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SERVICE LIFE ANALYSIS OF PVC GAS PIPES IN PRACTICE: A PREDICTABLE BEHAVIOUR !

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In the Netherlands about 20,000 km of uPVC (unplasticized PolyVinylChloride) gas pipes are in use. The oldest uPVC pipes have been in operation for over 30 years now. These systems were usually designed for a period of between 30 and 50 years. Probably, however, the actual service life will turn out to be much longer. An extensive research programme at VEG-GASINSTITUUT was set up to establish relations between physical-chemical behaviour and mechanical properties of these gas pipes in order to come to an experience-based prediction of the residual service life.

INTRODUCTION

Since the early seventies polyethylene (PE) has been the most generally applied pipeline material for the distribution of natural gas. However, in various countries thousands of kilometres of PVC gas pipes are still in operation.
The residual service life of PVC gas pipes depends on many factors, such as molecular weight distribution, K-value, degree of gelation of the material, additives and internal and external environmental influences.
This paper gives a description and some results of the research programme at VEG-GASINSTITUUT that was set up to establish relations between physical-chemical behaviour and mechanical properties of the PVC gas pipes.

The research programme featured the following steps:

Part 1: measurements carried out on fifty seven different pipe - materials, used in practice in various parts of the Netherlands. The different pipe materials originate from different locations in the distribution network. Conditions: unfortunately, little is known about the initial properties of the PVC pipes.

Part 2: measurements on well-defined pipe material, which has been in operation for six years. The reference pipes were stored at VEG-GASINSTITUUT.

Part 3: combining the results of part one and two to determine those critical factors that are essential to the service life of PVC gas pipes.

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The following techniques were used to determine the mechanical and physical/chemical behaviour of the pipe materials in this research programme:

a. mechanical behaviour:
   - deformation measurements of the buried pipes as a function of soil conditions (Alferink et al.(1));
   - internal water pressure tests at 60 °C and an operating hoop stress of 14 MPa, to determine a parameter for long-term behaviour;
   - measurements of the impact behaviour of the pipes in the instrumented falling-weight test

b. chemical/physical behaviour:
   - The resistance against dichloromethane at elevated temperatures (Experimental);
   - Infrared Spectroscopy to get a fingerprint of the composition of the pipe materials;
   - Differential Scanning Calorimetry to get information about the thermal history of the PVC material;
   - Gel Permeation Chromatography; measurements to get information about such molecular parameters as Mw, Mn and Mw/Mn (polydispersity);
   - Scanning Electron Microscopy with element analyser to obtain information about the inorganic elements used in pipe production, mostly processing aids for pipe extrusion.

Besides these techniques the pipes were visually inspected before and after the tests.

This paper will give only an overview of the most important critical factors found. Presenting all information would be too overwhelming and far too extensive.
The final paragraph will give a summary of all the conclusions found in this research programme.

DESCRIPTION OF THE PIPE MATERIALS

At different locations in the Netherlands pipe materials have been dug out for the research programme. The following table gives an overview of the pipe materials' origins.

Table I: Locations of the pipe materials (districts) as well as diameters.

	diameter 110mm	**diameter 160mm**	**diameter 200mm**	**total number**
District:				
Noord-Holland	11	8	2	21
Zuid-Holland	8	2	1	11
Zeeland	1	1	-	2
Noord-Brabant	-	1	-	1
Limburg	1	1	-	2
Gelderland	3	5	-	8
Drente	-	1	-	1
Friesland	2	-	1	3
Groningen	4	3	1	8
total number	**30**	**22**	**5**	**57**

The moments the pipe materials were installed for the distribution of natural gas range from 1959 to 1974. After 1974 no unplasticised PVC pipes were put into the ground for natural gas supply.

In 1982 well-defined PVC pipes were used in a special test network. A selection of these pipe materials has been stored at VEG-GASINSTITUUT for reference. Part of the various pipe materials were dug out at the end of 1988 and used for evaluation in the test programme of VEG-GASINSTITUUT.
The well-defined pipe materials were produced in 1978 and 1982 as pipe for water distribution. These pipes were manufactured by two different pipe production companies in the Netherlands.
The results will be described separately at the end of each paragraph.

EXPERIMENTAL

Resistance to dichloromethane at different elevated temperatures (MCT test)

When a poorly gelled PVC pipe is contacted with dichloromethane a white, or even worse, a powdery precipitate appears on the surface. A properly gelled pipe will not be attacked. The probability of the attack is controlled by the test temperature.

