

Bimodal PE's Contribution to the Life Expectancy Extension of Gas Distribution Pipelines

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Abstract

Material selection plays a critical role in the integrity of gas distribution pipelines. This paper examines the concept of robustness in gas distribution pipelines and how the selection of materials with high resistance to failure can increase pipeline integrity and extend the lifetime of a pipeline. The common failure modes in plastic piping systems in gas distribution related to material performance are examined and how bimodal MDPE and HDPE pipe materials address these failure modes is explored. Bimodal PE piping materials are seen to have very high levels of resistance to the primary exposures that lead to failure in PE gas piping systems, providing for high robustness in gas distribution pipelines.

Robustness in Gas Distribution Pipelines

Materials and components in a gas distribution pipeline play a critical role in the long-term safety and integrity of the pipeline. Through proper material selection, increased robustness can be engineered into a pipeline to improve long-term system integrity and reduce pipeline risk.

Risk in pipeline systems is commonly defined as the probability of failure (PofF) times the consequence of failure (CofF). Managing risk, therefore, involves trying to reduce the PofF, the CofF or both. For new pipeline installations, managing the PofF of the pipeline is a key focus in integrity activities.

One way of looking at the PofF is¹:

$$\text{PofF} = \text{exposure} \times (1 - \text{mitigation}) \times (1 - \text{resistance}) \quad (1)$$

where:

- *exposure* is an event which, in the absence of any mitigation, can result in failure if insufficient resistance exists
- *mitigation* is the effectiveness of all activities designed to stop the exposure
- *resistance* is an estimate of the ability of the component to absorb the exposure force without failure

Using vintage Aldyl piping materials as an example:

- exposure: rock impingement
- mitigation: installation practices to prevent rocks in the installation
- resistance: the ability of the Aldyl piping to absorb the rock impingement without failure

¹ K. Muhlbauer, Pipeline Risk Assessment: The Definitive Approach and Its Role in Risk Management, Clarion, 2015

As has been observed in the industry, Aldyl LDIW (Low Ductile Inner Wall) piping has much lower resistance to rock impingement than non-LDIW pipe; hence, LDIW pipe has shorter lifetimes and higher failure rates due to rock impingement².

In a very general sense, for a given time period, the reliability of a pipeline can be considered as:

$$\text{Reliability} = 1 - \text{PofF} \quad (2)$$

The resistance of the materials being installed in a pipeline, to all potential exposures, is a key factor in the PofF for the pipeline and, hence, the reliability of the pipeline. As the resistance of the material to a given exposure reaches 100%, the PofF drops to zero and the reliability goes to 100%—the target goal of all new pipeline installations. One key way of increasing the robustness and integrity of a pipeline is to increase the resistance of the pipeline materials to the exposures they will face throughout their lifetimes. The robustness of a pipeline and its ability to deal with non-standard conditions is improved as the resistance of pipeline materials is increased beyond the base level needed for performance under standard conditions; the greater the improvement in the resistance, the greater the robustness of a pipeline.

Potential Exposures for PE Gas Distribution Piping

In looking at the overall PofF for a pipeline, all potential exposures and the associated mitigations and resistances need to be considered. Though PE piping materials have proven to be very reliable—one of the key reasons they have come to dominate in gas distribution—field failures do occur, even in newly installed pipelines. For PE gas distribution pipelines, the types of exposures leading to potential failure have been assessed by the authors through historical performance data and fault tree analysis³. The primary potential failure modes impacted by material resistance and the key material parameters that resist these failure modes are summarized below.

Manufacturing Defects

Pipe wall defects, contamination and other manufacturing flaws can result in stress concentrations within a pipe and/or a decrease in the effective wall thickness of a pipeline. Resistance to such defects is primarily driven by the Slow Crack Growth (SCG) resistance and base material strength of the PE resin.

