**REPORT**

**on**

# REVIEW OF LITERATURE ON THE USE OF POLYETHYLENE (PE) PIPING IN NUCLEAR POWER PLANT SAFETY-RELATED CLASS 3 SERVICE WATER SYSTEMS

**to**

**The United States Nuclear Regulatory Commission**

**under**

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# 1. BACKGROUND

## 1.1 Rationale for use of Polyethylene (PE) Pipe in Nuclear Plants

General corrosion and microbiologically influenced corrosion (MIC) have plagued carbon steel piping in service water systems in operating reactors. Figure 1 shows a photograph of service water pipe used by Duke Energy at Catawba. Industry believes that the use of plastic piping, similar to that used in water, sewer, petrochemical and natural gas distribution applications, is quite viable for nuclear applications because of its resistance to general corrosion, bacteria, fungi and microbiological corrosion, fouling. In addition it has advantages that include

- Abrasion resistance
- Lower weight (~ one-seventh the density of steel)
- High flexibility, ductility and resistance to soil movement
- Superior flow characteristics due to lower hydraulic friction.

**Figure 1 Typical microbiological growth attaching to steel pipe creating flow restrictions**

Specifically, Duke Energy plans to submit a relief request (license amendment) to replace safety-related portions of the Catawba Nuclear Station low pressure service water system with polyethylene piping. Duke has proposed criteria for the production, design, material specifications, installation and inspection of the polyethylene piping. PE piping has already been used in *non-safety* related applications at Catawba for 10 years and Duke has apparently had excellent operating experience, see photograph in Figure 2 [Ref. 1].

**Figure 2 Polyethylene Pipe (black piping) used at Duke Energy Catawba Plant in *non-safety* Applications**

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Committee has formed a Special Working Group consisting of members from Section III and Section XI to prepare and accept a Code Case to specify requirements for the use of polyethylene piping in safety related applications for new construction and repair/replacement activities. To date this group has developed a draft of the Code Case N-755 [Ref. 2] titled "*Use of Polyethylene (PE) Plastic Pipe for Section III, Division 1, Construction and Section XI Repair/Replacement Activities*" that addresses the inquiry "*Under what conditions may polyethylene (PE) pipe be used for the construction of Section III, Division 1, Class 3, buried piping systems?*" The industry is developing the Code Case in support of Duke Energy pending application for a relief-request for use of PE pipe in Class 3 systems. For completeness, the latest version (Revision 6) of CC N-755 [Ref. 2] is provided in Appendix A.

Since a licensee and the ASME are both pursuing activities to allow using polyethylene piping in safety-related service that will require NRC approval, this work is undertaken to support these anticipated review needs.

## 1.2 Overview of Polyethylene (PE) Piping Materials

As a first step, it is worthwhile to provide an overview and background on PE materials, their classification and mechanical behavior. The following is provided as a general background on polyethylene (PE) materials as it is important to establish that PE covers a very large class of materials with varying properties and that *only a limited subset of PE materials* would eventually be considered for ASME Class 3 safety-related piping in nuclear plants. Therefore, while the literature may cover both safety and non-safety related applications, of particular interest would be technical information specific only to those grades of PE relevant for nuclear plant piping.

Plastics are generally classified into two groups - thermoplastics and thermosets. Thermoplastics becomes soft and moldable when heated and turn back into a solid when cooled and the process may be repeated without material degradation so long as the processing does not exceed a critical temperature. The other group of plastics, known as thermosets, undergoes a permanent chemical change upon processing into solids which is irreversible. Thermoplastics may further be categorized into amorphous and semi-crystalline materials. Amorphous thermoplastics, such as PVC, have a random molecular structure while semi-crystalline materials, such as PE or polypropylene (PP) have an amorphous phase as well as a structured molecular chains or a 'crystalline phase' that are called "spherulites." The amorphous phase provides strength while the semi-crystalline phase provides ductility. PE has a chemical formula $(C_2H_4)_n$. Figures 3a and 3b show respectively the molecular arrangement and a schematic of the amorphous and semi-crystalline phases of the material.

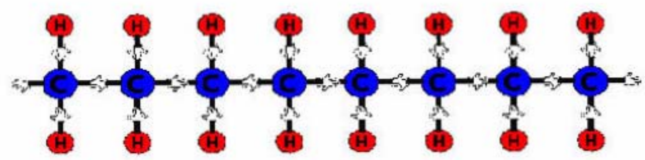


**Figure 3a – Molecular chain for Polyethylene (PE)**

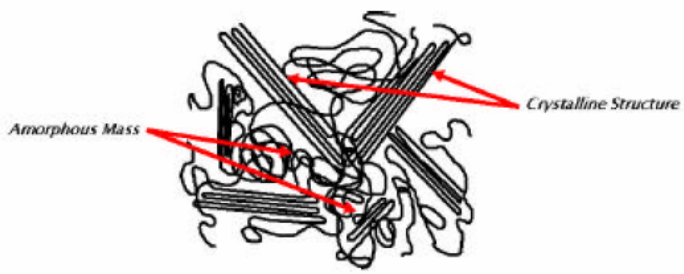



**Figure 3b** **Representation of the amorphous and semi-crystalline phases in PE microstructure**

*Polyethylene Material Classification*: PE along with polypropylene (PP) is classified as a 'polyolefin' material and together they account for half of all plastic products in the world. PE is an inexpensive and versatile polymer with numerous applications. Control of the molecular structure, and molecular weight distribution during production of PE results in various grades of the material that are broadly categorized by density as listed below:

- UHMWPE (ultra high molecular weight PE)
- HMWPE (high molecular weight PE)
- ***HDPE (high density PE) --[of interest to Nuclear Power Plant Applications]***
- HDXLPE (high density cross-linked PE)
- PEX (cross-linked PE)
- MDPE (medium density PE)
- LDPE (low density PE)
- LLDPE (linear low density PE)
- VLDPE (very low density PE)

Table 1 below provides the typical range of physical, mechanical and other property range for the various types of PE resin grades:

**Table 1 – Typical Range of Properties for PE Materials [Ref. 3]**

| PROPERTY | RANGE OF VALUES, SI UNITS | RANGE OF VALUES, ENGLISH UNITS |
|---|---|---|
| **Physical Poperties** | | |
| Density | 0.918 - 1.4 g/cc | 0.0332 - 0.0506 lb/in³ |
| Water Absorption | 0.01 - 1.5 % | 0.01 - 1.5 % |
| Environmental Stress Crack Resistance | 3 - 3000 hour | 3 - 3000 hour |
| **Mechanical Properties** | | |
| Hardness, Rockwell R | 60 - 65 | 60 - 65 |
| Hardness, Shore D | 55 - 69 | 55 - 69 |
| Tensile Strength, Ultimate | 10 - 50 MPa | 1450 - 7250 psi |
| Tensile Strength, Yield | 2.4 - 31.7 MPa | 348 - 4600 psi |
| Elongation at Break | 10 - 1500 % | 10 - 1500 % |
| Elongation at Yield | 6.9 - 15 % | 6.9 - 15 % |
| Tensile Modulus | 0.18 - 1.6 GPa | 26.1 - 232 ksi |
| Flexural Modulus | 0.179 - 1.7 GPa | 26 - 247 ksi |
| Flexural Yield Strength | 14 - 25 MPa | 2030 - 3630 psi |
| Compressive Yield Strength | 4 - 25 MPa | 580 - 3630 psi |
| Secant Modulus | 0.57 GPa | 82.7 ksi |
| Izod Impact, Notched | 0.21 - 8.01 J/cm | 0.393 - 15 ft-lb/in |
| Izod Impact, Unnotched | 2.7 - NB | 5.06 - NB |
| Charpy Impact Unnotched | NB | NB |
| Charpy Impact, Notched, Low Temp | 0.28 - 0.44 J/cm² | 1.33 - 2.09 ft-lb/in² |
| Charpy Impact, Unnotched Low Temp | NB | NB |
| Charpy Impact, Notched | 0.38 - 11 J/cm² | 1.81 - 52.4 ft-lb/in² |
| Tensile Impact Strength | 34 - 330 kJ/m² | 16.2 - 157 ft-lb/in² |
| Tensile Creep Modulus, 1 hour | 400 - 570 MPa | 58000 - 82700 psi |
| Tensile Creep Modulus, 1000 hours | 270 - 400 MPa | 39200 - 58000 psi |
| Dart Drop Test | 1.6 g | 0.00353 lb |
| **Electrical Properties** | | |
| Electrical Resistivity | 1e+006 - 1e+016 ohm-cm | 1e+006 - 1e+016 ohm-cm |
| Surface Resistance | 1e+006 - 1e+015 ohm | 1e+006 - 1e+015 ohm |
| Dielectric Constant | 3-Jan | 3-Jan |
| Dielectric Strength | 19 - 150 kV/mm | 483 - 3810 kV/in |
| Dissipation Factor | 0.0001 - 0.01 | 0.0001 - 0.01 |
| Arc Resistance | 100 - 180 sec | 100 - 180 sec |
| Comparative Tracking Index | 600 V | 600 V |
| **Thermal Properties** | | |
| Coefficient of Thermal Expansion, linear 20°C | 22 - 200 µm/m-°C | 12.2 - 111 µin/in-°F |
| Specific Heat Capacity | 2.2 J/g-°C | 0.526 BTU/lb-°F |
| Thermal Conductivity | 0.29 - 0.5 W/m-K | 2.01 - 3.47 BTU-in/hr-ft²-°F |
| Melting Point | 110 - 135 °C | 230 - 275 °F |
| Maximum Service Temperature, Air | 41 - 120 °C | 106 - 248 °F |
| Deflection Temperature at 0.46 MPa (66 psi) | 60 - 104 °C | 140 - 219 °F |
| Deflection Temperature at 1.8 MPa (264 psi) | 41 - 93 °C | 106 - 199 °F |
| Vicat Softening Point | 67 - 131 °C | 153 - 268 °F |
| Minimum Service Temperature, Air | -200 - -60 °C | -328 - -76 °F |
| Brittleness Temperature | -118 - -68 °C | -180 - -90.4 °F |
| Flammability, UL94 | HB - V-0 | HB - V-0 |

