“Increasing Importance of Rapid Crack Propagation (RCP) for Gas Piping Applications - Industry Status”

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I. Abstract

Polyethylene (PE) is the primary material used for gas piping applications. Because of its flexibility, ease of joining and long-term durability, along with lower installed cost and lack of corrosion, gas companies want to install PE pipe instead of steel pipe in larger diameters and higher pressures. As a result, rapid crack propagation (RCP) is becoming a more important property of PE materials. This paper will review the two key ISO test methods that are used to determine RCP performance (full scale test and small scale steady state test), and compare the values obtained with various PE materials on a generic basis. The RCP performance in these test methods is significantly superior for both bimodal PE 2708 and bimodal PE 4710 compared to the unimodal materials. We will also review the status of RCP requirements in industry standards; such as ISO 4437, ASTM D 2513 and CSA B137.4. In addition, we will review progress within CSA Z662 Clause 12 and the AGA Plastic Materials Committee to develop industry guidelines based on the values obtained in the RCP tests to design against an RCP incident. Finally, we will discuss how the superior RCP performance of bimodal PE 2708 and bimodal PE 4710 materials has led to a higher 0.45 design factor for gas applications in Canada. These materials are marked PE 2708 PLUS and PE 4710 PLUS to indicate they can use the 0.45 design factor.

II. Background

Although the phenomenon of RCP has been known and researched for several years (1), the number of RCP incidents has been very low. A few have occurred in the gas industry in North America and a few more in Europe. With gas engineers desiring to use PE pipe at higher operating pressures (up to 180 psig or 12 bar) and larger diameters (up to 30” or 750 mm), a key property of a PE piping material - resistance to rapid crack propagation (RCP) - becomes more important.

Most of the original research work conducted on RCP was for metal pipe. As plastic pipe became more prominent, researchers applied similar methodologies used for metal pipe on the newer plastic pipe materials, and particularly polyethylene (PE) pipe (2). Most of this research was done in Europe and through the ISO community.

Rapid crack propagation, as its name implies, is a very fast fracture. Crack speeds up to 600 ft/sec (200 m/sec) have been measured. These fast cracks can also travel very long distances, even hundreds of feet. The DuPont Company had two RCP incidents with its high-density PE pipe, one that traveled about 300 feet and the other that traveled about 800 feet. RCP cracks usually initiate at internal defects during an impact or impulse event. They generally occur in pressurized systems with enough stored energy to drive the crack faster than the energy is released. Based on several years of RCP research, the probability of an RCP failure in PE pipe is dependent on these factors:

1. Increase in pipe size/wall thickness
2. Increase in internal pressure
3. Decrease in temperature
4. Increase in resistance to RCP of the PE material

Typical features of an RCP crack are a sinusoidal crack path along the pipe, and “hackle” marks along the pipe crack surface that indicate the direction of the crack. At times, the crack will bifurcate into two directions as it travels along the pipe.

III. RCP Test Methods

The RCP test method that is considered to be the most reliable is the full-scale (FS) test method, as described in ISO 13478. This method requires at least 50 feet of plastic pipe for each test and another 50 feet of steel pipe for the reservoir. It is very expensive and time consuming.

Due to this high cost for the FS RCP test, Dr. Pat Levers of Imperial College developed the small-scale steady state (S4) test method to correlate with the full-scale test (3). This accelerated RCP test uses much smaller pipe samples (a few feet) and a series of baffles, and it is described in ISO 13477. The cost of conducting this S4 testing is still expensive, but less than FS testing. Several laboratories now have S4 equipment – below is a photo of the S4 apparatus used by Jana Laboratories:

![S4 apparatus](image)

