USING RCP DATA TO DESIGN POLYETHYLENE GAS DISTRIBUTION SYSTEMS IN THE UNITED STATES

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ABSTRACT:

Historically, polyethylene (PE) gas pipe systems in the United States have operated at service conditions for which the likelihood of a failure due to a rapid crack propagation (RCP) event has been nearly non-existent. The exceptional safety record for PE piping systems in this critical application has resulted in a more wide-spread use of these piping products and utilization of larger diameters and heavier walled pipe has become more prevalent. As the US gas distribution industry expands the use of PE piping systems, the need to understand and utilize responsible engineering design to minimize the potential for failure due to RCP has become more apparent.

The discussion provides a very basic review of the nature of RCP, how it is measured using industry-accepted standardized test methods, and what it means in relationship to the design and use of polyethylene gas pipe. Two key properties, the critical temperature and the critical pressure, and their relationship to the potential for an RCP occurrence are reviewed as well as the various parameters that influence this relationship.

From there, suggested design guidelines established by the US gas distribution industry to assist the designer, installer and operator in the safe and responsible use of tough, durable polyethylene gas distribution systems are reviewed. This paper then reviews the series of initiatives that have been undertaken within the United States to incorporate the use of RCP data in the responsible design of PE gas distribution piping systems. The discussion concludes with an understanding that to minimize the potential for an RCP occurrence the critical temperature should be lower than the system operating temperature, and the critical pressure should be greater than the system leak test pressure.

INTRODUCTION:

Polyethylene pipe's durability and toughness combined with its light weight, flexibility and corrosion resistance have resulted in sustained expansion in the use of these materials in gas distribution applications in the United States (US). The success of polyethylene pipe from both a safety and operational perspective in these applications has been well-documented. (1,2) As these products have advanced even further, the US gas distribution industry has witnessed an increase in the sizes used and in the maximum allowable operating pressure for these products as provided under Title 49 Code of Federal Regulation (CFR). (3)

As the use of these products continues to grow, it is only reasonable that the engineering properties of polyethylene pipe be more fully explored to ensure that this record of success is maintained. One polyethylene pipe property that has been the subject of considerable research is polyethylene's resistance to rapid crack propagation (RCP). While this property is not necessarily new to researchers and designers of PE piping systems, only recently has it become of more interest to the US gas distribution industry as the permissible operating pressure has been raised. In fact, extensive research has been undertaken to characterize the nature of RCP, PE pipe's resistance to its occurrence, and the service conditions that mitigate the likelihood of occurrence. In the paragraphs that follow, we will address three specific aspects of RCP as it relates to the use of PE pipe in gas distribution systems. These are:

- What is RCP?
- How are RCP properties determined?
- How is RCP data used in gas distribution systems design?

In this way, the designer, installer or operator may effectively consider this performance aspect as the use of PE pipes in natural gas distribution continues to expand.

WHAT IS RCP?

Rapid Crack Propagation, or RCP, refers to a rapidly progressing crack (typically >300 ft/sec) that results when a pressurized PE pipe is subjected to an instantaneous and intense impact or a pre-existing or consequently initiated crack or flaw. A rapid crack is said to have propagated if the crack length equals or exceeds 4.7 times the nominal outside diameter of the pipe when measured in the axial direction as defined in ISO 13477 or exceeds 90% of the test specimen length as defined in ISO 13478.

It should be noted that most materials can experience rapid crack propagation (RCP) and there have been documented instances of rapid crack propagation occurring in steel pipe, aluminum, PVC and even copper pipe or tubing. (4) As a result, the need to consider RCP as a function of material type and service conditions is not limited to PE pipe systems alone. In addition, the incidence of RCP in PE pipe is more generally of concern in those applications involving compressed gases where the compressed gas provides energy of sufficient magnitude to drive the crack forward. PE pipe used in the conveyance of liquids is much less likely to demonstrate RCP as the pressurized liquid provides a means for rapid dissipation of the energy required to sustain crack growth.

RCP occurrence in PE pipes is noted to be rare. However, its consequences can be very significant. Design practices, applications standards and installation guidelines are in place throughout the US gas distribution and North American PE pipe industry to minimize the potential for failure due to RCP. However, as the service range for PE pipe continues to broaden, responsible design practices warrant a more thorough understanding of RCP as it relates to gas distribution design.