As seen in Table 1 PE resins are available in a *wide range of properties* depending on performance specifications needed for the final product to be manufactured. Some key points to note are:

- Flexural or Tensile Modulus values are in the range of 25 to 250 ksi (172 to 1720 MPa), typically 100 to 175 ksi (690 to 1207 MPa) and are much lower than those for steels 30,000 ksi (206 GPa),
- Much higher elongation (strain) to failure (up to 1500%) than those for metals,
- Creep behavior at relatively low stress levels and temperatures, (modulus decreases by almost a factor of 2 over 1000 hour sustained loading),
- Much lower limits for operating temperature, as defined by Deflection Temperature Under Load (DTUL), less than 200 °F (93.3 °C) at 264 psi (1.82 MPa),
- Coefficient of Thermal Expansion for HDPE is as high as $1.1 \times 10^{-4}$ in/in/°F ($2.0 \times 10^{-4}$ in/in/°C) versus ~ 6.0 in/in/°F ($10.8 \times 10^{-6}$ in/in/°C) for steel.

Of the above grades of PE, *only a limited subset of HDPE resins is of interest to nuclear power plant service water applications*. These HDPE resins, frequently referred to as PE-4710 or PE-100, are "bimodal" in nature as they have two peaks in the molecular weight distribution as shown in Figure 4 below [Ref.4]. The combination of low and high molecular weight distributions provides an ideal balance of mechanical properties for safety-critical and high-performance piping applications.

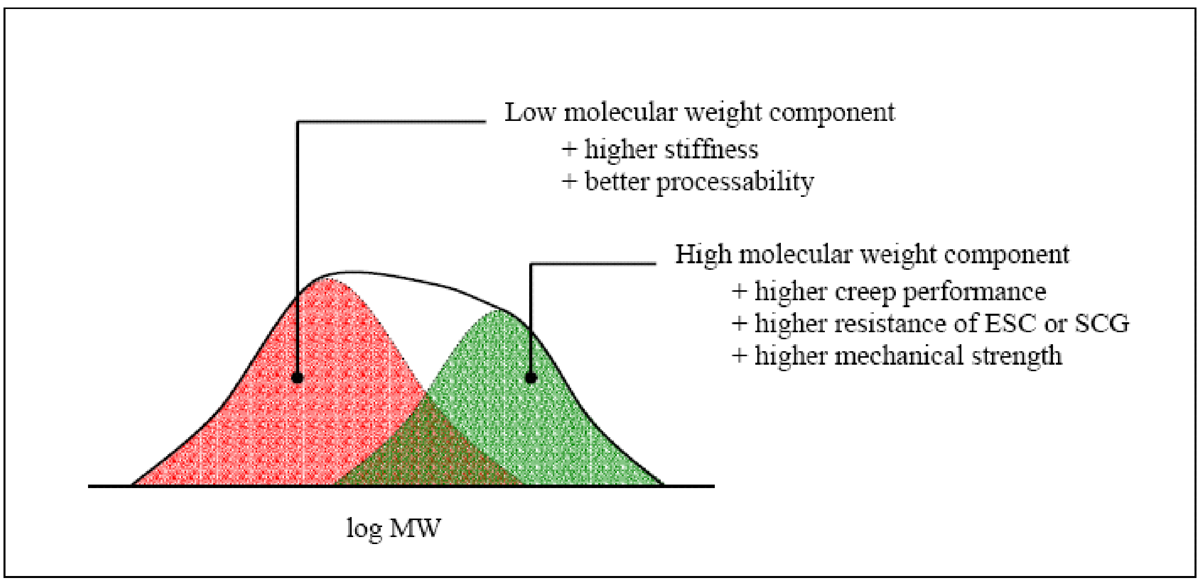



**Figure 4 Schematic of molecular weight distribution of bi-modal HDPE materials [MW = Molecular Weight; ESC = Environmental Stress Cracking and SCG = Slow Crack Growth]**

Further description of HDPE material specifications for piping is provided in Section 2.0 below.

*HDPE Piping History*: Since the discovery of a low-pressure pipe manufacturing process for

HDPE piping in the 1950s [Ref. 5], HDPE piping has been used for a variety of applications successfully for over 50 years. Today approximately _8.1 billion pounds (3,600,000 metric tons) of HDPE piping_ are used worldwide in outdoor applications including:

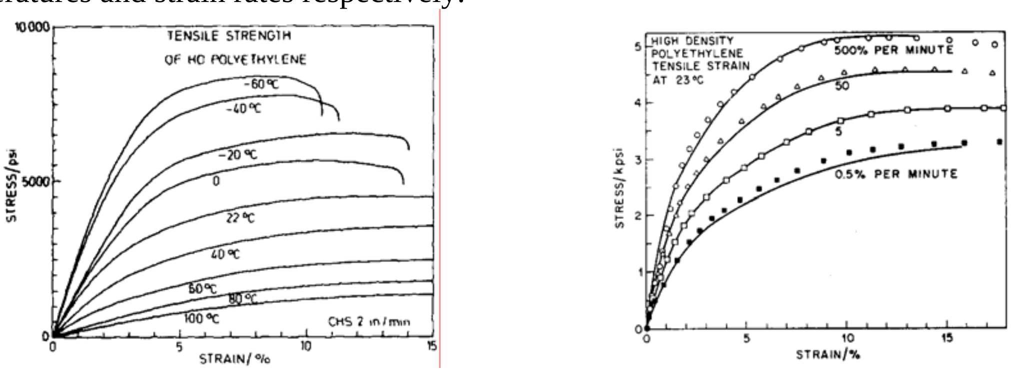
- Water (pressure and non/low pressure applications),
- Sewer and wastewater discharge systems,
- Natural gas distribution and gas gathering lines,
- Petrochemical Industry piping,
- Specialty applications for corrosive fluids,
- Nuclear power plants (non-safety related) piping, and
- Safety-related piping in nuclear power plants (in UK).

As may be surmised, the technical literature involving experience with HDPE piping is very vast covering the development of various generations of HDPE materials, piping, fittings, joining procedures, etc. over several decades. National and International conferences are held periodically to review the progress, developments, and problems with materials and applications. The most recent of these conferences Plastics Pipes XIII was held in Washington, DC from October 2-5, 2006. The proceedings and the papers presented at this conference provide a comprehensive overview of the industry as well as the latest technical issues and challenges facing the industry [Ref. 6].

Of specific interest to this project are those applications that involve: (i) elevated temperature for water piping; (ii) natural gas distribution (safety-related); and (iii) any past experience in nuclear power plants. Recently, HDPE has also been used in a safety-related nuclear power plant application in the UK at the Sizewell B plant [Ref. 7]. The literature review is therefore restricted to these issues.

