Nature of Hydrostatic Stress Rupture Curves

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Foreword

This report was developed and published with the technical help and financial support of the members of the PPI (Plastics Pipe Institute, Inc.). The members have shown their interest in quality products by assisting independent standards-making and user organizations in the development of standards, and also by developing reports on an industry-wide basis to help engineers, code officials, specifying groups, and users.

The purpose of this technical note is to provide general information on stress rupture curves used for plastic piping materials.

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I. Introduction

Service life prediction or estimation is an important tool used by design engineers to safely plan, install and operate plastic piping systems. Piping system service life is dependent upon resistance to stress and chemicals from the internal and external environment. Stresses may be internal from pressure or external from embedment, bending or shear. These stresses may be constant or varying. Internal pressure surges, temperature changes, and varying loads from traffic, tidal flows, and the like can also stress the material. Resistance to external or internal chemicals, temperature, and variations in these effects can combine to affect the service life of the piping system.

One component of service life, resistance to stress from constant internal pressure, can be estimated using hydrostatic stress-rupture testing. This Technical Note (TN) explains hydrostatic time to rupture curves, their use, how they are developed under ASTM D 2837 and ISO 9080 protocols, and a brief explanation of the differences between these two methods. This TN is not intended as a guide to determine pressure ratings; the user should consult the appropriate industry standard.

II. The Nature of Hydrostatic Time to Rupture Curves

The testing of pipe samples at different internal pressures in a laboratory environment generates time/stress failure data. However, these data do not form a straight line when plotted on regular graph paper, often called Cartesian coordinates (Figure 1). Detailed studies were performed to determine the best mathematical function to convert the data and the log-stress log-time linear equation was chosen. When plotted on log-log axes, the time/stress failure point data define a straight line, enabling a linear regression analysis (Figure 2). The nature of a time to rupture versus stress hydrostatic curve for a plastic piping material is that as the stress on pipe decreases the time-to-failure increases.

Figure 1 – Stress Rupture Data Plotted on Cartesian Coordinates

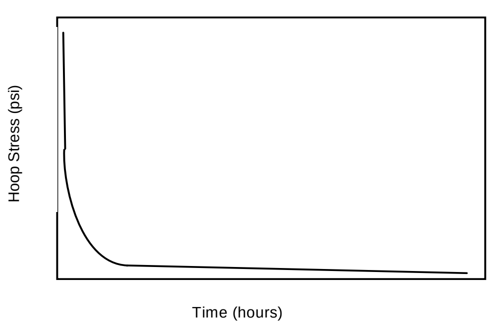
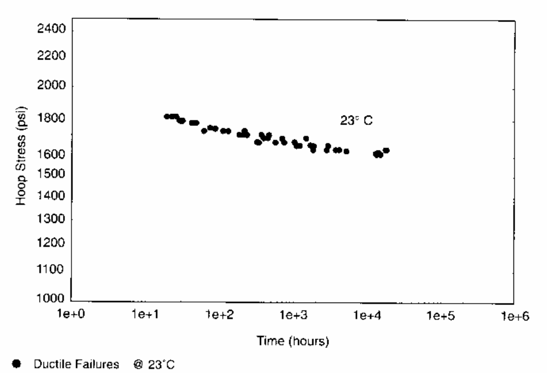


Figure 2 - ASTM D 2837 Hydrostatic Data



By evaluating stress rupture test data from pressure test of pipe made from the subject material, a piping material's stress rating can be determined from the material's ASTM D 2837 Hydrostatic Design Basis (HDB) or ISO 9080 / ISO 12162 Minimum Required Strength (MRS).

The HDB from ASTM D 2837 or MRS from ISO 9080 / ISO 12162 is the categorized long-term hydrostatic strength (LTHS) used to calculate the hydrostatic design stress (HDS) of a plastic piping material. The Plastics Pipe Institute lists the material's HDB and HDS, or MRS value in TR-4, "PPI Listing of Hydrostatic Design Bases (HDB), Pressure Design Bases (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe".