Due to the baffles, the critical pressure obtained with the S4 test method must be corrected to correlate with the FS critical pressure. There has been considerable research within the ISO community conducted in this area. Dr. Philippe Vanspeybroeck of Becetel chaired a working group – ISO/TC 138/SC 5/WG RCP – that conducted S4 and FS testing on several PE pipes (4). Based on their extensive research effort, the WG arrived at the following correlation formula (5) to convert the S4 critical pressure ($P_{c,s4}$) to the FS critical pressure ($P_{c,fs}$):

$$P_{c,fs} = 3.6 P_{c,s4} + 2.6 \text{ bar}$$

It is important to note that this S4/FS correlation formula may not be applicable to other piping materials, such as PVC or polyamide (PA). For example, Arkema has conducted S4 and FS testing on PA-11 pipe and found a different correlation formula for PA-11 pipe (6).
Whether conducting FS or S4 RCP testing, there are two key results used by the piping industry – one is the critical pressure and the other is the critical temperature.

The critical pressure is obtained by conducting a series of FS or S4 tests at a constant temperature (generally 0°C) and varying the internal pressure. At low pressures, where there is insufficient energy to drive the crack, the crack initiates and immediately arrests. At higher pressures, the crack propagates to the end of the pipe. The critical pressure is shown by the red line in Figure 1 as the transition between arrest at low pressures and propagation at high pressures. In this case, the critical pressure is about 145 psig (10 bar).

![Figure 1 – Critical Pressure (Plot of crack length vs. pressure)](image)

Data obtained at 32°F (0°C)

The critical temperature is obtained by conducting a series of FS or S4 tests at a constant pressure (generally 75 psig or 5 bar) and varying the temperature (7). At high temperatures the crack initiates and immediately arrests. At low temperatures, the crack propagates to the end of the pipe. The critical temperature is shown by the red line in Figure 2 as the transition between arrest at high temperatures and propagation at low temperatures. In this case, the critical temperature is 35°F (2°C).
IV. RCP Requirements in Industry Standards

A. ISO

The International Standards Organization (ISO) product standard for PE gas pipe, ISO 4437, has included an RCP requirement for many years (8). This is because there were some RCP failures in early generation European PE gas pipes, and the Europeans had conducted considerable research on RCP in PE pipes. Also, European gas companies were using large diameter pipes and higher operating pressures for PE pipes, both of which make the pipe more susceptible to RCP failures. Below is the current requirement for RCP taken from ISO 4437:

\[ \text{Pc} > 1.5 \times \text{MOP} \]

*Where: Pc = full scale critical pressure, psig  
MOP = maximum operating pressure, psig*

MOP is determined from the standard formula knowing the pipe SDR, the MRS (minimum required strength) and C (design coefficient). Once the gas company has determined its MOP, the RCP requirement is that the full-scale critical pressure of the pipe must be 1.5 times the MOP. This 1.5 factor is due to the leak test pressure, which is generally done at 1.5 times the MOP. Many RCP failures actually occur during the leak test, because this is when the pipe sees the highest internal pressure, and is most susceptible to RCP.

ISO 4437 also allows the pipe and resin manufacturers to use the S4 test, and it provides the following correlation equation between FS and S4:

\[ \text{Pc,FS} = 3.6 \times \text{Pc,S4} + 2.6 \text{ bar} \]
Most manufacturers use the S4 test to meet this ISO 4437 RCP requirement. If the requirement is not met, then the manufacturer may use the FS test.

These are additional RCP requirements taken from ISO 4437:

"RCP tests are applicable to PE pipes intended to be used in distribution systems with $0.1 < \text{MOP} < 4 \text{ bar and } d_n > 250 \text{ mm},$ or in distribution systems with $\text{MOP} > 4 \text{ bar and } d_n > 90 \text{ mm}$. Testing is only required when the wall thickness of the pipe is greater than the wall thickness of the pipe used in the RCP test to qualify the compound (see Table 2). For severe working conditions (e.g. sub-zero temperatures) RCP testing is also recommended to establish the critical pressure at the minimum working temperature”.

Note that the RCP resistance is dependent on wall thickness as opposed to the pipe diameter. This was found to be the case after several years of research, in which different PE materials of various pipe sizes and various DR’s were tested. The chart below is from the ISO RCP working group.