## 1.3 Mechanical Behavior of Polyethylene (PE) Materials

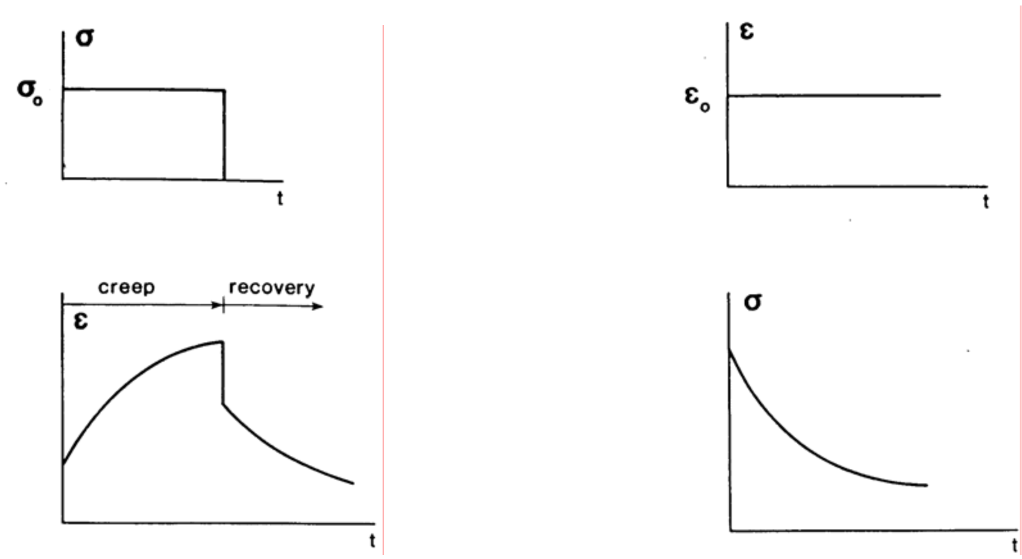
One key distinguishing feature of all polymeric materials including PE is that they are viscoelastic in nature. That is, their mechanical behavior is significantly influenced by time (or loading rate) as well as temperature. The constitutive model for PE is a stress-strain-time-temperature relationship that can be cast in several linear or nonlinear-viscoelastic forms [Ref. 8]. Stress-strain curves for PE materials increase with the increasing strain rate or decreasing temperature. Figures 5a and 5b show typical data for HDPE materials at tested at various temperatures and strain rates respectively.




(a) Temperature effects (b) Strain-rate effects

**Figure 5 Typical stress-strain curves for HDPE [Ref. 9]**

Under a constant sustained load, PE materials creep, that is, the strain increases with time with a constantly decreasing strain rate, see Figure 6a.  Upon removal of the load, the strain recovers even in the absence of any load.  And under deflection control, at constant strain HDPE exhibits stress-relaxation, where the stress decreases with time, see Figure 6b.




(a) Creep and Recovery (b) Stress Relaxation

**Figure 6 Schematic of typical (a) creep-recovery under constant stress, and (b) stress relaxation under constant strain**

Therefore a constitutive model for the mechanical behavior of HDPE consists of a relation between stress, strain, time, and temperature.  Depending on the experimental data used, there are many forms of linear or non-linear viscoelastic relations available to characterize this constitutive behavior [Ref. 10].  One form of this equation that represents the influence of both time and temperature on stress-strain behavior that has recently been used is as follows [Ref. 11].

$$\varepsilon = A * \sigma^m * t^n * \exp(T/T_0) \qquad [1]$$

where $\varepsilon$ = strain, $\sigma$ = stress, t = time, T = temperature.  A, m (>1.0), n (<1.0) and $T_0$ are material constants obtained from curve-fits of experimental data.

One key observation is the influence of temperature which occurs in the exponent in Equation (1).  Hence the effect of *increase in temperature on creep strain is exponential* and must be incorporated in all design considerations.  As described by Equation [1], under a constant load (stress) PE creeps, that is, the strain increases with time.  This is similar to what is observed in creep of metals at very high temperatures.  However, viscoelastic materials such as PE also exhibit stress relaxation at constant deflection where the stress decreases with time and therefore in deflection-controlled loading the material is "forgiving" in that the stresses decreases with time, see Figure 6b.

Because of the phenomena such as those shown in Figure 5 and 6 that characterize the mechanical behavior of plastics, the Time-Temperature-Superposition-Principle (TTSP) has been developed [Ref. 11] and provides a methodology to predict long-term behavior of PE materials based on short-term data conducted at elevated temperatures. This principle is also employed in developing the long-term hydrostatic strength (LTHS) and hydrostatic design basis (HDB) for PE piping and is discussed in Section 3.0 below.

# 2. HDPE PIPE MATERIAL SPECIFICATIONS

While density provides a first level classification of PE, there are other more precise methods to designate HDPE grades for piping. There are three approaches frequently used as detailed below.

## 2.1 ASTM Cell Classification of PE Materials for Piping

American Society of Testing and Materials International (ASTM) Committee F-17 on Plastic Piping System develops industry consensus standards and specification for HDPE piping. ASTM Standard D3350-05 [Ref. 12] provides a seven digit (6 numerical characters and a letter) cell classification method for specifying grades of PE pipes by resins density, melt index, flexural modulus tensile strength, stress crack resistance, hydrostatic design basis at 73 °F (23 °C), and UV stabilization, and color. Table 2 below shows these property values for the first 6 ‘cells’ from ASTM D-3350 where the cell classification numbers are the column headings. The stabilization/color code letter is described elsewhere in the standard. Such a cell classification is used to specify the exact type of resin grade that is to be used for PE pipe.

**Table 2 Cell Classification of PE Piping Materials per ASTM 3350 [Ref. 12]**

| Property | Test Method | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Density, g/cm$^3$ | D 1505 | Unspecified | 0.925 or lower | >0.925-0.940 | >0.940-0.947 | >0.947-0.955 | >0.955 | . . . | Specify Value | |
| 2. Melt index | D 1238 | Unspecified | >1.0 | 1.0 to 0.4 | <0.4 to 0.15 | <0.15 | [A] | | Specify Value | |
| 3. Flexural modulus, MPa [psi] | D 790 | Unspecified | <138 [<20 000] | 138-<276 [20 000 to <40 000] | 276-<552 [40 000 to 80 000] | 552-<758 [80 000 to 110 000] | 758-<1103 [110 000 to <160 000] | >1103 [>160 000] | Specify Value | |
| 4. Tensile strength at yield, MPa [psi] | D 638 | Unspecified | <15 [<2200] | 15-<18 [2200-<2600] | 18-<21 [2600-<3000] | 21-<24 [3000-<3500] | 24-<28 [3500-<4000] | >28 [>4000] | Specify Value | |
| 5. Slow Crack Growth Resistance | | | | | | | | | | |
| I. ESCR | D 1693 | Unspecified | | | | | | | | |
| a. Test condition (100% Igepal.) | | | A | B | C | C | . . . | . . . | . . . | Specify Value |
| b. Test duration, h | | | 48 | 24 | 192 | 600 | | | | |
| c. Failure, max, % | | Unspecified | 50 | 50 | 20 | 20 | | | | |
| II. PENT (hours) | F 1473 | | | | | | | | | |
| Molded plaque, 80°C, 2.4 MPa | | Unspecified | . . . | . . . | . . . | 10 | 30 | 100 | 500 | Specify Value |
| Notch depth, F 1473, Table 1 | | Unspecified | | | | | | | | |
| 6. Hydrostatic Strength Classification | | | | | | | | | | |
| I. Hydrostatic design basis, MPa [psi], (23°C) | D 2837 | NPR[B] | 5.52 [800] | 6.89 [1000] | 8.62 [1250] | 11.03 [1600] | . . . | . . . | | |
| II. Minimum required strength, MPa [psi], (20°C) | ISO 12162 | . . . | . . . | . . . | . . . | . . . | 8 [1160] | 10 [1450] | | |

[A] Refer to 10.1.4.1.
[B] NPR = Not Pressure Rated.

_The minimum cell classification for HDPE called for in CC N-755 [Ref. 2] is 445474C_, which may be interpreted as follows using the cell number that are in the column headings in Table 2:

**Table 3 Interpretation of HDPE Cell Classification 445474C In Proposed Code Case N-755 [see Appendix A]**

| Cell No. | Description |
|---|---|
| 4 | Density Range 0.948 to 0.955 gm/cc (59.182 to 59.618 lbs/ft^3) per ASTM D1505 |
| 4 | Melt index of < 0.15 gm/10 min (0.00529 oz/10 min) per ASTM D1238 |
| 5 | Flexural Modulus between 110 and 160 ksi (0.758 to 1.103 MPa) per ASTM D790 |
| 4 | Tensile Strength between 3500 to 4000 psi (24.1 to 27.6 MPa) per ASTM D638 |
| 7 | PENT Test Failure Time of > 500 hours per ASTM D 1473 |
| 4 | Hydrostatic Design Basis of 1600 psi (11.03 MPa) per ASTM D2837 |
| C | Black with 2% minimum carbon black |

## 2.2 PPI Designation of PE Materials

A second method for designation of HDPE resins for piping in the US was developed by the Plastic Pipe Institute (www.plasticpipe.org). The PPI is a trade association of the manufacturers and resin suppliers in the plastic pipe industry. The manufacturers generate proprietary experimental data on their resins/pipes per specific ASTM standards and provide it to the PPI for evaluation. The Hydrostatic Design Board of the PPI then evaluates these data confidentially and "assigns" the appropriate designation to the resin, such as PE 2306, PE 3408, or PE 4710 which may be interpreted as shown in Table 4 below [Ref. 13].

