Comparison of ASTM and ISO Requirements for PE-RT in Potable Water Applications

Keywords: PE-RT, Standards, ISO, ASTM, EN

Carl F. Baker, P.E.
The Dow Chemical Company, USA
E-mail:cbaker@dow.com

ABSTRACT

The performance requirements for flexible polyolefin potable water piping systems in North America are quite different than those in other areas of the world. PolyEthylene – Raised Temperature (PE-RT) products were developed in Western Europe in the early 1980's and since that time have evolved into the high performance products in use today as defined in the International Standards Organization (ISO) standards. Many countries have adopted the ISO standards for PE-RT products around the world but in the United States the American Society of Testing and Materials (ASTM) standards are utilized. Canada uses the Canadian Standards Association (CSA) standards which closely mirror the ASTM standards. A CSA standard is in development but currently there is no CSA standard for PE-RT products. An ASTM standard for PE-RT potable water plumbing applications was introduced in 2009 as ASTM F2769. The performance requirements for PE-RT in ASTM F2769 are the same as those found in ASTM F876 for Crosslinked Polyethylene (PEX) tube. In addition, the fittings standards specified for PEX tube are shared with PE-RT in most cases. ASTM F2769 has been incorporated into the 2012 version of the national building codes in the United States. The differences between the ISO and ASTM standards for PE-RT are quite extensive. One obvious difference is in tubing size where ISO standards utilize metric units and ASTM specifies English units and is based on Copper Tube Size (CTS). Another major difference is the oxidative stability requirement in the ASTM standard. This requirement will be highlighted and discussed. There are other less obvious differences including hydrostatic ratings, slow crack growth resistance, fitting qualification, malfunction requirements, and others. Each of these will be discussed as it relates to product design.

INTRODUCTION

This paper is intended to be a summary reference for those interested in the requirements of and the differences between the ISO and ASTM standards for PE-RT used in solid wall potable water tube. It is not intended to be used in place of the actual standards referenced or to make any decisions related to production or sale of any product. The test methods and requirements discussed here are complex and no attempt has been made to be all inclusive but rather the information has been summarized including only the aspects deemed necessary to illustrate the differences between the standards. Every effort has been made to provide useful and accurate

information, however, the author advises the reader to consult the reference standards to ensure accuracy.

The standards to be discussed are ISO 22391-1,-2,-3, & -5 *ISO (1)* and ASTM F2769 *ASTM (2)*. These standards rely heavily on other standards for test methods and procedures. In the interest of readability the use of ISO 22391 is meant to be inclusive of the various parts. In some cases the specific part will be referenced. Reference standards will be discussed to the extent necessary for the reader to understand the requirements. Due to the substantial differences between ISO 22391 and ASTM 2769, comparisons will be made between ½ inch Copper Tube Size (CTS) Standard Dimension Ratio 9 (SDR9) tube as per ASTM F2769 and application class 1, PE-RT type II, dimension class A, pipe series S4 as per ISO 22391.

HYDROSTATIC STRENGTH

Hydrostatic strength is the basis upon which the allowable design stresses are determined in both systems. The basic methodology is the same but the implementation and data treatment are quite different.

ISO 22391-2 requires testing in general accordance with ISO 1167-1 *ISO (3)* and 1167-2 *ISO (3)* at three temperatures, 20 (68), between 60 (140) & 70 (158), & 95°C (203°F) and evaluation according to ISO 9080 *ISO (4)*. A minimum of 30 samples must be tested at each temperature and a minimum of three samples each must fail within each of the following time ranges, 10 to 100, 100 to 1000, 1000 to 8,760, & greater than 8,760 hours with the exception that samples above 8,760 hours may be non-failures. In addition, 97.5% of the data points must be on or above the reference lines provided in the standard. These reference lines are taken from ISO 24033 *ISO (5)*. No brittle failures before 8,760 hours at any temperature up to 110°C (230°F) are allowed. ISO 22391 does not directly specify testing at 110°C (230°F) but the requirement that there be no brittle failures before 8,760 hours at temperatures up to 110°C (230°F) implies that a regression should be performed at 110°C (230°F). In addition, the reference lines are taken from ISO 24033 which does require testing at 110°C (230°F). Design stresses are not specified directly but rather are controlled by selecting PE-RT type and application class which leads to tables of dimensions and tolerances. The ISO standards for PE-RT are broad. The closest corollary to ASTM F2769 in ISO 22391 is application class 1, PE-RT type II, dimension class A, pipe series S4. This will give a pressure rating of 8 bar (116 psi) for application class 1 (assumes 60°C (140°F) for 49 years, 80°C (176°F) for one year and 95°C (203°F) for 100 hours).

