# DESIGNING AGAINST RAPID CRACK PROPAGATION IN PVC WATER PIPES

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## ABSTRACT
*Very occasionally PVC-U water pipes suddenly fail due to a long brittle crack with a length of many meters which propagates with the speed of sound along the pipe and causes extensive water loss. This phenomenon was recognized as Rapid Crack Propagation (RCP). Conditions for the occurrence of RCP are an operating pressure above the Critical Pressure ($P_C$) combined with a sudden pressure surge or water hammer which initiates the crack. S4 tests according to ISO 13477 on 25 pieces of water-filled 2.42 m long, 315 mm pipe segments were performed at 3 °C to assess how $P_C$ depends on the wall thickness. For water-filled pipes a thicker pipe wall clearly increases the resistance to RCP. Residual pipe extrusion stress has a distinct negative influence. A Multivariate Statistics Model and Fracture Mechanics Model were developed which describe these influences quantitatively and which can be used to calculate whether RCP is possible or not.*

## INTRODUCTION
Unmodified polyvinylchloride (PVC-U) pipes are used successfully by water distribution companies in Netherland for drinking water pipelines. On average 51% of the total pipeline length is made of PVC [1]. The oldest PVC pipelines date back to the late 1950s. The track record of PVC-U water pipes is good and several old PVC-U pipelines have exceeded their design life of 50 years. The question has arisen if they can be kept in operation for longer.
This can only be assessed if the most important failure mechanisms – apart from third-party damage – are understood. When pipeline quality is only based on failures due to Slow Crack Growth (SCG) a lifetime expectancy of another 30-50 years seems possible [2].
If SCG occurs typical crack growth rates are low, in the order of 0.1 to 1 mm per year.

However, in the last five years the water distribution sector has realised that in addition to SCG another failure phenomenon, which has often been overlooked, may occur as well. In some PVC pipes sudden longitudinal brittle fractures with a length of many meters have occurred (Figure 1). This is known as Rapid Crack Propagation (RCP).
So far, at least 53 cases of RCP in PVC-U water pipes and fittings were noted in Netherland since 2003, although data from several water distribution companies is not yet available. Such failures were partly due to pressure surges or water hammer and partly because SCG had already led to a minute pre-existing defect in the pipe wall. Although not many cases of RCP occur, the consequences are significant, because of the massive water loss (Figure 2).

The propagation speed of an RCP crack in a water-filled PVC pipe can reach 600 m/s [3]. Obviously, the pressure quickly falls off but in water-filled PVC pipes this decompression speed is lower, typically 450 m/s [3]. Consequently, the decompression speed cannot keep up with the crack propagation speed. This means that once an RCP crack in a water-filled PVC pipe is created there is nothing to stop it until a mechanical joint is reached, where an RCP crack always stops, but not at a butt-fused joint [4].
The difference in crack propagation speed compared to SCG cracking speed is huge.
Another difference is that an RCP crack propagates into areas well beyond the initiation site. At such distances propagation follows physical laws unrelated to the conditions at the initiation site.
However, SCG behaviour remains related to the initiation site at all times. Local stress concentrations (due to a small inclusion in the material or a point load) enhance crack initiation, but the SCG rate decreases when the crack approaches the boundary of the stress concentration area. For water pipelines this means that SCG causes small controllable leaks whilst RCP leads to large cracks and uncontrollable water losses.
When a pipeline suffering from RCP runs in the countryside, under a road verge or pavement, the consequences may be limited. However, when a pipeline is located in sensitive areas, like close to a motorway, railroad, dyke, underground station or car park the consequences may be more serious.

*Figure 1. PVC water pipe after RCP. The crack initiated in the middle and ran in two opposite directions. Both branches show bi- or tri-furcation.*

*Figure 2. Water flows through the snow after RCP in a PVC water pipe.*

For lab testing, two ISO methods exist for measuring RCP in plastic pipes, the Full Scale (FS) test [5] which simulates the conditions in a long pipeline and the S4 (Small Scale Steady State) test [6] on segments with a length of only about 7 times the nominal pipe diameter. These standards define that RCP occurs when a fast brittle crack exceeds the critical crack length, which is 4.7 times the nominal diameter. The water pressure at which this occurs is the critical pressure ($P_C$). Below $P_C$ crack arrest occurs.
The ISO standard [6] defines $P_C$ as the highest pressure at which arrest occurs, below the lowest pressure at which RCP occurs. The experiments described here aim to determine $P_C$ at various SDR values (Standard Dimension Ratio: diameter/wall thickness). In this case no pneumatic S4 tests on air-filled pipes were performed, but hydrostatic S4 tests on water-filled pipes.