**Table 4 Interpretation of HDPE Pipe Designations relevant to Class 3 Piping**

| | | |
|---|---|---|
| **PE 3408** | 3 | Density cell class 3 per D3350, 0.941 - 0.947 gm/cc (58.745 to 59.119 lbs/ft^3) |
| | 4 | SCG cell class 4 per D3350, PENT value > 10 hours |
| | 08 | 800 psi (5.51 MPa) hydrostatic deisgn stress for water at 73 °F (23 °C) |
| | | |
| **PE 4710** | 4 | Density cell class 4 per D3350, 0.948 - 0.955 gm/cc (59.182 to 59.618 lbs/ft^3); |
| | 7 | SCG cell class 4 per D3350, PENT value > 500 hours |
| | 10 | 1000 psi (6.89 MPa) hydrostatic design stress for water at 73 °F (23 °C) |

The PPI has published a Handbook of Polyethylene Pipe [Ref. 13], several Technical Reports and Technical Notes on various issues involving HDPE (and other plastic) piping [Ref. 14]. The Gas Technology Institute (formerly Gas Research Institute) has also published numerous reports on PE pipe used in gas distribution piping. A complete list of these documents is provided in Appendix B.

## 2.3 European System of Designating HDPE Pipe

Another system of designating HDPE pipe that was originally developed in Europe and is sometimes used in the US involves specifying the pipe by its Minimum Required Strength (MRS) per ISO Standard 12162 [Ref. 15]. In this case, the resin/pipe is referred to as PE80, PE100, or PE125, which implies that the MRS value for that grade of resin is 8, 10 or 12.5 MPa (1160, 1450, or 1813 psi) per the ISO Standard.

As may be noted there is both overlap (and some confusion) in the various methods to designate pipe. *The current version of the proposed ASME Code Case N-755 for Class 3 piping systems [see Appendix A] calls for using only **PE 4710** materials that meet or exceed the performance of PE with a cell classification of **445474C***. That is, amongst the numerous grades and classes of PE materials available, *only a very small subset that meets the cell classification 445474C is being considered for Class 3 piping in nuclear plants by the industry*. The European equivalent of this HDPE grade would be ***PE100*** or higher.

A series of ASTM Standards provide the specification and design methodology for PE piping. Those standards that are relevant to the Code Case N-755 are listed in Appendix C.

# 3. DESIGN OF HDPE PIPE

The primary basis for design of HDPE pipe or determining the "pressure rating" of a specific grade of HDPE resin involves the Hydrostatic Design Basis (HDB) protocol. This procedure is discussed in detail first and is followed by summaries of other design issues for HDPE piping.

## 3.1 Hydrostatic Design Basis (HDB)

ASTM D2837 [Ref. 16] along with the associated test method ASTM D1598 [Ref. 17] is used to determine the HDB for any grade of HDPE piping. This procedure is also detailed in PPI Report TR-3, TR-4 and ISO 9080 [Refs. 18-20]. An extensive amount of testing is first undertaken on short segments of HDPE pipe, typically less than 4-inches in diameter at various levels of sustained pressure and temperature. The test condition is maintained until the pipe fails due to leakage, at which point the time to failure is recorded. A graph of the stress rupture curve, that is the hoop stress in the pipe versus time to failure, is then developed on a logarithmic scale as shown in Figure 7 below.

Such a plot typically shows two straight line segments with a "knee" in the curve. At stress levels above the knee the type of failure observed in the HDPE pipe is ductile, i. e. a circumferential crack that occurs after extensive deformation as shown in Figure 8a. At stress levels below the knee axial slit failure occurs with very little deformation, i.e. an axial crack develops and grows through the wall of the pipe until failure occurs, see Figure 8b. The latter type of failure is typical of field failures that occur in HDPE pipe service due to 'slow crack growth'. Therefore the onset of this knee is used to define the design limit for the pipe which is also called the Long Term Hydrostatic Stress (LTHS).

*HDPE piping is never operated at temperatures and hoop stress levels that are in the range of ductile failure as shown in Figure 8a above*. Stress-rupture curves such as those in Figure 7 are a function of temperature and generally move upwards at lower temperatures as shown in Figure 9 [Ref. 16]. The time-temperature superposition principle (TTSP) is invoked to deduce the service life based on elevated temperature data. This is also based on what is known as the "Rate Process Method" which uses an Arrhenius type activation energy approach to describe the failure times as a function of stress and temperature [Ref. 16].

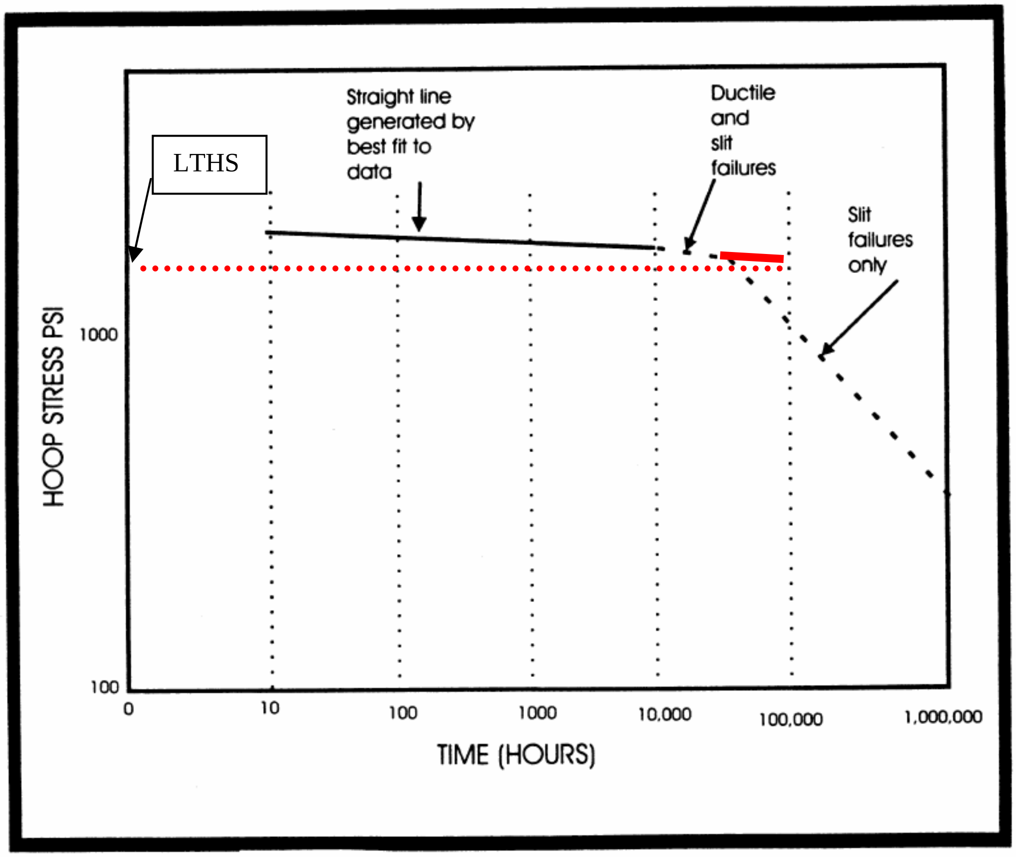



**Figure 7 Schematic of stress rupture data plot for plastic pipes tested to failure (LTHS = Long Term Hydrostatic Stress)**