ASTM F2769 requires a cell class of 3 (8.62 MPa (1250 psi) HDB at 23°C (73.4°F)) or 4 (11.03 MPa (1600 psi) HDB at 23°C (73.4°F)) for Hydrostatic Design Basis (HDB) at 23°C (73.4°F) in accordance with ASTM D3350 *ASTM (6)*. In addition, it requires a minimum Hydrostatic Design Stress (HDS) of 4.41 MPa (640 psi) at 23°C (73.4°F) and 2.76 MPa (400 psi) at 82.2°C (180°F) determined in accordance with ASTM D2837 *ASTM (7)* utilizing a design factor of 0.5 to establish the HDS from the HDB. The HDB is established by categorizing the Long Term Hydrostatic Strength (LTHS). LTHS is

establish by a minimum of 18 data points at the desired temperature with a failure time distribution as follows: a minimum of six data points less than 1000 hours, a minimum of three data points greater than10 hours but less than 1000 hours, a minimum of three data points greater than 1000 hours but less than 6000 hours, a minimum of three data points greater than 6000 hours, a minimum of one data point greater than 10,000 hours. Brittle failures before 10,000 hours, while not specifically prohibited, are practically excluded since their existence will result in failure to meet the required HDB/HDS. The HDB must be validated to ensure that the regression line is log linear to 100,000 hours. It should be noted that ASTM D2837 does not provide validation requirements at 82.2°C (180°F) in the body of the standard. However, both ASTM D2837 and F2769, refer to Technical Report 3 (TR-3) *PPI (8)* published by the Plastic Pipe Institute (PPI) and the Hydrostatic Stress Board (HSB). TR-3 provides procedures for establishing the validation requirements for PE-RT which will require an HSB special case. Generally validation is accomplished by using an ISO 9080 based method with testing at 110°C (230°F). Most producers will choose to list their products according to TR-3 which adds additional requirements including testing a minimum of three lots of tube. Dimensional requirements are limited to SDR9 in ASTM F2769 which results in minimum pressure ratings for the tube of 6.9 bar (100 psi) at 82.2 (180°F) and 11 bar (160 psi) at 23°C (73.4°F).

Obviously the methods are quite different but when compared for the conditions of hot potable water applications the results are very similar. It is possible for a material to meet the requirements of one standard and not the other but in general Type II PE-RT will meet the requirements of ASTM F2769 and vice versa in terms of hydrostatic strength.

OPACITY

ISO 22391-2 specifies an opacity requirement for pigmented compounds of 0.2% light transmission according to ISO 7686 *ISO (9)*. There is no analogous test in ASTM F2769.

LONGITUDINAL REVERSION

ISO 22391 specifies a Longitudinal Reversion test according to ISO 2505 ISO (10). 16 mm (0.630 inch) tube is tested at 110°C (230°F) for two hours. Three pieces are tested and the longitudinal reversion must be less than or equal to 2%. There is no analogous test in ASTM F2769.