Research has shown that the potential for RCP is a function of essentially four factors and the presence of an initiating event, such as a crack resulting from an impact, and a driving force such as the gas pressure. While a thorough discussion regarding each of these factors is clearly beyond the scope of this writing, some generalizations regarding RCP as it relates to PE gas distribution pipe can be derived from the extensive research that has been undertaken in their identification.

1) Service Temperature – The potential for RCP occurring in PE pipes increases as the service temperature decreases (5,6,7) The test methods to evaluate resistance to RCP can be used to establish a critical temperature, T_C, for a given PE pipe operating at specified pressures, above which the potential for failure via RCP is essentially non-existent. See Figure 1.

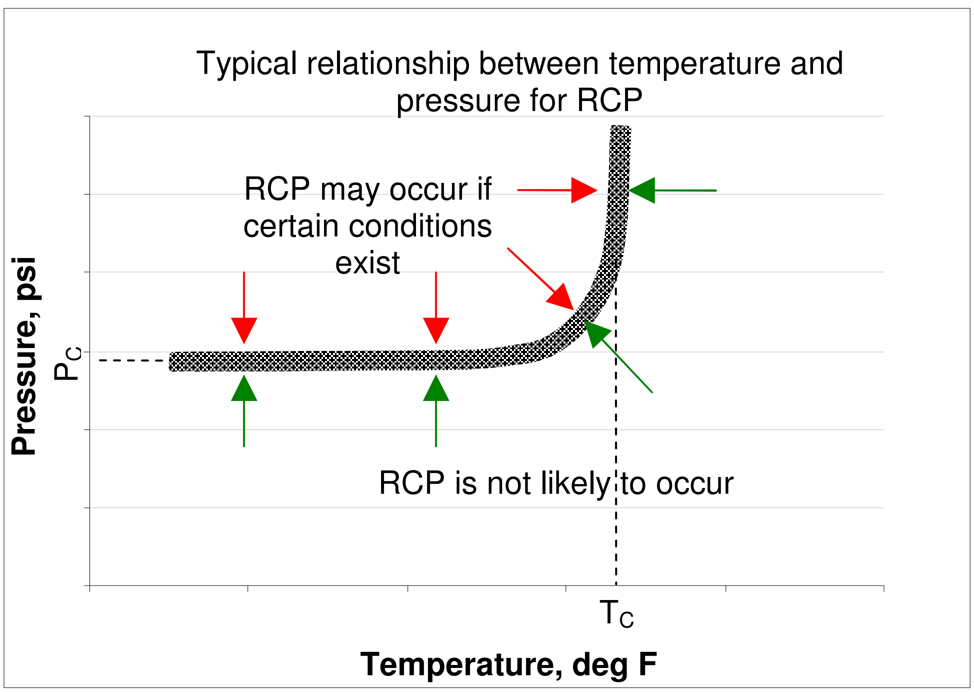

Figure 1: Critical Temperature, Tc and Critical Pressure, P_C

2) Internal Pressure – Additional research has revealed that RCP is also a function of the internal pressure in the pipe, which induces stress on the piping profile in the form of contained energy (8). The higher imposed stress on the PE pipe at the time of the initiating event creates a higher the potential for RCP occurrence. At any given temperature there exists a correlating critical pressure, P_C, for a specific pipe

produced from a particular PE compound, above which RCP may occur and below which the potential for RCP failure is significantly mitigated.

3) The geometry (OD and wall thickness) of the pipe – The pipe geometry, such as diameter and wall thickness, also plays a role in the resistance of pipes to RCP. (9, 10) For a given pipe material operating at a specific service pressure, P_S, and service temperature, T_S, the potential for RCP failure increases as diameter and wall thickness increases. The greater influence of RCP at higher wall thicknesses within a specific SDR pipe series has become known as the thickness effect and has resulted in required testing within ISO 4437 at the maximum anticipated wall thickness for a given SDR. (14)[1]

4) Pipe material characteristics -- The ability of the pipe material to constrain or arrest the energy that drives the axially accelerating crack has been studied as well. Figure 2 depicts the differences in RCP properties discovered by Leevers, et al as reported in 1993. (10) Similarly, Krishnaswamy reported even more detail in his research on molecular morphology versus RCP properties for various PE formulations in 2006. (11) This research underscores the need to know the RCP properties for pipe produced from a particular pipe material formulation and its overall capacity to resist failure via RCP.