**Figure 8a Photograph of typical "ductile" failure during stress-rupture testing to determine LTHS**

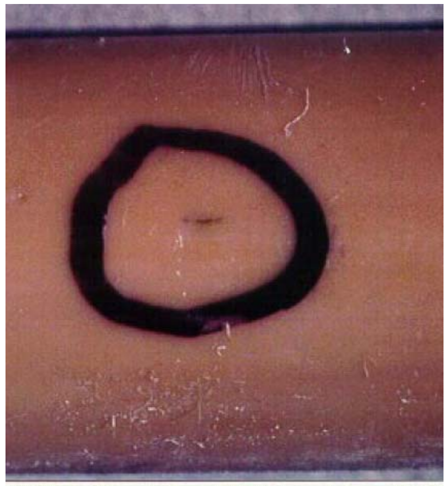


**Figure 8b Photograph of typical "brittle" axial-slit type of failure during LTHS determination**

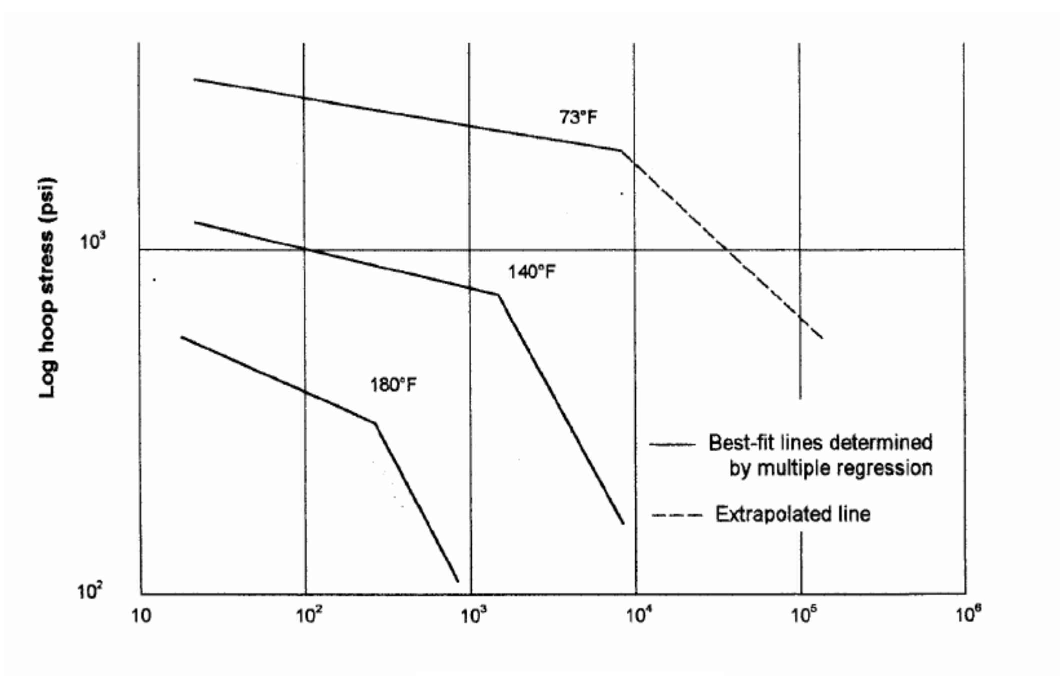



**Figure 9 Schematic of pipe stress rupture data at various temperatures shown as hoop stress versus time to failure [Ref. 16]**

A linear-fit of the ductile failure data is extrapolated to 100,000 hours (11.4 years) to establish what is termed as the <u>*LTHS for the specific grade of HDPE resin and pipe for the given temperature*</u>. This LTHS value is then rounded off to the nearest 10 psi (0.0689 MPa) per D2837 [Ref. 16] to establish the hydrostatic design basis for the specific resin and pipe grade. Further safety factors are applied depending on the application and the temperature to arrive at the recommended pressure rating for pipe with different wall thicknesses or SDRs (SDR or DR= Standard Dimension Ratio = Ratio of Outside Diameter to minimum wall thickness) which is the equivalent of the pipe schedule used for metallic pipes.

*The raw data from the stress-rupture experiments used to develop the HDBs for HDPE piping are considered proprietary and unavailable* to the end-users. Only the PPI's HDB Board reviews these data to assign the appropriate grade to the resin. A chart such as the one in Figure 10 below is then developed for defining the recommended pressures at various operating temperatures and provided by the resin supplier or pipe manufacturer to the end-user. ASTM D2837 does however provide end-users a method to validate the proposed HDB for any HDPE pipe using a reduced test matrix and elevated temperature testing.

| Temperature | | MRS/LCL [3] | | SDR | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 41 | 32.5 | 26 | 21 | 19 | 17 | 15.5 | 13.5 | 11 | 9 | 7 |
| °F | °C | Psi | Mpa | Pressure Rating, psig [4] | | | | | | | | | | |
| 50 | 10 | 1595 | 11.0 | 64 | 81 | 102 | 128 | 142 | 160 | 176 | 204 | 255 | 319 | 425 |
| 59 | 15 | 1523 | 10.5 | 61 | 77 | 97 | 122 | 135 | 152 | 168 | 195 | 244 | 305 | 406 |
| 68 | 20 | 1450 | 10.0 | 58 | 74 | 93 | 116 | 129 | 145 | 160 | 186 | 232 | 290 | 387 |
| 77 | 25 | 1374 | 9.5 | 55 | 70 | 88 | 110 | 122 | 137 | 152 | 176 | 220 | 275 | 366 |
| 86 | 30 | 1300 | 9.0 | 52 | 66 | 83 | 104 | 116 | 130 | 143 | 166 | 208 | 260 | 347 |
| 95 | 35 | 1229 | 8.5 | 49 | 62 | 79 | 98 | 109 | 123 | 136 | 157 | 197 | 246 | 328 |
| 104 | 40 | 1160 | 8.0 | 46 | 59 | 74 | 93 | 103 | 116 | 128 | 148 | 186 | 232 | 309 |
| 113 | 45 | 1095 | 7.6 | 44 | 56 | 70 | 88 | 97 | 110 | 121 | 140 | 175 | 219 | 292 |
| 122 | 50 | 1033 | 7.1 | 41 | 52 | 66 | 83 | 92 | 103 | 114 | 132 | 165 | 207 | 275 |
| 131 | 55 | 972 | 6.7 | 39 | 49 | 62 | 78 | 86 | 97 | 107 | 124 | 156 | 194 | 259 |
| 140 | 60 | 914 | 6.3 | 37 | 46 | 58 | 73 | 81 | 91 | 101 | 117 | 146 | 183 | 244 |

**Figure 10 Recommended pressures at various temperatures for HDPE resin for water piping [Courtesy: DOW Chemicals, PE100 Resin Grade; Trade Name Designation = DGDA 2490 Black Pipe]**

As seen in Figure 10, the highest recommended temperature for this grade of PE resin (PE 100) is 140 °F (60 °C). In general, even higher grades of HDPE pipe are not recommended for use above 140 °F (60 °C). *CC N-755 limits the maximum operating temperature and pressure to 140 °F* (60 °C) *and 150 psi (1.034 MPa) respectively for PE 4710 piping with minimum cell classification of 445474C*. For DR 11 piping ($OD/t_{min}$=11) the recommended pressure at 140 °F (60 °C) is 146 psi ( 1.00 MPa) for PE 100 piping in Figure 10 and is slightly lower than the value in the Code Case (150 psi (1.034 MPa)). Since temperature is a limiting factor for HDPE piping the proposed application in safety related Class 3 service water systems is at the upper limit of recommended operating temperature. Therefore, validation test data needs to be provided by manufacturers to substantiate the use of HDPE at these temperatures in nuclear power plant applications.

A list of all PE 4710 resin and pipe manufacturers in the US as approved by PPI is provided in their Technical Report TR-4 [Ref. 19].

## 3.2 Failure Modes of HDPE Piping

This section provides a review of different failure modes that have been considered to date for non-nuclear HDPE piping (gas, water, etc.). The failure modes that are relevant to nuclear plant service water lines are discussed in Section 6 below titled "HDPE Piping in Nuclear Applications."

**Slow Crack Growth (SCG)**

As described in the HDB Section above, the primary mode of failure in HDPE pipe over the long term involves slow crack growth (SCG) such as that illustrated in Figure 8b. Avoiding SCG type of failure constitutes one challenge in defining the design limits. Over the last two decades numerous laboratory-scale experiments on coupons that are machined from the pipe, or molded from resins have been proposed to study SCG [Ref. 21]. The overall objectives of these studies have been to:

- Develop a standard test method to compare the performance of various resins,
- Develop short-term tests for accelerating the long-term effects by using elevated temperatures and stress levels, and
- Develop a methodology for predicting long-term service life of HDPE piping using SCG data.

Some of the more common SCG test procedures and standards include:

- Three-point bending (TPB) of C-shaped specimens machined from pipe [Ref. 22],
- Pennsylvania Notch Test (PENT) developed at the University of Pennsylvania [Ref. 23],
- Notched Ring Test (NRT) [Ref. 24],
- Full Notch Creep Test (FNCT) [Ref. 25], and
- Notch Pipe Test (NPT), [Ref. 26].

Most of the above use semi-empirical correlation between stress levels or the fracture mechanics based stress-intensity factor level versus time to failure to achieve the above objectives. A recent comprehensive report has been developed by the GTI that correlates SCG with HDB testing and has been requested from the industry [Ref. 27 and 28].

