How to Design Against Long Running Cracks in Plastic Pipe for Water Applications

Dr. Gene Palermo
Palermo Plastics Pipe (P³) Consulting
www.plasticspipe.com
OUTLINE

- What is Rapid Crack Propagation (RCP)
- RCP Test Methods for Plastic Pipe
- RCP Test Data for PE and PVC Pipe
- RCP Field Failure Case Study
- Conclusions
What is Rapid Crack Propagation (RCP)?

- Rapid Crack Propagation is a very fast fracture. Crack speeds up to 1800 ft/sec (600 m/sec) have been measured in PVC pipe.

- These fast cracks can travel very long distances, even > 1000 ft in plastic or metal pipe.

- RCP cracks usually initiate at internal defects or at butt fusions, during an impact event, a leak pressure test, or the tapping operation.

- RCP generally occurs in pressurized systems with enough stored energy to drive the crack faster than the energy is released.
Rapid Crack Propagation (RCP) – Engineering Property

- RCP is an engineering performance property of the plastic or metal pipe material.
- Various piping materials will behave differently when an RCP event occurs.
- For some ductile materials, like PE, the rapid crack travel is arrested, because of the toughness of the material.
- For other materials that are more brittle, the pipe can shatter during an RCP event or can run for over one thousand feet.
PE Pipes

- PE is a semi-crystalline plastic material that is well above its glass transition temperature, and is not very susceptible to Rapid Crack Propagation due to its toughness.

- There have been very few RCP failures in PE pipe used in water applications – only about 0.0005 RCP incidents per million feet, and leading researchers report none in the past twenty years.

- In most European countries the amount of PE pipe used for all water applications varies from 50% to 90% - PE materials used in Europe are the same PE materials used in the US.
PVC Pipes

• PVC is an amorphous plastic material that is below its glass transition temperature, and thus is in a “glassy” or “brittle” state.

• In the US, there have been a few Rapid Crack Propagation failures that have occurred in bell-and-spigot joined PVC pipe – about 0.02 RCP incidents per million feet. These cracks only travel a few feet, then arrest at the B&S joint.

• Recently, at least 20 Rapid Crack Propagation incidents have occurred in PVC pipes joined by the butt fusion method – about 5 RCP incidents per million feet. These cracks travel for hundreds of feet through the BF joints.
Selection of Known PVC RCP (Rapid Crack Propagation) Field Failures