The test method applied was derived from the description given in reference 2. For the purpose of this test both ends of three 200mm lengths of pipe were machine chamfered.
One end of the test pieces was immersed for 30 minutes in dichloromethane (technical grade) that was kept at a temperature of 10 °C ± 0.5 °C. Afterwards the samples were dried in air and the chamfered surface was examined. If any attack had occurred the other end of the pieces was immersed in dichloromethane of 5°C; on the other hand if no attack was found the other end of the test piece was immersed in dichloromethane of 15°C.
This test will further be referred to as the MCT test.

The appearance of the attack at a certain temperature gives an indication of the level and homogeneity of gelation of the pipe. This characteristic is related to the mechanical properties and the long-term pressure resistance of the pipe.

Impact resistance measured using the Instrumented Falling-Weight Test (IFT test)

An important quality parameter of pipes is the impact resistance. Using the Instrumented Falling-Weight Test (IFW test) described by Rijpkema (3), the amount of energy absorbed before failure occurs can be measured.
Figure 1 schematically shows the energy to failure as a function of the test temperature. At a low test temperature the energy to failure is low and the pipe will break in a brittle way. At higher test temperatures ductile failure occurs with much higher energies to failure. At a certain temperature, or more accurately within a

certain temperature range, transformation into a brittle failure mode occurs. The temperature at which 50% of the pipe samples will break in a ductile way and 50% in a brittle way will be called the ductile-brittle transition temperature, further referred to as the transition temperature.
The curve shown in Fig. 1 can be shifted horizontally as well as vertically as a function of production quality or gelation of the pipes. The transition temperature can be analysed by performing the instrumented falling-weight test at at least two test temperatures and determining the percentage of ductile failures at each temperature. Ductile failure is represented by the force-deflection curve as shown in Figs. 1A and 1B.
For most of the pipe materials the IWT test was performed at three test temperatures. These three temperatures were 0 °C, +10 °C and +20 °C. Forty to fifty pipe samples were tested at each temperature to obtain significant test results followed by a calculation of the transition temperature by linear interpolation (Ref.4 & 5).

The reference pipes and the pipes from the test network were tested at two different test temperatures: 0 °C and 10 °C; by lack of pipe material no third test temperature could be used.

RESULTS

MCT

The following table (Table II) will summarize the MCT test results of the fifty seven different pipe materials. The location of the attack is in most cases the middle of the pipe wall. So for these old pipe materials gelation in the middle of the pipe wall is not as good as on the inside and outside of the pipe wall.

Table II: A summary of the different pipe materials tested. The following items are given: the mean test temperature of the three pipe samples tested where they showed attack after immersion in dichloromethane; the number of pipe materials showing attack at a certain test temperature (mean) and the number of pipe materials showing attack in the middle of the pipe wall (location: middle).

temperature (°C)	**number of pipe materials (3 samples each) (-)**	**location of attack (middle) (-)**
15	20	20
10	14	12
5	7	7
13.3	5	5
11.7	4	3
8.3	1	1
6.7	6	5
total number:	**57**	**53**

The four different well-defined pipe materials show slight attack at the test temperature of 15°C. So these pipe materials are of a good gelation quality.

IFW test

Some test results are presented in Table III.
The temperature at which the experiments were started was 10 °C.
In some cases the highest temperature at which the pipe samples were tested was 30 °C.

Table III: **Test results of the IFW test at three temperatures. In this table are given: the pipe code, the year in which the pipe was buried and the ductility percentage at the various temperatures**

pipe code (..-..)	**buried** (year)	**ductile fracture percentage at:** 0°C (%)	10°C (%)	20°C (%)	30°C (%)
89-17	1959	58	90	--	
89-18	1967	9	48	--	
89-19	1968	19	55	--	
89-20	1969	--	2	6	60
90-07	1969	0	13	55	
90-08	1972	20	56	88	
90-09	1964	38	76	100	
90-10	1969	--	12	30	62
90-11	1969	--	2	26	64
90-12	1967	6	50	87	

By linear interpolation the transition temperature can be calculated.
The transition temperature of the various materials varied considerably: from -5 °C till more than +30 °C.
About half of the pipe materials had a transition temperature below 10 °C, whereas the rest showed a transition temperature above 10 °C. This means that some materials are rather brittle at ambient temperatures (the soil temperature around gas pipelines varies between about 5 and 12 °C). But some other materials will show ductile behaviour at ambient temperatures.