External Loads

External loading on the pipeline, such as rock impingement, bending stresses and deflection, increases the overall stress, and hence exposure, beyond that generated by the internal pressure in the pipe. This is one of the most common failure modes for vintage PE piping materials⁴. Resistance to these external loads is driven by the slow crack growth resistance (SCG) of the PE resin.

Installation and Operational Damage

Damage to the pipeline during handling and installation can introduce scratches and gouges on the pipe which can act as stress concentration points and reduce the load-carrying

² K. Oliphant et al., *A Risk Based Approach to Prioritizing Aldyl Piping Replacements in Gas Distribution System*, PP XVII, Chicago, October 2014.

³ JANA Gas Distribution Fault Tree Database, proprietary

⁴ PLASTIC PIPING DATA COLLECTION INITIATIVE STATUS REPORT, December 2014

capability of the pipeline. Operational activities, such as squeeze-off, can also introduce damage into the pipeline. Resistance to this damage is driven primarily by the slow crack growth resistance (SCG) of the PE resin and the pressure strength of the resin.

Rapid Crack Propagation (RCP)

For all situations in which a crack or defects exists in the pipe, the pipe material's resistance to Rapid Crack Propagation (RCP), a rare but catastrophic failure event, is also an important factor.

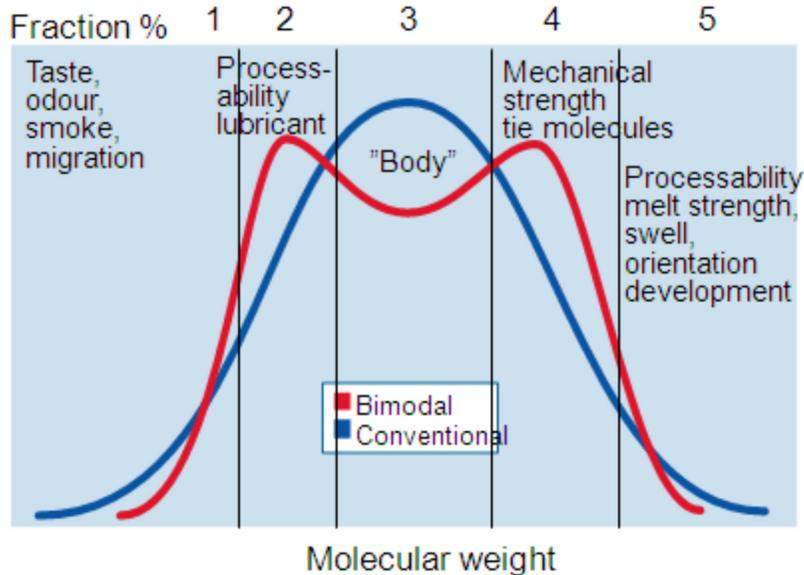
The ideal situation is to ensure that these potential exposures do not come to bear on the pipe through the application of effective mitigations. However, as has been observed in the field, mitigations are not 100% effective, and manufacturing defects, external loads and installation do occur. Materials with increased resistance to these exposures will have increased robustness, providing an additional layer of protection to a pipeline. Based on the primary failure modes, key parameters that can provide increased robustness of a pipeline include: SCG resistance, RCP resistance and resistance to defects and external damage.

Bimodal MDPE and HDPE Gas Piping Materials

In North America, polyethylene pipe has been used in natural gas distribution since the 1960s and has come to dominate this application due to its many advantages. Polyethylene pipe is flexible, corrosion free, chemically resistant, tough and light weight. Since its introduction, there has been significant evolution in the properties of PE piping materials. The first unimodal PE pipe materials were significantly improved upon through controlling the molecular structure, and subsequent unimodal materials have much higher performance properties. In the early 2000s, the first bimodal polyethylene pipe resins, made from a gas phase dual reactor process, were commercialized. These resins, known as “bimodal” resins, have performance properties that far exceed the previous generations of PE gas piping resins, resulting in a step change in the evolution of PE gas pipe performance.