<table>
<thead>
<tr>
<th>No.</th>
<th>RCP Failure Location</th>
<th>Date of RCP Failure</th>
<th>Pipe size and DR</th>
<th>Length of RCP crack</th>
<th>Joined by butt fusion</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Winter Park, FL</td>
<td>2004</td>
<td>8” DR 18</td>
<td>200 ft</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>Danville, CA</td>
<td>2006</td>
<td>20” DR 18</td>
<td>400 ft</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>Collier County, FL</td>
<td>2007</td>
<td>30” DR 25</td>
<td>1100 ft</td>
<td>Y</td>
</tr>
<tr>
<td>4</td>
<td>Greencastle, IN</td>
<td>2007</td>
<td>10” DR 21</td>
<td>800 ft</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>Greencastle, IN (2)</td>
<td>2007</td>
<td>10” DR 21</td>
<td>43 ft</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>Pittsburgh, PA</td>
<td>2007</td>
<td>24” DR 25</td>
<td>160 ft</td>
<td>Y</td>
</tr>
<tr>
<td>7</td>
<td>Clay County, FL</td>
<td>2008</td>
<td>20” DR 18</td>
<td>600 ft</td>
<td>Y</td>
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<tr>
<td>8</td>
<td>Clay County, FL</td>
<td>2008</td>
<td>20” DR 18</td>
<td>1600 ft</td>
<td>Y</td>
</tr>
<tr>
<td>9</td>
<td>Des Moines, IA</td>
<td>2008</td>
<td>20” DR 18</td>
<td>1100 ft</td>
<td>Y</td>
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<tr>
<td>10</td>
<td>Troy, NY</td>
<td>2009</td>
<td>24”</td>
<td>1200 ft</td>
<td>Y</td>
</tr>
<tr>
<td>11</td>
<td>Tampa, FL</td>
<td>2009</td>
<td>8” DR 25</td>
<td>200 ft</td>
<td>Y</td>
</tr>
<tr>
<td>12</td>
<td>Baton Rouge, LA</td>
<td>2009</td>
<td>36” DR 32.5</td>
<td>300 ft</td>
<td>Y</td>
</tr>
<tr>
<td>13</td>
<td>Baton Rouge, LA</td>
<td>2009</td>
<td>24” DR 25</td>
<td>900 ft</td>
<td>Y</td>
</tr>
<tr>
<td>14</td>
<td>Collier County, FL</td>
<td>2010</td>
<td>30” DR 25</td>
<td>750 ft</td>
<td>Y</td>
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<tr>
<td>15</td>
<td>Springfield, IL</td>
<td>2011</td>
<td>18” DR 25</td>
<td>850 ft</td>
<td>Y</td>
</tr>
<tr>
<td>16</td>
<td>Springfield, IL (2)</td>
<td>2011</td>
<td>18” DR 25</td>
<td>Cracked again</td>
<td>Y</td>
</tr>
<tr>
<td>17</td>
<td>Springfield, IL (3)</td>
<td>2011</td>
<td>18” DR 25</td>
<td>Cracked again</td>
<td>Y</td>
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<tr>
<td>18</td>
<td>Fremont, CA</td>
<td>2011</td>
<td>12” DR 25</td>
<td>2000 ft</td>
<td>Y</td>
</tr>
<tr>
<td>19</td>
<td>Green Bay, WI</td>
<td>2011</td>
<td>16” DR 18</td>
<td>300 ft</td>
<td>Y</td>
</tr>
<tr>
<td>20</td>
<td>Evansville, IN</td>
<td>2012</td>
<td>12” DR 18</td>
<td>11 ft</td>
<td>Y</td>
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</tbody>
</table>
Rapid Crack Propagation Field Failure in 30” DR 25 PVC Pipe – 1100 ft

Duvall/Edwards reported RCP failure due to contractor error
Rapid Crack Propagation Field Failure in 20” DR 18 PVC Pipe – 1600 ft

Reported cause of RCP to be due to contractor error
RCP Crack Travels Through Butt Fusion Joint in 30” DR 25 PVC

Malcolm Pirnie, Inc Report – April 2010
Need to Design to Prevent RCP

- RCP failures no longer occur in PE pipe
- RCP failures occur in PVC pipe joined by bell- and-spigot, but the cracks only travel a few feet to the next joint
- Since long-running RCP cracks occur in butt fused PVC pipe, we need to understand the RCP phenomenon so that we can design the pipeline to prevent RCP failures from occurring
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RCP Test Methods

- Full Scale (FS) Test – ISO 13478
  - long pipe samples
  - very expensive

- Small Scale Steady State (S4) - ISO 13477
  - smaller pipe samples
  - test done in a laboratory
  - easier to get data and correlates to FS test
S4 RCP Critical Pressure
S4/Full Scale Correlation per ISO 13477

\[ P_{c,FS} = \text{Full Scale Critical Pressure} \]

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

“This equation is independent of pipe size, material and fluid.”
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S4 Critical Pressure – PE

![Graph showing the relationship between S4 Critical Pressure and % Air Volume.](image-url)
FS Critical Stress – DR 11 PE (based on Dr. Leever’s* data)

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

\[ P_{c,FS} = 3.6 \times (3 \text{ bar}) + 2.6 \text{ bar} \]

\[ = 13.4 \text{ bar} \]

\[ P_{c,FS} = 194 \text{ psig for DR 11 PE pipe} \]

\[ = 970 \text{ psi critical stress} \]