The four different well-defined pipe materials showed almost no difference in impact behaviour. These pipe samples were tested at two different temperatures. All four have a transition temperature near 5 °C.

No difference was found between impact behaviour of the reference pipe materials and the pipes that had been in operation for six years in a special test network. The transition temperature of these pipes is near 5°C.

DISCUSSION

The impact results of the instrumented falling-weight test at 10°C show the most extreme differences in percentage of ductile failures of the various PVC pipe materials tested.
In Fig. 2 the transition temperature is given as a function of the ductility percentage at 10 °C for the various materials.
By performing impact tests at just one temperature it will be possible now to distinguish between differences in impact quality.
For unplasticised PVC this temperature is recommended to be +10 °C.
It must be remarked, that the results of the used IFW test are not comparable with the results of the conventional falling-weight test (Ref. 6).

Comparison of MCT test results and IFW test results

This shows the great influence of gelation on the impact resistance of the pipe materials. Especially when the results of the MCT test show considerable attack at 5 °C the impact test results show a high number of low energy failures. Most of the failures were brittle at 0 °C and 10 °C.
Fourteen pipe materials showing attack after immersion in dichloromethane at 5 °C (at least one of the three pipe samples) have a transition temperature above +10 °C.
For nine of these pipe materials the transition temperature will be above +20 °C.
The pipe materials exhibiting almost no attack after immersion in dichloromethane at 15 °C were found to have a transition temperature of between +11 °C and -4 °C.

CONCLUSIONS

This paragraph includes a summary of conclusions found with techniques used, but not described in detail in this paper.

* The various analysed pipe materials show differences in pipe quality. These pipe materials are still in use as part of the distribution network. The pipe materials were dug out for research reasons, not because of the poor behaviour in practice. No spontaneous leakage has occurred in the distribution network.

* The resistance to dichloromethane at different elevated temperatures, by the MCT test, gives a good indication of the level and homogeneity of gelation of the pipe material. This also gives valuable information about the initial quality of the pipe material. When pipe material shows attack when immersed in dichloromethane at 5 °C, the pipe material is not of a good quality which means that the initial quality was poor.

* Instrumented falling-weight tests might be carried out at one temperature to give an indication of the impact behaviour of the pipe material. This test temperature will be +10 °C for unplasticized PVC (uPVC) for the used test configuration (3). When the pipe samples show more ductile failures than brittle

failures and no pipe samples break with a energy below 10 Joule, the pipe material will have good resistance to external impacts.

- No difference was found between impact behaviour of the reference pipe materials and the pipes that had been in operation for six years. So the impact resistance is unaffected by the time in operation.

- The initial quality is the most important factor for field performance of the pipe.

- Deformation measurements show that point loading gives the highest stresses found independent of the type of soil but depending on the laying conditions. Sometimes crazes were found at the location of point loading, but these did not affect impact behaviour. Some pipe materials were highly deformed. This will give problems at the joints and in making a new branch.

- Burst pressure test results show that all the pipe materials tested are still meeting the requirements stated in the then used ISO requirements (Ref. 6). No relation was found between the number of years in operation and time to failure

- DSC measurements give a good indication of the thermal history of the pipe materials. The information is only representative for a very local spot of the pipe circumference. The results of the MCT test show poor homogeneity in producing most of the older pipe materials. In future these DSC analyses could best be done after the MCT test procedure for the pipe materials taken from practice. The location of sampling can be chosen more optimally then.

- Infrared Spectroscopy gives just additional information about the organic components in the pipe material. These organic components, apart from the PVC itself, are mostly processing aids. Within the processing period of the "older" PVC pipes no correlation was found in components detected and year of production.

- The results of Gel Permeation Chromatography show a range of polydispersities (Mw/Mn), the values differing from 1.9 to 3.5. The manufacturers state a normal value of 2.2. No relations were found with mechanical behaviour of the pipe materials.

- The fractured surfaces of pipes failed in the burst pressure - test were analysed by Scanning Electron Microscope. The results show that every failure has started from a location were particles were found with sizes of 50-250 μm, or at a location of an agglomerate of smaller particles (3-10 μm). Most of these particles (in all the pipe materials analysed) contained the following elements: Aluminium, Silicon, Calcium and Lead. In addition, Natrium, Sulphur, Iron and Phosphorus were detected. Most of these elements are present in processing aids. No relation between these elements and the year of production was found.