Leevers and Greenshields [7-12] have shown that for water-filled PVC pipes the critical pressure in the FS test is the same as the critical pressure in the S4 test:

$$P_C\ (S4) = P_C\ (FS) \qquad (1)$$

although this is definitely not true for air-filled polyethylene and polyamide pipes [13,14].

## MATERIALS AND METHODS

Existing equipment for pneumatic S4 tests was converted to perform hydrostatic S4 tests on water-filled Ø315 mm PVC pipes, produced in 2010 and 2012 by a well-known Dutch pipe manufacturer. Twenty-five segments of 2.42 m length each were tested at 3 °C, being the lowest observed drinking water temperature in Netherland.
Pipes with three different wall thicknesses were tested: SDR26, SDR34 and SDR41. For each SDR value 3 pipes with a length of 10 m were cut in 12 segments each with a length of 2.42 m. Each segment was tested at 3 °C. The equipment and the crack length definition were described previously [15].

## RESULTS

Typical RCP behaviour is shown in Figure 3 and complete initiation resistance in Figure 4. Figure 4 only shows two notches, no crack. The intermediate phenomenon is arrest (not shown), a rapid crack which stops before its length exceeds 4.7 times the diameter [6]. Arrest, a very common result with air-filled PVC pipes [16] and PE pipes, is not typical for hydrostatic S4 tests on water-filled PVC pipes, because it occurred only once in 25 cases. Hence, for water-filled PVC pipes the behaviour is almost binary. There is no crack initiation at all when the water pressure is below $P_C$ and RCP until the end of segment length when the water pressure is above $P_C$. The results have been published earlier [15].

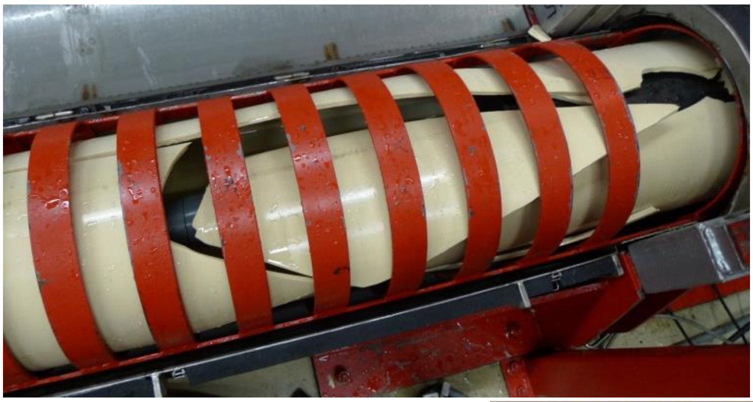

*Figure 3.* (Left) *RCP after an S4 test above $P_C$ on a water-filled 315 mm PVC pipe segment. The crack propagated from the right up to the end of the segment on the left (not shown).*

*Figure 4. (Right) External pipe surface of an "inert" segment tested below $P_C$, which showed no crack initiation. The knife bounced once creating a second smaller notch, also axial.*

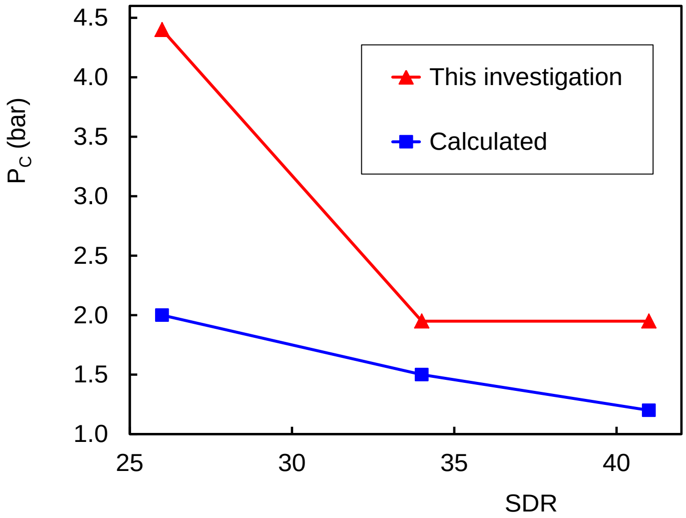


*Figure 5. Influence of the SDR on the $P_C$ of 315 mm PVC pipes in the hydrostatic S4 test and values calculated using the method proposed by Leevers et al [7-12]. Data point for SDR34 pipes in the upper curve appears to be too low.*

Figure 5 shows how the measured $P_C$ is influenced by the SDR. This Figure also shows $P_C$ values calculated according to the method proposed by Leevers et al [7-12]. In both curves $P_C$ decreases with SDR, i.e. $P_C$ increases with increasing wall thickness. This is very important, because common believe expected the opposite. It was not investigated why the calculated values are lower than the measured ones. Possibly the absence of baffles during the measurements plays a part.
The measured data point for SDR34 pipes appears to be too low. Therefore, it was investigated if the SDR34 pipes are in any way different from the SDR41 and the SDR26 pipes, by measuring the degree of gelation, material composition, residual stress and pipe extrusion rate.