“Bimodal” refers to the shape of the data curve that plots the molecular weight distribution of the polymer. Figure 1 provides a comparison of unimodal and bimodal molecular weight distribution, showing the characteristic single peak (unimodal) and dual peaks (bimodal). The bimodal process uses two reactors, which enables the resin manufacturer to custom engineer the molecule for optimum performance. Various resin properties are controlled by placement of short chain molecules across a controlled distribution of molecular weights.

Figure 1: Comparison of Bimodal and Unimodal PE Molecular Weight Distributions



This paper examines the impact of bimodal resins on pipeline robustness based on analysis of the properties of Dow Chemical’s CONTINUUM™ DGDA-2490 HDPE (PE4710 & PE100) and DGDA-2420 MDPE (PE2708 & PE80) Bimodal Polyethylene Resins, produced using UNIPOL™ II Gas Phase Process Technology.

Resistance of Bimodal MDPE and HDPE Gas Piping Materials

The unique performance properties of bimodal MDPE and HDPE resins is seen to result in high resistance to the potential failure modes for PE gas distribution pipelines, resulting in a high level of pipeline reliability.

As discussed, the key material parameters that can provide for increased robustness of a pipeline include:

- SCG Resistance
- RCP Resistance
- Resistance to defects and external damage

Slow Crack Growth Resistance (SCG)

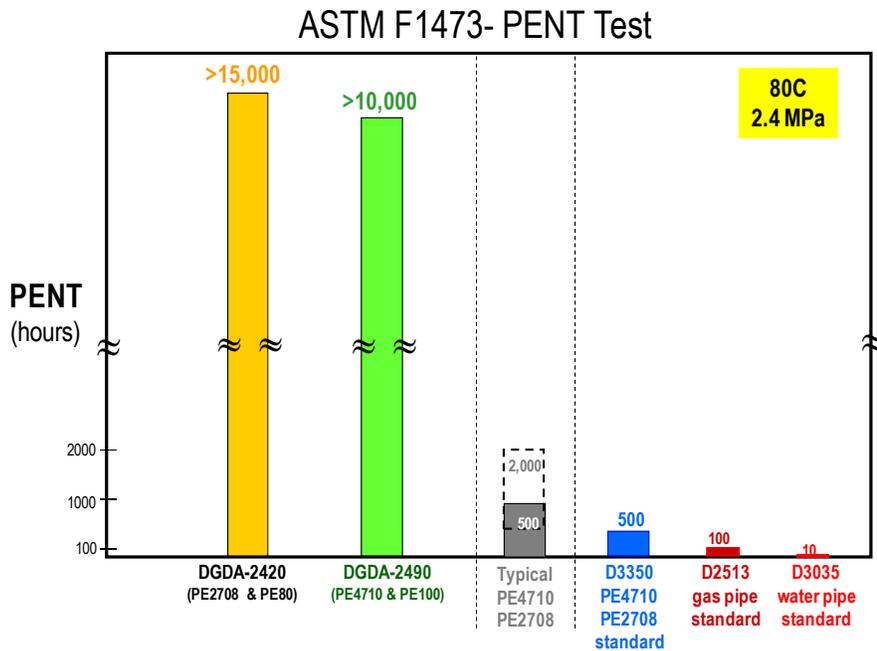
Slow crack growth (SCG) is a failure mechanism involving crack initiation at a stress concentration point (defect, scratch or gouge, external loading, etc.) and then propagation of that crack in a stepwise fashion through the wall of the pipe to result in ultimate failure. In this study, SCG resistance was assessed using PENT testing and elevated temperature sustained pressure testing.

PENT Testing

The PENT test involves testing of molded specimens with a specific notch geometry, which provides a stress concentration point, at elevated temperature under load to accelerate the

slow crack growth mechanism. For reference, the PENT values for early generation Aldyl piping materials are on the order of several hours. Figure 2 provides a comparison of the typical SCG resistance of bimodal MDPE and HDPE materials based on the ASTM F1473 PENT test.