IN CONCLUSION:

- The initial pipe quality is the most critical factor which determines the performance of uPVC gas pipes
- The service life of uPVC pipes will extend 50 years, though the pipes are rather vulnerable to impact loading.

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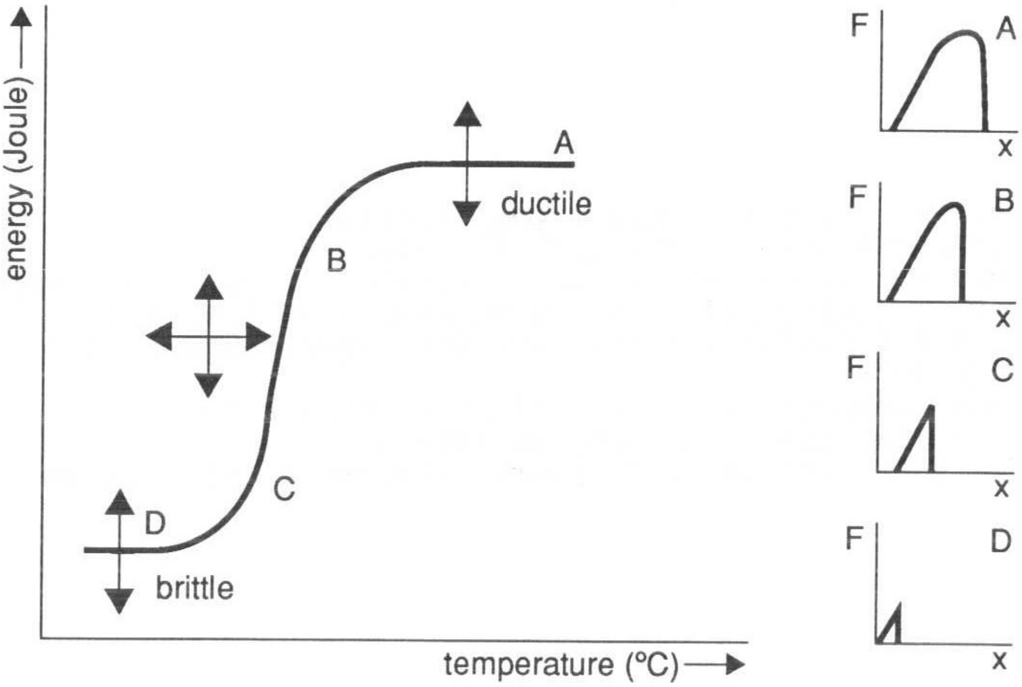

FIGURE 1: The fracture energy (Joule) as a function of the test temperature (main figure). In this main figure the codes A, B, C & D are given. Beside the main figure the force-deflection-(F-x) curves given at the locations of code A, B, C & D.