**Degree of Gelation and PVC Composition**
The degree of gelation was determined according to EN 1452, but with a different evaluation method, which specifies 4 gelation levels: very low, under gelled, optimally gelled and over gelled. All investigated pipes (irrespective of their SDR class) proved to be over gelled, because none were attacked by dichloromethane at 15 °C. Over gelling leads to poorer impact resistance [17-22] compared with optimal gelation.
The composition of the pipes was compared using infrared spectroscopy. No differences between pipes with various SDR values were noted.

**Residual Stress and Extrusion Rate**

That PVC pipes contain residual stress becomes obvious after a practical case of RCP (Figure 6). The edges immediately move towards each other and overlap, quickly at first and later more slowly. The segments tested in the lab using the S4 test also show this effect. From an intact part of the tested pipes a bar was cut according to the method of Janson [23]. For each of the three SDR values the overlap (OVL) was measured in percentage of the circumference at regular time intervals, up to 1,150 hours. The SDR34 pipes showed more shrinkage after 1,150 hours than the SDR41 and SDR26 pipes (Table 1) and hence had a higher residual stress.

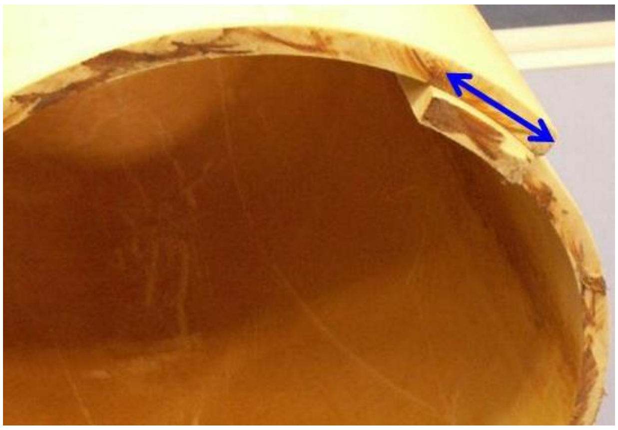

*Figure 6. Overlap of the pipe wall (blue arrow) in tangential direction after RCP in practice illustrating frozen-in extrusion stress.*

*Table 1. Overlap (1,150 hours after cutting a bar from pipes with three SDR values) and the extrusion rate.*

| SDR | Overlap OVL (%) | Extrusion rate (m/min) |
|---|---|---|
| 26 | 3.40 | 0.57 |
| 34 | 4.83 | 0.93 |
| 41 | 4.16 | 0.55 |

The extrusion rates of the pipes were determined from the time prints on the pipe surfaces. The SDR34 pipes were extruded much faster than the SDR26 and the SDR41 pipes (Table 1). Possibly, the deviating OVL and hence the higher residual stress of the SDR34 pipes was caused by the higher extrusion rate.

Residual stresses in old excavated pipes were also assessed (Figure 7). It is remarkable that such pipes, even after 30 or 40 years in the soil, still contain considerable residual stress, up to 8.5 MPa.

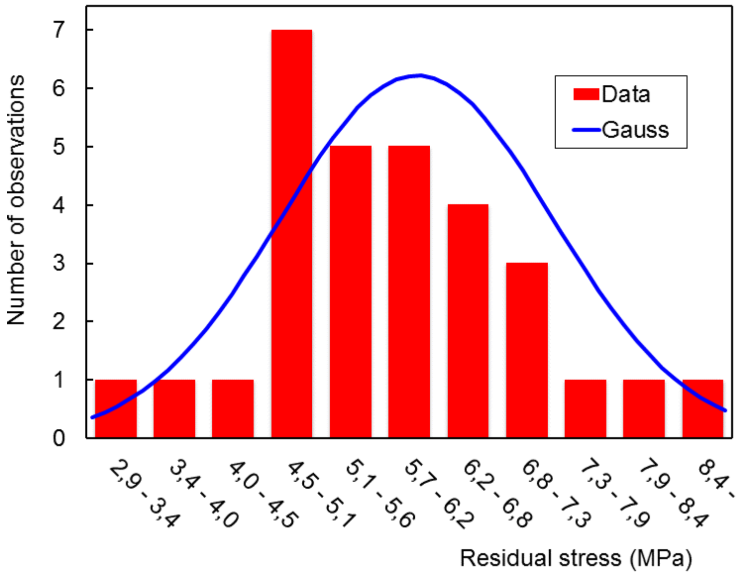


*Figure 7. Residual stress in circumferential pipe direction of 30-40 years old excavated PVC water pipes. Diameters 200 - 500 mm. Most of these pipes had failed.*

