TECHNICAL REPORT

ASTM F2023:
A DECADE LATER

October 30, 2009

ASTM F2023: A Decade Later

ASTM F2023 *Standard Test Method for Evaluating the Oxidative Resistance of Crosslinked Polyethylene (PEX) Tubing and Systems to Hot Chlorinated Water*[1] evaluates the chlorine resistance performance of plastic piping materials intended for the conveyance of chlorinated potable water. Testing is conducted on actual end-use samples under pressure in a flowing system. Samples are tested to failure under typical end-use conditions of chlorine level, pH and pressure. Elevated temperatures are used to accelerate the testing and an extrapolated chlorine resistance lifetime is calculated based on Miner's Rule. Below is a review of the different components of ASTM F2023 that are used to assess the chlorine resistance of plastic piping systems.

1.0 ASTM F2023 Model and Statistics

ASTM F2023 consists of the following:

1. Testing:
    - Test data with a minimum of 12 individual data points (failures).
        - Two data points are required at each test condition.
        - A minimum of six test conditions:
            - Three test temperatures are required (typically 95, 105, 115°C for PEX).
            - At each temperature, a minimum of two test hoop stresses.
    - Test conditions are selected to generate Stage III brittle oxidative failures.
2. Regression analysis using Rate Process Method (RPM) equation:
    - Temperature and pressure dependence are modeled using the RPM equation.
3. Estimate the Time-to-Failure at end-use conditions:
    - RPM equation is used to project performance at 82°C, 60°C and 23°C.
    - Miner's Rule is used to estimate the cumulative impact of varying temperature history on pipe life.

1.1 RPM Equation

The RPM equation is an established equation used to model the effects of temperature and stress on damage rates within the plastic piping industry. The RPM equation is the basis of the ISO9080[2] pressure rating system and is used to model, separately, both the Stage I ductile and Stage II brittle failure modes. The RPM is also used to model the Stage III brittle oxidative failure mode. The Plastics Pipe Institute (PPI) has reviewed and accepted the validity of the RPM, as presented in PPI TN-16 *Rate Process Method for Projecting Performance Polyethylene Piping System*[3] and the RPM is used as one of the options for determining the 140°F Long-Term Hydrostatic Strength (LTHS) as well as validating the 140°F Hydrostatic Design Basis (HDB). Since the inception of ASTM F2023, no other model has been proposed as an alternative to the RPM equation.

The full RPM equation has four terms (four parameters) and is presented below:

$$\log_{10} ft = A + \frac{B}{T} + C\log_{10} S + \frac{D\log_{10} S}{T} \qquad (1)$$

Where:

ft = time to failure (h)
T = absolute temperature (K)
S = hoop stress (psi)
A, B, C and D = coefficients derived from a particular data set

In ASTM F2023, the three parameter equation is typically used:

$$\log_{10} ft = A + \frac{B}{T} + \frac{C\log_{10} S}{T} \qquad (2)$$

ASTM F2023 permits the use of either equation based on best fit to the data. Jana's experience with over 30 data sets is that the best fit is achieved with the three parameter equation. Experience has shown that the quality of fit of the data to the three parameter is excellent with correlation coefficient (R^2) values typically between 0.95 to 0.99 and as high as 0.996. The ASTM F2023 minimum requirement is an R^2 greater than 0.9. Jana has not observed a data set to date that has not met this requirement.

1.2 Extrapolations

The RPM equation is fitted to the data set using multivariate regression software. The software allows extrapolation to the lower temperatures of 180°F (82°C), 140°F (60°C) and 73°F (23°C) at a pressure of 80 psi. The software provides the expected (mean) lifetime at these temperatures with the associated confidence limits.

The range of the confidence limits on either side of the mean is typically significant. It is fairly typical for an ASTM F2023 data set that the Lower Confidence Limit (LCL) (95% two sided) is between 50 and 70% of the expected value. The magnitude of this range is a result of the number of data points generated and the inherent variability within an individual replicate specimen. It is not a result of the improper application of the RPM equation. In contrast, ISO9080 achieves narrower confidence limits (An LCL that is ≥ 90% of the mean) by requiring 90 data points over the three temperatures as compared to the 12 data points required by ASTM F2023. The quality of the ASTM F2023 extrapolations is better than the PPI TN-16 published data set which shows an LCL that is 40% of the mean value using 29 data points. PPI concluded, "Mathematically, these RPM projections are sound"[3]. ASTM F2023 provides superior projections with lower confidence ranges as a result of the Stage III failure mode that results in more narrowly distributed failure times at each test condition.