MELT MASS FLOW RATE

ISO 22391 specifies a melt Mass Flow Rate (MFR) test that compares the MFR of tubing to the virgin compound. The test is conducted in accordance with ISO 1133-1 *ISO (11)*. Test conditions are 190°C (374°F), 5 kg (11 lbs.) weight, 10 minutes. Three pieces are tested and the difference between the tube sample and the virgin compound must have a difference of 30% or less. ASTM F2769 requires a cell class of 2, 3, 4, or 5 for melt index. This test is conducted according to ASTM D1238 *ASTM (12)*. Test conditions are 190°C (374°F), 2.16 kg (4.76 lbs.) weight, 10 minutes. The melt Index must be less than or equal to 1.

DIMENSIONS

The dimensional requirements for tubing produced to ISO 22391 are quite diverse and depend on PE-RT type, application class, dimension class, and pipe series (if applicable). ASTM F2769 is limited to CTS SDR9 tube. The closest corollary to ASTM F2769 in ISO 22391 is application class 1, PE-RT Type II, dimension class A, pipe series S4. For example ½ inch CTS (15.9 mm OD) tube has an outside diameter (OD) of 15.88 mm (0.625 inch) +/- 0.1 (0.004) and a Wall Thickness (WT) of 1.78 mm (0.070 inch) +0.28 (0.010) / -0.0. 16 mm (0.630 inch) tube in dimension class A, pipe series S4 has an OD of 16 mm (0.630 inch) +0.3 (0.012) / -0.0 and a WT of 1.8 mm (.071 inch) +0.3 (0.012) / -0.0.

BURST TESTING

ISO 22391-3 requires a mechanical characteristics test that is comparable to the sustained pressure and burst pressure test in ASTM F2769. The ISO test requirements specify that three tubes be tested and shall not burst under the following conditions: 20°C (68°F), hoop stress 10.8 MPa (1566 psi), one hour; 95°C (203°F), hoop stress 3.9 MPa (566 psi), 22 hours; 95°C (203°F), hoop stress 3.7 MPa (537 psi), 165 hours; 95°C (203°F), and hoop stress 3.6 MPa (522 psi), 1000 hours. This test is on the tube itself and does not include fittings qualification. There is also an internal pressure test that includes the fittings and is performed in accordance with ISO 1167-1 and -2. PE-RT type II, application class 1, at 8 bar (116 psi) requires that three joint assemblies be tested at 95°C (203°F), 8.1 MPa (1174 psi), for 1000 hours with no leaks.

ASTM F2769 requires a sustained pressure test and a burst pressure test. Both are conducted on tubing and fitting assemblies. The test pressure depends on tube size and the HDB of the material used. In the case of (15.9 mm OD) tube with a 11.03 MPa (1600 psi) HDB at 23°C (73.4°F) the test pressures are: 2.79 MPa (405 psi) at 23°C (73.4°F) and 1.34 MPa (195 psi) at 82.2°C (180°F). The hoop stresses under these conditions are 11.03 MPa (1600 psi) at 23°C (73.4°F) and 5.31 MPa (770 psi) at 82.2°C (180°F). Six assemblies are tested in accordance with ASTM D1598 *ASTM (13)* for 1000 hours and failure of two or more assemblies constitutes a test failure. If one assembly fails then the test may be repeated with six additional assemblies. The burst pressure test is conducted in accordance with ASTM D1599 *ASTM (14)*. The test pressure depends on tube size and the HDB of the material used. In the case of ½ inch CTS (15.9 mm OD) tube with a 11.03 MPa (1600 psi) HDB at 23°C (73.4°F) the test pressures are: 5.03 MPa (730 psi) at 23°C (73.4°F) and 1.86 MPa (270 psi) at 82.2°C (180°F). The hoop stresses under these conditions are 19.99 MPa (2900 psi) at 23°C (73.4°F) and 7.34 MPa (1065 psi) at 82.2°C (180°F). The pressure is ramped up at a rate such that the required test pressure is reached between 60 and 70 seconds without failure prior to reaching the required test pressure.

PULL-OUT TEST

ISO 22391-5 requires a pull-out test conducted according to EN712 *EN (15)*. This is a tube and fitting assembly test. Application class 1, 8 bar (116 psi), 16 mm (0.630 inch) tube must withstand a pull-out force of 301.6 N (67.8 lbs.) at 23°C (73.4°F) and 160.8 N

(36.2 lbs.) at 90°C (194°F) without separation. There is no analogous test in ASTM F2769.