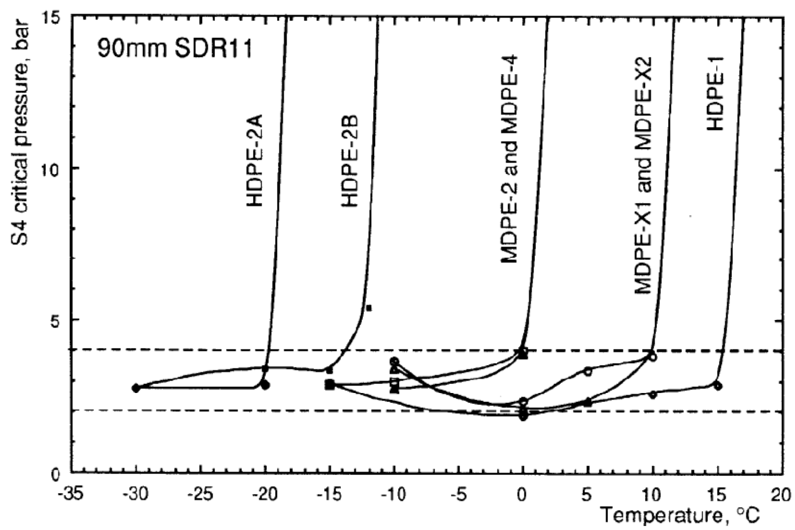

Figure 2: RCP Characteristics of Various PE Pipe Grades (10)

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1 Additional RCP testing could be conducted across a series of SDRs produced from the same PE pipe material formulation to generate a family of curves for a specific PE pipe formulation. To date, very little testing of this nature has been published so little can be inferred about the applicability of RCP resistance for one SDR of pipe to that of another SDR and/or diameter of pipe produced from the same material formulation. Some research has suggested that a correlation across various SDRs based on wall thickness has no clear applicability.(15) Further, some testing results have suggested that S4 testing for RCP of thinner walled pipes may be affected, to some degree, by flexing within the containment cage thereby affecting our understanding of any correlations produced using this methodology. These findings and other areas of interest are the subject of continued research within the industry.

It should be noted that the data presented in Figure 2 is original research presented by Leevers et al in 1993 and has not been converted from bars to psi or from degrees C to degrees F. See references. (10)

DETERMINING RCP PROPERTIES:

Internationally, the PE pipe industry has developed two test methods for assessing the resistance of a pipe to RCP. The two test methods are the Full-Scale test (FS test) conducted in accordance with ISO 13478, and the Small-Scale Steady State test (S4 test) conducted in accordance with ISO 13477. (12, 13)

The Full Scale test is conducted on a long length of pipe, approximately 60 ft and directly measures the critical pressure. The S4 test is conducted on a much smaller test specimen that has been constrained. In all cases, the full scale test method is the reference test method. However, where full scale test data are not known, an empirically derived equation can be used to correlate the results of the S4 test to the Full Scale test. Leis et al reported that the relationship between P_C and $P_{C\text{-}S4}$ varies to some degree depending on the specific material analyzed and concluded on the following as a conservative relationship for all polyethylene materials evaluated at that time. (4)

$$P_C = (3.6 \times P_{C\text{-}S4}) + 2.6 \qquad \text{(Eq. 1)}$$

Where P_C and $P_{C\text{-}S4}$ are in bars and 1 bar = 14.5psi

Recent research (16) has shown that the actual correlation between S4 test results and FS test results for certain current polyethylene materials may vary from Equation 1 based on specific material properties. However, Equation 1 is be used for PE pipes where the exact correlation is not known.

Both the Full Scale and the S4 test methods entail a series of tests in which the critical pressure at 0º C (32º F), is determined for a PE pipe of a particular PE material in accordance with the requirements of ASTM D2513. Alternatively, the pressure may be held constant, usually at 72.5 psi (5 bar), and the critical temperature, T_C, may be determined. Note that due to the configuration of the test apparatus, the S4 test has been shown to be unsuitable for and, in fact, unreliable for either critical temperature or critical pressure testing at S4 test pressures in excess of 72.5 psi (5 bar). This is due to an observed "cloche effect" that results in false arrests on the propagation side of the Pc –Tc curve. (17) Full scale testing can be used without a test pressure limitation to determine the critical temperature.