A substantial narrowing of the confidence limits could be achieved by the addition of more data points at more test conditions. The testing costs increase and the statistical benefits decrease as the number of data points are added. The original technical committee that developed ASTM F2023 decided that the appropriate balance was achieved by the current test requirements.

1.3 Pass/Fail Requirements

ASTM F876[4], F2389[5] and F2769[6] are product standards in which the oxidative resistance requirements are based on the expected (mean) test lifetime and not the LCL. The minimum requirement is 50 years expected (mean) test lifetime regardless of the classification achieved. The use of the mean expected value in the product standards and in ASTM F2023 is consistent with the practice established in ASTM D2837[7] for pressure rating and validation of piping. ISO9080 uses the LCL value for pressure rating pipe.

As with any comparison of statistical test results to minimum specified requirements, there exists a risk that the True predicted test lifetime (as determined by infinite data points) is on the other side of the performance requirement threshold compared to the mean predicted value based on ASTM F2023. This may occur if the material is border-line in passing the requirement. The assumption has been that the test conditions and stipulated end-use conditions are inherently conservative which implies that they represent only the very worst case and a very small fraction of the population. This conservatism allows for a higher tolerance of error associated with the results of the testing. This assumption is investigated in the remainder of this white paper.

2.0 Water Quality

ASTM F2023 defines the test water quality with the following requirements:

- Source: Tap, De-Ionized (DI), Reverse Osmosis (RO)
- pH: 6.5 to 8.0
- Chlorine: 2.5 to 5.0 ppm
- ORP > 825 mV for RO and DI water or 825 ± 30 mV for Tap water

The ORP (Oxidative Reduction Potential) is a measure of the overall oxidation-reduction driving force of the solution. Maintenance of the ORP level above the minimum threshold will narrow the operating pH and chlorine (Cl_2) concentration. The practical operating window is approximately 6.5 to 7.0 pH and 3.5 to 5 ppm Cl_2.

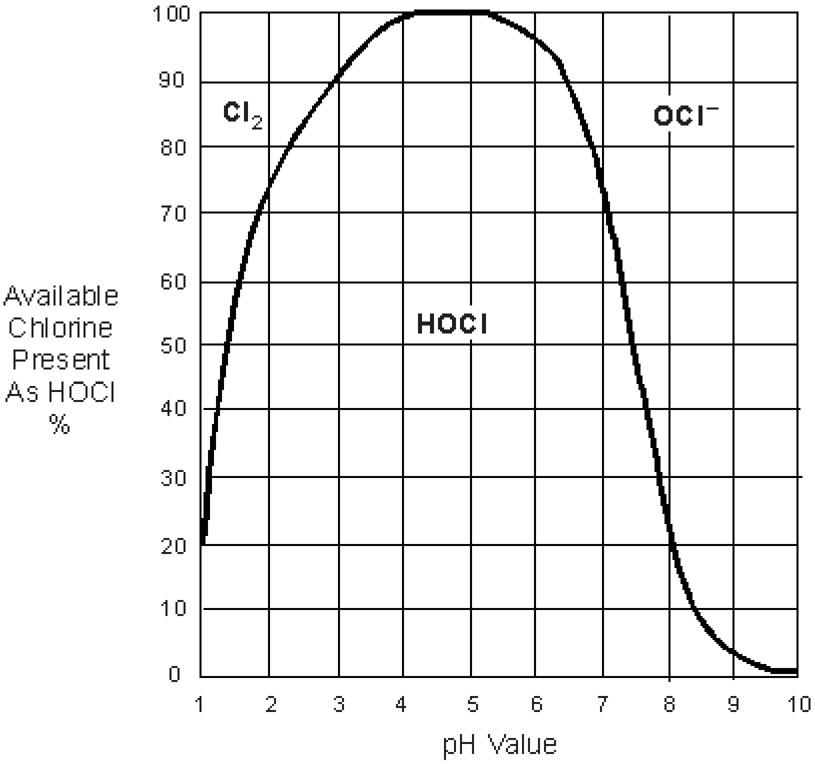
2.1 pH and Chlorine Concentration

The pH and chlorine concentration of the test solution affect the aggressiveness of the solution. The pH and chlorine ranges typically used in testing result in an aggressive water quality thereby representing the worst case water for oxidative degradation in chlorinated water applications. This is a result of the pH affecting the equilibrium balance of the two main forms of chlorine in solution: hypochlorous acid (*HOCl*) and hypochlorite (OCl^-) as shown by Equations (3) and (4). As shown in Figure 1, the former is favored by low pH levels and is the more oxidatively aggressive species. Therefore ORP values decrease with increasing pH given the same concentration of Cl_2 in solution.

