees of Freedom, $N - 2$	Students "t"[A]
1	12.7062	46	2.0129	91	1.9864
2	4.3027	47	2.0117	92	1.9861
3	3.1824	48	2.0106	93	1.9858
4	2.7764	49	2.0096	94	1.9855
5	2.5706	50	2.0086	95	1.9853
6	2.4469	51	2.0076	96	1.9850
7	2.3646	52	2.0066	97	1.9847
8	2.3060	53	2.0057	98	1.9845
9	2.2622	54	2.0049	99	1.9842
10	2.2281	55	2.0040	100	1.9840
11	2.2010	56	2.0032	102	1.9835
12	2.1788	57	2.0025	104	1.9830
13	2.1604	58	2.0017	106	1.9826
14	2.1448	59	2.0010	108	1.9822
15	2.1315	60	2.0003	110	1.9818
16	2.1199	61	1.9996	112	1.9814
17	2.1098	62	1.9990	114	1.9810
18	2.1009	63	1.9983	116	1.9806
19	2.0930	64	1.9977	118	1.9803
20	2.0860	65	1.9971	120	1.9799
21	2.0796	66	1.9966	122	1.9796
22	2.0739	67	1.9960	124	1.9703
23	2.0687	68	1.9955	126	1.9790
24	2.0639	69	1.9949	128	1.9787
25	2.0595	70	1.9944	130	1.9784
26	2.0555	71	1.9939	132	1.9781
27	2.0518	72	1.9935	134	1.9778
28	2.0484	73	1.9930	136	1.9776
29	2.0452	74	1.9925	138	1.9773
30	2.0423	75	1.9921	140	1.9771
31	2.0395	76	1.9917	142	1.9768
32	2.0369	77	1.9913	144	1.9766
33	2.0345	78	1.9908	146	1.9763
34	2.0322	79	1.9905	148	1.9761
35	2.0301	80	1.9901	150	1.9759
36	2.0281	81	1.9897	200	1.9719
37	2.0262	82	1.9893	300	1.9679
38	2.0244	83	1.9890	400	1.9659
39	2.0227	84	1.9886	500	1.9647
40	2.0211	85	1.9883	600	1.9639
41	2.0195	86	1.9879	700	1.9634
42	2.0181	87	1.9876	800	1.9629
43	2.0167	88	1.9873	900	1.9626
44	2.0154	89	1.9870	1000	1.9623
45	2.0141	90	1.9867	∞	1.9600

[A] Two-sided 0.05 level of significance. The values in this table are taken from the tables on pages 28–30 of "The Handbook of Statistical Tables," by D. B. Owen, Addison-Wesley Publishing Co., Reading, MA, 1962, by permission of the author, publishers and the United States Atomic Energy Commission.

X4. LEAST SQUARES CALCULATIONS FOR CIRCUMFERENTIAL EXPANSION-TIME PLOT

X4.1 The following symbols are used (Note X4.1):

N' = number of points on the time versus circumferential expansion plot,
c = logarithm of circumferential expansion in percent,
C = arithmetic average of all c values,
g = logarithm of time, h, and
G = arithmetic average of all g values.

X4.2 The equation of the straight line is:

$$c = a' + b'g \tag{X4.1}$$

X4.2.1 Compute the two quantities:

$$U' = \sum g^2 - \left[\left(\sum g \right)^2 / N' \right] \left(or \sum g^2 - N'G^2 \right) \tag{X4.2}$$

$$W' = \sum cg - \left[\left(\sum c \right) \left(\sum g \right) / N' \right] \left(or \sum cg - N'CG \right) \tag{X4.3}$$

X4.2.2 Calculate *a'* and *b'* as follows:

$$b' = W'/U' \tag{X4.4}$$

and

$$a' = C - b'G \tag{X4.5}$$

If *b′* is negative, the data are unsuitable for evaluating the material.

X4.2.3 Substitute the value, *a'* and *b'* into the equation:

$$c = a' + b'g \tag{X4.6}$$

X4.2.4 Arbitrarily select three convenient values of *g* and calculate *c* for each. The values of *g* should not be chosen too close to one another. Plot these three pairs of values for *g* and *c*. If these three points do not lie on a straight line, there is a mistake in the calculations.

NOTE X4.1—All logarithms are to the base 10. Use 4-place tables for calculations.