Pressure Rating (PR)

PR is the lower of the two following calculations:

1) \( PR = \frac{2 \times (HDB) \times (DF)}{(DR - 1)} \)

2) \( P_{c,FS} > 1.5 \times PR \)
   \( PR < \frac{P_{c,FS}}{1.5} \)

*Leak Test Pressure = 1.5 X PR
   = 1.5 X OP

Operating Pressure (OP) at water utility may be below the Pressure Rating. PR is the Maximum Operating Pressure for the pipe.
Pressure Rating – DR 11 PE (based on Dr. Leever’s data)

1) PR = 2 \( (\text{HDB}) (\text{DF}) / (\text{DR} -1) \)
   \[ = 2 \times (1250 \text{ psi}) \times (0.5) / (11 -1) \]
   \[ \text{PR} = 125 \text{ psig} \]

2) Full Scale RCP Critical Stress = 970 psi
   \[ \text{Pc}_{FS} = 194 \text{ psig for DR 11} \]
   \[ \text{PR} < \text{Pc}_{FS} / 1.5 \]
   \[ \text{PR} = 130 \text{ psig} \]

In this case, the PR is limited by the HDB and is 125 psig for DR 11 PE pipe.
Pressure Rating – DR 11 New PE 4710 Pipe

1) PR = 2 (HDB) (DF) / (DR -1)
   = 2 (1600 psi) (0.63) / (11 -1)
   PR = 200 psig

2) Full Scale RCP Critical Stress = 3250 psi
   \( P_{c,FS} = 664 \) psig for DR 11
   
   PR < \( P_{c,FS} / 1.5 \)
   PR = 440 psig

In this case, the PR is limited by the HDB and is 200 psig for DR 11 PE 4710 pipe.
S4 Critical Pressure - PVC
FS Critical Stress – DR 19 PVC (based on Dr. Leever’s data)

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

\[ P_{c,FS} = 3.6 \ (1.6 \text{ bar}) + 2.6 \text{ bar} \]

\[ = 8.36 \text{ bar} \]

\[ P_{c,FS} = 121 \text{ psig for DR 19 pipe} \]

\[ = 1100 \text{ psi critical stress} \]
Pressure Rating – DR 19 PVC

1) \[ PR = \frac{2 \times (HDB) \times (DF)}{(DR - 1)} \]
   \[ = \frac{2 \times (4000 \text{ psi}) \times (0.5)}{(19 - 1)} \]
   \[ PR = 222 \text{ psig} \]

2) Full Scale RCP Critical Stress = 1100 psi
   \[ Pc_{FS} = 121 \text{ psig for DR 19} \]

   \[ PR < \frac{Pc_{FS}}{1.5} \]
   \[ PR = 80 \text{ psig} \]

In this case the PR is limited by RCP and is only 80 psig for DR 19 PVC pipe.
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Actual Field Experience – Springfield, IL

- Butt fused 18” DR 25 PVC pipe was held at a pressure of 60 psig for a few days – no problems

- For PVC pipe, based on S4 RCP data and the ISO S4/FS correlation equation, the full scale critical pressure for DR 25 pipe is 91 psig (1100 psi)

- When the pressure for this 18” DR 25 PVC pipe was increased for the leak test, an RCP crack initiated when the pressure reached 100 psig and propagated 850 feet, going through 21 PVC butt fusion joints. This RCP failure occurred just above the RCP critical pressure - 91 psig
Pressure Rating – DR 25 PVC

1) $\text{PR} = 2 \times (\text{HDB}) \times (\text{DF}) / (\text{DR} - 1)$
   
   $= 2 \times (4000 \text{ psi}) \times (0.5) / (25 - 1)$
   
   $\text{PR} = 165 \text{ psig}$

2) Full Scale RCP Critical Stress = 1100 psi

   $P_{c,FS} = 91 \text{ psig}$ for DR 25

   $\text{PR} < P_{c,FS} / 1.5$

   $\text{PR} = 60 \text{ psig}$

   Leak test pressure = 90 psig

In this case the PR is limited by RCP and is only 60 psig for DR 25 PVC pipe.
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RCP Failure Rate