BENDING TEST

ISO 22391-5 requires a bending test only for sizes > 32 mm (1.26 inch). The test is conducted on a tube and fitting assembly that is bent to the minimum bending radius recommended by the manufacturer. PE-RT type II, application class 1, 8 bar (116 psi) tubing is tested at 20°C (68°F) and 24.5 bar (355 psi) and may not leak for one hour.

ASTM F2769 requires that the tube be subjected to a bending test where the tube is bent at a radius of six times the diameter at a minimum angle of 90 degrees. The tube is tested according to sustained pressure test as discussed above. No failures are allowed before 1000 hours. This test only applies to 25.4 mm (1 inch) and smaller tube and does not test the fittings.

LEAK TIGHTNESS UNDER VACUUM

ISO 22391-5 requires this test for tube and fitting assemblies and is conducted according to EN 12294 *EN (16)*. Three assemblies are tested. The test is conducted at 23°C (73.4°F), -0.8 bar (-11.6 psi) for one hour and the pressure may not increase more than 0.05 bar (0.76 psi). There is no analogous test in ASTM F2769.

THERMAL CYCLING TEST

ISO 22391-5 requires a thermal cycling test for tube and fitting assemblies according to EN 12293 *EN (17)*. Application class 1, 8 bar (116 psi) tubing is cycled between 90°C (194°F) and 20°C (68°F) for 5,000 cycles at 8 bar (116 psi). The test cycle is 15 minutes at the highest temperature, 15 minutes at the lowest temperature, and an overall cycle time of 300 minutes. No leakage is allowed. It should be noted that this test includes a bent tube when testing flexible tubes and therefore should be considered as a bent tube test as well.

ASTM F 2769 requires a thermal cycling test where an assembly with six joints is thermally cycled between 15.6°C (60°F) and 82.2°C (180°F) with an internal pressure of 6.9 bar (100 psi). The cycle time is two minutes in 82.2°C (180°F) water, two minutes in ambient air, and two minutes in 15.6°C (60°F) water. The cycle is repeated for 1,000 cycles. No leakage is allowed.

PRESSURE CYCLING TEST

ISO 22391-5 requires a pressure cycling test for tube and fitting assemblies according to EN 12295 *EN (18)*. Three pieces of 8 bar (116 psi) tube is cycled between 12 bar and 0.5 bar (7.25 psi) for 10,000 cycles at 23°C (73.4°F). The cycle rate is 30 cycles/minute. No leakage is allowed. There is no analogous test in ASTM F2769.

OUT OF ROUNDNESS

ASTM F2769 has a specification for out of roundness of the tube. The tube is measured prior to coiling. The average OD is compared to the maximum and minimum measured OD and the difference must be less than the tolerance given for a particular

diameter. ½ inch CTS (15.9 mm OD) tube may have a maximum out of roundness of 0.4 mm (0.016 inch). There is no analogous test in ISO 22391.

EXCESSIVE TEMPERATURE AND PRESSURE CAPABILITY

ASTM F2769 specifies an excessive temperature and pressure capability test. This test is conducted in accordance with ASTM D1598. This test is conducted on tube and fittings with at least six joints. The test temperature is 99°C (210°F) and the internal pressure is 1.03 MPa (150 psi). The samples must not fail in less than 720 hours. There is no directly analogous test in ISO 22391, however, this is a system malfunction test and the ISO standard includes malfunction conditions as part of the hydrostatic strength requirements. The hydrostatic strength rating includes malfunction conditions of 95°C (203°F) for 100 hours.