Hydrostatic testing performed under ASTM or ISO methodologies is applicable to all known types of thermoplastic pipe materials and for any suitable temperature and medium. PPI's TR-4 lists the HDB and MRS values for specific formulations of the thermoplastic materials listed below.

PVC	Polyvinyl Chloride
CPVC	Chlorinated Polyvinyl Chloride
PE	Polyethylene
PEX	Crosslinked Polyethylene
PB	Polybutylene
POM	Polyoxymethylene, polyacetal
PFA	Perfluoroalkoxy
PA	Polyamide, nylon
PVDF	Poly(vinylidene difluoride)

III. Brief Comparison of ASTM and ISO Methods

Both ASTM D 2837 and ISO 9080 analyze stress rupture data to estimate the long-term strength of a plastic piping material. In ASTM D 2837, the HDB for the material is determined by categorizing the mean LTHS value at 100,000 hours (11 years). In ISO 9080, the lower prediction limit (LPL) of the LTHS at 50 years (438,000 hours) is determined then categorized into a MRS as defined in ISO 12162. Both ASTM D 2837 and ISO 9080 / ISO 12162 have served users well for many years. Whether HDB or MRS is determined for a material, the actual long-term performance will be the same under the same service conditions.

While both ASTM D 2837 and ISO 9080 are used to develop hydrostatic time to rupture curves, there are some differences between the methods. Table 1 presents a summary of differences.

Table 1
Comparison of ASTM D 2837 and ISO 9080

	ASTM D 2837	**ISO 9080**
Classification	HDB	MRS
Linearity	Assumes linearity (validation required for polyethylene materials) (Note 1)	No assumption (Note 2)
Regression	Individual temperatures	All points combined
Coefficients	2	3 or 4
Extrapolation temperature	23°C is normal, but many others are used	20°C
Extrapolation time	100,000 hours and 50 years	50 years
Intercept	Mean LTHS	97.5% LPL of LTHS
Units	psi	MPa

Note 1 – ASTM D 2837 assumes a linear extrapolation to the 100,000-hour intercept. For polyethylene materials, a validation procedure is applied to confirm this assumption. Polyethylene materials that exhibit a knee in the 73°F stress rupture curve before 100,000 hours do not "validate" the extrapolation and are not given a HDB rating.

Note 2 – ISO 9080 uses an extrapolation that includes characterization of a possible knee in the stress rupture curve before the 438,000-hour intercept. The knee in the regression curve typically, but not always, corresponds to a change between ductile failure and brittle (slit) failure modes in polyolefin materials.

Temperature has an inverse effect on the LTHS for thermoplastic materials; that is, at higher temperature, the LTHS is lower for the same extrapolation time. ASTM D 2837 does not specify the LTHS temperature, but 23°C is typically used when characterizing the LTHS for stress rating. ISO 9080 specifies 20°C.

IV. ASTM D 2837

A. Methodology

ASTM D 2837 does not stipulate the size of pipe to be tested or the number of material lots. ASTM D 2837 specifies the minimum number of failure points at a particular temperature with a distribution over three log-decades on the time axis to give the regression more statistical significance. The established method of regression analysis is a 2-coefficient equation:

