A REVIEW OF SERVICE LIFE PREDICTION MODELS FOR HIGH DENSITY POLYETHYLENE PIPING FOR NUCLEAR SAFETY-RELATED APPLICATIONS

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ABSTRACT

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Codes Committee (BPVC) has published Code Case N-755 that describes the requirements for the use of Polyethylene (PE) pipe for the construction of Section III, Division 1 Class 3 buried piping systems for service water applications in nuclear power plants. The code case was developed by Special Working Group–PE Pipe (SWG-PP) within Section III (Design) of the BPVC. *The US Nuclear Regulatory Commission (USNRC) has not as yet approved this Code Case for use in regulatory decisions*. However, two Relief Requests for installation of PE Piping in safety-related applications at US Nuclear Power plants have been approved by the USNRC.

The paper focuses on the susceptibility of PE pipe to premature failure due to slow crack growth (SCG) - specifically, the various forecasting models and accelerated testing protocols that are used to analyze short term experimental results to predict long term (50 years and beyond) service life. A critical review of these models with regard to the acceleration factors for temperature, stress, and stress intensity factors is provided in the paper. As expected, elevated service temperature has the *most significant impact* on the predicted service life using the various models. Areas where improvements are needed in these forecasting models for newer generation PE100 or PE4710 bimodal resins are identified.

INTRODUCTION AND BACKGROUND

The nuclear power industry intends to use high density polyethylene (HDPE) piping in safety related nuclear piping for service water applications. In support of this work, Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Committee (BPVC) has recently formed a Special Working Group on Polyethylene Pipe (SWG-PP) to develop Code Case(s) for the use of HDPE piping in safety related nuclear power plant applications.

To date, this SWG has published Code Case CC N-755 titled "*Use of Polyethylene (PE) Plastic Pipe for Section III, Division 1, Construction and Section XI Repair/Replacement*

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Activities" (1). This code case defines the allowable stresses for the use of PE piping at various temperatures and the expected service life. Table I below shows these values as defined in Table 3021-1 in CC N-755 Rev. 0 (1). The recommended resins for use in nuclear service water piping must meet or exceed Cell Classification PE 445474C per ASTM D 3350 (2). The highlighted items in Table I indicate the extreme cases the allowable stress and temperature for highest load duration of 50 years and the load duration and stress values at the highest temperature of 60°C (140°F).

Table I - Allowable stress values for PE piping per Code Case N-755 Rev. 0 (1)

Table 3021-1	**Allowable Stress S for PE, MPa (psi)**				
Temp °C (°F)	Duration (years) at temperature				
	10	20	30	40	50
< 21.1 (70)	5.79 (840)	5.79 (840)	5.65 (820)	5.65 (820)	5.52 (800)
40.0 (104)	4.27 (620)	4.27 (620)	4.27 (620)	4.27 (620)	**4.27 (620)**
48.9 (120)	3.59 (520)	-	-	-	-
60.0 (140)	**2.96 (430)**	-	-	-	-

Also in the Code Case, the allowable surface flaw in PE piping during manufacture and installation is specified as 10% of the wall thickness per Section 2310a in CC N-755 Rev. 0(1). There are no other definitions provided regarding the allowable flaw size with regard to length, shape, location or notch acuity.

To date, the US Nuclear Regulatory Commission has NOT accepted CC N-755 (1) as a basis for design, installation, inspection, and operation of PE piping for Class 3, safety-related service water applications in nuclear power plants. The reason for this is two-fold:

- Lack of non-destructive volumetric inspection of PE piping (especially for butt joints) upon installation, and
- Lack of experimental data to support the 10% allowable flaw rule in large diameter (> 304.8 mm or 12 inches) PE piping, especially at elevated temperatures, for the expected service life (load duration) which represent typical application for service water piping.

However, since the publication of CC N-755 Rev. 0 (1), two relief requests from Catawba (Duke Energy) and Callaway (Ameren) nuclear plants were submitted to and have received conditional approval by the USNRC consists of HDPE resins with cell class 445574C (3, 4).