Many of the field failures observed in gas distribution piping from older generation HDPE materials involve SCG type of failures. These are detailed in National Transportation Safety Board (NTSB) investigations of PE pipe failures. These failures have prompted the agency to prepare a failure analyses report and also a Special Investigation Report on SCG in PE pipes [Refs. 29 to 32].

While SCG is one of the most critical issues in the use of HDPE natural gas pipe at elevated temperatures in safety-related systems, *most of the data and experiments to date involve older generation MDPE and HDPE resins and materials*. The evolution of the latest generation of high-performance HDPE materials has been prompted by increase in resistance to slow crack growth, by as much as a factor of 10. For example, the failure times in the PENT test have increased from ~10 hours for the resin grades in the 1980s to over 500 hours for HDPE bimodal resins today.

Specific SCG data for PE 4710 (PE 100) with a minimum cell classification of 445474C that is of interest to CC N-755 is limited. These data have been requested from the industry for evaluation for safety-related Class 3 piping systems.

**Rapid Crack Propagation (RCP)**

Another mode of failure that defines the design limits for HDPE gas pipe involves rapid crack propagation (RCP). This is a phenomenon where an axial crack initiated from third party damage can propagate at very high speeds (~600 to 1200 ft/sec or 183 to 366 m/sec) over long distances especially when the pipe is at low temperatures (< 32 °F or 0 °C ). The propensity for RCP is governed by

- Hoop stress level,
- Low temperature fracture toughness of the material,
- Pipe diameter (and DR), the driving force for RCP increases at large diameters (>>6 in or 152 mm diameter pipe), and
- Decompression behavior of the fluid in the pipe upon initiation of RCP.

While a fast propagating fracture such as RCP is an important design criterion for gas and other water piping, for Class 3, safety-related application, it may not be as significant for nuclear plant piping. Even if RCP is initiated in such pipe, the decompression wave speed in the fluid (water) is significantly higher than the crack velocity and hence such a crack would arrest very quickly. This is also based on the fact that there is *NO AIR GAP* in the service water HDPE piping. Even a small air gap (5%) can significantly increase the propensity for RCP. The other scenario under which RCP is significant is a phenomenon termed 'ring-off' under which an RCP type of crack does not propagate axially but instead turns in a circumferential direction around the pipe creating [Ref. 33] a full bore opening or a double ended guillotine break.

There are several studies on RCP of HDPE piping that are available [Ref. 33, 34] including a standard test method that has been developed by ISO [Ref. 35]. Specific data on RCP for the HDPE resins specified in CC N-755 have been requested from the industry for further evaluation. We have also any data or reports involving RCP in HDPE water piping from the industry.

## 3.3 Effect of Secondary and External Loading

In addition to internal pressure loading, HDPE piping is also subjected to external secondary loads. There are several studies undertaken by the gas industry and the Gas Research Institute (now Gas Technology Institute) and others to address

- Longitudinal loads during installation and service (freeze thaw) [Ref. 36],
- Compression loading (ring deflection) under buried conditions [Ref. 37],
- Bending limits [Ref. 38], and
- Fatigue and Ratcheting Effects [Ref. 39].

Again, much of the work on the effect of secondary loads has been carried out on older generation HDPE materials. While the principles involved in the evaluation of external loading effects on buried piping are relevant, the material response for older resins versus PE 4710 grades would be vastly different. Of specific interest to the CC N-755 are the following two studies that have been used to develop much of the technical basis in the Code Case:

- Welding Research Council report on plastic pipe [Ref. 39], and
- The Electric Power Research Institute (EPRI) studies on PE Pipe [Ref. 40, 41] undertaken recently to develop the technical basis for CC N-755 [Ref. 2]

One specific external loading scenario of interest to safety-related Class 3 piping systems is the effect of seismic loading due to earthquakes or soil movements on PE piping. There is anecdotal information, such as the photograph in Figure 11 below (PE pipe after landslide), on the excellent performance of HDPE piping in seismic conditions due to its high ductility and flexibility. The EPRI study [Ref. 40, 41] lists various efforts undertaken with regard to the behavior of HDPE piping under seismic loading. This study provides the basis of the proposed design for seismic loading in CC N-755. A recent Japanese report [Ref. 42] has also been obtained and translated that details the HDPE pipe evaluation under seismic conditions.

EPRI is also undertaking an extensive experimental program to develop a database on PE 4710 type materials in support of the CC N-755 and any other follow-up Code Cases. The results from this program will be presented at the new Special Working Group on Plastic Pipe at the ASME Section III Meetings.

**Figure 11 Photograph of PE pipe after landslide**

# 4. MANUFACTURING AND ASSEMBLY

## 4.1 HDPE Pipe Manufacturing

Performance of all plastic products including HDPE piping is a function of three major factors– microstructure of the material/resin, processing (manufacturing) conditions and history, and material properties. These three factors are intimately tied to determine the performance of piping. The resin (material) suppliers qualify the quality of the resin with basic physical, mechanical and thermal properties per ASTM standard tests. A typical property sheet for resin is shown in Figure 12. The HDPE resin is first melted and then extruded into pipe of the required diameter and wall thickness using specific processing conditions (temperature, pressure and cooling cycles) per the suppliers recommendation using proprietary technology in many cases.

Once extruded, the dimensions and properties have to meet ASTM standards for HDPE piping [Ref. 43]. A typical data sheet for HDPE pipe from a manufacturer is shown in Figure 13 below. Small diameter piping (< 4 inches or 101.6 mm in diameter) is supplied in coils, while larger diameters are supplied in straight sections 40-feet to 60-feet (12.2 to 18.3 m) in length as required.

While the pipe may meet dimensional tolerance and minimum specified properties, depending on the processing (cooling after extrusion) conditions, the diameter and wall thickness of the pipe the residual stress field in the pipe wall can vary significantly. Since the pipe is typically cooled externally, a compressive residual stress develops on the outer surface, while a tensile (a bending, self-equilibrating) stress occurs on the inner surface, that is, if a small section of the circumference is cut out of the pipe wall the ring closes on itself. While this fact may not affect the dimensional tolerance, installation or performance it could play a significant role if a flaw or crack is present in the pipe wall in the tensile residual field. We have requested such data from the industry for evaluation of safety-related applications.

Other piping components and fittings are generally molded (instead of extruded) using the same resin grade as that used for piping. Since the performance characteristics of the PE product are dependent both on resin material properties AND processing conditions, fittings could possibly have very different performance properties. Dimensional tolerances and specification for properties for fittings are also specified in ASTM Standards and by PPI [Ref. 44, 13].

Resin for Pipe Extrusion and Pipe Fittings

Dow Plastics

# CONTINUUM DGDC-2480 NT

## Bimodal Polyethylene Resin

Industrial Standards Compliance:
- ASTM D 3350: cell classification
  - Natural – PE445574A
  - Black – PE445574C(1)
- Plastics Pipe Institute (PPI): TR-4
  - Natural Pipe – CONTINUUM DGDC-2480 BK 3408 (2)
    - ASTM PE4710 pipe grade – 1600psi HDB @ 73°F (E-4)
  - Black Pipe – CONTINUUM DGDC-2480 BK 3408 (2)
    - ASTM PE4710 pipe grade – 1600psi HDB @ 73°F and 1000psi HDB @ 140°F
    - ISO PE80 pipe grade – MRS 8 20°c
- National Sanitation Foundation (NSF): Standard 14 and 61
  - Natural Pipe - DGDC-2480 NT 3408(2)
  - Black Pipe - DGDC-2480 Black 3408(2)

Consult the regulations for complete details.

CONTINUUM* DGDC-2480 NT Bimodal Polyethylene Resin is produced using UNIPOL™ II process technology. This product may be utilized for pipe applications where long-term hydrostatic strength combined with outstanding resistance to slow crack growth and rapid crack propagation are desired. Suitable applications include natural gas distribution pipes, industrial piping, mining, sewage, and municipal water service lines.

| Physical Properties | Test Method | Values(3) English (SI) |
|---|---|---|
| **Resin Properties** | | |
| Melt Index ($I_2$) @190°C/2.16 kg, g/10 min | ASTM D 1238 | 0.08 |
| Flow Rate ($I_{21}$) @190°C/21.60 kg, g/10 min | ASTM D 1238 | 8.5 |
| Density (natural resin), g/cc | ASTM D 792 | 0.949 |
| Density(2), g/cc | ASTM D 792 | 0.959 |
| Thermal Stability, °F (°C) | ASTM D 3350 | >428 (>220) |
| **Mechanical Properties(4)** | | |
| Tensile Strength at Yield, psi (MPa) | ASTM D 638 | 3600 (24.8) |
| Elongation at Break, % | ASTM D 638 | 740 |
| Flexural Modulus, psi (MPa) | ASTM D 790, method 1, procedure B | 150,000 (1034) |
| Notched Izod Impact @ 23°C, ft·lbf/in. (J/m) | ASTM D 256, method A | 9.1 (488) |
| Brittleness Temperature, °F (°C) | ASTM D 746, procedure A | <-103 (<-75) |
| Slow Crack Growth PENT, hours | ASTM F 1473 | >4000 |
| **Pipe Properties(2)** | | |
| Resistance to Rapid Crack Propagation(5), Pc, psi (bar) | ISO 13477 | >174 (>12) |
| Resistance to Rapid Crack Propagation(5), Tc, °F (°C) | ISO 13477 | <2 (<-17) |

**Fabrication Conditions:**
- Screw Type: High quality HDPE (preferably barrier for complete melting)
- Melt Temperature Range: 380-440°F (193-225°C)

*Trademark of The Dow Chemical Company

†Dow Plastics, a business group of The Dow Chemical Company and its subsidiaries.