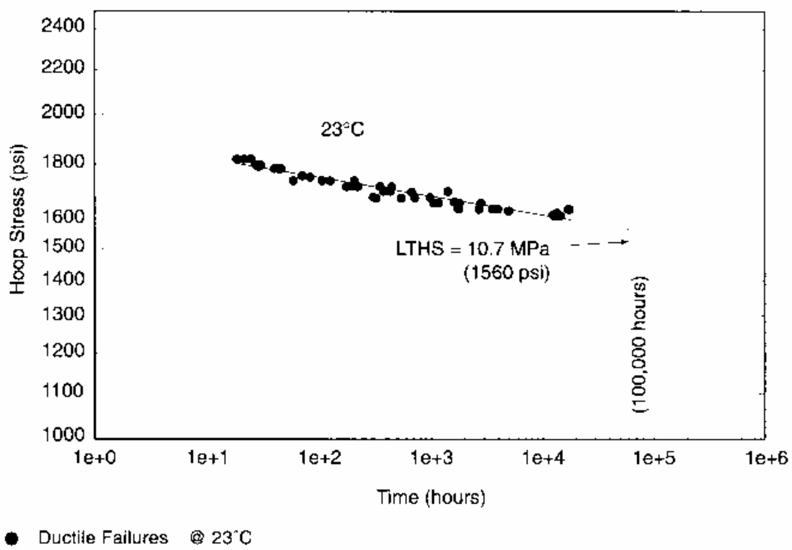
$$\log t = A + B * \log S$$

Where: A, B = constants

t = time (hours)
S = Hoop Stress (psi)

Once the regression equation describing the line is determined, the line is extrapolated to 100,000 hours and the corresponding mean stress can be calculated. This mean stress intercept at 100,000 hours is the LTHS of the material (Figure 3). Since ASTM D 2837 uses a 2-coefficient equation with the time (t) and stress (S) as variables, the temperature (T) is constant. The LTHS, therefore, is for the temperature at which the data are obtained. For many materials the common temperature selected is 73°F (23°C), but other temperatures may be used. (Recommended temperatures are 73°F, 140°F, 180°F and 200°F).

Figure 3 - ASTM D 2837 Regression and Extrapolation

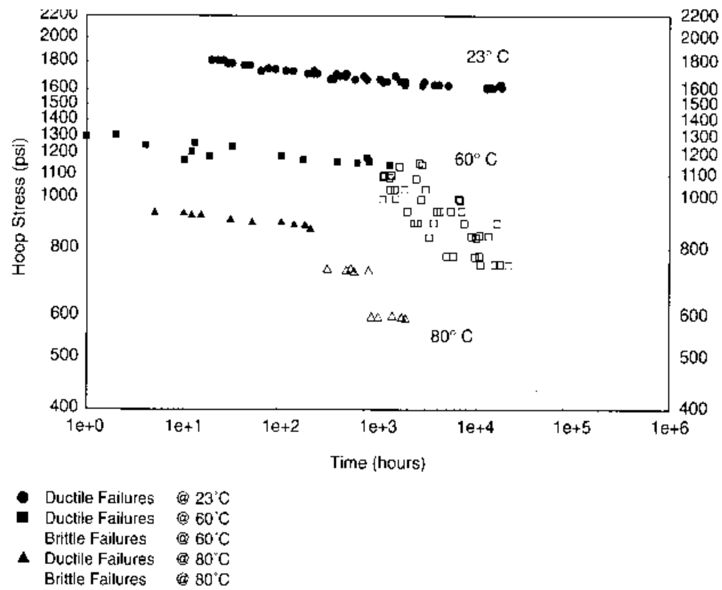


The data are checked for suitability of use through 1) calculation of the 97.5% lower confidence limit at 100,000 hours and comparing it to the LTHS. If the values differ by less than 15%, the data are considered statistically significant and suitable for use, and 2) calculation of the 50-year long-term hydrostatic strength. The 100,000-hour LTHS must be less than 125% of the 50-year value. If the 50-year LTHS is less than 80% of the 100,000 hour LTHS, then use the 50-year LTHS to establish the HDB. If the data are suitable, the Hydrostatic Design Basis (HDB) for the material is determined by categorizing the LTHS within limits specified in ASTM D 2837. Standard HDB categories are based on the R10 preferred number series and result in stress increments of 25%. The lower limit of the HDB range is set to include mean LTHS stresses that are 4% below the HDB value in order to take into account some inherent testing variation..