TECHNICAL ISSUES IDENTIFIED

The major technical issues surrounding the use of HDPE piping including premature failure due to SCG have been identified as follows:

- Effect of elevated temperature,
- Effect of allowable flaw size of 10% of wall thickness,

- Design factor for safety-related water piping
- Analytical models for long-term service life predictions, and
- Integrity and non-destructive volumetric inspection of butt joints.

Each of the above issues was discussed and summarized in a previous paper (5). This paper specifically focuses on the long-term service life prediction models for PE piping using short-term accelerated testing experimental data.

SERVICE LIFE PREDICTION MODELS

The primary reason for developing analytical models is to predict long term service life (50 years or more) using short term accelerated test methods. Elevated temperature is used as the acceleration factor for the short term tests invoking the classical Time Temperature Superposition Principle (TTSP) for long term prediction (6). The four models currently available for prediction of useful service life of PE piping are:

1. The Rate Process Method or RPM (7),
2. The Bi-Directional Shift Approach (8),
3. The PENT-Service Life Correlation (9), and
4. Integration of Time to Flaw Initiation and Growth to Failure (10).

Each of these models is described below along with an example problem, if needed. Since very little data are currently available for PE4710 (or PE 100) type materials with a Cell Classification of 445574C per ASTM D3350 (2) results from older generation materials are used in the analyses.

The Rate Process Method (RPM)

The most widely used model for long term service life prediction of PE piping is the Rate Process Method (RPM) that is described in Technical Note TN-16 from the PPI (7). The RPM uses an Arrhenius-type activation energy approach to describe the failure times as a function of stress and temperature (7).

The RPM approach uses data from long term stress rupture testing of *unflawed* pipe and has been used to determine the Hydrostatic Design Basis (HDB) for PE piping for 40 years based on time to failure of small diameter PE piping (< 4-inch diameter) at various hoop stress levels. However, the reduction in service life due to the presence of a dominant allowable flaw, such as the 10% of the pipe wall flaw in CC N-755 Rev. 0 (1), *is not accounted for in the RPM method*. While there is an ISO standard for stress rupture testing of PE piping with axial surface notches (11) there is very little data available for newer PE resins (Cell Class 445474C or 445574C) that are under consideration for nuclear applications per CC N-755 (1). Another limitation is that there is no established basis for extrapolating results from small diameter test data to very large diameter pipe performance (> 24-inch diameter), especially in the presence of a flaw.

The general form of the equation used in ASTM D 1598 (12) to correlate the time to failure ‘t’ in hours, at a hoop stress level σ in MPa, and temperature T in degrees K, is as follows

$$\log t = A + \frac{B}{T} + \frac{C \log \sigma}{T} \tag{1}$$

where A, B and C are material constants obtained from stress rupture data at various stress and temperature values. For the SCG mode of failure in one example case for a specific grade of HDPE material for non-nuclear applications (13), the values of these constants are as follows: A = 13.57, B = 5649.93, and C = -748.81. For an allowable hoop stress of 500 psi (or 3.5 MPa), the time to failure, t_T, for any temperature T may be normalized to the failure time at 20 C (or 293 K), t_{20}, as follows:

$$\ln\left(\frac{t_T}{t_{20}}\right) = 12083 * \left(\frac{1}{T} - \frac{1}{293}\right) \tag{2}$$

For the above example case. Equation (2) above will be used to compare the effect of temperature in the RPM to other service life prediction models detailed next.

