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"Rate Process Method Applied to Service Life Forecast of PE Molded Fittings"

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I. Abstract

This paper will review several of the applications for the Rate Process Method; such as, validation of the PE material hydrostatic design basis per ASTM D 2837, and service life forecast of old generation PE pipe still in service and correlation with actual field failures. We will also investigate a recent application in which the Rate Process Method was used to determine the service life forecast of a molded PE heat fusion fitting, that the manufacturer had flagged during a routine post-production quality check. Since several of these fittings had already been installed for gas distribution, the manufacturer wanted to know what the projected service life would be.

II. Background

During a routine quality check, a fitting manufacturer noted a problem with one of their fittings – a ¾" IPS SDR 11 x ½" CTS 0.090" butt fusion reducer made from a PE 2406 material. The manufacturer noted that these fittings were failing prematurely in the knit line. They also determined that this phenomenon was limited to these butt fusion reducers produced during a defined timeframe.

Some of these butt fusion reducers had already been shipped to a gas utility company. The manufacturer immediately contacted the gas company to alert them about these fittings. The gas company responded that some of the fittings had already been installed.

The manufacturer then contacted the author to determine what testing could be done to determine the projected life of these butt fusion reducer fittings that had already been installed. The Rate Process Method (RPM) was recommended as being the best test method available to determine the projected life of these PE 2406 butt fusion reducer fittings.

III. Rate Process Method

The Rate Process Method utilizes a three coefficient equation that relates time, temperature and pressure (or hoop stress). It is based on two very well known scientific principles:

1. There is a linear relationship between the log of stress and the log of time
2. There is a linear relationship between the log of time and the inverse of temperature (absolute temperature in degrees Kelvin). This is the principle of Arrhenius.

Both of these principles are true for all thermoplastics piping materials. By combining these two relationships, the Rate Process Method 3-coefficient equation results:

$$\log(time) = A + \frac{B}{T} + \frac{C\log(P)}{T}$$

where: *time* = failure time (hours)
T = temperature (K)
P = internal pressure (psig) or internal hoop stress (psi)
A, *B*, *C* = three coefficients

Dr. Chester Bragaw originally described the concept and mathematical basis for using the Rate Process Method for polyethylene (PE) pipe and fitting service projections (1) (2). The Plastics Pipe Institute (PPI) Hydrostatic Stress Board (HSB) conducted an extensive evaluation of this and other methods for forecasting the effective long-term performance of PE thermoplastic piping materials. Basically, all of these methods require elevated temperature sustained pressure testing of pipe that result in brittle type failures as would be observed in the field. The failure data at the elevated temperatures are used to predict the performance of a material at end-use/service temperature and pressure conditions. Details of these evaluations and conclusions are reviewed and discussed in “Rate Process Concepts Applied to Hydrostatically Rating Polyethylene” (3).

As a result of these studies, the HSB determined that the three-coefficient RPM equation provided the best correlation between calculated long-term performance projections and the known field performance of several PE piping materials. Further validation of the RPM has been provided by research that compares RPM projections based on elevated temperature data with actual room temperature laboratory failures of PE pipe and fittings (4). The RPM also has an additional advantage in that it provides the best probability for extrapolation of data based on the statistical “lack of fit” test. As a result, the RPM has been in use for approximately 20 years. A published protocol for the Rate Process Method is provided by PPI (PPI TN-16) (5).

IV. Applications for the Rate Process Method

Many resin and pipe producers, as well as users, are using the RPM to one degree or another to make relative judgments on specific materials and/or piping products. One example is testing exhumed PE pipe and then using the RPM to project the remaining life of the PE pipe in service (6). The gas engineer may use this projection, along with other considerations, as confirmation that the pipe can be left in the ground or if it may be time to replace the pipeline. These projections are based on the primary load (the internal pressure) and the service temperature. The effects of secondary loads such as indentation (rock impingement), squeeze-off, bending or deflection can also be examined using the RPM.

Another use of the RPM is to project the performance of polyethylene fittings (7) (8). When the RPM is used to test and evaluate fittings, it is very important that all of the failure modes in the laboratory testing are the same as the anticipated ultimate failure mode in the application. Fittings have a higher likelihood of different failure modes at different test conditions because they can have different and complex geometries. As a result, the three RPM coefficients from each fitting will be different. This RPM test protocol is not intended for non – polymeric mechanical fittings.

The RPM can also be used to determine the life of heat fusion joints such as butt-fused joints. There are two methods for evaluation:

1. To evaluate the performance of butt-fused joints that currently exist in a system: Butt fused joints would be exhumed and subjected to RPM testing. The results would provide an estimate of the remaining life of butt fusion joints in the ground.
2. To evaluate the performance of future butt-fused joints in a system: Pipe would be exhumed and butt-fused and then subjected to RPM testing. The results would provide an estimate of how long a butt fusion joint would last if it were done today on the existing system (if it needed to be repaired).

For both of the above evaluations, the failure modes of all of the tested specimens would need to be the same - a slit that initiates at the butt fusion notch and propagates through the pipe wall from the ID to the OD.