B. Validation using ASTM D 2837

When extrapolating a time/stress data regression line to a point in the future, it is assumed that this regression line will continue in a linear manner. This assumption holds true for most thermoplastics except for the polyolefins, which include polyethylene, polypropylene, and polybutylene. These polyolefin materials may exhibit a change in failure mode from ductile to brittle, or slit failures. This change in failure mode typically decreases the material's long-term strength as the slope of the regression line changes in the brittle zone. Figure 4 shows a typical hydrostatic time versus stress plot for polyethylene with data taken at various temperatures. This plot illustrates both how temperature impacts the curves and the ductile-brittle transitions.

Figure 4 – Typical Hydrostatic Curves for PE at Various Temperatures



Higher temperatures shorten the time-to-failure and the time to ductile-brittle failure mode transition (i.e. Arrhenius relationship) . This is the basis for validating the HDB to improve the confidence of the extrapolated regression line. In other words, higher temperature tests show whether the ductile-brittle transition does or does not occur within the extrapolated time frame at lower temperatures.

ASTM D 2837 and PPI TR-3 *Policies and Procedures for Developing Hydrostatic Design Bases (HDB), Pressure Design Bases (PDB), Strength Design Bases (SDB), and Minimum Required Strengths (MRS) Ratings for Thermoplastic Piping Materials or Pipe*, Part F.4 defines validation procedures for polyethylene materials. Three methods are described.

The Standard method entails placing pipe samples on test at either 80°C or 90°C at a prescribed stress depending on the categorized HDB to be validated. The log average failure time of the samples must exceed the minimum values shown in ASTM D 2837 and TR-3, Part F.4.1.

For materials that exhibit brittle failures before 10,000 hours the Alternate Method is used for PE materials that have brittle mode failures at high temperatures in a reasonable time. This validation method includes testing pipe samples under three stress and temperature conditions. An example is shown in Table 2.

Table 2 – Typical Conditions for Validation Testing of PE for a 73°F HDB

Condition 1	80°C	5.7 MPa (825 psi)
Condition 2	80°C	5.0 MPa (725 psi)
Condition 3	60°C	5.7 MPa (825 psi)

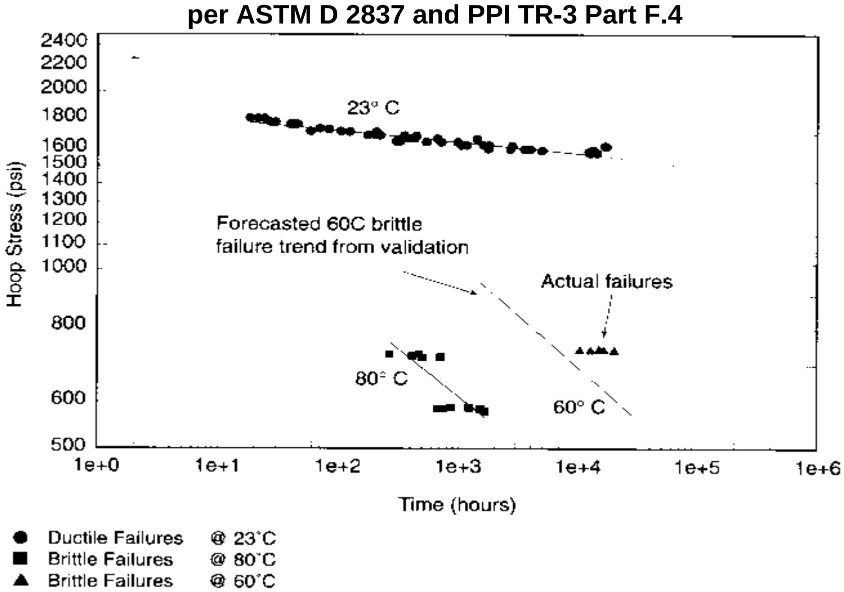
To validate the LTHS at the HDB temperature, the Rate Process equation is solved using data derived from Conditions 1 and 2. The calculated LTHS at 100,000 hours is used for the third point. Solving these three equations and unknowns yields the coefficients for the 3-coefficient rate process extrapolation equation:

$$\text{Log } t = A + B/T + (C * \log S) / T$$

Where: A, B, C = constants
t = time (hours)
T = Temperature (°K)
S = Hoop Stress (psi)