X5. LEAST SQUARES CALCULATIONS FOR CIRCUMFERENTIAL EXPANSION-STRESS PLOT

X5.1 The following symbols are used:

N'' = number of points on the circumferential expansion-stress plot,
c = logarithm of circumferential expansion in percent,
C = arithmetic average of all c values,
r = logarithm of stress, psi, and
R = arithmetic average of all r values.

X5.2 The equation of the straight line is:

$$c = a'' + b''r \tag{X5.1}$$

X5.2.1 Compute the two quantities:

$$U'' = \sum r^2 - \left[\left(\sum r \right)^2 / N'' \right] \left(or \sum r^2 - N''R^2 \right) \tag{X5.2}$$

$$W'' = \sum cr - \left[\left(\sum c \right) \left(\sum r \right) / N'' \right] \left(or \sum cr - N''CR \right) \tag{X5.3}$$

X5.2.2 Calculate *a″* and *b″* as follows:

$$b'' = W''/U'' \tag{X5.4}$$

and

$$a'' = C - b''R \tag{X5.5}$$

If *b″* is negative, the data are unsuitable for evaluating the material.

X5.2.3 Substitute the value, *a″* and *b″* into the equation:

$$c = a'' + b''r. \tag{X5.6}$$

X5.2.4 Arbitrarily select three convenient values for *r* and calculate *c* for each. The values of *r* should not be chosen too close to one another. Plot these three pairs of values for *c* and *r*. If these points do not lie on a straight line, there is a mistake in the calculations.

X6. DERIVATION OF FORMULAS

X6.1 The basic equation is:

$$h = a + bf + \text{error} \tag{X6.1}$$

which can also be written:

$$h - H = b(f - F) + \text{error} \tag{X6.2}$$

Consider an assigned value for *h* (for example *h* = 5, corresponding to a failure time of 100 000 h). Denote it by h_0. The problem is to evaluate the uncertainty of the corresponding value of f_0. The value f_0 is evaluated by the equation:

$$b(f_0 - F) = h_0 - H \tag{X6.3}$$

Let

$$z = b(f_0 - F) - (h_0 - H) \tag{X6.4}$$

Then the expected value of *z* is zero (because of Eq X6.3):

$$E(z) = 0 \tag{X6.5}$$

and the variance *z*, *V*(*z*), is given by:

$$V(z) = (f_0 - F)^2 V(b) + V(H) \tag{X6.6}$$

By least squares theory we know that:

$$V(H) = \sigma^2/N \tag{X6.7}$$

and

$$V(b) = \sigma^2/(f - F)^2 - \sigma^2/U \tag{X6.8}$$

where σ^2 is the variance of the error in the determination of any single *h* value.

Introducing Eq X6.5 and Eq X6.6 into Eq X6.4 gives:

$$V(z) = \sigma^2 \left[\frac{(f_0 - F)^2}{U} + \frac{1}{N} \right] \tag{X6.9}$$

The estimate for σ^2 is:

$$s^2 = [1/(N-2)][V-(W^2/U)] \qquad \text{(X6.10)}$$

and is evaluated with (N – 2) degrees of freedom. Consequently, an estimate for *V(z)* is given by:

$$V(z) = \frac{1}{N-2}\left[V-\frac{W^2}{U}\right]\cdot\left[\frac{(f_0-F)^2}{U}+\frac{1}{N}\right] = s^2\left[\frac{(f_0-F)^2}{U}+\frac{1}{N}\right] \qquad \text{(X6.11)}$$

and the estimated standard deviation of z is:

$$s_z = s\sqrt{\frac{(f_0-F)^2}{U}+\frac{1}{N}}$$

The quantity $(z - E(z)/s_z)$ has Student's t – distribution with $(N - 2)$ degrees of freedom. Let t denote the critical value of Student's t, for $(N - 2)$ degrees of freedom and for the chosen level of significance. Then the following inequity holds with probability equal to the applicable confidence coefficient.

$$(1 - \text{level of significance}): -t \leq [z - E(z)]/s_z \leq +t \qquad \text{(X6.12)}$$

which is equivalent to:

$$[(z - E(z)]^2/V(z) \leq t^2 \qquad \text{(X6.13)}$$

The limits of this interval are given by:

$$[z - E(z)]^2 = t^2\,V(z) \qquad \text{(X6.14)}$$

which, in view of Eq X6.3 and Eq X6.9, becomes:

$$z^2 = t^2 s^2\left[\frac{(f_0-F)^2}{U}+\frac{1}{N}\right] \qquad \text{(X6.15)}$$