$$Cl_2 + H_2O \Leftrightarrow HOCl + H^+ + Cl^- \tag{3}$$

$$HOCl \Leftrightarrow OCl^- + H^+ \tag{4}$$

Figure 1: Relationship between Chlorine Equilibrium and Solution pH[8]



The U.S. EPA secondary drinking water regulations recommend a pH in the range of 6.5 to 8.5 which is similar to the allowed ASTM F2023 pH range. Jana reviewed the data presented in the AWWA Drinking Water Survey[9] which shows that typical water pH values are in the range of 6.5 to 8.9 with some utilities providing water at a pH as low as 6.1. Although the pH used in testing (6.5 to 7.0) does not represent the average pH, it is representative of a portion of the population that will receive water with a pH within this range that tends to be more oxidatively aggressive.

The EPA recommended minimum chlorine concentration within any point in the water distribution system is 0.2 ppm. As chlorine decays within the distribution, utilities are obliged to dose their outgoing water at a higher level in anticipation of this decay. Additionally, many use field chlorine booster stations to augment the chlorine concentration in sections of the pipeline that are distant from the primary treatment plant. Actual household chlorine concentrations will vary depending on the water utilities practice and the location within the distribution system relative to the primary treatment plant and field dosing stations. Chlorine concentration will vary as well with the seasons and water usage levels with a tendency for higher concentrations during hotter months.

The chlorine decay within the distribution network is manageable as even a small concentration of chlorine significantly increases the water ORP and disinfectant effectiveness. As shown in Figures 2 and 3, even 0.2 ppm chlorine at a low pH will raise the water ORP level from the ~500 mV range to the 700 – 800 mV range.

Figure 2: Relationship between ORP, pH and Chlorine[10]