With these coefficients, the model is used to calculate the mean time to failure for pipes placed on test under Condition 3. When the pipes placed on test under Condition 3 surpass the log average time-to-failure projection generated by the rate process equation, then the extrapolation at the HDB temperature has been validated. In other words, the ductile-brittle transition occurs after the 100,000 hour intercept at the HDB temperature (as shown in Figure 5). An example of this procedure is detailed in ASTM D 2837 Appendixes.

Figure 5 – Validation by Standard Method per ASTM D 2837 and PPI TR-3 Part F.4



A third method for validation of a 140°F (60°C) HDB is based on ISO 9080 K-factor principles. For this method a ductile failure regression line is established at either 80°C or 90°C. The log average failure time of the five longest running specimens must exceed the minimum time as shown in TR-3, Part F.4.3. When this minimum time is exceeded, the extrapolation of the 140°F stress regression line is considered valid – meaning the ductile/brittle transition is past 100,000 hours.

ASTM D 2513, *Thermoplastic Gas Pressure Pipe, Tubing and Fittings*, requires a further substantiation of the linearity of the stress regression line to 438,000 hours (i.e. 50 years). This supplemental validation shows that the ductile/brittle transition is beyond the 50-year intercept. This is a requirement of D 2513, in addition to validation of the HDB as described above. The procedure for this substantiation is in TR-3,Part F.5.

V. ISO 9080 and ISO 12162

A. Methodology

ISO 9080 "Plastic piping and ducting systems – Determination of the long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation", requires data at two or three temperatures, such as 20°, 60° and 80°C. The data required are at least 30 failure points at each temperature with distribution over three log decades. There must be at least five different stress levels with at least two specimens at each stress level for each temperature. This procedure does not stipulate size of pipe to be tested or number of material lots, though typically only one material lot is used to develop the data in order to minimize the statistical scatter in the data.

ISO 9080 allows for two equations to calculate the LTHS and LPL depending on the statistical fit of the data. The procedure requires that the 4-coefficient model be used for the initial analysis. If after calculating the 4-coefficients the probability of c3 is greater than 0.05, then the 3-coefficient model may be used.

4-Coefficient Equation $\log t = c1 + c2/T + c3 \log S + c4 (\log S)/T$

3-Coefficient Equation $\log t = c1 + c2/T + c4 (\log S/)T$

Where: c1, c2, c3, c4 = constants
t = time (hours)
T = Temperature (°K)
S = Hoop Stress (MPa)

ISO 9080 Standard Extrapolation Method (SEM) does not differentiate between ductile and brittle failures. A mathematical test on the regression line determines if a "knee" is present and a failure type A or B is assigned to the data. If it is determined that a knee is present, there must be a sufficient number of each failure type in order to perform a statistically meaningful analysis. If the ductile/brittle transition occurs before 50 years, then this change in slope is considered in the extrapolated LTHS value. This means a potential stress-rating decrease when extrapolated to 50 years.