ENVIRONMENTAL STRESS CRACKING

ASTM F2769 specifies an Environmental Stress Cracking Test (ESCR). Six random samples ten inches long are notched on the inside of the tube to a depth of 10% of the wall thickness for a length of one inch. The tubes are filled with a 5% solution of Igepal CO-630 in water. In the case of ½ inch CTS (15.9 mm OD) tube with a 11.03 MPa (1600 psi) HDB at 23°C (73.4°F) the test pressures are: 2.79 MPa (405 psi) at 23°C (73.4°F) and 1.34 MPa (195 psi) at 82.2°C (180°F). The hoop stresses under these conditions are 11.03 MPa (1600 psi) at 23°C (73.4°F) and 5.31 MPa (770 psi) at 82.2°C (180°F). If any of the samples leak within 100 hours the test is failed. There is no analogous test in ISO 22391.

SLOW CRACK GROWTH RESISTANCE

ASTM F2769 specifies a Slow Crack Growth (SCG) test. This test is conducted in general accordance with ASTM F1473 *ASTM (19)*. The test specimens are machined from a compression molded plaque produced in accordance with ASTM F1473. Typical test specimen dimensions are 25 mm (0.984 inch) wide by 50 mm (1.968 inch) long by 10 mm (0.394 inch) thick. The samples are notched on three sides. The main notch is across the width and the side notches are coplanar to the main notch on both sides. The side notches are always 1 mm +/- 0.1 mm (0.039 +/- .004 inch) deep. The main notch depends on the sample thickness. The main notch is 3.5 mm (0.138 inch) +/- 0.05 (0.002) deep on a 10 mm (0.394 inch) thick sample. Two samples are tested at a load of 2.4 MPa (348.1 psi) at 90°C (194°F). Note that standard conditions for this test are at a load of 2.4 MPa (348.1 psi) at 80°C (176°F). The 10°C (18°F) higher test temperature for PE-RT further accelerates SCG and therefore it is a more rigorous test than that performed at the standard conditions. The load is calculated based on the un-notched cross sectional area of the sample. When the average test time is greater than or equal to 500 hours the test is passed. There is no analogous test in ISO 22391.

THERMAL STABILITY

ISO 22391-2 specifies a thermal stability test. In the case of type II PE-RT this test exposes one sample to 2.3 MPa (333.6 psi) at 100°C (212°F) in general accordance

with ISO 1167. The sample must not fail before 8,760 hours. There is no analogous test in ASTM F2769.

OXIDATIVE RESISTANCE IN POTABLE CHLORINATED WATER APPLICATIONS

ASTM F2769 specifies an oxidative resistance requirement for PE-RT in potable chlorinated water applications. This test is conducted in accordance with ASTM F2023 *ASTM (20)*. The test fluid is flowing chlorinated water at a minimum Oxidative Reduction Potential (ORP) of 825 mV. The flow rate for ½ inch CTS (15.9 mm OD) tube is 0.23 LPM (0.06 gpm). The pH is maintained between 6.5 and 8.0 and the free chlorine level is maintained 2.5 and 5.0 ppm. The selected pH and chlorine levels must be the same for all specimens and test conditions within a single test. A minimum of twelve tube specimens are tested at a minimum of six conditions. Three temperatures are tested and the temperatures selected must have at least 10°C (18°F) difference in test temperature. The maximum test temperature is 115°C (239°F). Two stress levels (internal pressure) are tested at each temperature. The internal pressure selected must have a difference of at least 1.38 bar (20 psi). Alternative data distributions conforming to PPI TN-16 *PPI (21)* are acceptable as well. All samples are run to failure and the data is analyzed using the Rate Process Method (RPM) and shifted to 5.52 bar (80 psi) at 60°C (140°F) with a life prediction in years. There are three possible ratings: Level 1 assumes that the temperature is 23°C (73.4°F) 75% of the time and 60°C (140°F) 25% of the time, Level 3 assumes that the temperature is 23°C (73.4°F) 50% of the time and 60°C (140°F) 50% of the time, Level 5 assumes that the temperature is 60°C (140°F) 100% of the time. The data are typically represented in a graphical format as seen in figure I (courtesy of JANA Laboratories Inc.) *Oliphant et al (22)*. There is no analogous test in ISO 22391.