Note there is a linear relationship between critical stress and pipe wall thickness. These data formed the basis for the ISO 4437 RCP requirement being dependent on wall thickness, and also for the subsequent ASTM and CSA requirements.

B. **ASTM**

ASTM D 2513 had not addressed RCP at all for several years (9). Although there have not been very many RCP failures in gas piping systems in North America, the few that have occurred resulted in the AGA Plastic Materials Committee (PMC) requesting that an RCP requirement be added to ASTM D 2513, similar to the RCP requirement currently in the ISO PE gas pipe standard ISO 4437. PMC unanimously approved a motion to add the RCP critical pressure requirement of ISO 4437 to ASTM D 2513. This request was made several years ago, and it was just completed in the balloting process within ASTM. The current status is that the manufacturers have agreed to include a requirement in ASTM D 2513 that RCP testing (FS or S4) must be performed. The required values for critical pressure must be available upon request, but the ASTM product standard D 2513 does not include any required values, as does ISO 4437.
PMC has agreed with this approach, and they will develop their own industry requirement in the form of a "white paper" (10). Several drafts have been issued within PMC with the following proposed requirement:

To minimize the potential for RCP occurrence, the critical temperature should be lower than operating temperature, and the critical pressure should be greater than the leak test pressure, which is 1.5 times the maximum operating pressure.

This draft of course needs to be revised and approved by AGA PMC.

C. CSA

Recently, the Canadian gas companies agreed they wanted to address RCP in their gas pipe standards. A project was initiated to revise CSA B137.4, which is the Canadian product standard for PE gas pipe (11). The project was balloted and approved a year later. B137.4 now has the following RCP requirement:

4.2.4.6 Rapid Crack Propagation (RCP) Requirements

RCP testing shall be conducted to determine the RCP critical pressure for a PE compound with a particular pipe wall thickness. Testing on pipe is only required when the wall thickness of the pipe is greater than the wall thickness of the pipe used in the RCP test to determine the RCP critical pressure for the PE compound.

RCP testing shall be conducted using test method ISO 13477 (S4 test) or ISO 13478 (full scale test) at 0°C to determine the critical pressure ($p_c$). In case of conflict, the RCP results of ISO 13478 shall apply.

NOTE: additional RCP testing may be conducted for working temperatures below 0°C. The critical pressure and full scale/S4 correlation factor are defined by the following formulas:

$$p_c = p_{c,FS}$$

$$p_{c,FS} + p_{atm} = 3.6 (p_{c,S4} + p_{atm})$$

where:

- $p_c$ = critical pressure
- $p_{c,S4}$ = small scale steady state (S4) critical pressure as determined by ISO 13477
- $p_{c,FS}$ = full scale critical pressure as determined by ISO 13478

Basically, CSA followed the direction of ASTM in that the product standard, CSA B137.4, requires that the RCP testing must be done. The values of the RCP test are then stipulated in CSA Z662 Clause 12, which is the Code of Practice for gas distribution in Canada. Clause 12 has approved the RCP requirement as shown below:

12.4.3.6 Rapid Crack Propagation (RCP) Requirements

When tested in accordance with B137.4 requirements for PE pipe and compounds, the standard PE pipe RCP Full-Scale critical pressure shall be at least 1.5 times the maximum operating pressure. If the RCP Small-Scale Steady State method is used, the RCP Full-Scale critical pressure shall be determined using the correlation formula in B137.4.

CSA decided to have the same RCP requirement as ISO 4437, which is also consistent with the AGA PMC draft White Paper.
V. RCP Test Data

In Europe, PE materials used for gas distribution are designated as PE 80 and PE 100. In North America, they are designated as PE 2406 or PE 2708 (MDPE or medium density PE) and PE 3408 or PE 4710 (HDPE or high density PE). By far, the majority of North American gas pipe is MDPE, perhaps as much as 90% in Canada and 75% in the US. PE 80 could be either MDPE or HDPE and PE 100 is all HDPE. The gas companies prefer MDPE because of its greater flexibility (coiling, bending, squeeze-off) and ease of joining by heat fusion compared to HDPE. The only drawback of MDPE is its lower resistance to RCP. The gas pipe RCP failures that have occurred have been with MDPE pipe.

