ELEVATED TEMPERATURE TESTING AND VALIDATION OF POLYETHYLENE PIPING MATERIALS

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TEST METHODS TO DETERMINE LONG TERM STRENGTH

- Thermoplastic piping products are qualified as to their long term strength by three different mathematical analysis methods:

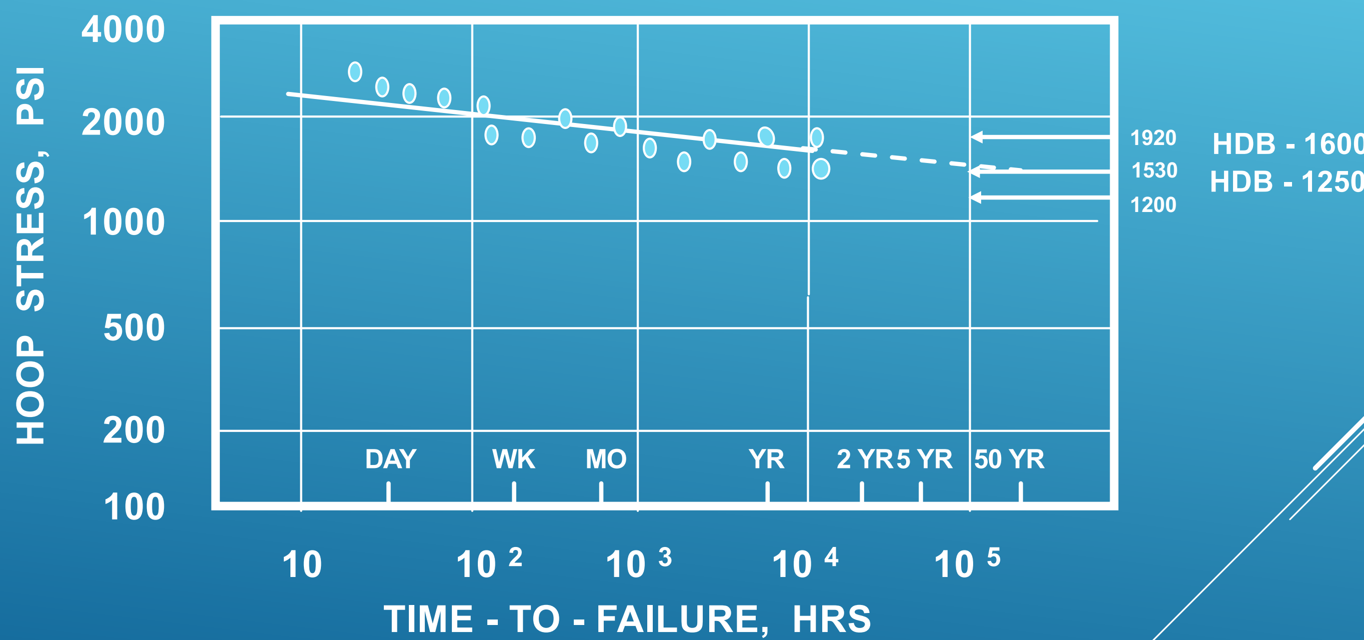
- American Society for Testing and Materials (ASTM)
  - ASTM D2837: Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products
  - ASTM D2992: Standard Test Method for Obtaining Hydrostatic Design Basis for Fiberglass (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings
- International Organization for Standardization (ISO)
  - ISO 9080: Plastic Piping Ducting Systems – Determination of Long-term Hydrostatic Strength of Thermoplastics Materials in Pipe Form by Extrapolation

DETERMINATION OF LONG TERM STRENGTH USING ASTM D2837

- TIME DEPENDENT EQUATION
  - LOG (T) = A + B LOG (P)
  - A AND B ARE EXPERIMENTALLY DETERMINED FROM LINEAR REGRESSION ANALYSIS OF BURST DATA
  - T = TIME-TO-FAILURE, Hours
  - P = HOOP STRESS, psi