Where test results for all pipe sizes are not available, Lauder reported on the use of the Irwin-Corten equation to determine the critical pressure for a given PE material. (18) Figure 3 illustrates P_C test data obtained on an FS test apparatus such as that shown in

Figure 3 plotted against the Irwin-Corten equation projections. There is good agreement within a single DR family for this particular pipe material.[2]

The Irwin-Corten relationship is provided below:

$$P_C = [1/SDR] \times [8/(\pi \times OD)]^{0.5} \times K_D \qquad \text{(Eq. 2)}$$

Where: P_C = FS Critical Pressure in bars and 1 bar = 14.5 psi
SDR = OD/min wall
OD = Outside diameter in inches
K_D = Material specific constant

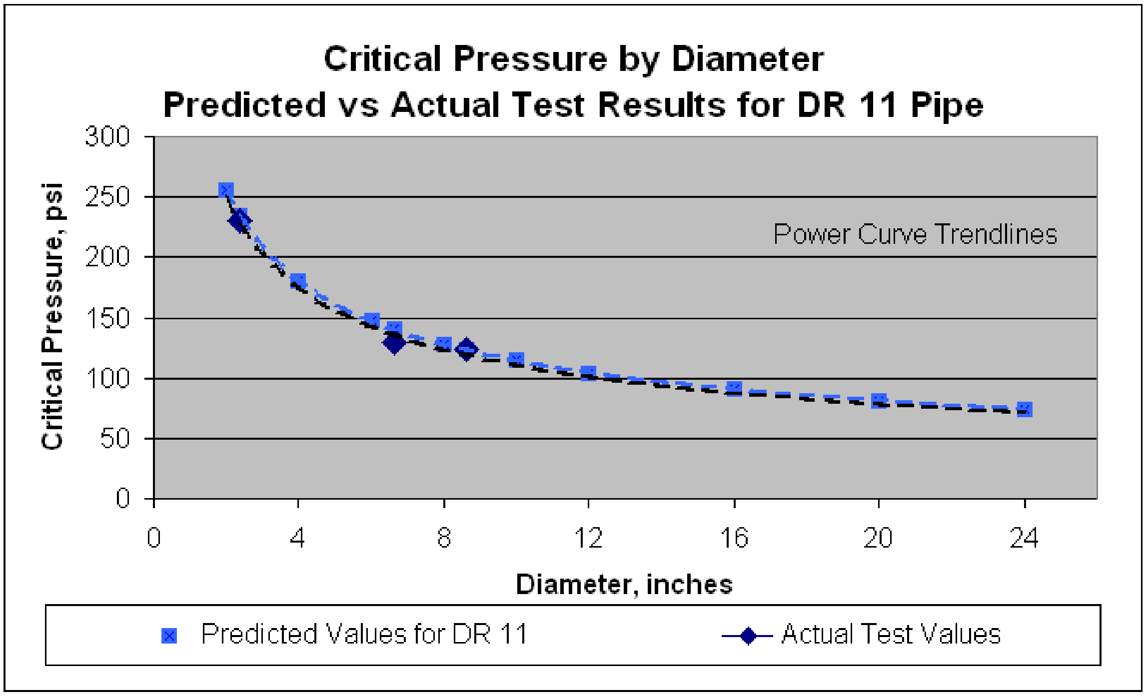

Figure 3: Critical Pressure by Diameter – Predicted versus Actual Test Values

DESIGN METHOD FOR USING RCP DATA

In consideration of the research findings on RCP, the factors influencing RCP phenomenon, and the approach demonstrated in the preceding section, a simplified method for incorporating RCP data in the design of gas distribution systems may be developed.

[2] Leevers et al (10) report that the Irwin-Corten equation significantly underestimates the critical pressures for lower wall thicknesses (higher DRs). B. Hauger and M. Lamborn published data in their 2005 AGA paper showing the Irwin-Corten relationship is not useful for exactly estimating the critical pressure between pipe of equal diameter but different DR ratios.   Care should be taken in applying the equation across different DR families.

Step 1 – Initial Assessment

Determine the critical temperature, T_C, for the pipe material using ISO 13477, the S4 test method. If the critical temperature is below the minimum temperature that the pipeline will experience during standardized leak testing then RCP is not likely to occur. While this approach is very straight forward, the determination of a relationship between the S4 and the Full Scale, or other reference test methods has not been established. Similarly the relationship of critical temperature, T_C, to pipe geometry has also not been fully established if the design method is limited to Step 1. Therefore the determination of critical temperature, while a useful tool for initial risk assessment, does not in and of itself provide specific design information. For that purpose, P_C is of greater engineering significance and should be established in accordance with the requirements of ASTM D2513.