Bi-Directional Shift Approach

A second approach to predicting long-term service life is the so-called bi-directional method, that was originally developed for use of PE pipe in the gas distribution industry (8). This approach is applicable to both unflawed and flawed piping and involves both horizontal (a_T) and vertical (b_T) shift functions given as:

$$a_T = \text{Exp}\,[-0.109*(T-T_R)] \tag{3}$$

$$b_T = \text{Exp}\,[0.0116*(T-T_R)] \tag{4}$$

where the temperature, T, and the reference temperature, T_R, are in degrees Celsius. The predicted time-to-failure time (service life), $t_f(T_R)$, at a stress, $\sigma(T_R)$, is given by:

$$\sigma(T_R) = \sigma(T) * b_T \tag{5}$$

$$t_f\,(T_R) = t_f\,(T) / a_T \tag{6}$$

Figure 1 below shows a schematic of the basic approach and the three step process for obtaining the horizontal and vertical shift functions in Equations (3) and (4) above. When originally developed (8, 14), the material constants in Equations (3) and (4) were claimed to be universally applicable to *ALL* grades of medium and high-density PE resins available at the time in the late 1980s and early 1990s. With the improvements in PE resins over the last 15 years, it is not clear if the bi-directional shift approach along with the original constants in the equations are applicable. Therefore, some modifications to the predictive schemes may be needed before being used.

The effect of temperature, T, on service life (time to failure) is predicted by Equation (6) above. The normalized temperature factor for this model is obtained by equation (6) as follows:

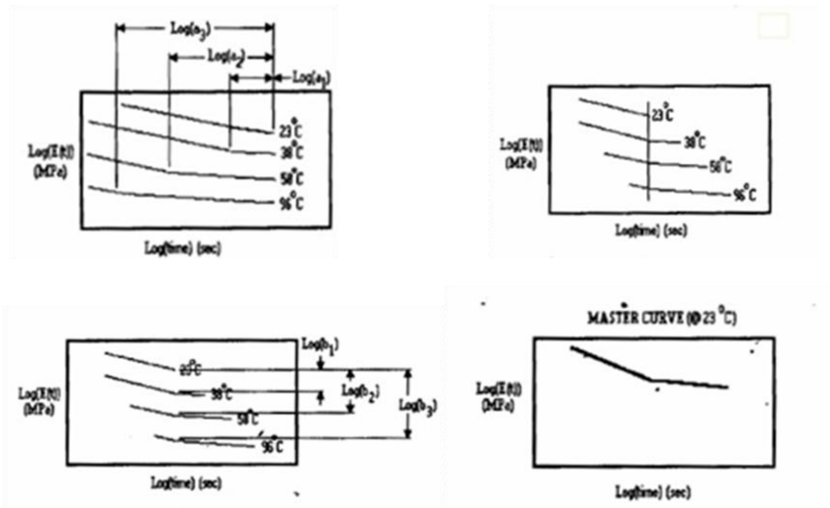

Figure 1 – Schematic of Bi-Directional shift approach used to determine the shift functions a_T and b_T (Courtesy: Wooster, M.S. Thesis, Ohio State University, 1991)

$$\ln\left(\frac{t_T}{t_{20}}\right) = 0.109*(293 - T) \qquad (7)$$

where T is in degrees K. Again Equation (7) will be used to compare with the temperature factor in the RPM model as represented by Equation (2) above for an example case.

PENT-Service Life Correlation

Originally, the PENT test as described in ASTM D1473 (15) was developed to compare the SCG resistance of various PE resin for ranking, cell classification (2), and for quality control purposes. Subsequently the PENT test has been used to correlate and predict the service life of PE pipe with flaws (9) even though this methodology does not have industry wide acceptance (16)

The PENT-Pipe service life correlation is given by the following equation

$$t = t_{PENT} * \left[\frac{0.468}{K}\right]^n * Exp\left[\left(\frac{Q}{R}\right)\left(\frac{1}{T} - \frac{1}{353}\right)\right] \qquad (8)$$

where the constants in the above equation are obtained for a typical PENT specimen (15) as K = 0.468 MPa-m$^{1/2}$; and the temperature = 353 K, and

t = predicted service life of PE piping in hours,
t_{PENT} = the time to failure of PENT specimens in hours,
K= Stress intensity factor for specific flaw in the pipe; function of the pipe and flaw geometry, applied nominal stress, and flaw depth in MPa-m$^{1/2}$,
T = is the service temperature of the pipe in degrees K,
R = universal gas constant = 0.00831 kJ/mol/K,
Q = activation energy for PE that varies between 85 and 110 kJ/mol, and

n = material constant for a given PE resin that varies between 2.5 and 4; a value of 3 is most commonly used