Figure 2: PENT Performance of MDPE and HDPE Pipe Materials



The exceptionally high PENT values (greater than 10,000 hours) indicate a very high level of slow crack growth resistance. As per Equation 1:

$$PofF = \text{exposure} \times (1 - \text{mitigation}) \times (1 - \text{resistance}) \quad (1)$$

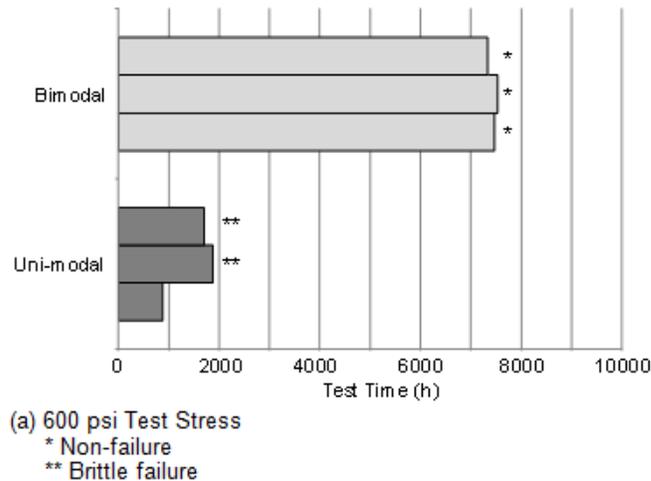
This high level of resistance provides for high robustness of the pipeline and resistance to failure due to exposures such as external loading, installation damage, manufacturing defects, etc.

Sustained Pressure Testing

Sustained pressure testing at elevated temperatures also provides a measure of the SCG resistance of PE piping materials. Three pipe specimens of each material were tested at a constant stress at elevated temperatures. Figure 3 provides a comparison of SCG resistance of bimodal and unimodal PE2708 (MDPE). The SCG resistance of the bimodal MDPE at these test conditions is over three and a half times that of the unimodal PE⁵. Again, per Equation 1, this increased resistance leads to higher resistance to failure against any exposures that could lead to SCG type failures and, hence, higher robustness in the pipeline.

⁵ JANA-Polypipe Report 11-3880, "Performance Comparison of Bimodal and Unimodal PE Gas Pipe with Simulated External Damage"

Figure 3: 90°C Sustained Pressure Testing of Bimodal and Unimodal Pipe Materials



Rapid Crack Propagation (RCP)

Rapid Crack Propagation (RCP) refers to a rare but significant catastrophic pipe failure mode that results in a rapidly progressing crack (typically >300 ft/sec) when a pressurized pipeline is subjected to a sudden or intense impact or pressure surge. RCP can also be the result of a pre-existing flaw or crack in the pipe. RCP can occur in most piping materials, including steel and PVC pipes. RCP is generally of greater concern in piping systems that are used to convey compressed gasses, as the rapid energy dissipation from a compressed gas provides the energy required to sustain crack growth.

RCP is dependent on service temperature, internal operating pressure, pipe size/wall thickness and the pipe material properties (i.e. resistance to RCP).