Introducing Eq X6.2, Eq X6.13 can be written:

$$[b(f_0-F)-(h_0-H)]^2 = t^2 s^2\left[\frac{(f_0-F)^2}{U}+\frac{1}{N}\right] \qquad \text{(X6.16)}$$

Writing

$$L = f_0 - F \qquad \text{(X6.17)}$$

$$D = h_0 - H \qquad \text{(X6.18)}$$

and solving Eq X6.15 for L , we obtain:

$$L = \frac{bD + ts\sqrt{[b^2-(t^2s^2/U)/N]+(D^2/U)}}{b^2-\dfrac{t^2s^2}{U}} \qquad \text{(X6.19)}$$

Let

$$M = b^2 - (t^2s^2/U) \qquad \text{(X6.20)}$$

Then, the lower limit for L is given by:

$$L_{\text{lower limit}} = \frac{bD - ts\sqrt{(M/N)+(D^2/U)}}{M} \qquad \text{(X6.21)}$$

Consequently, in view of Eq X6.15, the lower limit for f_0 is given by:

$$f_0,\ \text{lower limit} = L_{\text{lower limit}} + F. \qquad \text{(X6.22)}$$

X7. SAMPLE CALCULATION ACCORDING TO APPENDIX X2

X7.1 Table X7.1 shows a sample calculation according to Appendix X2.

TABLE X7.1 Sample Calculation

Data Point	Time, h	Stress, psi	Log Time, h	Log Stress, f	h^2	f^2	fh
1	9	5500	0.95424	3.74036	0.910574	13.990293	3.569201
2	13	5500	1.11394	3.74036	1.240862	13.990293	4.166537
3	17	5500	1.23045	3.74036	1.514007	13.990293	4.602326
4	17	5500	1.23045	3.74036	1.514007	13.990293	4.602326
5	104	5200	2.01703	3.71600	4.068410	13.808656	7.495283
6	142	5200	2.15229	3.71600	4.632352	13.808656	7.997910
7	204	5200	2.30963	3.71600	5.334391	13.808656	8.582585
8	209	5200	2.32015	3.71600	5.383096	13.808656	8.621677
9	272	5000	2.43457	3.69897	5.927131	13.682379	9.005401
10	446	5000	2.64933	3.69897	7.018949	13.682379	9.799792
11	466	5000	2.66839	3.69897	7.120305	13.682379	9.870295
12	589	4800	2.77012	3.68124	7.673565	13.551528	10.197477
13	669	4700	2.82543	3.67210	7.983055	13.484318	10.375262
14	684	5000	2.83506	3.69897	8.037565	13.582379	10.486802
15	878	4600	2.94349	3.66276	8.664133	13.415811	10.781297
16	1299	4800	3.11361	3.68124	9.694567	13.551528	11.461946
17	1301	4700	3.11428	3.67210	9.698740	13.484318	11.435948
18	1430	4800	3.15534	3.68124	9.956171	13.551528	11.615564
19	1710	4800	3.23300	3.68124	10.452289	13.551528	11.901449
20	2103	4800	3.32284	3.68124	11.041266	13.551528	12.22172
21	2220	4500	3.34635	3.65321	11.198058	13.345943	12.224919
22	2230	4400	3.34830	3.64345	11.211113	13.274728†[A]	12.199364
23	3816	4700	3.58161	3.67210	12.827930	13.484318	13.152030
24	4110	4700	3.61384	3.67210	13.059840	13.484318	13.270382
25	4173	4600	3.62045	3.66276	13.107658	13.415811	13.260839
26	5184	4400	3.71466	3.64345	13.798699	13.274728†[A]	13.534178
27	8900	4600	3.94939	3.66276	15.597681	13.415811	14.465668

TABLE X7.1 *Continued*

Data Point	Time, h	Stress, psi	Log Time, *h*	Log Stress, *f*	h^2	f^2	fh
28	8900	4600	3.94939	3.66276	15.597681	13.415811	14.465668
29	10900	4500	4.03743	3.65321	16.300841	13.345943	14.749580
30	10920	4500	4.03822	3.65321	16.307221	13.345943	14.752466
31	12340	4500	4.09132	3.65321	16.738899	13.345943	14.946451
32	12340	4500	4.09132	3.65321	16.738899	13.345943	14.946451

[A] † Editorially corrected.