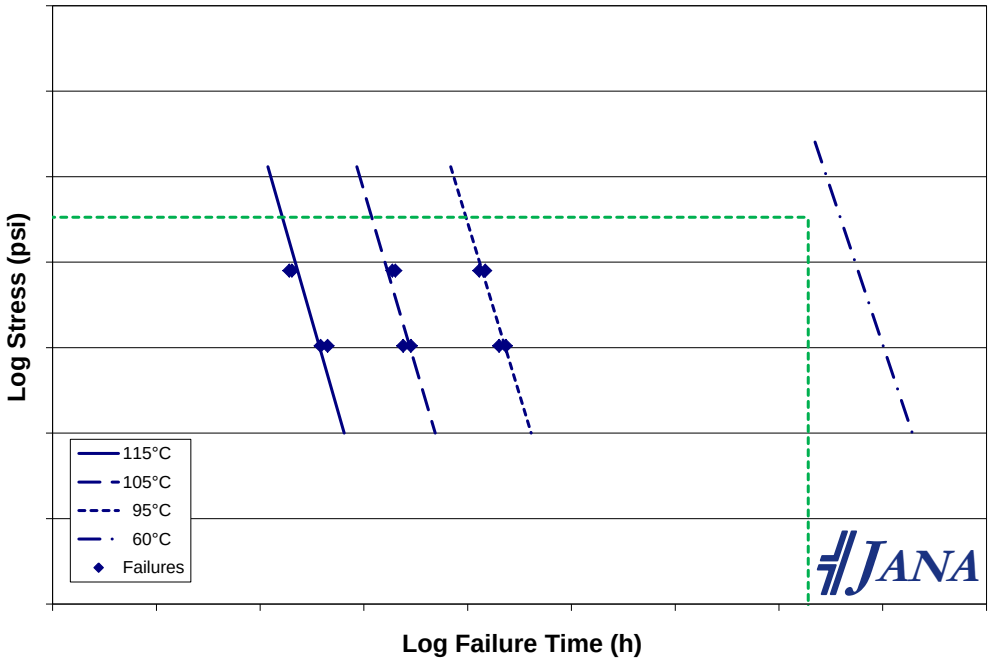

Figure I
ASTM F2023 Example Dataset

SUMMARY

The ISO and ASTM PE-RT standards have many similarities but many difference as well. Generally PE-RT type II materials as defined in ISO 22391 will meet the material requirements of ASTM 2769 with four possible exceptions. The oxidative resistance test found in ASTM 2769 is very rigorous and there is no analogous requirement in ISO 22391. Therefore it is unknown if materials designed to meet the ISO standards will pass this test. The excessive temperature and pressure test found in ASTM F2769 is another test that is very rigorous and some PE-RT type II materials may not be able to pass this test requirement. The SCG and ESCR requirements in ASTM 2769 are additional question marks for PE-RT Type II materials since there are no analogous requirements in ISO 22391.

Materials designed to meet ASTM 2769 in general will meet the requirements of ISO 22391. However, there are some questions marks here as well. There are three requirements that are unique to ISO 22391. The pull-out, leak tightness under vacuum, and pressure cycling tests are quite rigorous and depending on the type of fitting used could pose problems. In addition, the thermal cycling test in ISO 22391 is more rigorous than that found in ASTM 2769.

If hydrostatic testing is planned carefully it is possible to share data in order to meet the requirements of both standards. Virtually all the other test requirements are different enough that they will have to be repeated. The oxidative resistance requirement in ASTM F2769 is the major difference between the standards. In order to meet the highest level of oxidative resistance many PE-RT materials will take two to three years to complete this test.