**DISCUSSION**

That the resistance of water-filled PVC pipes increases with increasing wall thickness (Figure 5) is an unexpected result. The general agreement in the field of pneumatic S4 tests is that the reverse is true.

Three websites still mentioned this in 2013. However, the calculations based on the method proposed by Leevers et al (Figure 5) confirm that for water-filled PVC pipes the RCP resistance increases with increasing wall thickness. This is a very important result, because it changes how RCP in PVC water pipes is understood.

Next, the influence of residual extrusion stress is discussed. As Figure 7 shows, it is remarkable that the magnitude of the residual stress after several decades is much higher than generally assumed. This is due to a shape factor, the ring shape of the PVC pipe. Because this shape minimises the relaxation of residual extrusion stress, it remains “frozen-in”, at least for several decades. This “shape factor” is comparable to the principle of a Roman bridge from Ancient Times (Figure 8). The manner in which the stones in the bow had been placed was crucial to prevent deformations and obtain a stable structure. The stones in the bows keep each other in place.

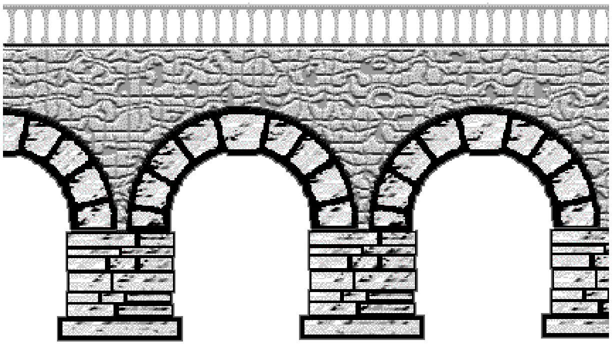

*Figure 8. Shape and placement of the stones prevented collapse of a bow bridge in Roman Antiquity.*

**Multivariate Statistics (Descriptive) Model**
A statistical (descriptive) model was developed to assess the influence of residual extrusion stress from the experimental data [15], using the commercial software SigmaStat ® [24].
OVL is taken as a measure of the residual stress. The only other variables in the model are the water pressure (P) and the SDR. As described previously [15] 3 data outliers were removed and the 22 remaining relative crack length values were converted to binary values (0 or 1). Equation (2) shows how the three variables govern the binary crack length:

$$\text{Logit } L = a_0 + a_1 \,.\, P + a_2 \,.\, SDR + a_3 \,.\, OVL \qquad (2)$$

Logit L is related to the binary crack length L through equation (3):

$$L = 1 / (1 + \exp(-\text{Logit } L)) \qquad (3)$$

These combined equations form the logistical statistical model, which can describe binary values. The software determines the best fit for all 22 data points together. This fit is shown in Figure 9 and Figure 10 and it is very good. The values of $a_0$ until $a_3$ are known to the authors.

The statistical model also makes it possible to investigate the influence of residual stress (or OVL in this case) on $P_C$ separately. If it is assumed that the OVL value of the SDR34 pipes is not 4.83 % as in Table 1, but the average of the OVLs of the other two pipes (3.78 %) instead, then a clear increase in the $P_C$ of the SDR34 pipes is found (Figure 11). This indicates that a relative small decrease in the residual pipe stress already leads to a relatively large improvement (increase) in $P_C$.
Support for the influence of residual stress is provided by pneumatic S4 tests on PVC pipes. After tempering an intact segment for 1 week at 50 °C residual stress was partly relaxed which increases $P_C$. The influence of physical ageing was not large, as that would have reduced $P_C$ [15]. These results support the finding for water-filled PVC pipes that decreasing residual extrusion stress increases the resistance to RCP (higher $P_C$).