Using a value of Q = 90 kJ/mol, the normalized temperature factor for the model in Equation (9) is given by

$$\ln\left(\frac{t_T}{t_{20}}\right) = 10830 * \left(\frac{1}{T} - \frac{1}{293}\right) \qquad (9)$$

Again, Equation (9) will be compared with temperature factor for the previous models given in Equations (8) and (2).

Integration of Time to Flaw Initiation and Growth to Failure

The fourth methodology involves combining the time to incubation of a flaw in a PE pipe until initiation, with subsequent time for flaw growth using the SCG rates until failure (10,17,18). Typical SCG rates for PENT type specimens for one grade of PE material is shown below (10).

As seen in Figure 2, the SCG rate is again an exponential function of temperature and is given by

$$\left(\frac{da}{dt}\right) = A * Exp\left(\frac{Q}{RT}\right) * K^p \qquad (10)$$

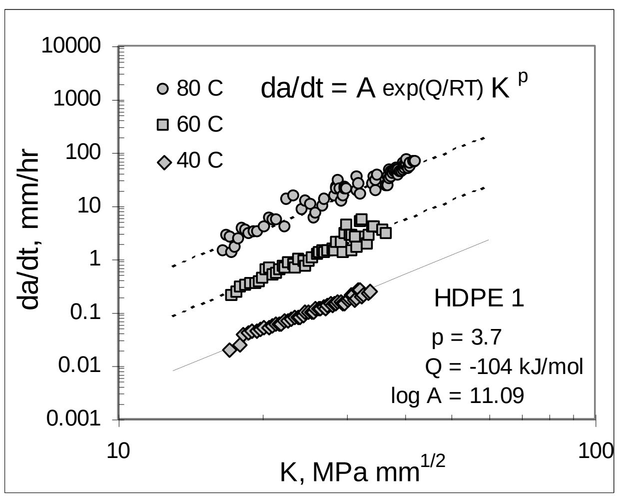

Figure 2 Typical SCG rates for one grade of PE materials (10); [Courtesy: Corleto, C, PPXIII]

where Q = 104 kJ/mol; p =3.7, and log A =11.09. Again based on the SCG data, the normalized temperature factor for this model that may be used to predict time to failure [or 1/(da/dt)] is obtained as

$$\ln\left(\frac{t_T}{t_{20}}\right) = \ln\left(\frac{da/dt_{20}}{da/dt_T}\right) = 12515*(\frac{1}{T} - \frac{1}{293}) \qquad (11)$$

COMPARISON OF SERVCIE LIFE MODELS – EFFECT OF TEMPERATURE

For all four models reviewed above, the service life (or time to failure) is given as

Service Life = f(stress, geometry, Stress Intensity Factor, material) * **Exp(T)**

That is, temperature has an 'exponential' effect in accelerating the time to failure due to SCG in PE piping. It is therefore interesting to compare the four models, specifically with regard to their normalized temperature factor in Equations (2), (7), (9) and (11). Figure 3 below shows this comparison as a graph of the normalized accelerating temperature factor for the four models as a function of temperature.