Several RPM experiments have been conducted on butt-fused joints and also on butt fusion fittings. The RPM projected performance for the butt fusion joint is often observed to be longer than the RPM projected performance for the control pipe. The projected performance is consistent to what is observed in the field - field failures are not typically observed for properly made butt fusion joints. We have also conducted several RPM experiments on socket fusion and saddle fusion joints.

The RPM can also be used to establish an appropriate single-point elevated temperature stress rupture test for quality control purposes after the coefficients have been determined by RPM analysis (9).

V. Rate Process Method Test Program

A test program was proposed to the manufacturer to conduct testing on the same lot of butt fusion reducer fittings that were shipped to the gas company. In the program, three test temperatures were selected (70°C, 80°C and 90°C). Based on considerable experience with RPM testing of PE 2406 materials, the maximum suitable test temperature is 90°C. This maximum test temperature will assure that:

1. The PE 2406 material tested in the laboratory has the same physical characteristics as the PE 2406 installed in the field
2. The Arrhenius principles are maintained within this temperature range
3. Testing is performed below the melting temperature for PE 2406 materials
4. The failure mode observed in the laboratory is the same as in the field failure

Based on RPM experience, the recommended test temperatures of 70°C, 80°C and 90°C for this PE 2406 material will satisfy all the RPM requirements for sound technical projections. Although the minimum recommended difference between temperatures for RPM testing is 10°C, a total temperature difference of 20°C was recommended to provide more confidence in the RPM projection.

In selecting appropriate test pressures (hoop stresses), it is important that the test pressures be selected at each temperature to assure that the failure mode is a slow crack growth (SCG) failure mode. This is the demonstrated long-term failure mode for PE materials in the field. Test pressures are selected based on the following considerations:

1. If the pressure is too high, ductile failures will occur
2. If the pressures are too low, the samples will take a considerably long time to fail
3. Test pressures are selected to ensure failures occur below the “knee cap” area. This is an area where the failure mode transitions from the ductile failure mode to the SCG failure mode. Sometimes the only way to find this “knee cap” area is by conducting the laboratory experiments and observing the slope of the log stress versus log time regression curve

The minimum recommended difference between hoop stresses to conduct an RPM experiment is 100 psi. A hoop stress difference of 200 psi at the test highest temperature was recommended to provide more confidence in the projection.

The test conditions for this RPM program were:

Test Temperature (°C)	**Test Stresses (psi)**
90	470, 370, 270
80	570, 420
70	670, 570

VI. Rate Process Method Projections

Using the laboratory data from the test conditions as shown on the previous page and the RPM computer program, the following RPM equation is generated for the butt fusion reducers:

$$\log(time) = -27.589 + \frac{14496}{T} - \frac{1633.3\log(P)}{T}$$

Correlation Coefficient = .79
No. of data points = 74

LACK-OF-FIT TEST RESULT:

There are 7 T,P groups. They are:
70/570 70/670 80/420 80/570 90/270 90/370 90/470
LACK OF FIT: F = 1.0097
Probability associated with F is .41

A total of 74 data points were included in the regression. Each data point represents a butt fusion reducer specimen that was tested at the specified temperature and hoop stress. The failure mode of all the specimens was a SCG failure at the weld line.

The “correlation coefficient” is a measure of how well a data set fits a mathematical model. With typical scatter in SCG data, the RPM correlation coefficient is commonly observed to be in the range of 0.7 to 0.9. The correlation coefficient for this data set is 0.79.

The “lack-of-fit test” is a measure of the probability of extrapolating beyond the data set. In general, if the “probability associated with F” is 0.05 or higher, there is good probability that the RPM equation provides a statically significant fit to the data. The probability for this data set is 0.41 and therefore, it is suitable to be used for projections.

Figure 1 shows a plot of the 74 data points on a log stress versus log time scale. The 90°C data points are in green, 80°C data points in red and 70°C data points in blue. Based on the RPM equation, the regression lines for each temperature are also included in the plot. Quite a bit of scatter is observed in the data. SCG types of failure are generally observed to have some variability in the test times. Since the failures occurred at the weld line, this has likely increased the variability in test times. Although there is a lot of scatter, all the failures were the same - SCG type failures at the weld line. Therefore, all of the data was included in the analysis.

By knowing the three coefficients from the laboratory data, projections to end-use temperature and pressure conditions can be estimated. As detailed by the gas company, the average annual ground temperature in their location is about 54°F or 12°C. Figure 2 shows the data and the RPM projected regression line for 12°C.

The average operating pressure, as provided by the gas company, is 55 psig. Therefore, using the RPM equation, the average projected failure time for the fittings at 12°C and 55 psig can be calculated as shown below. Since the pipe used was SDR 11, an internal pressure of 55 psig corresponds to a hoop stress of 275 psi.

FORECAST OF SERVICE LIFE:

Input Temperature (°C) : 12
Input Stress (psi) : 275
Input Lower Confidence Limit (%) : 1

LOWER SPECIMEN LIMIT = 2492 YEARS

The 1% LCL is approximately 2500 years which indicates that there is a 99% probability that the fittings will not fail due to slow crack growth at least 2500 years at the conditions of 54°F (12°C) and 55 psig (275 psi stress).