Form No 305-02867-0304X

**Figure 12 – Typical specification sheet for HDPE Resin Used for Piping [Courtesy Dow Chemical Company]**

For more information and technical assistance contact:

Performance Pipe, a division of
Chevron Phillips Chemical Company LP
P.O. Box 269006
Plano, TX 75026-9006
800.527.0662

DRISCOPLEX®

**Driscopipe® 8100 Series**
**PE 3408/PE4710 - PE100**
**Technical Data Sheet**
**Gas Pipe and Fittings**

**MEETS ASTM D2513 GAS STANDARD FOR GAS PRESSURE PIPE, TUBING AND FITTINGS**
**Typical Material Physical Properties of Driscopipe® 8100 Series**
**PE3408/4710-PE100 Polyethylene Materials**

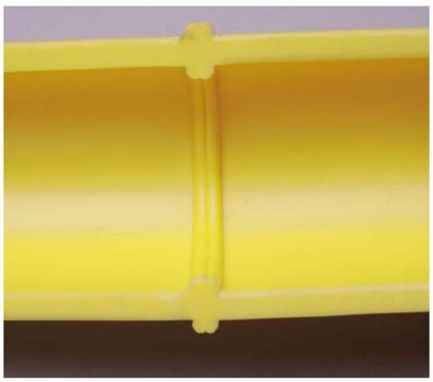
| Property | Unit | Test Procedure | Typical Value |
|---|---|---|---|
| PPI Listing Designations(1) | -- | PPI TR4 | PE 3408(2)<br>PE 4710(2)<br>PE 100 |
| Cell Classification | --- | ASTM D-3350-05 | 445576C(3) |
| Density | g/cm$^3$ | ASTM D-1505 | 0.961 (black) |
| Melt Flow, MI (2.16 Kg/190°C) | g/10 mins | ASTM D-1238 | 0.11 |
| Melt Flow, MI (21.6 Kg/190°C) | g/10 mins | ASTM D 1238 | 8.00 |
| Thermal Expansion/Contraction | in/in/°F | ASTM D 696 | $1 \times 10^{-4}$ |
| Flexural Modulus | psi | ASTM D-790 | 140,000 |
| Tensile Strength @ Yield | psi | ASTM D-638 | >3,700 |
| Slow Crack Growth (PENT) | hours | ASTM F-1473 | >5,000 |
| Color; UV Stabilizer | --- | ASTM D-3350 | Yellow shell UV stabilized for up to 4 years unprotected outdoor storage. |
| Color; UV Stabilizer | % | ASTM D-3350 | >2 on base pipe. |
| Elastic Modulus | psi | ASTM D-638 | 200,000 |
| Brittleness Temperature | °F (°C) | ASTM D-746 | < -180 (< -118) |
| Vicat Softening Temperature | °F | ASTM D-1525 | 255 |
| Hardness | Shore D | ASTM D-2240 | 65 |
| Hydrostatic Design Basis @ 73°F (23°C) | psi | ASTM D 2837 | 1,600 |
| Hydrostatic Design Basis @ 140°F (60°C) | psi | ASTM D 2837 | 1,000 |
| Minimum Required Strength (MRS) @ 20°C (68°F) | Mpa (psi) | ISO 9080 | >10 (>145) |
| Rapid Crack Propagation (RCP)<br>Critical Pressure (Pc), 0° C(4)<br>Critical Temperature (Tc), 5bar(5) | bar (psi)<br>0°C (°F) | ISO 13478<br>ISO 13477 | >30 bar (>435 psi)<br><-24°C (<-11°F) |

**Figure 13 – Typical data sheet for HDPE piping [Courtesy Performance Pipe]**

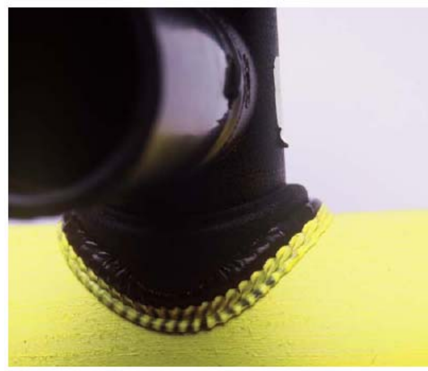
## 4.2 HDPE Pipe Assembly and Joining

The Plastic Pipe Institute (PPI) has developed an industry consensus procedure for assembly and joining of HDPE piping [Ref. 14]. Several joining methods are used for HDPE piping including butt fusion, saddle fusion, socket fusion, and electrofusion in addition to mechanical joining via flanges. Also recommended procedures for flange mechanical connections between metal and HDPE piping have been developed. Photographs of each type of fusion joint are shown in Figures 14a through Figure 14d [Ref. 40]. Figure 15 shows a photograph of a typical flange connection between HDPE and steel piping used by Duke Energy in a non-safety related application.

Of the various joining methods, butt fusion joining of PE pipe using a hot plate to melt the material and fuse it together is by far the most common practice in the US.  Several equipment manufacturers make butt-fusion equipment including those that have an automated data logger that records the temperature and pressure history used to make each joint.  The data logger records may be compared with the recommended conditions for joining to determine if the optimal conditions were used or not.  The data logger also serves as a quality control tool, i.e., if a joint procedure did not meet the recommended conditions, the joint is cut out of the pipe and then is re-made.  For coiled piping in addition to the temperature and pressure history the drag force on the pipe must be monitored during the fusing process so as to avoid misalignment of the joint leading to inadequate fusing (cold joint) and failure in gas piping [Ref. 28].



(a) Butt fusion



(b) Saddle fusion

(c) Socket fusion

(d) Electro-fusion

**Figure 14  Photographs of HDPE pipe fusion joints**

**Figure 15 Flanged connection from HDPE to steel piping [Courtesy: Duke Energy]**

## 5. NDE INSPECTION

The Plastic Pipe Institute (PPI) Handbook has provided extensive recommendations on Inspection and Testing of Plastic Pipe [Ref. 13, 14]. These recommendations include special procedures for "Handling and Storage" of pipe including:

- Receiving Inspection of PE pipe
  - Product packaging
  - Checking order
  - Load inspection
  - Receiving report & reporting damage
- Unloading instructions
  - Unloading site requirements
  - Handling equipment for unloading pipe
  - Unloading large fabrications, manhole and tanks
- Pre-installation storage including pipe stacking heights
- Exposure to UV and weather
- Cold weather handling

The primary NDE method for the inspection of HDPE piping joints is visual. Under the sponsorship of the Gas Research Institute extensive research was conducted in the 1980s to use ultrasonic techniques to detect flaws in butt joints. Equipment to inspect small diameter gas piping was also developed and commercialized by McElroy (a leading manufacturer of butt fusion joining equipment) in Tulsa, OK. However, the gas industry did not adopt this volumetric inspection method and the manufacturer discontinued this product. The visual examination of the bead-size, shape, and roll-over characteristics coupled with the joining parameters as recorded in the data-logger have been considered adequate to detect cold joints in PE piping. PPI [Ref. 13 and 14] also recommends visual examination as the primary inspection method for joints. Hydrostatic testing to detect leaks is also recommended as part of the installation protocol in CC N-755.

The visual inspection involves the need to train operators to recognize the size, shape and roll-over of the bead that develops during butt-joining of pipes. In addition as described above, the data logger on a butt-fusion machine is used also for comparison to recommended conditions to determine the quality of the joints. The industry considers that these two methods provide adequate data to insure the quality of the joint.