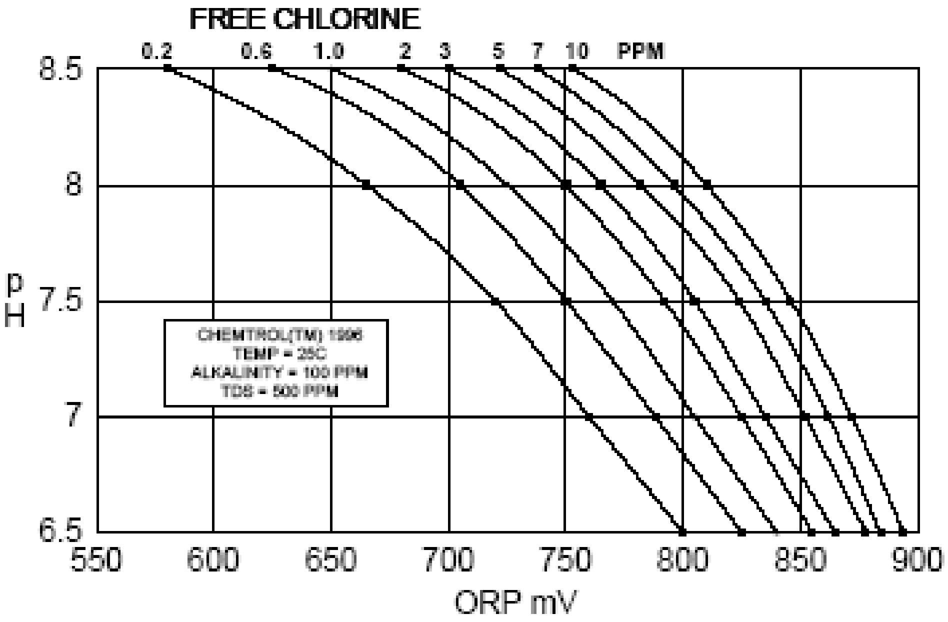
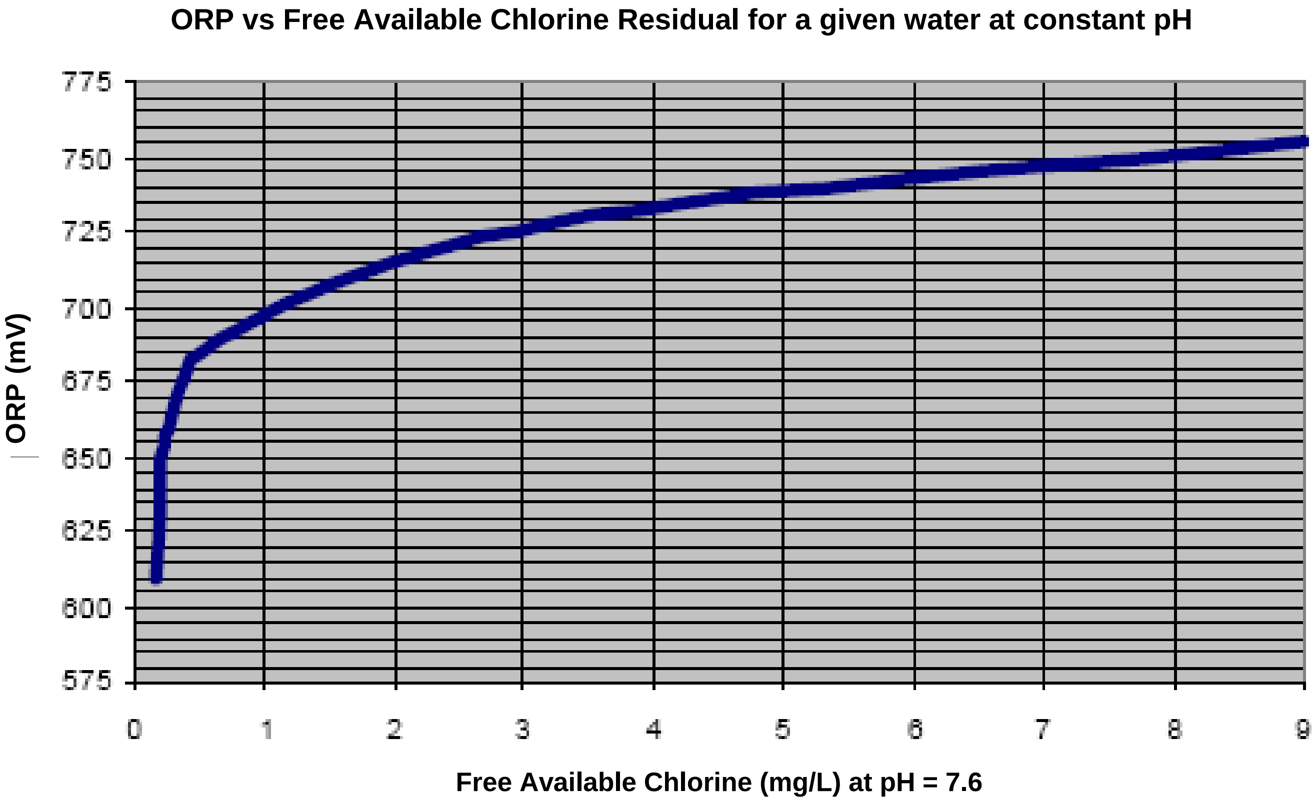


Figure 3: Logarithmic Relationship between ORP and Cl_2 Concentration at a Constant pH[11]



Based on the AWWA Drinking Water Survey[9], the reported chlorine concentrations range from 0.1 to 4.0 ppm. PPI selected some of the most aggressive states, as predicted by this same study, for field measurements. The field measurements found chlorine concentrations at the utilities ranging from 1.8 to 2.9 ppm[12].

Testing is performed in a chlorine range of 3.5 to 4.5 ppm. This range is selected because:

- It represents the upper range of the chlorine concentration that can be observed within a distribution system.
- The minimum ORP level, as specified in ASTM F2023, is attainable.
- The aggressiveness of the test water (as measure by ORP) at these concentrations is less sensitive to changes in chlorine concentration as shown in Figure 2. As a result, testing within this range is largely comparable.

The chlorine/pH test water combination results in a consistent and aggressive test medium for exposure to pipe. The resulting ORP of greater than 825 mV, which is above the observed ORP in the PPI field analysis[12], is aggressive yet remains plausible as a real water quality observable in the field.

As the bulk of plumbing systems will be exposed to water with significantly lower chlorine concentrations (~1 ppm) and higher pH values, the vast majority will see much less aggressive water and therefore, is expected to have lower degradation rates. Therefore, the test water quality is conservative.