ESTABLISHING THE HDB AT 73°F - ASTM D2837

BASED ON CONSTANT PRESSURE TESTS CONDUCTED ON PIPE



HYDROSTATIC DESIGN BASIS

- CATEGORIZATION OF A RANGE OF LTHS VALUES INTO THE HYDROSTATIC DESIGN BASIS - HDB
- DESIGN CALCULATIONS ARE GENERALLY BASED ON THE HDB NOT SPECIFIC LTHS VALUES

HYDROSTATIC DESIGN BASIS CATEGORIES FOR POLYETHYLENE PIPE PRODUCTS - ASTM D 2837

RANGE OF CALCULATED LTHS VALUES, psi	HYDROSTATIC DESIGN BASIS (HDB), psi
1530 - <1920	1600
1200 - <1530	1250
960 - <1200	1000
760 - <960	800

PLASTIC COMPOUND MATERIAL STRENGTH RECOMMENDATIONS AND LISTINGS – PPI TR-4

TR-4/2007a

HDB/HDS/SDB/PDB/MRS

Listed Materials

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

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- PPI started evaluating and listing plastic materials for pressure applications more than 40 years ago.
- PPI publishes Technical Report 4 (TR-4) annually or more often.

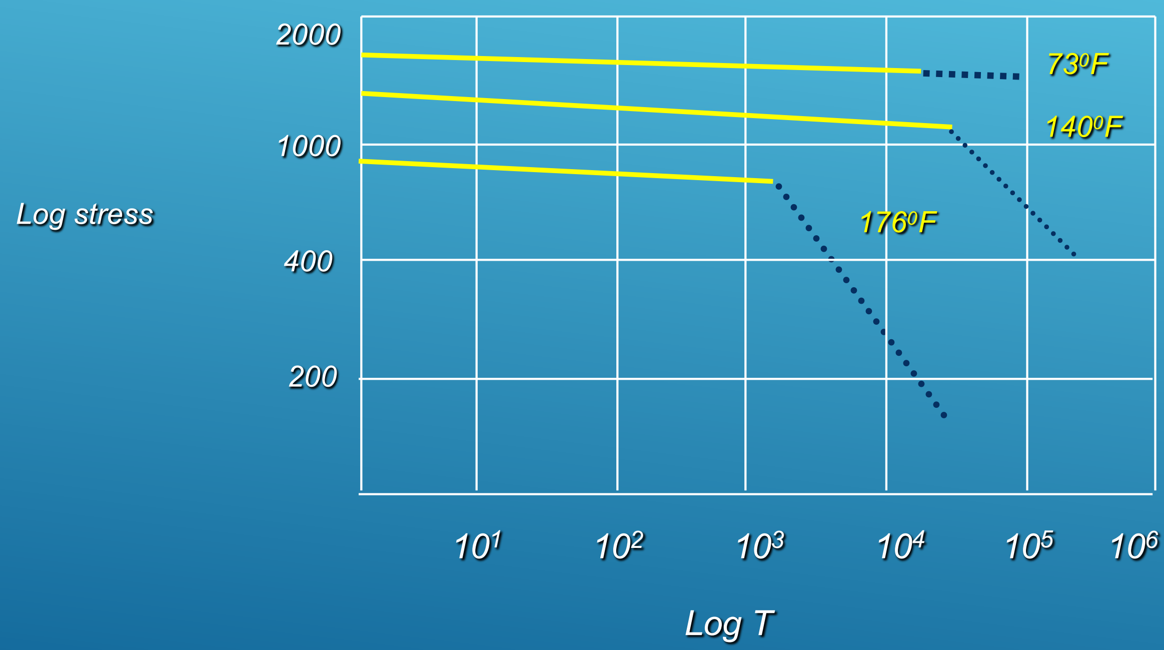
DEVELOPMENT OF VALIDATION METHODS

Early in the development of polyethylene piping materials long term testing at elevated temperatures found that there occurred a transition from ductile failure to a brittle type of failure and that the anticipated extrapolation of the long term strength was affected.