The findings suggest that the slow crack growth failure mode observed in the accelerated laboratory testing will not occur through the service life of the fittings. It is important to note that the above RPM projections only take into consideration the effect of internal pressure, which is the primary load. Field performance is also dependant on secondary loads such as bending, deflection and earth loading. Therefore, safety/design factors are also often taken into consideration with the above values.

VII. Conclusion

By using the Rate Process Method to test the suspected fittings, the manufacturer was able to determine that the fittings were not projected to fail by slow crack growth at the weld. Although there was a lot scatter in the data due to the variability of the failure mode at the weld line, the Rate Process Method accounts for this scatter in the calculation of the lower confidence limit (LCL). At the gas company end use conditions of an average annual ground temperature of 55°F (12°C) and an operating pressure of 55 psig (hoop stress of 275 psi), the 1% LCL was well beyond the intended service life. Based on this information from the Rate Process Method, the gas company decided to not remove any of the suspect butt fusion fittings.

VIII. References

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3. E. F. Palermo, “Rate Process Concepts Applied to Hydrostatically Rating Polyethylene Pipe”, Ninth Plastic Fuel Gas Pipe Symposium, New Orleans, November 1985.
4. E. F. Palermo, “Using Laboratory Tests on PE Piping Systems to Solve Gas Distribution Engineering Problems”, Tenth Plastic Fuel Gas Pipe Symposium, New Orleans, October 1987.
5. Plastics Pipe Institute Technical Note 16, “Rate Process Method for Projecting Performance of Polyethylene Piping Components”.
6. E. F. Palermo and K. Oliphant, “Correlating Aldyl ‘A’ and Century PE Pipe RPM Projections With Actual Field Performance”, Plastics Pipes XII (2004)
7. C. G. Bragaw, “Prediction of Service Life of Polyethylene Gas Piping Systems”, Seventh Plastic Fuel Gas Pipe Symposium, New Orleans, October 1980.
8. D. Hale, “Designing PE Piping Systems: Old Questions and New Answers”, Pipeline and Gas Journal, May 1982.
9. E. F. Palermo, “Rate Process Method as a Practical Approach to a Quality Control Method for Polyethylene Pipe”, Eighth Plastic Fuel Gas Pipe Symposium, New Orleans, November 1983.

Figure 1 - RPM ANALYSIS OF BF REDUCER

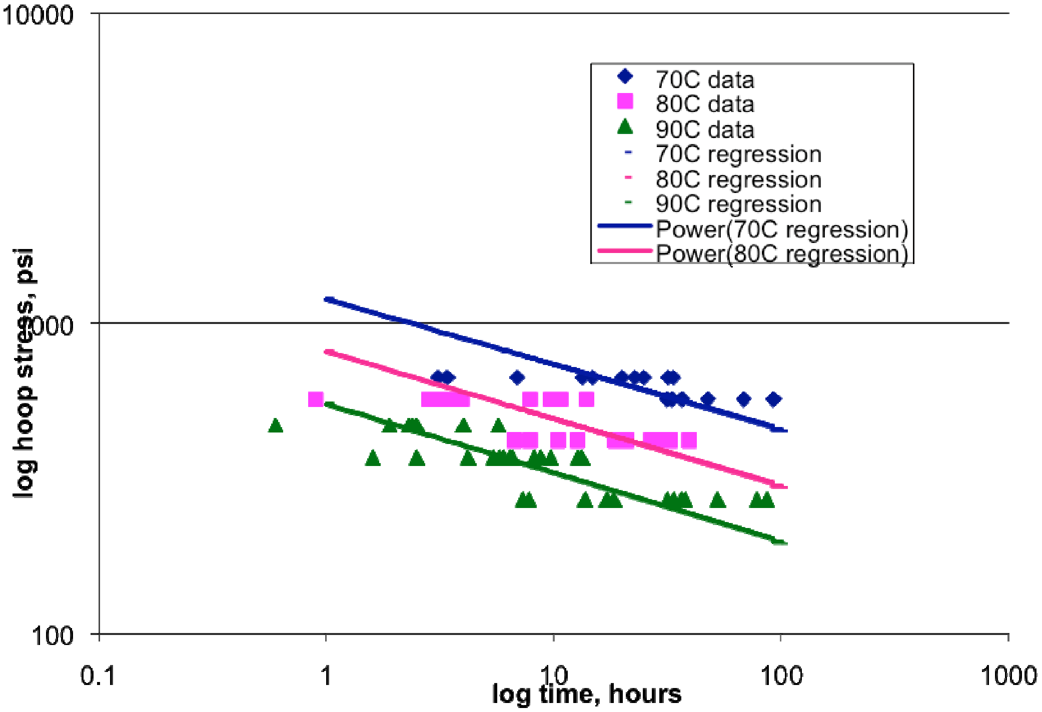

Figure 2 - RPM ANALYSIS OF BF REDUCER