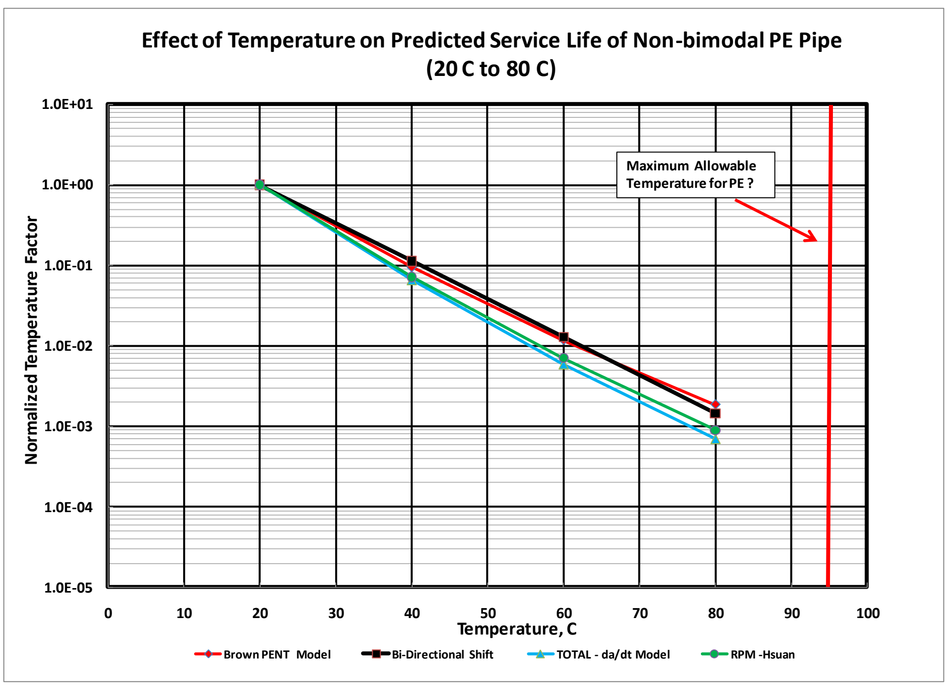

Figure 3 – Comparison of the Normalized Temperature Factor for the Four Service Life Prediction Models

The following critical observations can be made from Figure 3:

- The temperature factor in ALL four models are in relatively close agreement with one another,
- The effect of increase in temperature on decrease in service life is exponential (Figure 3 is a semi-logarithmic graph), and

- Most importantly, *<u>for every 20 degree C rise in temperature (between 20 C and 80 C), the temperature factor drops by approximately one order of magnitude, i. e., the expected service life is lowered by a factor of 10</u>*.

The fact that the four models developed independently for various grades of PE resins over several decades are so consistent in capturing the effect of temperature on failure times is significant. Unless otherwise shown, it is likely that the newer resins that have significantly improved SCG resistance also have similar temperature dependence.

IMPLICATIONS FOR NUCLER SAFETY PE PIPING

The above work has significant implications in developing the basis for Service Life Prediction of PE piping for nuclear applications. Before discussing the implications, an important point to emphasize is that the above data and temperature factors were developed for non-bimodal, older generation PE resins that are typical more susceptible to SCG than the more recent bimodal resins – PE4710 or PE100. The newer resins (Cell Class 445574C per ASTM D3350) are the only ones being considered for Class 3, safety-related, service water application in nuclear power plants in the US. Whether any of the above service life prediction models and the same accelerating factors due to temperature hold for the newer resins has yet to be established.

For nuclear applications, the more recent drafts of Revision 1 of the ASM Code Case CC N-755 (1) require that PE pipe operate at 140 F (60 C) at 500 psi hoop stress for 50 years with an allowable flaw size that is 10% of the pipe wall regardless of diameter and thickness.

In reviewing Figure 3 with this requirement in mind - a 50 year life at 60 C warrants that short-term experimental data in the laboratory for confirmation of this has to be conducted at temperatures greater than 60 C. However, there is an upper limit of 95 C, above which the PE material undergoes a transition. If the above temperature degradation by a factor of 10 for every 20 C holds for the newer resins, the short-term tests will have to be carried out for 5 years at 80 C (176 F) or ~0.67 years (8 months) at 95 C – all other factors (stress, geometry, flaw depth) being identical. Therefore, given that the PENT requirement for the bimodal resin is only 500 hours (0.057 years), extensive experimental data will be required to substantiate a 50 year life for PE piping at the elevated temperature of 60 C with adequate tolerance for flaw initiation and growth.

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