The critical pressure is the pressure below which, RCP will not occur. The higher the critical pressure, the less likely the gas company will have an RCP event. In most cases, as the pipe diameter or wall thickness increases, the critical pressure decreases. Therefore, RCP is more of a concern with large diameter or thick-walled pipe. Since the Europeans first started using large diameter gas pipe thirty years ago, they were aware of RCP and introduced RCP into their product standards and ISO standards. As North American gas companies are considering the use of large diameter gas pipe, RCP has been recently added to the ASTM and CSA standards.

Here are some typical critical pressure values for various generic PE materials.

<table>
<thead>
<tr>
<th>PE Material</th>
<th>S4 Critical Pressure $(P_{C,S4})$ at 32°F (0°C)</th>
<th>Full Scale Critical Pressure $(P_{C,FS})$ @ 0°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>12” Unimodal MDPE</td>
<td>1 bar (15 psig)</td>
<td>6.2 bar (90 psig)</td>
</tr>
<tr>
<td>12” Bimodal MDPE</td>
<td>10 bar (145 psig)</td>
<td>38.6 bar (560 psig)</td>
</tr>
<tr>
<td>10” Unimodal HDPE</td>
<td>2 bar (30 psig)</td>
<td>9.8 bar (140 psig)</td>
</tr>
<tr>
<td>10” Bimodal HDPE (PE 100+)</td>
<td>12 bar (180 psig)</td>
<td>45.8 bar (665 psig)</td>
</tr>
</tbody>
</table>

In general, the RCP resistance is greater for HDPE (high density PE) than MDPE (medium density PE). There is a significant difference, however, when comparing a unimodal PE to a bimodal PE material, about a ten-fold difference. Bimodal PE technology was developed in Asia and Europe in the 1980’s. This technology is known to provide superior performance for both slow crack growth and RCP, as evidence by the table above. For the bimodal PE 100+ materials used in Europe, the S4 critical pressure minimum requirement is 10 bar (145 psig), which converts to 560 psig full-scale critical pressure. This means that with these bimodal PE 100+ materials, RCP will not be a concern. Today, there are several PE resin manufacturers that use bimodal technology. The original bimodal PE materials were all HDPE. Recently, a new bimodal MDPE material has been introduced for the gas industry (12,13), with a significantly higher S4 critical pressure compared to unimodal MDPE, 10 bar compared to 1 bar. The charts below compare the RCP probability for a unimodal PE 2708 to a bimodal PE 2708 as a function of pipe size and pressure.
The RED zone in the Unimodal PE 2708 chart indicates a combination of pipe size and pressure where RCP is possible. RCP is possible for pipe sizes greater than 4” IPS and for operating pressures above 60 psig (leak test pressure of 90 psig). The green zone is a combination of pipe size and pressure, which is safe from RCP. The yellow zone is a caution area.

The Bimodal PE 2708 chart is GREEN for all combinations of pipe size and pressure. With a bimodal PE 2708 material, the probability for an RCP occurrence has been significantly reduced!
Another measure of RCP resistance is the critical temperature. This is defined as the temperature above which, RCP will not occur. Therefore, a gas engineer wants to use a PE material with a critical temperature as low as possible. Although critical temperature is not used as a requirement in the product standards, it is an important parameter, and perhaps should be given more consideration.

Here are some typical critical temperature values for various generic PE materials.

<table>
<thead>
<tr>
<th>PE Material</th>
<th>Critical Temperature (Tc) at 5 bar (75 psig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12” Unimodal MDPE</td>
<td>15°C (60°F)</td>
</tr>
<tr>
<td>12” Bimodal MDPE</td>
<td>-2°C (28°F)</td>
</tr>
<tr>
<td>10” Unimodal HDPE</td>
<td>9°C (48°F)</td>
</tr>
<tr>
<td>10” Bimodal HDPE</td>
<td>-17°C (1°F)</td>
</tr>
</tbody>
</table>

We see that RCP performance for HDPE is slightly better than MDPE, but there is a significant difference between bimodal PE and unimodal PE. The bimodal MDPE and HDPE materials have the lowest critical temperatures, which means the greatest resistance to RCP.