Step 2 – Determine critical pressure.

Determine the critical pressure, P_C, for the maximum wall thickness of the pipe being designed using the full scale test method, ISO 13478 at the minimum temperature that will occur during testing or operation of the system. If full scale test method data are not available, determine the critical pressure using the S4 test method, ISO 13477, and determine the correlating full scale critical pressure, P_C, using Equation 1.

Step 3 – Evaluate the pipeline conditions

Review the pipeline operating and leak test conditions in relation to the critical pressure for the pipe sizes being considered to determine if there is a pressure or a size limitation for the material being evaluated. Examples of how the data and system operating parameters may be utilized follow.

Example 1:

Consider the following example that is based on a Material A. The information that we have for Material A is as follows:

Material A RCP Test Results on 8" DR 11 PE4710 pipe:

- Critical temperature, T_C = 25° F (-4° C)
- S4 Critical Pressure, $P_{C\text{-}S4}$ > 174 psi (> 12 bar)
- Correlated Full scale Critical pressure, P_C > 664 psi (> 45.8 bar)

Material A has excellent resistance to rapid crack propagation as evidenced by the low critical temperature and very high critical pressure (no failure seen at 174 psi S4 test pressure). For materials such as these with exceptional RCP characteristics, the potential for RCP occurrence is extremely low over the range of gas service applications defined in Title 49 CFR 192. None the less, consideration should still be given to the MAOP and MOP to be established for the system that is comprised of this particular material.

For examples 2 and 3, consider the test data presented in Figure 4 for Material B. Figure 4 is a representation of a pipe material where the critical temperature, Tc, is 64º F (18º C), which is significantly higher than the lowest operating temperature of the pipeline. Therefore, critical pressure needs to be considered.

Several points are noteworthy with respect to Figure 4. As one would expect, the maximum design pressure rating is constant at 80 psi in accordance with Title 49 CFR Part 192 because the SDR is constant across all diameters. However, the critical pressure to determine resistance to RCP, P_C, reduces the maximum test pressure (and hence the maximum operating pressure) as the diameter increases above 8 inch nominal diameter pipe.

<u>Example 2:</u>
For Material B as shown in Figure 4, a pipeline is leak tested at 120 psi thereby establishing an MAOP of 80 psi. Based on system component configuration, the LDC (local distribution company) establishes an operating pressure (or MOP) of 80 psi for this system. From Figure 4 we can conclude that the potential for RCP during leak testing does not become a design constraint for Material B until pipe sizes above nominal 8 inch diameter are considered.

