“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. 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.

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 12 bar or 180 psig) and larger diameters (up to 30”), a key component 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 200 m/sec (600 ft/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, whether an RCP failure occurs in PE pipe is dependant on several factors:
1. Pipe size  
2. Internal pressure  
3. Temperature  
4. PE material properties/resistance to RCP  
5. Pipe processing

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. The cost to obtain the desired RCP information can be in the hundreds of thousands of dollars (Euros).

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 it is about an order of magnitude less than FS testing. Several laboratories now have S4 equipment – below is a photo of the S4 apparatus used by Jana Laboratories:
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 10 bar (145 psig).

**Figure 1 – Critical Pressure (Plot of crack length vs. pressure)**  
Data obtained at 0°C (32°F)
The critical temperature is obtained by conducting a series of FS or S4 tests at a constant pressure (generally 5 bar or 75 psig) 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).

![Figure 2 – Critical Temperature (Plot of crack length vs. temperature)](Data obtained at 5 bar (75 psig))

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:
Pc > 1.5 x MOP

Where: Pc = critical pressure, psig
      MOP = maximum operating pressure, psig

MOP is determined from the standard formula knowing the pipe SDR, and of course the MRS (minimum required strength) and C (design coefficient). Once the gas company has determined its MOP, the RCP requirement is that the critical pressure of the pipe (in this case the FS critical pressure) must be 1.5 times the MOP. This 1.5 increase 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:

\[ P_{c,FS} = 3.6 P_{c,S4} + 2.6 \text{ bar} \]

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 < MOP < 4 bar and \( dn > 250 \) mm, or in distribution systems with MOP > 4 bar and \( dn > 90 \) 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”.

Therefore, the ISO 4437 product standard requires that RCP testing be done, and also provides values for the RCP requirement. In general the resin manufacturer conducts the RCP test on the largest pipe wall thickness available. If a pipe manufacturer produces pipe with that wall thickness or smaller, no additional testing is required.

B. ASTM

ASTM D 2513 currently does not address RCP at all (9). Although there have not been very many RCP failures in gas piping systems in North America, the few that have occurred have 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 is still 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 will not include any required values.

PMC has agreed with this approach, and they will develop their own industry requirement in the form of a “white paper” (10). The first draft was just issued within PMC with the following proposed requirement:

1. Insure the critical temperature, \( T_C \), is below the minimum anticipated service temperature, \( T_S \)
2. Determine the critical pressure, \( P_C \), at the minimum anticipated serviced temperature, \( T_S \); insure that the maximum anticipated service pressure, \( P_S < P_C \) for the largest diameter in a specific series of SDR determined at the minimum anticipated service temperature, \( T_S \)

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:
\[ p_c = \text{critical pressure} \]
\[ p_{c,S4} = \text{small scale steady state (S4) critical pressure as determined by ISO 13477} \]
\[ p_{c,FS} = \text{full scale critical pressure as determined by ISO 13478} \]

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 will be stipulated in CSA Z662 Clause 12, which is the Code of Practice for gas distribution in Canada. Clause 12 is currently reviewing the latest draft, which is shown below:

12.4.3.6 Rapid Crack Propagation (RCP) Requirements

As stipulated in CSA B137.4, RCP tests are applicable to PE pipes intended to be used under the following conditions:
1) In distribution systems with an MOP > 0.1 bar (1.5 psig) and pipe size ≥ 250 mm
2) In distribution systems with an MOP > 4 bar (60 psig) and pipe size ≥ 90 mm

B137.4 requires testing on a PE compound to initially qualify the PE compound with a particular pipe size. 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 qualify the compound.

When tested in accordance with B137.4 requirements, the PE compound and/or PE pipe shall conform to the requirements given in the table below.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>Requirements</th>
<th>Test Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance to rapid crack propagation (RCP): S4 test</td>
<td>bar</td>
<td>[ p_c \geq 1.5 \times \text{MOP} ]</td>
<td>[ 0^\circ \text{C} ]</td>
</tr>
<tr>
<td>(wall thickness ≥ 15 mm)</td>
<td></td>
<td>with [ p_c = 3.6 \times p_{c,S4} + 2.6 \text{(bar)} ]</td>
<td></td>
</tr>
</tbody>
</table>

\[ a \] Full scale/S4 correlation factor is equal to 3.6 and is defined by the formula: \[ p_{c,FS} + p_{\text{atm}} = 3.6 \ (p_{c,S4} + p_{\text{atm}}) \]

If the requirement is not met, then retest using the full-scale test. In this case: \[ p_c = p_{c,FS} \]

where:
\[ p_c = \text{critical pressure} \]
\[ p_{c,S4} = \text{small scale steady state (S4) critical pressure} \]
\[ p_{c,FS} = \text{full scale critical pressure} \]
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 is being added to the ASTM and CSA standards.

Here are some typical critical pressure values for various generic PE materials. For most cases, the pipe size tested is 12” SDR 11 pipe.

<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>Unimodal MDPE</td>
<td>1 bar (15 psig)</td>
<td>6.2 bar (90 psig)</td>
</tr>
<tr>
<td>Bimodal MDPE</td>
<td>10 bar (145 psig)</td>
<td>38.6 bar (560 psig)</td>
</tr>
<tr>
<td>Unimodal HDPE</td>
<td>2 bar (30 psig)</td>
<td>9.8 bar (140 psig)</td>
</tr>
<tr>
<td>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 operating 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.

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. It was good to see that critical temperature was referenced in the draft AGA PMC White Paper, “Insure the critical temperature, T_c, is below the minimum anticipated service temperature, T_s.”.

Here are some typical critical temperature values for various generic PE materials. For most cases, the pipe size tested is 12” SDR 11 pipe.

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

Again 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.

Also, here is a table of critical temperature data for commercially available PE pipe materials taken from the draft AGA PMC White Paper:

<table>
<thead>
<tr>
<th>Critical Temperature, deg F 8” DR 11 Pipes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin Type</td>
</tr>
<tr>
<td>HDPE-1</td>
</tr>
<tr>
<td>HDPE-2</td>
</tr>
<tr>
<td>HDPE-3</td>
</tr>
<tr>
<td>HDPE-4</td>
</tr>
<tr>
<td>HDPE-5</td>
</tr>
<tr>
<td>MDPE-1</td>
</tr>
<tr>
<td>MDPE-2</td>
</tr>
</tbody>
</table>
We see the same trend here, unimodal HDPE (3, 4, and 5) is slightly better than unimodal MDPE, but bimodal HDPE (1 and 2) is significantly better than unimodal HDPE (3, 4 and 5).

VI. 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 PP XIV paper by Philippe Vanspeybroeck (14). 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 are currently being added to the CSA Code of Practice in CSA Z662 Clause 12 for gas piping. ASTM is still in the process of adding an RCP requirement to its gas pipe standard ASTM D 2513. The project to require that RCP testing be conducted is still in the balloting process. The AGA PMC project to develop RCP recommendations for required values from RCP testing is in progress. The first draft of the AGA PMC White Paper has just been issued.

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.
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”.