A disagreement occurred between the North American plastic piping community and the European pipe community.

Each group proceeded independently to develop testing methodologies toensure the long term performance of polyethylene piping products.

STRESS RUPTURE PERFORMANCE FOR OLDER PE PIPING GRADES



DEVELOPMENT OF VALIDATION METHODS

The European piping community developed ISO TR908 and employed elevated temperature testing requirements at three different temperatures to develop a family of stress rupture curves.

A graphical interpretation method was employed to estimate the ductile to brittle transition ("knee") in the 20°C stress rupture curve and project the intercept to 50 years (438,000 hours).

The North American community developed Validation Concepts based on the Arrhenius theory, where elevated temperature testing was used to accelerate the dominant failure mechanism and mathematics were used to project the 100,000 hour (11.1 year) projected Long-Term-Hydrostatic Strength. (LTHS).

Arrhenius Equation

In 1889, Arrhenius pointed out that a reasonable equation for the variation of the rate constant of a chemical reaction with temperature would be the following:

Equation 1: $$\frac{d \ln k}{d T} = \frac{Ea}{RT^2}$$

Where:
k is the rate constant for the reaction
T is the temperature (degrees Kelvin)
Ea is the activation energy of the reaction
R is the gas constant
ln is the natural logarithm

If Ea is not temperature dependent, Equation 1, upon integration, yields the following:

Equation 2: $$\ln k = \frac{-Ea}{RT} + \ln A$$

Where A is the constant of integration

Arrhenius Equation

This equation is also written as the following

Equation 3: $k = Ae^{-\in/kT}$

Where k is the average rate constant for the reaction

A is the pre-exponential factor, frequently termed the frequency factor and is independent of temperature

$\in a$ (E_a) is the Arrhenius Activation Energy and provides a value for some characteristic energy that must be added to the reactants for the reaction to occur.

VALIDATION CONCEPTS

- Validation of the LTHS values for polyethylene pipe materials are based on Arrhenius' theory.
- Arrhenius' theory states that the rate of chemical reactions increase as the temperature increases.
- Arrhenius found that for reactions of gases, the reaction rate doubled for every 10°C increase.
- Elevated temperature testing is thus used to accelerate the fundamental failure mechanism for polyethylene.
- However, as polyethylene is not a gas the change in the reaction rate is different.

TR-3 PE SPECIFIC POLICIES ALTERNATIVE VALIDATION METHOD

- Using only ductile failures determine the linear regression equation and the ductile LTHS at 100,000 hours.
- To determine the brittle failure performance, solve for the three coefficients of the rate process equation per procedure 1 of ASTM D2837. All failures used in the calculation must be brittle.
- Using the brittle failure model calculate the stress intercept value at 100,000 hours for the temperature at which the HDB is desired. This is the brittle LTHS.
- The LTHS used to determine the HDB shall be lower value of the ductile failure LTHS from section 2.1 of the brittle LTHS.

ASTM D2837 PROCEDURE L VALIDATION METHOD

- Select an elevated temperature not greater than 95⁰C for testing.
- Select a stress at this temperature at which all failures are brittle.
- Test at least six specimens at this condition (I) until failure.
- At the same temperature, select a stress between 75 to 150 psi lower than the initial stress (Condition II). Test at least six specimens until failure.
- Select a second temperature between 10⁰C and 20⁰C lower than Condition I. Using the same higher stress from Condition I, test six specimens.
- To validate the LTHS on a give pipe lot, take the data developed at Conditions I and II and the LTHS value at ambient temperature and calculate the three coefficients for the following equation: $Log(T) = A + B/T + C/T * Log(S)$
- Using this equation calculate the mean failure time for Condition III.
- When the average failure time for the specimens on test at Condition III exceeds this calculate failure time, the material has been validated.