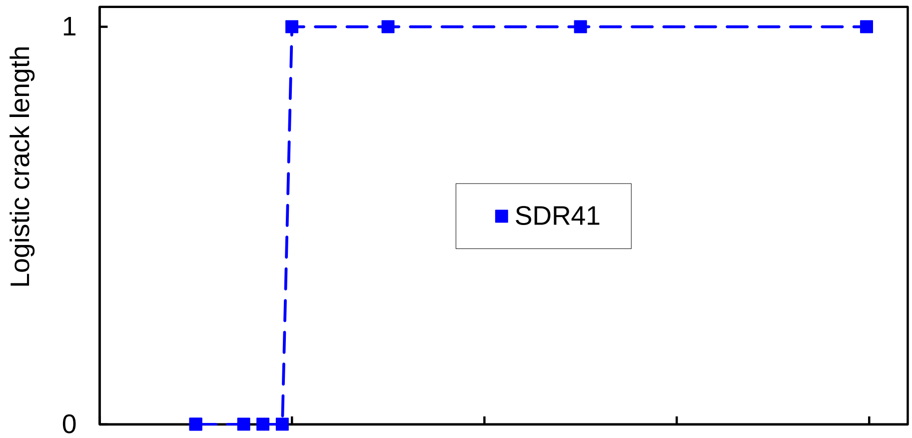


*Figure 9. Description of the binary crack length (L) of SDR41 segments with the statistical model. The same model with the same coefficients was used for Figure 10.*

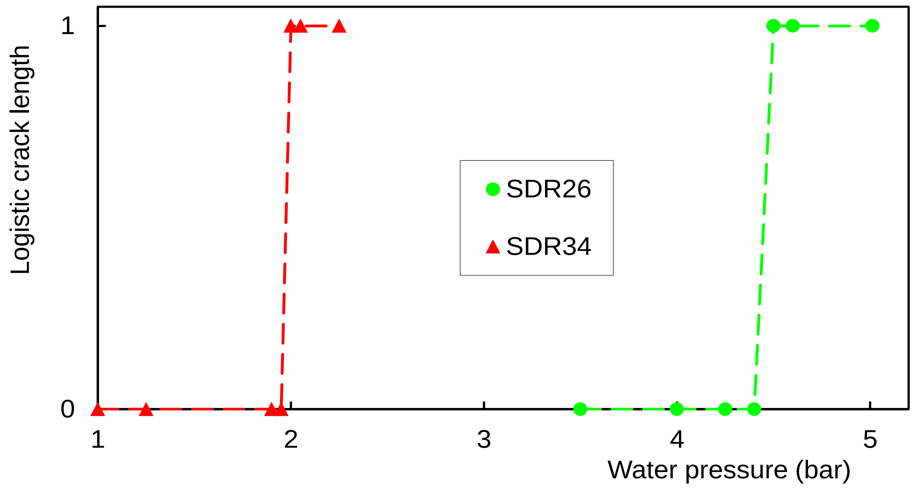


*Figure 10. Description of the binary crack length (L) of SDR34 and SDR26 segments with the statistical model, using the same coefficients as in Figure 9.*

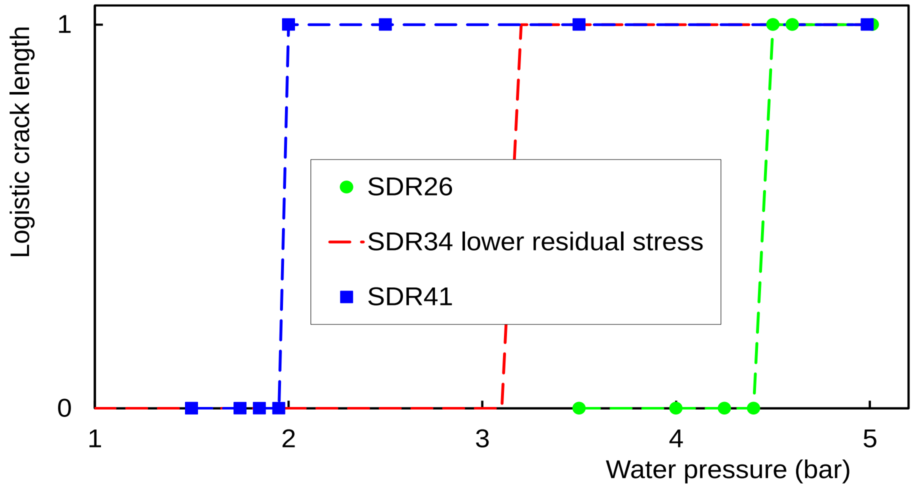


*Figure 11. Prediction of the binary crack length of SDR34 segments using the statistical model, assuming a lower residual stress. Here, $P_C$ increases from 1.95 to 3.1 bars (red dotted line). The curves of the SDR41 and SDR26 segments are not influenced.*

**Fracture Mechanics Model**

The Fracture Mechanics model is not based on the experimental data in Figure 9 and Figure 10, but on material characteristics of PVC from literature. Fracture mechanics is the field of solid mechanics that deals with the behaviour of cracked bodies subjected to stresses and strains [25]. Fracture mechanics defines the material properties, which determine the resistance to crack growth [26]. The corresponding material properties depend on raw material quality and processing.