2.2 *Chloramines*

Chloramines are used as the primary disinfectant by many utilities in place of chlorine as they have a longer residual lifetime within the distribution systems and they generate fewer undesirable byproducts. Jana's own research[13] and research performed in conjunction with PPI[14] has shown that chloramines are less aggressive towards PEX pipe than chlorine.

2.3 *Oxidative Reduction Potential (ORP)*

ORP is a measure of the oxidative strength of a solution. ASTM F2023 requires an ORP of >825 mV for test solutions based on Reverse Osmosis or De-Ionized water and 825 ± 30 mV for Tap water based test solutions.

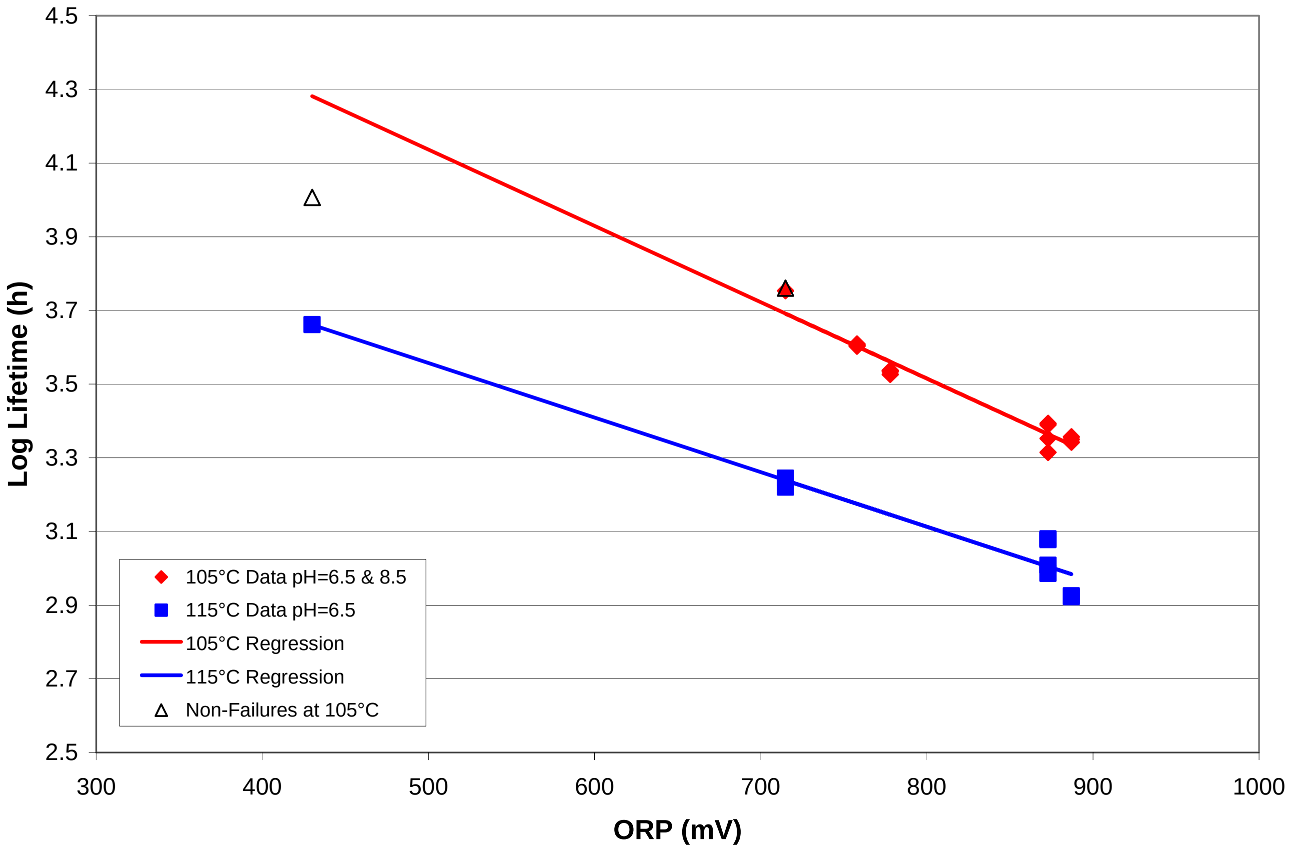
ORP is a good measure of the overall aggressiveness of the test solution as it provides a single value resulting from the pH, chlorine concentration and other components within the system. ORP is, however, difficult to measure in fairly pure chlorinated water systems (e.g. RO, DI, etc.) and for this reason is not typically used for monitoring and control in water treatment plants or for the ASTM F2023 method. This difficulty stems from very slow response times of ORP probes in chlorinated solutions.