$\sum h = 93.77592$
$(\sum h)^2 = 8793.9231718$
$H = 2.930498$
$\sum h^2 = 300.349955$
$N = 32$

$\sum f = 117.91991$
$(\sum f)^2 = 13905.1051744$
$F = 3.684997$
$\sum f^2 = 434.562639$
$\sum fh = 344.769246$

Step 1:

$U = 434.562638 - 13905.1051744/32$
$U = 0.028102$
$V = 300.349955 - 8793.9231718/32$
$V = 25.539856$
$W = 344.7693246 - (117.91991 \times 93.77592)/32$
$W = 0.794755$

Step 2:

$b = 0.794755/0.028102 = -28.28108$
$a = 2.930498 - (-28.28108 \times 3.684997)$
$a = 107.14619$

Step 3:

$h = 107.14619 - 28.28108\ f$

Step 4:

Calculate stress at 100 000 h and 50 years from the equation in Step 3.

Period	Stress
100 000 h	4091 psi
50 years	3883 psi

A computer program calculation to eight decimals gives:

$h = 107.13634$
$f = 28.27840$
Stress at 100 000 h = 4091 psi
Stress at 50 years = 3883 psi

Step 5:

Calculate Lower Confidence Limit of stress at 100 000 h

Calculate $f_{100\,000} = (5 - a) / b$
$= (5 - 107.13634) / 28.27840$
$= 3.611815$

Calculate $D = (5 - H)$
$= 5 - 2.930497$
$= 2.069503$

Calculate $s^2 = [1/(N-2)][V - (W^2/U)]$
$= (1 / 30)\ [23.53983 - (-0.7947791^2 / 0.028105)]$
$= 0.102158$

Calculate $s = \sqrt{s^2}$
$= \sqrt{0.102158}$
$= 0.319622$

Look up *t*, 30 degrees of freedom, 2-sided, 95 % confidence level = 2.0423

Calculate $M = b^2 - (t^2 s^2 / U)$
$= -28.2783952 - (2.0423^2 \times 0.102158 / 0.028105)$
$= 784.5068$

M is positive; proceed.

Calculate $L = \{bD - ts\sqrt{[(D^2 / U) + (M / N)]}\} / M$
$= \{-28.28108 \times 2.069503 - 0.319622 \times 2.0423 \sqrt{[(2.069503^2 / 0.028102) + (784.5068 / 32)]}\} / 784.5068$
$= -0.08566$

Calculate $\log(LCL) = L + F$
$= -0.08566 + 3.684997$
$= 3.599334$

Calculate $LCL = 10^{\log(LCL)}$
$= 10^{3.599334}$
$= 3975$ psi

Calculate *LCL* ratio $= 3975/4091$
$= 97.16\ \%$

X8. EXAMPLES FOR 5.3.2

X8.1 A PVC compound has a long-term hydrostatic strength of 4110 psi, a 50-year strength of 3950 psi, and a stress of 6060 psi is required to give 5 % expansion at 100 000 h. The expansion for 4110 psi at 100 000 h is 2.1 %. Because 3950/4110 = 0.961, the selection is between 4110 and 6060 psi. Therefore, the hydrostatic design basis is 4000 psi.

X8.2 A PVC compound has a long-term hydrostatic strength of 4320 psi, a 50-year strength of 3310 psi, and a stress of 4400 psi is required to give 5 % expansion at 100 000 h. Because 3310/4320 = 0.77, the selection is among 4320, 3310, and 4400 psi. Therefore, the hydrostatic design basis is 3150 psi.

X8.3 A PE compound has a long-term hydrostatic strength of 810 psi, a 50-year strength of 600 psi, and a stress of 560 psi is required to give 5 % expansion at 100 000 h. Because 600/810 = 0.74, the selection is among 810, 600, and 560 psi. Therefore, the hydrostatic design basis is 500 psi.

X8.4 An ABS compound has a long-term hydrostatic strength of 3320 psi, a 50-year strength of 3020 psi, and a stress of 4870 psi is required to give a 5 % expansion at 100 000 h. Because 3020/3320 = 0.91, the selection is between 3320 and 4870 psi. Therefore, the hydrostatic design basis is 3150 psi.

X9. EXAMPLES FOR 5.6.1 (PROCEDURE I)

X9.1 *Example Calculation No. 1*—For a PE Material, the Test Method D2837 calculated LTHS at 23°C (73°F) (296°K) is 1605 psi. To validate this LTHS, pipe specimens must be tested at three conditions.