- PE 4710 – NO failures/million feet
- PE – 0.0005 failures/million feet
- PVC B&S – 0.02 failures/million feet
- PVC BF – 5 failures/million feet
# Pressure Rating (PR) Based on HDB and RCP

<table>
<thead>
<tr>
<th></th>
<th>PVC-BF (DR 19)</th>
<th>PVC-BF (DR 25)</th>
<th>PE 4710 (DR 11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated RCP Full-Scale Critical Pressure, psig</td>
<td>121</td>
<td>91</td>
<td>664</td>
</tr>
<tr>
<td>Leak Test Pressure, psig based on RCP</td>
<td>120</td>
<td>90</td>
<td>660</td>
</tr>
<tr>
<td>Pressure Rating (PR), psig based on RCP</td>
<td>80</td>
<td>60</td>
<td>440</td>
</tr>
<tr>
<td>Pressure Rating (PR) psig, based on HDB</td>
<td>222</td>
<td>165</td>
<td>200</td>
</tr>
</tbody>
</table>
Preventing Rapid Crack Propagation in PE Pipe

- The best way to design against a Rapid Crack Propagation occurrence in PE pipe is to select a PE material that has high resistance to RCP.

- Most PE materials have high resistance to RCP. The RCP Critical Pressure is generally higher than 1.5 times the leak test pressure.

- With high performance PE 4710 materials, RCP will never occur – the RCP critical pressure is over 650 psig.
The RCP Critical Pressure for butt fused PVC pipe is only half of its pressure rating. This is why there have been so many RCP field failures with butt fused PVC pipe.

- RCP Full Scale Critical Pressure > Installation Leak Test Pressure (LTP = 1.5 times Operating Pressure)

Need to lower the Pressure Rating, or

- Water engineer needs to use thicker wall pipe (lower DR pipe).
“Although it is difficult to estimate the maximum crack speed for a particular material, experimental data from transducer measurements give 600 ms\(^{-1}\) for PVC-U and 300 ms\(^{-1}\) for PE-80 at 3° C just above the critical pressure. These wave speed values correspond to a minimum DR 13 for PVC and DR 29 for PE-80. Although such high DR’s are rarely seen in PE-80, almost all PVC pipe is 'thin-walled' (at least higher than DR 13) and as such is capable of sustaining RCP in 100 percent water pressurized pipe.”

Ref: Greenshields and Leevers
How to Design to Prevent Rapid Crack Propagation

- To prevent long running cracks due to RCP in PVC pipe, the water design engineer should:
  1) lower the pressure rating (PR) of the pipe to PR < \( P_{c,FS}/1.5 \), or
  2) use thicker wall pipe (lower DR for given pipe size) – DR 13 pipe or lower.

- To prevent long running cracks due to RCP in PE pipe, the water design engineer should:
  1) use DR 29 pipe or lower, or
  2) use a high performance PE 4710 material.
Key Benefits of Plastic Pipe Compared to Metal Pipe

- No corrosion
- Excellent long-term performance
- Lower total installed cost
- Easy to join - No leaks with butt fusion
- Easy to install
- Lighter weight
- Easier to handle
Conclusion - Future

- Whether PVC or PE pipe, the future is very bright for plastic pipe as a key piping material to replace the current failing metal water piping infrastructure.

- With knowledge of Rapid Crack Propagation, water design engineers can design their plastic water pipe systems to avoid long running cracks, and have a safe, reliable and cost-effective plastic piping system for their water pipe needs.
THANK YOU

Prepared by
Palermo Plastics
Pipe (P³) Consulting.