LIST OF REFERENCES

1. ASTM F2769-10, *Standard Specification for Polyethylene of Raised Temperature (PE-RT) Plastic Hot and Cold-Water Tubing and Distribution Systems*, ASTM International, West Conshohocken, PA, USA.
2. ISO 22391-1, -2, -3, -5:2009, *Plastics piping systems for hot and cold water installations -- Polyethylene of raised temperature resistance (PE-RT)*, International Organization for Standardization, Geneva, Switzerland.
3. ISO 1167-1, -2:2006, Thermoplastics *pipes, fittings and assemblies for the conveyance of fluids -- Determination of the resistance to internal pressure)*, International Organization for Standardization, Geneva, Switzerland.
4. ISO 9080:2003, *Plastics piping and ducting systems -- Determination of the long-term hydrostatic strength of thermoplastics materials in pipe form by extrapolation*, International Organization for Standardization, Geneva, Switzerland.
5. ISO 24033:2009, *Polyethylene of raised temperature resistance (PE-RT) pipes -- Effect of time and temperature on the expected strength*, International Organization for Standardization, Geneva, Switzerland.
6. ASTM D3350-12, *Standard Specification for Polyethylene Plastics Pipe and Fittings*, ASTM International, West Conshohocken, PA, USA.

7. *ASTM D2837-11, 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, USA.
8. PPI TR-3 2010, Policies and Procedures for Developing Hydrostatic Design Basis (HDB), Pressure Design Basis (PDB), Strength Design Basis (SDB), and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe, Plastics Pipe Institute, Irving, Texas, USA.
9. ISO 7686:2005, *Plastics pipes and fittings -- Determination of opacity*, International Organization for Standardization, Geneva, Switzerland.
10. ISO 2505:2005, *Thermoplastics pipes -- Longitudinal reversion -- Test method and parameters*, International Organization for Standardization, Geneva, Switzerland.
11. ISO 1133-1:2011, *Plastics -- Determination of the melt mass-flow rate (MFR) and melt volume-flow rate (MVR) of thermoplastics -- Part 1: Standard method*, International Organization for Standardization, Geneva, Switzerland.
12. ASTM D1238-10, *Standard Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer*, ASTM International, West Conshohocken, PA, USA.
13. ASTM D1598-02(2009), *Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure*, ASTM International, West Conshohocken, PA, USA.
14. ASTM D1599-99(2011), *Standard Test Method for Resistance to Short-Time Hydraulic Pressure of Plastic Pipe, Tubing, and Fittings*, ASTM International, West Conshohocken, PA, USA.
15. EN 712:1993, *Thermoplastics piping systems - End-load bearing mechanical joints between pressure pipes and fittings - Test method for resistance to pull-out under constant longitudinal force*, European Committee for Standardization, Brussels, Belgium.
16. EN 12294:1999, *Plastics piping systems - Systems for hot and cold water - Test method for leak tightness under vacuum*, European Committee for Standardization, Brussels, Belgium.
17. EN 12293:1999, *Plastics piping systems - Thermoplastics pipes and fittings for hot and cold water - Test method for the resistance of mounted assemblies to temperature cycling*, European Committee for Standardization, Brussels, Belgium.
18. EN 12295:1999, *Plastics piping systems - Thermoplastics pipes and associated fittings for hot and cold water - Test method for resistance of joints to pressure cycling*, European Committee for Standardization, Brussels, Belgium.
19. ASTM F1473-11, *Standard Test Method for Notch Tensile Test to Measure the Resistance to Slow Crack Growth of Polyethylene Pipes and Resins*, ASTM International, West Conshohocken, PA, USA.
20. ASTM F2023-10, *Standard Test Method for Evaluating the Oxidative Resistance of Crosslinked Polyethylene (PEX) Tubing and Systems to Hot Chlorinated Water*, ASTM International, West Conshohocken, PA, USA.
21. PPI TN-16 2008, Rate Process Method for Projecting Performance of Polyethylene Piping Components, Plastics Pipe Institute, Irving, Texas, USA.

22. K. Oliphant, J. Couch, P. Vibien, A. Chudnovsky, B. Zhang, W. Zhou, *Chlorine Resistance Testing of Cross-linked Polyethylene Piping Materials*, Society of Plastics Engineers Annual Technical Conference (ANTEC), Dallas, USA, 2001.