X9.1.1 *Tests at Condition I:*

T = 90°C (194°F) (363°K)
S = 600 psi hoop stress (approximately 120 psig for SDR 11 pipe)

At this condition, the following slit failure mode data were obtained:

Failure Time (h)	*Log Failure Time*
97	1.9867
148	2.1553
218	2.3384
256	2.4082
357	2.5526
408	2.6106

Average of log failure times = 2.3420
Average failure time (log basis) = 220 h
(220 is the anti-log of 2.3420)

X9.1.2 *Tests at Condition II:*

T = 90°C (194°F) (363°K)
S = 500 psi hoop stress (approximately 100 psig for SDR 11 pipe)

At this condition, the following slit failure mode data were obtained:

Failure Time (h)	*Log Failure Time*
815	2.9111
1250	3.0969
1930	3.2855
2250	3.3521
2651	3.4234
3785	3.5780

Average of log failure times = 3.2745
Average failure time (log basis) = 1882 h

X9.1.3 *Calculate A, B, C*—To calculate the three constants *A*, *B*, and *C*, we must solve the following three simultaneous equations:

$$\log 220 = A + \frac{B}{363} + \frac{C\log 600}{363} \tag{X9.1}$$

$$\log 1882 = A + \frac{B}{363} + \frac{C\log 500}{363} \tag{X9.2}$$

$$\log 100000 = A + \frac{B}{296} + \frac{C\log 1605}{296} \tag{X9.3}$$

$$A = -36.6843$$

$$B = 26054.1$$

$$C = -4276.85$$

X9.1.4 *Tests at Condition III—Minimum Time Requirement for Validation:* T = 80°C (353°K) (176°F)
S = 600 psi

$$\log t = -36.6843 + \frac{26054.1}{353} - \frac{4276.85\log 600}{353} \tag{X9.4}$$

$$t = 2800\ h$$

When the average time (log basis) for six specimens tested at Condition III exceeds 2800 h, the Test Method D2837 extrapolation to 1605 psi has been validated for this PE pipe lot.

X9.2 *Example Calculation No. 2*—For a PE material, the Test Method D2837-calculated LTHS at 23°C is 1365 psi. To validate this LTHS, pipe specimens must be on test at three conditions.

X9.2.1 *Tests at Condition I:*

T = 80°C (353°K) (176°F)
S = 660 psi hoop stress (approximately 132 psig for SDR 11 pipe)
t = 136, 148, 182, 215, 216, 287 h

X9.2.2 *Tests at Condition II:*

T = 80°C (353°K) (176°F)
S = 450 psi hoop stress (approximately 90 psig for SDF 11 pipe)
t = 779, 821, 864, 956, 1201, 1560 h

X9.2.3 *Calculate A, B, C*—Determine the average failure time (log basis) for Conditions I and II. Remember that the average must be determined on a log basis. Solve three simultaneous equations.

$$\log 191 = A + \frac{B}{353} + \frac{C\log 660}{353} \tag{X9.5}$$

$$\log 998 = A + \frac{B}{353} + \frac{C\log 450}{353} \tag{X9.6}$$

$$\log 100000 = A + \frac{B}{296} + \frac{C\log 1365}{296} \tag{X9.7}$$

$$A = -20.2812$$

$$B = 12265.1$$

$$C = -1524.04$$

X9.2.4 *Tests at Condition III—Minimum Time Requirement for Validation:* T = 60°C (333°K) (140°F)
S = 660 psi hoop stress

$$\log t = -20.2812 + \frac{12265.1}{333} - \frac{1524.04\log 660}{333} \tag{X9.8}$$

$$t = 4325\ h$$

X10. EXAMPLES FOR VALIDATION 5.6.3 AND 5.6.4

X10.1 *Example Calculation No. 3*—Validation of a PE material by 5.6.4 the Test Method D2837 calculated LTHS at 140°F. According to Table 8, minimum data requirements for a 193°F (90°C) regression are an "E-6" data level (per PPI TR-3) and a t_{max} of 5 000 h. The following data are obtained: See Table X10.1.

SUMMARY OF CHANGES

Committee F17 has identified the location of selected changes to this standard since the last issue (F2837–11) that may impact the use of this standard.

(1) Revised Table 1 for HDB categories to use the R20 series steps above 1600 psi HDB category.

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