VALIDATION CONCEPTS

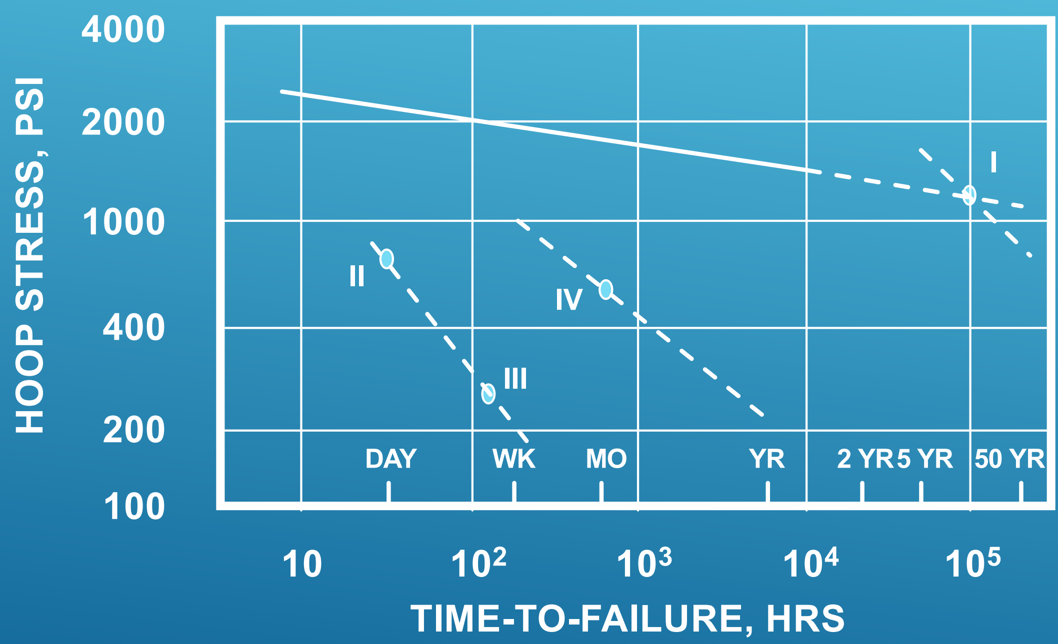
Rate Process Method Equation

Equation 3: $\log t = A + \frac{B}{T} + \frac{C \log S}{T}$

Where: t = time, hours
T = absolute temperature, °K (°K = °C + 273)
S = hoop stress, psi
A, B, C = constants

VALIDATION OF ASTM D2837 EXTRAPOLATION

$$\text{Log } t = A_O + \left(\frac{A_O}{T}\right) + \left(\frac{A_2 \text{ Log}^s}{T}\right)$$



TR-3 PE SPECIFIC POLICIES HDB SUBSTANTIATION FOR PE MATERIALS

- Using the 12 data points from Conditions I and II from Procedure I of ASTM D2837 along with the LTHS at 50 years, solve for the three coefficient rate process extrapolation equation.
- Calculate the mean estimated failure time for Condition III.
- When the log average time for six specimens tested at Condition III have reached this time, linear extrapolation of the 73^0F (23^0C) stress regression curve to 50 years (438,000 hours) is substantiated.

POPELAR SHIFT FUNCTION EQUATIONS

Equation 4: $\alpha\tau = \exp[-0.109\ (T - TR)]$ $\beta\tau = \exp[0.0116\ (T - TR)]$

The time to failure t_f of PE depends upon the applied stress (σ) and the temperature (T).

Where: $\sigma(TR) = \sigma\ (T)\ \beta\tau$ and $t_f(TR) = t_f(T)/\ \alpha\tau$

Where T = testing temperature (°K), TR = reference temperature (°K) and (T - TR) is the difference between the two temperatures.