As mentioned above and shown in Figures 2 and 3, ORP is impacted by chlorine concentration and pH. It can also be impacted by other chemical species in the water although these typically reduce the ORP of the solution. The relatively pure water used in testing maximizes the ORP and aggressiveness of the test solution. The lower ORP permitted by ASTM F2023 for Tap water was an accommodation incorporated at the time the standard was established to allow acceptance of existing data. This practice has been discontinued.

The ORP of chloraminated water is significantly lower than for chlorinated water. Jana's experience has shown that at a similar concentration (~4 ppm), the chloraminated solution will have an ORP in the 500 – 600 mV range while the chlorinated solution will have an ORP >825 mV.

Jana research has shown a good correlation with pipe test lifetime and ORP in the ORP range of 400 to 900 mV as shown in Figure 4. This figure shows that pipe tested in lower ORP water has significantly higher test lifetime. This shows that the ASTM F2023 test conditions will provide a conservative estimate of the worst case plumbing environment.

Figure 4: Logarithmic Relationship between Lifetime and ORP[15]



2.4 *Source Water*

The base water used in testing is an important parameter in testing. As good control of this parameter is important for test repeatability, RO or DI water is preferred as they have very low concentrations of other molecules (i.e. salts, organics, etc.). Although ASTM F2023 does not specify control parameters for the base water, because Tap water also can vary significantly, it is not ideal for controlled testing. The use of RO or DI water, as purified waters, will provide higher ORP values and as a result, be more aggressive and provide conservative results.

3.0 End-Use Temperatures

A potable water supply system is complex, with many factors influencing the water temperature. Ambient temperature is a dominant factor, heavily influencing water temperature at all stages of the system. It is useful to break the system into three parts:

i) Supply - including source, treatment, and storage
ii) Mains - the mains distribution line from the storage tank to the house
iii) House - the piping from mains to the house boundary and the internal piping of the house.

The piping of interest here is the internal piping of the house made from PEX materials.

Hypothesis: The two temperatures used in ASTM F2023 in calculating the traditional domestic and the continuous recirculation end-use conditions are appropriate. The two temperatures are:

- 73°F (23°C) for the cold water temperature
- 140°F (60°C) for the hot water temperature

3.1 End-Use Temperatures for Traditional Domestic (TD)

The internal piping of the house generally has a significant effect on the temperature at the end-use points[16]. After a period of several hours with no draw, the water in the piping will be at the temperature of the house. The draw-off temperature starts out steady at the house temperature (typical average of 70°F) until a volume of water equal to the volume of upstream piping is drawn. The end-use point temperature then decays to the water temperature of the mains (average of 60°F). The mains water temperature in the U.S. can vary from 40 to 90°F (e.g. summer in Arizona) as the temperature is heavily influence by the ambient air temperature of the region. Therefore, using a temperature of 73°F (23°C) in calculating the cold water temperature for the TD end-use conditions is appropriate and a realistic assumption of the actual temperature.

The most severe condition for the PEX tubing system is from the hot water side and in particular the tubing close to the hot water system (i.e., a hot water tank). There are two opposing risks when it comes to water temperature inside domestic water heaters: the risk of scalding and exposure to *Legionella*, the bacteria responsible for Legionnaires' disease (pulmonary legionellosis)[17]. In most North American homes, hot water heaters are set at 140°F (60°C). For many years this temperature had been the standard. However, the U.S. Consumer Product Safety Commission (CPSC) and most safety experts recommend a thermostat setting of 120°F (49°C) for residential water heaters to reduce or eliminate the risk of tap water scald injuries. For canteens and professional kitchens, a temperature of 150°F is usually required to satisfy most hygienic standards[18].