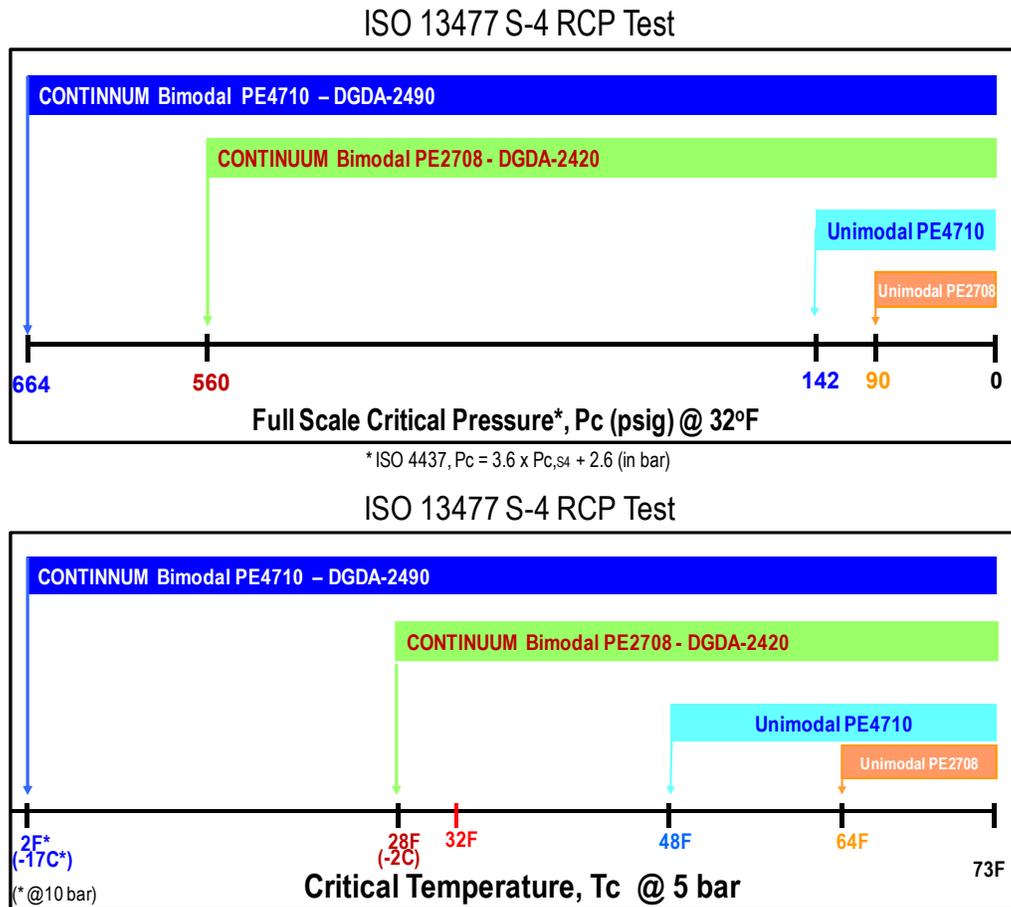
- As service temperature decreases, the potential for RCP increases.
- As internal pressure increases, the potential for RCP increases.
- As pipe diameter and wall thickness increase, the potential for RCP increases.

An RCP event is possible if:

- The pipeline system is operating below the critical temperature, or
- The pipeline system is operating or being pressure tested above the critical pressure.

Figure 4 provides a comparison of the RCP resistance for bimodal PE pipe materials and the typical performance for unimodal pipe materials, in terms of both Critical Pressure (Pc) and Critical Temperature (Tc). The high resistance of bimodal PE is again seen to provide robustness in the pipeline for these types of exposures.