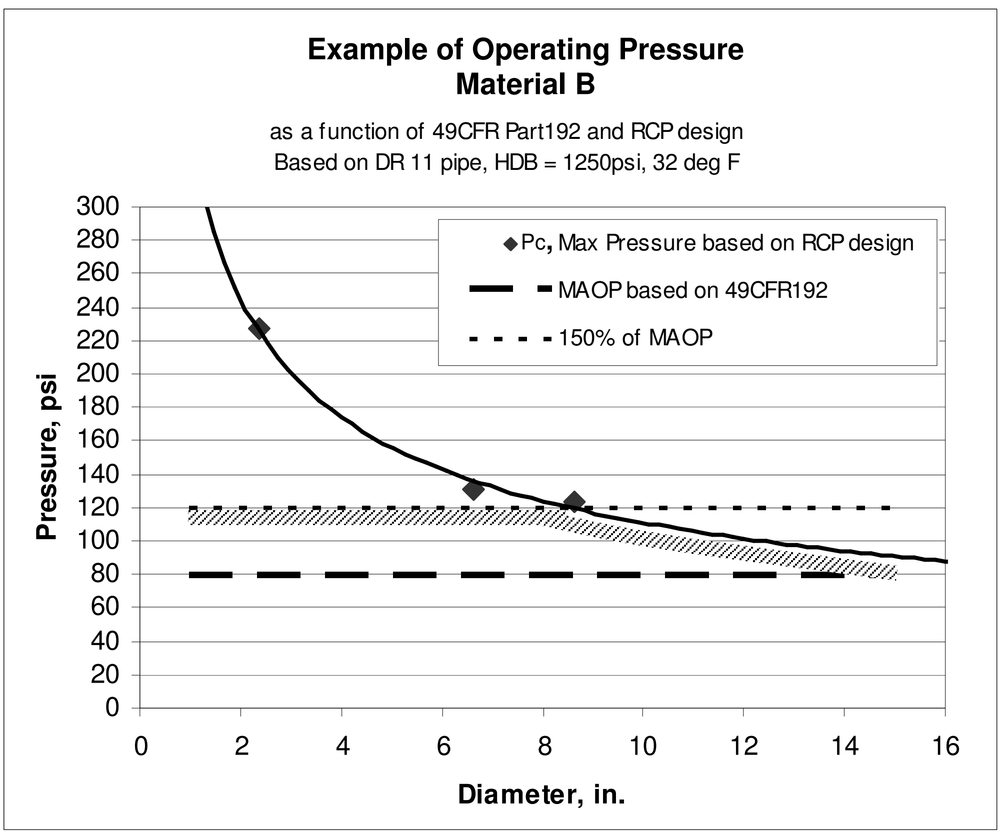

Figure 4: Operating Pressure as a Function of Diameter and Full scale Critical Pressure, P_C

Example 3:
For Material B as shown in Figure 4, now consider a pipeline that is leak tested to 75 psi. The MAOP of the pipeline is therefore 50 psi but the LDC has established an operating pressure (or MOP) of 25 psi based on overall system components and configuration. From Figure 4, we see that the potential for RCP during leak testing does not become an operational constraint for pipe produced from Material B over the range of diameters shown in Figure 4.

RCP INITIATIVES IN THE US:

Historically, concerns regarding RCP in US gas distribution systems have been largely mitigated by federal legislation that limited the use of PE pipe to systems with operating pressures of 100 psi or less. In the 2005, the CFR Title 49, Part 192 was modified to allow for the use of PE gas distribution pipe up to 125 psi provided that the pipe met all of the requirements of CFR Title 49 and was manufactured after July 14, 2004.

As a consequence of this change in Title 49 and the resulting implications on operating and test pressures for PE gas distribution pipe in the US, ASTM D2513 was revised to include consideration of RCP properties for PE gas distribution piping products in the US. In 2008, Mandatory Annex A1 of ASTM D2513 was revised to require that PE pipe and tubing producers provide RCP data obtained on their product offerings. While this requirement in ASTM D2513 is significant, the revision does not provide any guidance on incorporation of RCP data in the design of gas distribution systems.

The US gas distribution and PE pipe producer community have been engaged in building consensus around a design methodology for the use of PE pipe that includes consideration of RCP properties. At the time of this writing, a final design approach consistent with that presented here has been developed and is currently under final review by the Managing Committee of AGA. This design approach is anticipated to be published as an AGA white paper in the very near future.

CONCLUSION:

When a pressurized PE pipe in gas service is subjected to an instantaneous and intense impact, a pre-existing or consequently initiated crack or flaw may propagate axially at high speeds. Such an event is referred to as RCP, or Rapid Crack Propagation. While RCP occurrence in PE pipes is extremely rare, its consequences can be significant. Because of this, gas pipe applications should be designed to avoid conditions which could lead to RCP. This has led to the development of the Full-Scale (FS) and the Small-Scale-Steady-State (S4) tests to evaluate the pipe and the pipe material's resistance to RCP.

This discussion has shown how these tests allow the user to determine if RCP needs to be considered in the pipeline design. Furthermore, if service conditions warrant the consideration of RCP, this paper has shown how to utilize the test data generated in the pipe design to effectively minimize the potential for RCP in service.

In this paper, we identified two key properties to be used in the design of PE gas distribution piping systems to minimize the potential for RCP occurrence. These are: critical temperature, T_C, and critical pressure, P_C. From a basic understanding of these properties, as presented here, and the methods by which they are obtained we conclude the following:

1) In situations where the critical temperature, T_C, is substantially below the operating temperature of the PE gas pipe system produced from a specific PE pipe resin formulation, the potential for an occurrence of RCP is reduced to a level of limited engineering significance.
2) In cases where the PE piping system produced from a specific resin formulation is operating at a level below the T_C or in situations where T_C has not been established, the critical pressure, P_C, can be determined at the lowest anticipated operating temperature for a range of pipe sizes produced from that formulation. This data can then be utilized to adjust the leak test or stand-up test pressure. This in turn, may reduce the MAOP and, hence, the MOP in those sizes of pipe over which the potential for an RCP event becomes significant. In this way, P_C acts potentially as a constraint to establish a limit state in the design of PE gas pipe produced from a specific resin formulation.