Several non-destructive testing methodologies have been developed over the decades for the inspection of butt fusion joints (which is the most commonly used fusing process). These include Microwave Inspection (Evisive), Ultrasonic Phase Array, Ultrasonic Time of Flight Diffraction, and Radiography as described in the presentation by Duke Energy to the NRC, see Appendix D. Of these only the ultrasonic technique (UT) is currently available commercially for pipes smaller than 12-inches (304.8 mm) in diameter. Commercial equipment is available in the US, Europe and Asia, though it is not used for gas piping. Therefore volumetric inspection capability of HDPE pipe butt joints especially in larger diameters have yet to be fully developed and evaluated for commercial use.

There are research and development effort occurring to develop volumetric inspection equipment for PE piping. The EPRI NDE Center has recently conducted a study on assessing the effectiveness of NDE techniques for PE piping. The report is entitled; “Technical Support for Proposed Polyethylene Pipe Code Case” that is EPRI report number 1011628 that was published in December 2005. This report is on the ASME Code website as a public document and provides the technical assessment conducted of their completed study on evaluating all of the technologies mentioned above. This report has not yet been obtained and reviewed but will be. In discussions with the EPRI program manager, Jack Spanner, RT was found to be ineffective and will not be pursued. Success was reported for some of the other techniques but the report needs to be obtained and reviewed before more can be stated about these other NDE techniques.

The Edison Welding Institute on a NETL program developed a laser technique that detected flaws based on thermography and was claimed to be effective for cold fusion welds. Information on this work can be found on the Edison Welding Institute website. A limitation with this approach is that it requires removing the fusion bead and “polishing” the surface in order to have adequate sensitivity for the very small and subtle changes with small flaws.

It has been learned that Rochester Gas and Electric is currently conducting a very large study on assessing the effectiveness of NDE for PE piping. More will need to be learned about this study and the schedule that is being pursued. It should be noted that EPRI is not part of the study.

Recently [Ref.45] the use of UT for determining joint quality for electrofusion joints has been developed and demonstrated to work successfully in detecting flaws and other imperfections.

# 6. HDPE PIPING IN NUCLEAR APPLICATIONS

## 6.1 Non-Safety Nuclear Piping

Duke Energy has used HDPE piping for water application in Nuclear Power Plants in non-safety related applications for approximately 10 years. These involved 6-inch and 8-inch (152 to 203 mm) DR 11 piping that has operated successfully without any corrosion of fouling problems. A presentation was made by Duke to the US NRC in June 2005 that covers their experience to date. For completeness a copy of this presentation has been provided in Appendix D. Duke Energy has also extended an invitation to the NRC and its contractors to visit the Catawba site and view the HDPE piping that have been installed to date and review their service experience and history with this material.

## 6.2 Safety-Related Nuclear Piping

The only known safety-related application of HDPE piping in nuclear power plant is in the UK. In 2005 Sizewell B installed 150 meters (492 feet) of HDPE pipe, some of it 600 millimeters (23.6 inches) in diameter and up to 30 mm thick (1.18 inches) [Ref. 46]. While temperature and pressure conditions for operation of this pipe were not available a photograph of this application at British Energy is shown in Figure 16. We have requested further information from British Energy regarding this application.

Duke Energy has indicated that their initial relief request for the use of HDPE Pipe in Class 3 application would involve a 12-inch diameter (302 mm), DR 11 (Dimension Ratio = Outer Diameter/ Minimum Wall thickness) pipe for use at 110 psi (0.758 MPa) and up to 100 °F (37.8 °C) for underground (buried) applications at their Catawba Plant on the suction side of the service water line.

However, the CC N-755 currently covers temperatures up to 140 °F (60 °C) and pressures up to 150 psi (1.034 MPa) for a projected 50-year service life. The NRC’s comments on this Code Case, which forms the basis of their negative vote (at the August 2006 ASME Section III/XI Meeting) are provided in Appendix E. The response of the industry to NRC’s comments is also included in Appendix E.

**Figure 16 – HDPE pipe (black) installed at Sizewell B by British Energy**

## 6.3 Additional Issues and Failure Modes

The EPRI Study [Ref. 40] that was undertaken in developing a basis for Code Case N-755 apparently considered the following failure modes:

- Viscoelastic (stress-rupture) failure of the pipe wall,
- Exceeding axial bending strain limits from earthquake deflections, ground and building settlement, etc.,
- Through-wall ring bending strains,
- Unconstrained buckling in the ring mode (ovalization) caused by compressive overpressure,
- Constrained buckling in the ring mode (ovalization) caused by compressive overpressure,
- Lateral buckling of the pipe from axial loads,
- Axial buckling by warping,
- Crushing of the sidewalls from compressive hoop stresses,
- Bending fatigue from seismic and other bending loads,
- Buoyancy effects on buckling, pipe bending, and trench breakout, etc.,
- Failure of mechanical joints (if any).

*Additional Technical Issues:* Based on the literature reviewed to date, the following additional information is being compiled to address various issues and other possible failure modes and design limitations regarding safety-related Class 3 applications of HDPE piping in nuclear power plants:

- Experimental data on the Hydrostatic Design Basis (HDB) for PE 4710 materials (Minimum Cell Classification 445474C) at 140 °F (60 °C),
- Experimental data on Slow Crack Growth in PE 4710 type materials to substantiate a 50-year service life at 140 °F (60 °C),

- Experimental data on Rapid Crack Propagation design limits for PE 4710 materials including possibility of ring-off failure leading to a full bore opening and a double ended guillotine break,
- Creep data (stress-strain-time-temperature data) of PE 4710 materials at elevated temperatures (> 73 °F or 23 °C) and stress levels ( up to 1000 psi or 6.9 MPa),
- Fatigue loading data on PE 4710 materials,
- Experimental data in support of proposed stress indices in CC N-755,
- CC N-755 permits a flaw that is 10% of the wall thickness, the service life prediction of 50 years based on SCG data and permissible flaw size needs to be substantiated,
- Inspection, detection and evaluation of flaws in HDPE piping and joints and their effect on predicted service life,
- A determination of the critical flaw sizes as a function of the various degradation processes that need to be reliably detected for guiding the assessment of NDE methods,
- A more comprehensive assessment is needed of NDT inspection methods for the reliable detection and accurate characterization and sizing of flaws in PE piping butt joints and electrofusion joints,
- A full evaluation of potential degradation processes in PE piping and the types of flaws that are produced along with their NDE responses. Flaws are being simulated such as using thin aluminum disks to simulate cold fusion and these simulated flaws must be assessed regarding their NDE response for simulating the respective type of flaw condition,
- As these PE materials age, are there new degradation processes or flaw sizes that need to be detected or need to be insured were not created during joint manufacture?

*Significance of Failure Modes:* The significance of the various failure modes needs to be viewed from the purpose of the application of plastic pipe. For instance, in the natural gas industry, the occurrence of small stress-rupture cracks is very important for leakage of flammable natural gas in residential areas. For nuclear piping service water lines, some of the failure modes may not be as critical as for natural gas applications. For instance, extremely small water leaks (less than 0.01 gpm (0.038 lpm)) from a service water line is not important from the functionality of the line and environmental or safety considerations. A large break that causes full loss of the water supply line is very important. Hence some classification of failure modes by amount of leakage or flow loss might be important to create.

An example classification might be the following:

- Full flow loss – This is a cross-sectional break similar to double-ended-guillotine (DEGB) break for steel pipes. An example failure mechanism might be rapid crack propagation (RCP), where even though the pipe will rapidly depressurize so that extended axial breaks would not occur, the opening area could be large enough to completely disrupt fluid flow. Another failure mechanism might be a butt weld with a large amount of cold fusion that fails with axial loading.
- Limited but tolerable flow loss – this might correspond to an amount of flow loss that could still be tolerated in the safety-related service water piping system. Some countries use an opening area of 10-percent of the cross section for flow loss considerations. The magnitude of this opening area, is dependant on the service water line system demands,

and needs to be determined. Axial ductile rupture as per Figure 8a might correspond to such an opening area.

- Insignificant but annoying flow losses – this might correspond to failure mechanisms that give numerous small leaks of very small flow losses. These degradation mechanisms are not of structural significance when viewed individually. Figure 8b shows an example of an axial slit that formed during long-term hydrostatic loading at higher temperatures. The amount of fluid loss in this particular flaw (maybe not all slit failures), would be so insignificant that it would never be noticed. The only concern here is whether so many of these cracks might form that a critical size is reached for rapid crack propagation (RCP).

Such a classification would give guidance on how future research efforts should be prioritized by the NRC.

# 7. REFERENCES


1. Presentation by Duke Energy on the Use of PE Pipe in Non-Safety Related Service Water Piping at Catawba Nuclear Station, 2006. (See also Appendix D of this report).
2. ASME Code Case N-755 “Use of Polyethylene (PE) Plastic Pipe for Section III, Division 1, Construction and Section XI Repair/Replacement Activities”, Revision 6a, September 12, 2006. (See Appendix A in this report).
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