Figure 4: RCP Performance of Bimodal and Unimodal PE Pipe Materials



Resistance to Defects and External Damage

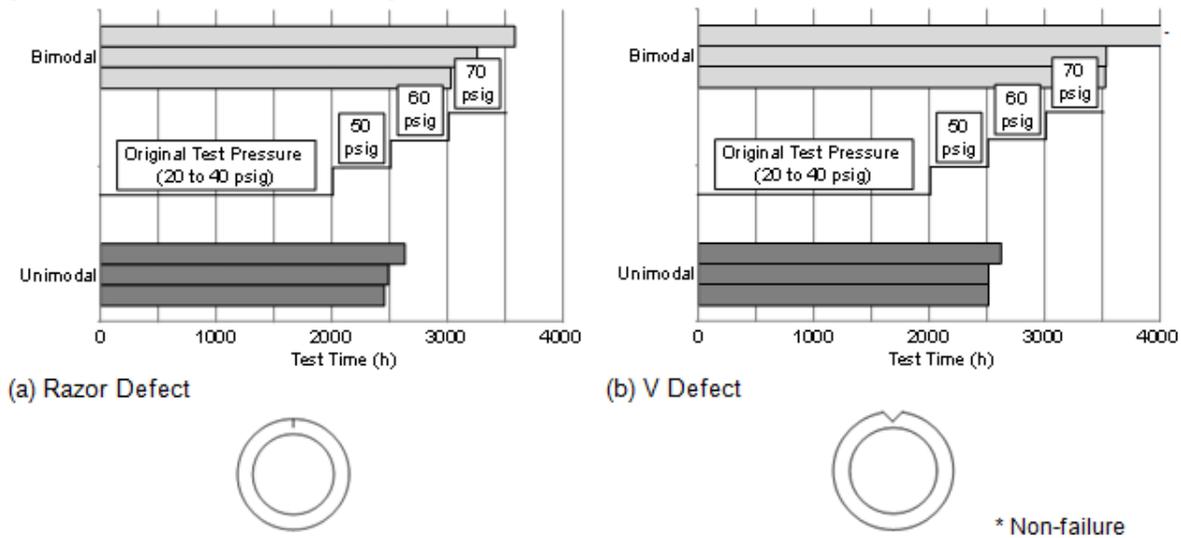
Resistance to defects and external damage is a function of slow crack growth and the base material strength. To assess the performance of bimodal resin for these factors, sustained pressure testing of pipe with simulated defects was conducted. The bimodal PE resins are seen to have a high level of resistance.

Figure 5 provides a comparison of sustained pressure testing results of bimodal and unimodal MDPE with simulated defects in the pipe⁶. Testing was conducted using specimens with both a razor defect (to simulate a sharp gouge in the pipe) and a V defect (to simulate a large gouge or manufacturing defect). The original test pressure was 20 to 40 psig. After 2,000 hours of testing, the pressure of the specimens was increased 10 psig every five hundred hours until 70 psig was reached. Specimens were tested until failure (or termination of the test). For the razor defect, the failure time ranged from 3,033 (70 psig) to 3,584 (70 psig) for bimodal and 2,492 (50 psig) to 2,648 (60 psig) for unimodal,

⁶ JANA-Polypipe Report 11-3880, "Performance Comparison of Bimodal and Unimodal PE Gas Pipe with Simulated External Damage"

and for the V defect, from 3,524 (70 psig) to 5,897 (non-failure at 70 psig) for bimodal and 2,516 (60 psig) to 2,623 (60 psig) for unimodal. The high resistance of the bimodal MDPE is again seen to provide increased robustness in the pipeline in relation to these types of exposures.

Figure 5: Sustained Pressure Testing of Bimodal and Unimodal MDPE Pipe Materials with Simulated Defects



Overall, the Dow Chemical CONTINUUM™ DGDA-2490 HDPE (PE4710 & PE100) and DGDA-2420 MDPE (PE2708 & PE80) Bimodal Polyethylene Resins examined are seen to have high levels of resistance to SCG, RCP, defects and external damage and exhibit high strength fusion joints. The high material resistance increases the reliability of the pipeline for the key identified pipeline exposures, providing an additional layer of protection for the pipeline.

Higher Robustness Pipelines – Bimodal MDPE and HDPE Pipe

For new pipeline installations, the resistance of the materials installed to the primary exposures that lead to failure is a key factor in determining the future reliability of the pipeline. As the resistance of a material to exposure to a given threat is increased, the probability of failure (PofF) decreases. The robustness of a pipeline and its ability to deal with non-standard conditions is improved as the resistance of pipeline materials is increased beyond the base level needed for performance under standard conditions; the greater the improvement in the resistance, the greater the robustness of a pipeline. As demonstrated in this paper, bimodal PE piping materials have very high levels of resistance to the primary exposures that lead to failure in PE gas piping systems, providing for high robustness gas distribution pipelines.