RCP will only occur when the resistance to crack propagation of the material is insufficient. That is when the energy dissipated during crack propagation is lower than the energy which is released during crack propagation. The PVC crack resistance properties are related to the applied PVC-compound and pipe processing, especially the realised gelation level [21,22] and crazing.

Crack initiation needed for crack propagation can be provided by impact loads, slowly increasing loads, long term fatigue loads and water hammer.

The Fracture Mechanics model starts with the consideration of the energy. Crack propagation will become unstable and herewith rapid when the energy released during crack growth is larger than the energy needed to create the new surfaces of the growing crack. The energy released in a pipe wall is:

- the stored mechanical energy in the pipe wall due to the hoop stress related to the water pressure in the pipe;
- the stored mechanical energy in the pipe wall due to residual stresses related to the production process in which the pipe is cooled from the outer wall after extrusion.

Special attention is given to the contribution of the energy due to the residual stresses [25,27]. Figure 12 shows the crack growth over a length of $l_2$ after an initial crack length of $l_1$. When the internal water pressure is dropped to atmospheric pressure over this length of $l_2$, the mechanical energy stored in this pipe length is released.

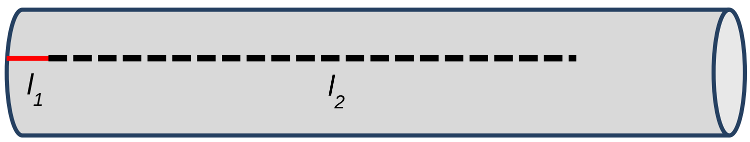


*Figure 12. Schematic illustration of a pipe segment with initial crack (length $l_1$, red line) and a crack propagated over a large distance (length $l_2$, black dotted line).*

**Crack propagation without residual stress**

The modelling of RCP for PVC pipes without residual stress over the pipe wall is based on articles of Leevers et al. [10-12]. The energy of the pressure pulse (for example water hammer), which starts the RCP is neglected. Only the mechanical energy in the pressurised pipe wall is considered. This mechanical energy is released during crack growth. The released mechanical energy per unit area of crack surface growth is called here *M* (equation 4).
The crack resistance, that is the energy required for crack growth per unit area [25], is called *G*. *G* is a material constant defined in fracture mechanics. The G value of plastics is a function of molecular structure, additives, processing (gelation level [22]), degradation and temperature.

The mechanical energy released per unit crack growth surface (M) is given by:

$$\frac{U_{mec\,h,pressure}}{A_{crack}} = \frac{\pi \times p^2 \times (SDR-1)^3 \times e}{8 \times E} = M \qquad (4)$$

Here *p* is the internal water pressure, *E* the E-modulus (modulus of elasticity) of the pipe wall material, *e* the wall thickness of the pipe and *SDR* the ration between the outer diameter and the wall thickness. The fracture surface $A_{crack}$ as shown in Figure 12 is *e* x $l_2$.

No crack growth occurs when *M*, the mechanical energy released at crack growth is smaller than *G*, the energy required for crack propagation [25]. The pipe is then considered inert to crack initiation. The transient peak in mechanical energy due to a water pulse (for example water hammer) can cause a small crack extension which shows arrest. However, when *M* is exceeding *G* continuously, the crack growth becomes instable and turns into RCP.

**Residual stress**

The residual stress in a pipe wall due to the outer wall cooling after extrusion can be measured experimentally but can also be modelled.
The temperature gradient over the pipe wall thickness during the pipe extrusion was calculated for different cooling lengths using the heat equation [28]. A finite element method solution of the cooling process results in a changing temperature gradient versus the cooling length. Figure 13 illustrates that the average wall temperature and it gradient decrease with increasing cooling length, as expected.

Using the temperature gradient over the pipe wall during cooling (Figure 13), the residual stress over the pipe wall can be calculated after a certain cooling length *l*. The material properties required for this calculation are the temperature dependent E-modulus and thermal expansion coefficient. An example of the residual stress over the pipe wall is presented in Figure 14. The absolute value of the compressive stress at the outer wall is larger than that of tensile stress at the inner wall. This stress gradient over the pipe wall means that additional mechanical energy (*M* in equation (4)) is stored in the pipe wall which is released when the pipe wall is cut or cracks in length direction.