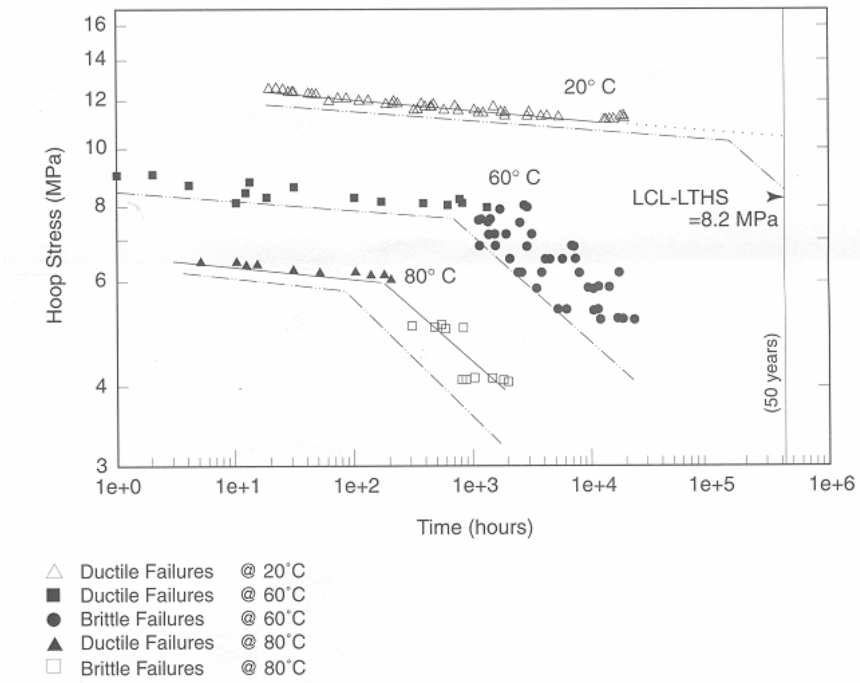
ISO 9080 establishes the LTHS based on the statistical 97.5% lower prediction limit (LPL) of the mean extrapolation of the stress regression equation to 50 years.

To aid in the calculations there is a software package for the SEM calculations available from BECETEL vzw in Melle, Belgium. For information email info@becetel.be. This software package has been approved by the Ad Hoc SEM working group of ISO/TC 138/ SC5.

B. MRS/CRS

The Minimum Required Strength (MRS) is derived from ISO 12162 "Thermoplastic materials for pipe and fittings for pressure applications – Classifications and designations – Overall service (design) coefficient". This standard establishes the MRS category stress ranges. The 97.5 % LPL long-term hydrostatic strength (LTHS) derived from ISO 9080 is categorized, like in ASTM D 2837,.to establish a MRS for the material. The regression line from the 20°C data is extrapolated to 50 years (438,000 hours). The stress at the 50-year intercept is the mean LTHS for the material, as illustrated in Figure 6.

Figure 7 – ISO 9080 Regression and Extrapolation with Lower Confidence Limits



VI. Summary

Two recognized methods are used to determine the long-term hydrostatic strength of thermoplastic materials – ASTM D 2837 (HDB) and ISO 9080 (MRS). Both methods use data from sustained hydrostatic pressure tests of pipe specimens, but the extrapolation protocols are slightly different. However, for a given material, the actual long-term performance under an internal pressure and temperature will be the same regardless of the method used to forecast the LTHS.

HDB or MRS values are only a basis and must be used in conjunction with the appropriate de-rating factors to determine allowable pressure ratings based on plastic pipe dimensions and a safety factor appropriate for the piping application. In general, service design factors (DF) are used with the HDB, and service design coefficients (C) are used with MRS. Information on design factors and design coefficients can be found in PPI document TR-9 "Recommended Design Factors and Design Coefficients for Thermoplastic Pressure Pipe".

VII. Conclusion

This Technical Note describes how a thermoplastic piping material's long-term internal stress rating, HDB or MRS, is determined and validated using hydrostatic time to rupture curves. Both methodologies are based on the Arrhenius principles of time and temperature response. The time to which the stress regression line is extrapolated should not be confused with a design or service lifetime. Each method gives a basis for determining the maximum operating hydrostatic design stress (HDS) when coupled with the appropriate design factors or design coefficients for the application and service conditions.

The design engineer should select the appropriate DF for the HDB or C for the MRS after evaluating application service conditions and the engineering properties of the specific material under consideration. Alternatively, the authority having jurisdiction may specify it.