Water temperature sampling performed by Rehau[19] in the U.S. measured an average hot water temperature of 119.7°F (81 data points) with the majority of the measurements taken at commercial establishments or hotels. This average value may be partially explained by the fact that the commercial locations tend to operate at moderate temperatures to minimize any scalding liability. The Rehau data for residences had an average of 121.1°F with a standard deviation of 9.45°F. Assuming that this sample set is representative and that the population is normally distributed, 98% of residential applications will be covered if 140°F is used as the temperature for hot water systems. On the other hand, the review of Stevens Institute's study[20] on pattern of hot water use in 50 single family homes in California and Florida gives an average hot temperature of 142°F. Forty-two percent of the homes had hot water temperatures between 140 and 160°F, however, the study was conducted in 1992 and 1993. Long history has shown that the vast majority of residential hot water systems operate in the vicinity of 140°F. There are trends in recent history, primarily the issue of scalding that may effectively reduce this temperature to 120°F in the future. A water temperature of 140°F has traditionally been assumed to be the temperature of hot water plumbing systems and is regarded as the appropriate hot water temperature in calculating the TD end-use conditions.

3.2 End-Use Temperature in Continuous Recirculation (CR)

The continuous recirculation system considered in this paper is only for potable water applications and does not cover the radiant heating applications as the chlorine resistance does not apply in those cases. Hot water circulating systems are systems that circulate hot water through the hot water piping such that obtaining hot water is nearly instantaneous. Types of circulating systems include continuously circulating, timer controlled, temperature controlled, demand type, and combinations of all of the above. One method to obtain instant hot water is to circulate the water in a big loop from the outlet of the water heater, past each fixture and back to the into the water heater.

3.2.1 Commercial Type Applications

Mainly used for commercial type applications, the CR system is often installed in a hotel to accelerate the access of hot water. The recirculation line maintains the hot water and feeds the system. This is frequently combined with a mixing system that manages the temperature of the water.

3.2.2 Domestic Recirculation Systems

Most domestic plumbing systems do not experience continuous hot water conditions and several energy codes do not allow for continuous recirculation. The CR system with a dedicated return line can be used for larger residences with a timer system in order to minimize the loss of heat. This type of application is marginal and represents a very small percentage of home systems.

For the same reason as in TD systems, hot water at greater than 120°F is a necessity for hospitals and food service establishments and the hot water temperature seen by the piping system for homes is certainly comparable. Therefore, a temperature of 140°F is also appropriate for recirculating installations.

4.0 End-Use Pressure (Stress)

Hypothesis: A pressure of 80 psi represents what is observed in domestic potable water systems and therefore is an appropriate end-use extrapolation parameter used in ASTM F2023. This value is used for design purposes.

According to the *Handbook of Public Water Systems*[21], it is important to establish criteria for minimum and maximum system pressures occurring during the peak hour of demand. It is also desirable to establish maximum pressure fluctuations within the water distribution system. Typically, minimum acceptable water distribution system pressures are between 35 to 40 psi, and maximum pressures are 100 to 120 psi. A minimum system pressure of 35 to 40 psi ensures adequate flow to the individual consumers and allows for reasonable operation of home-type irrigation/sprinkler systems. Generally speaking, the maximum daily static service pressure delivered from local water authority is about 100 psi. Due to losses of pressure, special equipment installed and the code limit of 80 psi, the average pressure seen by the PEX plumbing systems in residential and commercial buildings is in the range of 50 to 70 psi. This level of system pressure provides adequate flows and working pressures for most typical residential and commercial uses. Where main pressures exceed 100 to 110 psi, individual pressure-reducing valves are usually installed on each service. Therefore for domestic plumbing applications, the most aggressive end-use internal pressure is 80 psi. The end-use pressure is expected to be below this value the majority of the time.

5.0 Miner's Rule Analysis - Cumulative Damage Model

Miner's Rule is a method of assessing the cumulative damage to a PEX pipe exposed to varying pressure and temperature conditions. This method can only be applied to specimens exhibiting the same failure mechanism, i.e. Stage III oxidative degradation for potable water applications. The model is based on two temperatures and the use of Miner's Rule is applicable in evaluating the lifetime of the following plastic piping systems:

- The TD system, where the water is modeled at a temperature of 140°F for 25% of the exposure time and 73°F for the remaining 75% of the exposure time.
- The intermittent CR system, where the water is modeled at a temperature of 140°F for 50% of the exposure time and 73°F for the remaining 50% of the exposure time. The system is considered off during the night.

According to the study carried out by Paschal et al[22] on traditional domestic systems, the Miner's Rule can be effectively used and validated for some PEX materials under standard hydrostatic test conditions, but deviations can also occur depending on the material. In this work, it was found that the measured lifetimes can be significantly lower than the ones predicted by Miner's rule for some materials. Miner's rule should be considered as generally applicability with an understanding of the limitations. Additional research in this area may be warranted.