**Crack growth with residual stress**

The residual stress corresponding to the stress gradient over the pipe wall (Figure 14) is released when the pipe breaks (Figure 6). This stress contribution to the critical water pressure $P_C$ was calculated for different SDR classes, pipe diameters and magnitude of the residual stress.

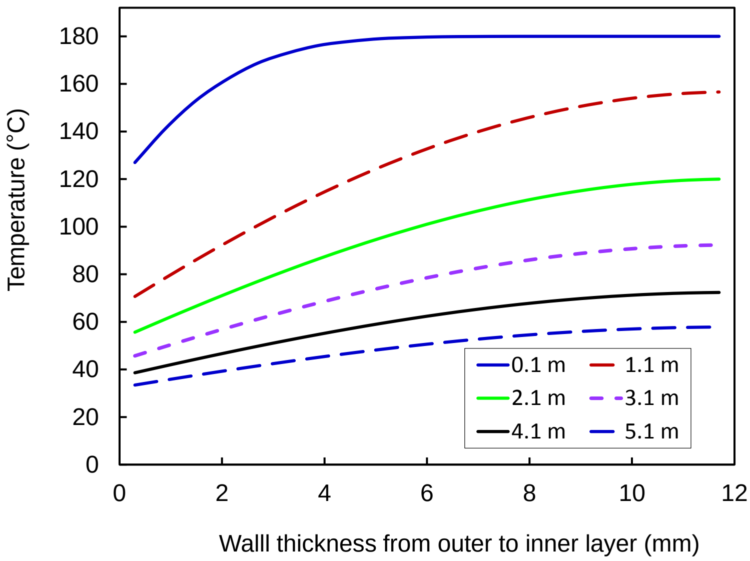


*Figure 13. Calculated temperature gradients over the wall thickness (12 mm from outer to inner layer) of a 315 mm SDR26 pipe at 6 different cooling lengths (0.1 until 5.1 meter). The outer wall corresponds with 0 mm and the inner wall with 12 mm.*

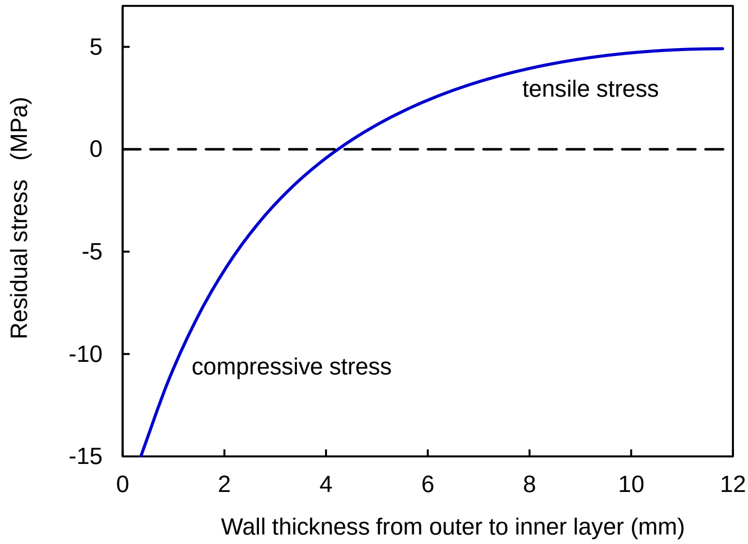


*Figure 14. Calculated residual stress over the wall of 315 mm SDR26 pipe after a cooling length of 25 meter. The outer wall corresponds to 0 mm as in Figure 13. The tensile stress in the inner wall is positive and the compressive stress in the outer wall is negative.*

Excavated pipes still show an overlap of 2 to 8% of the circumference (Figure 7). About 8% is the highest value found. The calculation shown in Figure 14 corresponds to an overlap of 6 %.

Starting from the calculations resulting in stress gradients shown in Figure 14, the critical pressure $P_C$ (in bar) above which crack propagation occurs can be approximated by:

$$p_c \approx \frac{20}{SDR-1}\sqrt{\frac{2 \times E \times G}{\pi \times e \times (SDR-1)} - \frac{(n \times \sigma_{i0})^2}{2n+1}} \qquad (5)$$

where *n* is a constant which is related to the non–linear behaviour of the residual stress over the wall thickness (Figure 14) and $\sigma_{i0}$ the residual stress at the inner wall (about 5 MPa in Figure 14).