σ (TR) = stress at the reference temperature

σ (T) = stress at the testing temperature

t_f (T) = time to failure at the testing temperature

t_f (TR) = time to failure at the reference temperature

ISO TR9080 EXTRAPOLATION TIME FACTORS

- ISO TR 9080 developed extrapolation time factors (K_e) as a function of δT based on the following equation:

$$\delta T = T_{max.} - T_S$$

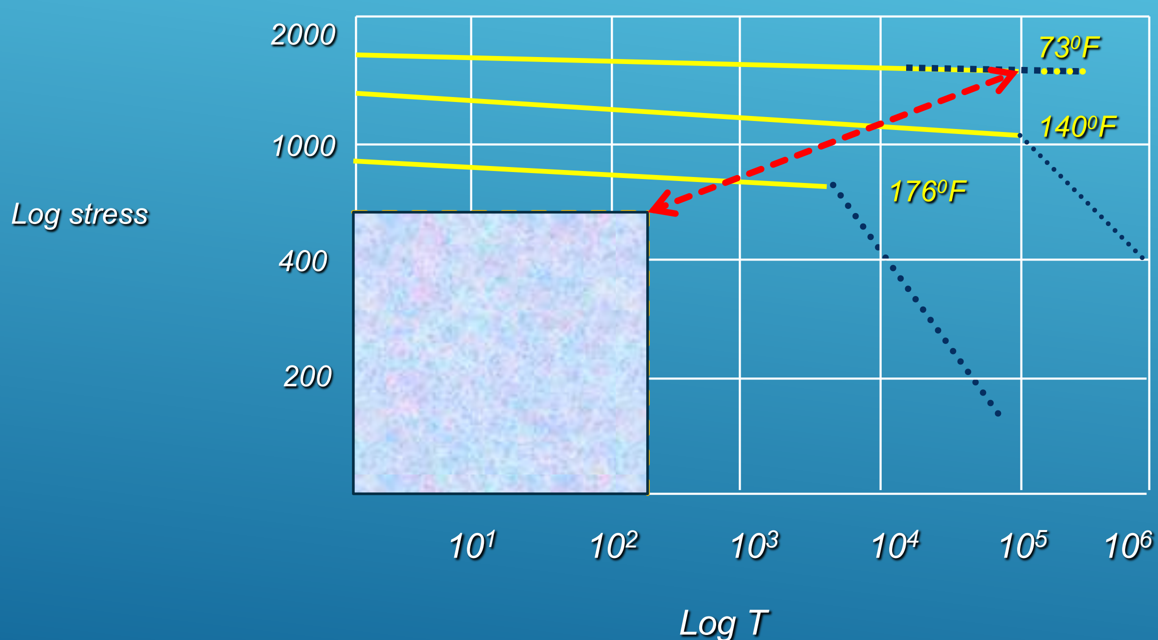
- Where $T_{max.}$ is the maximum test temperature, and T_S is the service temperature.
- The extrapolation time t_e can be calculated using the following equation:

$$t_e = K_e \, t_{max}$$

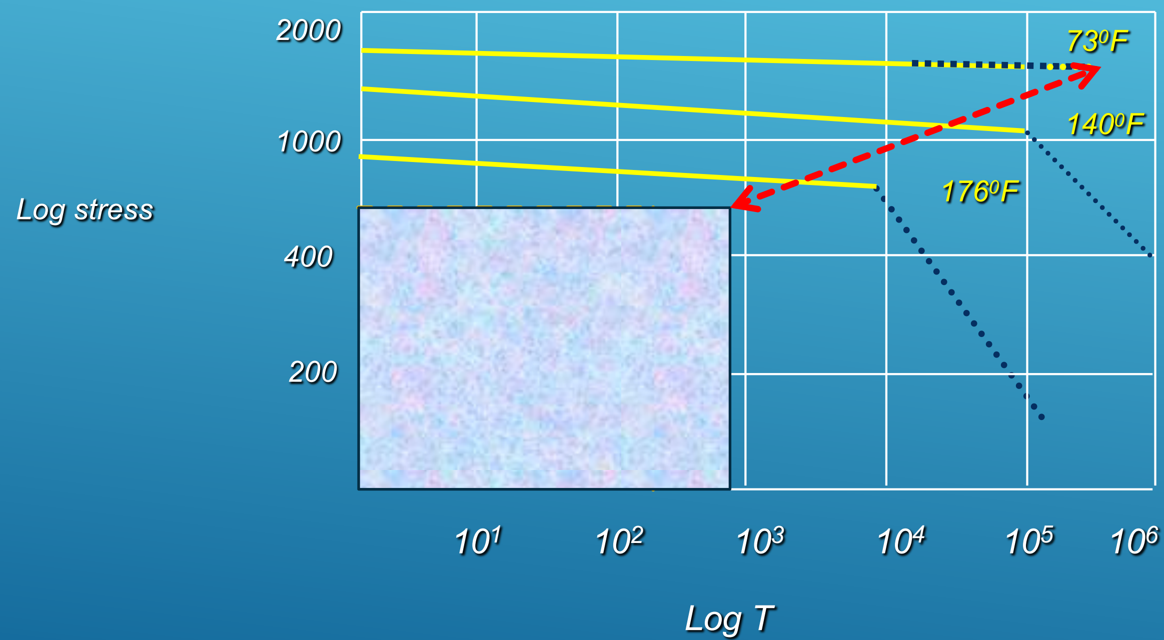
Relation between δT (= $T_{max.}$ - T_S) and K_e in TR 9080

δT (^{0}K) >	δT (^{0}K) ≤	K_e
0	10	1
10	15	3
15	20	5
20	25	9
25	30	16
30	35	28
35	40	50

ASTM D 2837 VALIDATION TESTING PROCEDURE FOR PE HDBS (200 HRS AT 180F)



ASTM D 2837 VALIDATION TESTING PROCEDURE FOR PE 50 YEAR LTHS (1000 HOURS AT 176^{o}F)



TR-3/2018
HDB/HDS/PDB/
SDB/MRS/CRS
Policies

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

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TR-3 PE SPECIFIC POLICIES VALIDATION OF 73^{0}F (23^{0}C) HDB

HDB to validate	193^{0}F (90^{0}C) Stress (psi)	193^{0}F (90^{0}C) Time (hrs)	176^{0}F (80^{0}C) Stress (psi)	176^{0}F (80^{0}C) Time (hrs)
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

TR-3 PE SPECIFIC POLICIES VALIDATION OF 140^{0}F (60^{0}C) HDB

HDB to validate	193^{0}F (90^{0}C) Stress (psi)	193^{0}F (90^{0}C) Time (hrs)	176^{0}F (80^{0}C) Stress (psi)	176^{0}F (80^{0}C) Time (hrs)
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

CURRENT VALIDATION METHODS

PPI TR3 contains the following methods:

- A standard method for Validation of the HDB, which provides stresses and minimum testing times for various HDB classes. These are shown in the previous tables.
- A Rate Process Based Method (RPM) for Validation of the HDB, which employs the original validation methodology adopted in the late 1980's.
- The ISO 9080 Based Method for Validation of 140°F (60°C)HDB, which provides specific instructions for testing for the development of brittle or slit type failures.

CURRENT SUBSTANTIATION METHODS

PPI TR3 contains the following methods:

- If the 140°F HDB has been validated, then the 73oF extrapolation is considered to be substantiated linear to 50 years.
- Rate Process Method testing, where the 50-year intercept is used to solve the 3-coefficient rate process extrapolation equation and the six tested specimens exceed the projected minimum time without brittle failure.
- When log average failure time of six test specimens at 176°F (80°C) surpasses 6000 hours or at l93°F (90oC) surpasses 2400 hours at a stress no more than 100 psi below where all failures are ductile.