VI. HDB Design Factor of 0.45

The Plastics Pipe Institute (PPI) recently addressed the dilemma that for the same PE material and the same pipe DR, the pressure rating for ISO 9080 PE 100 pipe was higher than corresponding ASTM D 2837 PE 3408 pipe by 45% (14). In an attempt to bring these two pressure rating methods closer together, PPI increased the design factor from 0.5 to 0.63 for water pipe and from 0.32 to 0.4 for gas pipe. The materials that qualify for the higher design factor are called “high performance” PE materials and require a PENT value (ASTM F 1473) of 500 hours. The new pipe material designation code for PE 3408 became PE 4710 and the new code for PE 2406 became PE 2708 to indicate that these high performance materials qualified for the higher design factor. However, even with this higher design factor, there was still a gap of 15% between the ASTM and ISO pressure rating methods.

In Canada, CSA Z662 Clause 12 had already increased the design factor for gas applications from 0.32 to 0.40 in 1996 – 14 years ago. As a result when PE 2708 and PE 4710 were introduced in Canada for gas pipe applications, there was no difference in pressure rating compared to a PE 2406 or PE 3408, respectively. The Canadian gas companies wanted to recognize the higher performance for the superior bimodal PE materials, and so they introduced a 0.45 design factor. With this even higher design factor of 0.45, the pressure rating for PE 4710 and PE 100 became the same. Canada actually closed the gap between the ASTM and ISO pressure rating methods with the introduction of this 0.45 design factor for gas piping applications in CSA Z662 Clause 12.

12.4.2.2

The design factor (F) to be used in the design formula in Clause 12.4.2.1 (a) for HDB-rated materials shall be 0.40, or 0.45 for PLUS performance PE compounds described in 12.5.2.3.

To indicate that a PE material could use the higher 0.45 design factor, Clause 12 introduced the term “PLUS” after the pipe material designation code – for example, PE 2708 PLUS or PE 4710 PLUS.
The Canadian gas companies wanted to assure that only the superior performing bimodal PE materials would qualify for the higher design factor designation (PLUS). To assure a very high level of slow crack growth resistance, Clause 12 requires a PENT value of 2000 hours. This is consistent with the 2000-hour PENT requirement for PE 100 materials in Clause 12. To assure a very high level of rapid crack propagation resistance, Clause 12 requires an S4 critical pressure of 10 bar (1000 kPa) at 0°C (32°F). This is consistent with the S4 RCP critical pressure requirement for PE 100 materials in Clause 12. Thus both the HDB rated PE 2708 PLUS and PE 4710 PLUS and the MRS rated PE 100 have the same stringent SCG and RCP requirements in Clause 12, as shown below.

12.5.2.3 PLUS Performance PE compounds

The minimum PENT value for HDB-rated plus performance PE compounds using the 0.45 design factor shall be 2000 hours, and the minimum RCP Small-Scale Steady State value shall be 1000 kPa at 0°C per Clause 12.4.3.6. These plus performance PE compounds that qualify for a 0.45 design factor shall be designated with a PLUS after the pipe material designation code; for example, PE 2708 PLUS or PE 4710 PLUS.