Finally, in this paper we reviewed the status of initiatives within the US to include consideration of RCP properties in the design and use of PE gas distribution systems and how those developing guidelines are consistent with the design approach presented here.

REFERENCES:

1. Gross, S., and S. Mruk, "Plastic Pipe in Gas Distribution; Twenty-Five Years of Achievement", Gas Industries, November, 1985.
2. Sandstrum, S.D., "Polyethylene Gas Pipe… Here Today, Here Tomorrow", Proceedings of the Seventeenth Plastic Fuel Gas Pipe Symposium, American Gas Association, San Francisco, CA., 2002.
3. Title 49, Code of Federal Regulations, Part 192., National Archives and Records Administration, Washington DC, 2006
4. Leis, B.N., "Rapid Crack Propagation in Polyethylene Gas Piping Distribution Systems", Proceedings of the Eleventh Plastic Fuel Gas Pipe Symposium, American Gas Association, San Francisco, CA., 1989
5. Yayla, P. and P. Leevers, "A Small Scale Pipe Test for Rapid Crack Propagation", Proceedings of the Eleventh Plastic Fuel Gas Pipe Symposium, American Gas Association, San Francisco, CA., 1989
6. Brown, N. and Xici Lu, "Charpy Impact Test that Prevents Rapid Crack Propagation", Proceedings of the Seventeenth Plastic Fuel Gas Pipe Symposium, American Gas Association, San Francisco, CA., 2002
7. Leevers, P., "S4 Critical Temperature Tests: Procedure and Interpretation", Proceedings of Plastics Pipes XII, Milan, Italy., 2004

8. Leevers, P., L. Moreno, and A. Paizis, "The Ductile-Brittle Transition in Pipe-Grade Polyethylenes", Proceedings of Plastics Pipes XI, Munich, Germany., 2001
9. Mamoun, M, "S-4 Test to Mitigate Rapid Crack Propagation (RCP) Failures in PE Gas Pipes", Proceedings of the 2003 Operating Section, American Gas Association, American Gas Association, Washington, DC., 2003.
10. Leevers, P., G.P. Venizelos and R.E. Morgan, "Strategies for Avoiding RCP in Gas-Pressurized PE Pipe", Proceedings of the Thirteenth Plastic Fuel Gas Pipe Symposium, American Gas Association, San Antonio, TX., 1993.
11. Krishnaswamy, R.K., et al, "Rapid Crack Propagation (RCP) Failures of HDPE Pipes: Structure-Property Investigations", Proceedings of Plastics Pipes XIII, Washington, DC, 2006.
12. ISO 13477, "Thermoplastics Pipes for the Conveyance of Fluids – Determination of Resistance to Rapid Crack Propagation (RCP) – Small Scale Steady- State Test (S4 Test)", International Organization for Standardization.
13. ISO 13478, "Thermoplastics Pipes for the Conveyance of Fluids – Determination of Resistance to Rapid Crack Propagation (RCP) – Full Scale Test (FS Test)", International Organization for Standardization.
14. ISO 4437, "Buried Polyethylene (PE) Pipes for Supply of Gaseous Fuels – Metric Series – Specifications", International Organization for Standardization.
15. Lamborn, Mark J., "Dependence of Small Scale Steady State (S4) Test Results on Pipe Size", Plastics Pipes XIII, Washington, DC, 2006.
16. Maeger, Sukhadia, and Lamborn, "A Study of the Correlation Factor between Full-Scale and S4 Rapid Crack Propagation Testing in Gas Piping Applications", AGA Operations Conference, Phoenix AZ, 2008.
17. P. Leevers, "S4 Critical Temperature Tests: Procedure and Interpretation", Plastics Pipe XII, Milan, Italy, April 19-22 (2004).
18. T. Lauder, "Can PE Gas Pipe Really Replace Large Diameter Cast Iron and Steel Gas Pipe?" AGA Operations Conference, Phoenix AZ, 2008.