6.0 The Approach of ASTM F2023

The test method and analysis approach of ASTM F2023 are based on the following:

- The water quality is aggressive yet remains plausible as a real water quality observable in the field.
- The cold end-use temperature represents a typical, average temperature that would be observed in the field.
- The hot end-use temperature, the temperature of greater concern and risk, represents an aggressive temperature that can be observed but is not typically observed in the field.

- The end-use pressure is based on the maximum allowable pressure in the field. Typical pressures within a home are generally lower than this pressure.

The above test conditions and selected end-use conditions are aggressive and represent only the very worst case and a very small fraction of the population. As a result, the minimum specified extrapolation requirements are highly conservative and allow for a higher tolerance of error with the test method. Therefore, ASTM F2023 appears to be a good method of evaluating the oxidative resistance of PEX pipe materials for potable water applications.

References

[1] ASTM F2023 *Test Method for Evaluating the Oxidative Resistance of Cross-linked Polyethylene (PEX) Tubing and Systems to Hot Chlorinated Water*, ASTM International, West Conshohocken, PA, 2008.

[2] ISO9080 *Plastics piping and ducting systems -- Determination of the long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation*, ISO, Geneva, 2003.

[3] PPI TN-16 *Rate Process Method for Projecting Performance of Polyethylene Piping Components*, Plastic Pipe Institute, Irving, TX, 2008.

[4] F876 *Standard Specification for Crosslinked Polyethylene (PEX) Tubing*, ASTM International, West Conshohocken, PA, 2009.

[5] F2389 *Standard Specification for Pressure-rate Polypropylene (PP) Piping Systems*, ASTM International, West Conshohocken, PA, 2007.

[6] F2769 *Standard Specification for Polyethylene of Raised Temperature (PE-RT) Plastic Hot and Cold-Water Tubing and Distribution Systems*, ASTM International, West Conshohocken, PA, 2009.

[7] D2837 *Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products*, ASTM International, West Conshohocken, PA, 2008.

[8] http://www.edstrom.com/Resources.cfm?doc_id=164

[9] AWWA *Water Stats: The Water Utility Database 1996 Survey*, American Water Works Association, Denver, CO, 2000.

[10] Steininger, JM and Pareja, C. *ORP Sensor Response in Chlorinated Water*, NSPI Water Chemistry Symposium, NSPI Symposium Series, Vol. 1, Phoenix, AZ, 1996.

[11] http://www.water.siemens.com/SiteCollectionDocuments/Product_Lines/Stranco_Products/Brochures/Stephan%20Andree%20Paper%20-0Utilizing%20Both%20ORP%20and%20Chlorine.pdf

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[12] Rubeiz, C. *PPI HTD ORP Field Measurements Results*, Plastic Pipe Institute, Irving, TX, September, 2005.

[13] Jana/PPI Projects 04-2256 and 05-2134 Final Report *Examination of the Relative Oxidative Aggressiveness of the Common Potable Water Disinfectants of Chlorine, Chloramines and Chlorine Dioxide on PEX Pipe Materials.*

[14] PPI *Statement A - Relative Oxidative Aggressiveness of Chloramines and Free Chlorine Disinfectants Used in Treated Potable Water on Crosslinked Polyethylene (PEX) Pipe*, Plastic Pipe Institute, Irving, TX, January, 2007.

[15] Oliphant K et al, *Environmental Factors in Performance Forecasting of Plastic Piping Materials*, Plastics Pipes XI, Munich, 2001 (Available upon request).

[16] Burch J and Christensen C. *Towards development of an algorithm for mains water temperature*, National Renewable Energy Laboratory, Golden, CO, 2007.

[17] http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2094925

[18] http://www.engineeringtoolbox.com/design-hot-water-system-d_92.html

[19] Rehau measurements, data supplied to PPI task group.

[20] Stevens Institute of Technology. *Pattern for Hot Water Use in Single Family Homes*, Center for Environmental Engineering, Hoboken, NJ.

[21] HDR Engineering, Inc. *Handbook of Public Water Systems*, Second ed. New York, NY: John Wiley and Sons, 2001.

[22] Paschal J and Hassinen J. *Development of a validation method for the use of Miner's Rule in predicting the oxidative resistance of polyolefins*, Plastics Pipes XII, Milan, 2004.

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