Tables 1 and 2 below compare the maximum operating pressure for MDPE (medium density PE) and HDPE (high density PE) materials used in SDR 11 pipe:

Table 1: Maximum Operating Pressure (MOP) for MDPE SDR 11 Pipe – Gas Applications

<table>
<thead>
<tr>
<th></th>
<th>PE 2406</th>
<th>PE 2708</th>
<th>PE 2708 PLUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDB, psi</td>
<td>1250</td>
<td>1250</td>
<td>1250</td>
</tr>
<tr>
<td>Design factor</td>
<td>0.40</td>
<td>0.40</td>
<td>0.45</td>
</tr>
<tr>
<td>MOP for SDR 11, psig</td>
<td>100</td>
<td>100</td>
<td>112</td>
</tr>
</tbody>
</table>

Table 2: Maximum Operating Pressure (MOP) for HDPE SDR 11 Pipe – Gas Applications

<table>
<thead>
<tr>
<th></th>
<th>PE 3408</th>
<th>PE 4710</th>
<th>PE 4710 PLUS</th>
<th>PE 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>HDB, psi</td>
<td>1600</td>
<td>1600</td>
<td>1600</td>
<td></td>
</tr>
<tr>
<td>MRS, MPa</td>
<td></td>
<td></td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Design factor</td>
<td>0.40</td>
<td>0.40</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Design coefficient</td>
<td></td>
<td></td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>MOP for SDR 11, psig</td>
<td>125</td>
<td>125</td>
<td>145</td>
<td>145</td>
</tr>
</tbody>
</table>
From Table 2, you can see that:
- the pressure rating for PE 3408 and PE 4710 is the same,
- the pressure rating for PE 4710 PLUS is 15% higher than PE 4710, and
- the pressure rating for PE 4710 PLUS and PE 100 are the same.

VII. Conclusion

As gas companies use PE pipe in more demanding applications, such as larger pipe diameters and higher operating pressures, the resistance of the PE pipe to rapid crack propagation (RCP) becomes more important. In this paper we have discussed the phenomenon of RCP and the two primary test methods used to determine RCP resistance – the S4 test and the Full Scale test. We reviewed the correlation formula between the FS test and S4 test for critical pressure, and this discussion continues today, as evidenced by the recent PP XIV paper by Philippe Vanspeybroeck (15). We have also discussed the two primary results of RCP testing – the critical pressure and the critical temperature.

ISO standards were the first to recognize the importance of RCP, especially in larger diameter pipe sizes, and incorporated RCP requirements in product standards, such as ISO 4437. The Canadian standards soon followed, and an RCP test requirement has been added to CSA B137.4. The required values for RCP testing have also been added to the CSA Code of Practice in CSA Z662 Clause 12 for gas piping. ASTM has added an RCP requirement to its gas pipe standard ASTM D 2513 that the testing must be done. The AGA PMC project to develop RCP recommendations for required values from RCP testing is in progress.

In this paper, we also discussed some results of RCP testing. In general, the high-density PE or HDPE materials have slightly greater RCP resistance than medium-density or MDPE materials used in the gas industry. A more significant difference is observed when comparing unimodal PE materials to bimodal PE materials. Existing data indicate that bimodal HDPE materials show a significant increase in critical pressure compared to unimodal HDPE materials, and also have considerably lower critical temperature values. Many of these bimodal HDPE materials are commonly known as PE 100+ materials. In addition, this bimodal technology has now just been introduced for MDPE. This bimodal MDPE material also has a significantly higher S4 critical pressure (10 bar vs. 1 bar) and a lower critical temperature than unimodal MDPE materials. With several PE resin manufacturers being able to produce bimodal PE materials, it is likely that in the near future, all PE materials used for the gas industry will be bimodal materials because of their superior RCP resistance, especially since bimodal PE is very cost-competitive with unimodal PE.

Finally, we discussed the recent change in CSA Z662 Clause 12 to incorporate a 0.45 design factor for gas pipe applications in Canada. To use this higher design factor, the PE material must have an SCG PENT value of 2000 hours and an RCP S4 critical pressure of 10 bar (1000 kPa). The materials that meet these stringent SCG and RCP requirements are designated PE 2708 PLUS and PE 4710 PLUS.
VII. References

8. ISO 4437, “Buried polyethylene (PE) pipes for the supply of gaseous fuels — Metric series — Specifications”.
11. CSA B137.4, “Polyethylene (PE) Piping Systems for Gas Service”.