Literature values obtained at 20 °C were used because the values at 3 °C are unknown. The critical pressures using $E$ = 3 GPa, $G$ = 3 kJ/m$^2$, $n$ = 3 and nominal values of the wall thicknesses have been calculated given different values for the tensile stress in the inner pipe wall. These calculated values are presented in Table 2 for 315 mm and 110 mm pipes, at three SDR values.

*Table 2. Calculated critical pressures for 315 mm diameter PVC pipes (above) and 110 mm pipes (below). E = 3 GPa, G = 3 kJ/m$^2$, n = 3 at 20 °C.*

| 315 mm | | $P_C$ (bar) | |
|---|---|---|---|
| $\sigma_{i0}$ (MPa) | SDR = 26 | SDR = 34 | SDR = 41 |
| 0 | 3,5 | 2,6 | 2,2 |
| 1 | 3,4 | 2,5 | 2,1 |
| 2 | 3,0 | 2,2 | 1,8 |
| 3 | 2,2 | 1,6 | 1,3 |
| 110 mm | | $P_C$ (bar) | |
| $\sigma_{i0}$ (MPa) | SDR = 26 | SDR = 34 | SDR = 41 |
| 0 | 5,9 | 4,4 | 3,6 |
| 1 | 5,8 | 4,3 | 3,6 |
| 2 | 5,6 | 4,2 | 3,5 |
| 3 | 5,2 | 3,9 | 3,2 |

The calculations show that larger diameter pipes are more vulnerable for RCP than the smaller diameter pipes. That is the critical pressure for RCP is higher for the smaller diameter pipes. This conclusion is in agreement with literature and practical experience. Furthermore, $P_C$ increases with increasing wall thickness (decreasing SDR) which is in agreement with Figure 5.
Furthermore, the Fracture Mechanics model shows that the critical pressure for RCP is decreased when the residual stress is higher. This phenomenon is in agreement with the experimental data.

The material model thus confirms that the residual stress provides additional energy which results in a lower critical pressure for RCP.
The results given in Table 2 show that RCP cannot be excluded in PVC water pipes at operation water pressures which are allowed according to their pressure class. Notwithstanding this conclusion, the number of RCP failed pipes is limited to several cases per year in the tap water distribution system in Netherland. Therefore, a water pressure exceeding the critical pressure for RCP only results in RCP in a limited number of pipes within 50 to 100 years. Other conditions, which have to be fulfilled to obtain RCP, are for example crack initiation and water hammer.

## CONCLUSIONS AND RECOMMENDATIONS

1. At 3 °C the $P_C$ values found in this investigation (1.95 to 4.4 bars) for water-filled 315 mm PVC pipes lie in the normal operating pressure range for PVC water pipes in Netherland (up to 6.5 bars). Moreover, the results obtained with 2.42 meter long segments are also valid for longer pipes. This explains why since 2003 at least 53 cases of RCP have been observed in old PVC water pipes and fittings in Netherland.
2. The behaviour of water-filled PVC segments is almost binary. At low water pressures, below $P_C$, the segments show complete resistance to any crack initiation, whilst above $P_C$ RCP occurs with a crack usually propagating through the entire segment length, up to the end cap on the other end. The reason is that the decompression speed of the water is lower than the crack speed in the PVC wall. There was only one case of arrest where a fast brittle crack that had already been initiated stopped before the critical crack length of 4.7 times the diameter was reached.
3. The wall thickness (SDR value) of water-filled 315 mm pipes has a large influence. $P_C$ increases from 1.95 bars for thin-walled SDR41 pipes to 4.40 bars for thick-walled SDR26 pipes. This means the risk of RCP fractures in PVC water pipes decreases by choosing a thicker pipe wall. This new result contradicts previous beliefs and convictions among testing labs and helps water distribution companies when they want to install pipes in risky areas.

4. Residual extrusion stress in the PVC pipes should be minimised to prevent a large negative influence on the resistance to RCP of water-filled PVC pipes.
5. All investigated pipes were over gelled. A slightly lower degree of gelation, to reach an optimal level, provides a better impact resistance and probably a better RCP resistance as well.
6. It is advised to reduce the occurrence of water hammer and pressure surges in those existing pipelines which are operated above $P_C$.

## FURTHER RESEARCH

1. Bi-axially oriented PVC (PVC-O) sheet shows a resistance to impact loading which is 10-16 times higher than PVC-U sheet [29]. It is expected that the resistance to RCP of PVC-O pipes will also be much higher than that of PVC pipes. This makes PVC-O pipes a very interesting new development.
2. Investigate the influence of higher water temperatures, other pipe diameters, the degree of gelation and the magnitude of the residual stress on $P_C$.

## ACKNOWLEDGEMENTS

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