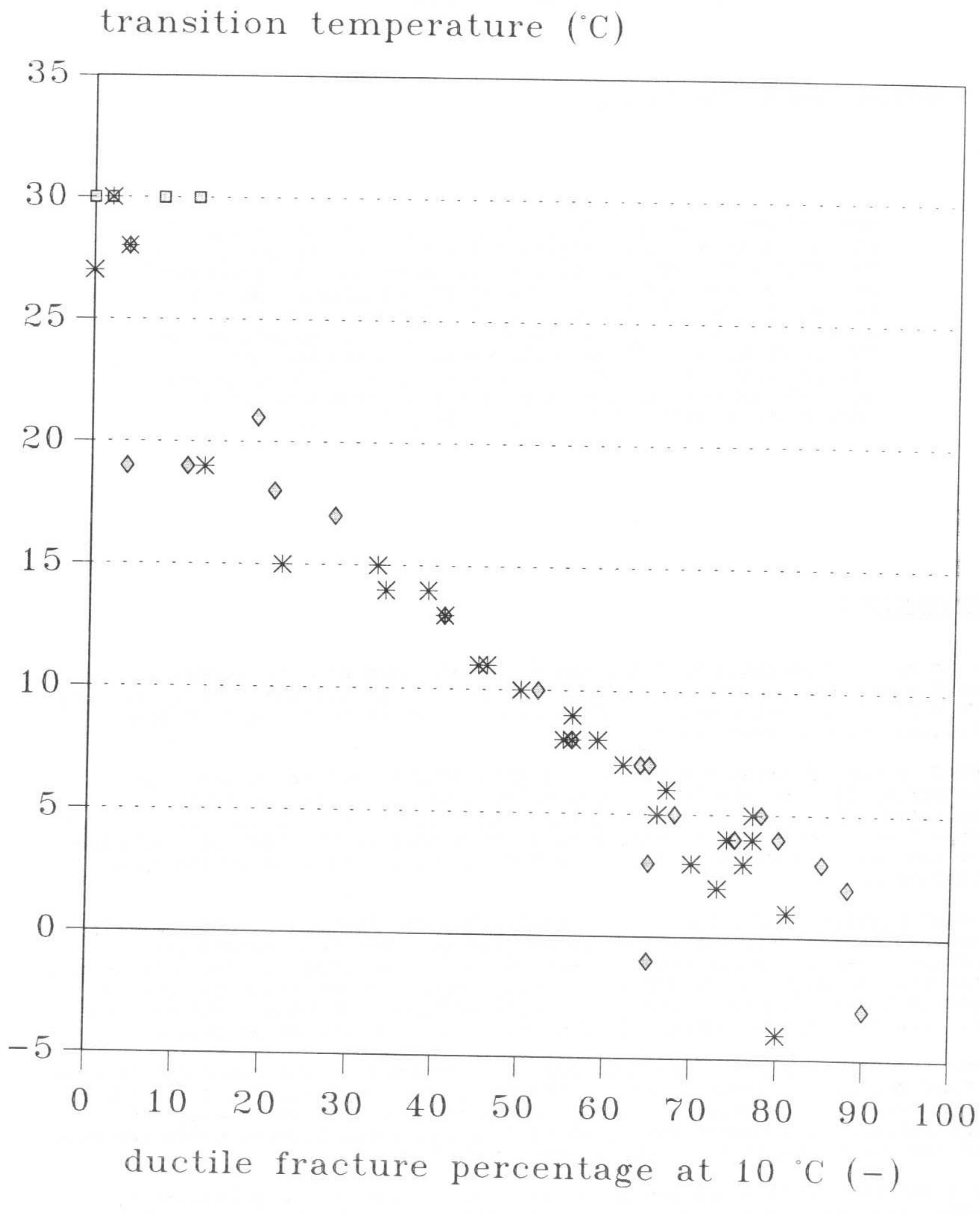

FIGURE 2: The transition temperature as a function of ductile fracture percentage at 10 °C. In the figure the following symbols are used:
- * results of pipes with a diameter of 110mm;
- ♦ results of pipes with a diameter of 160mm;
- ■ results which give a transition temperature above 30 °C

AN EVALUATION OF TOUGHENED PVC-U PRESSURE PIPES

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The relatively high safety factors used in the design of PVC-U pressure pipes reflect concern about the possibility of brittle failure in service. Toughness may be improved by the addition of impact modifiers and plasticisers but normally strength is impaired. In this paper we show that pipes exhibiting a high resistance to crack growth may be obtained while still maintaining long term strength (50 yr) over 25 MPa. We also discuss new and alternative test procedures which we feel would be essential if a reduction in safety factor is to be justified.

INTRODUCTION

It is quite remarkable that the two materials used so extensively in the manufacture of thermoplastic pressure pipes are so different in properties. PVC-U is strong but prone to brittle failure while PE has a much lower strength, but is very tough.

PVC-U is around three times stronger than PE but because of its higher susceptibility to brittle failure, this advantage cannot be fully exploited. Based on the widely used safety factors of 2.0 and 1.25 respectively, the wall thickness of a PVC-U pipe is 50% that of a PE pipe for the same operating pressure and not 33% as it would be purely on a strength basis.

Impact modified PVC materials are available. For instance, these materials are used extensively for window frame profiles. The Netherlands gas industry uses an impact modified PVC pipe for services and there is an ISO standard for high impact PVC pipes (1). However, these materials are so heavily modified, their strength is much reduced, and this combined with the high cost of the additives rules out their use for water pipes.

Over recent years much attention has been focussed on the toughness of PVC-U pipe materials, particularly in the UK. It has been shown that increased toughness may be achieved by judicious combinations of processing and formulations (2). Nevertheless, there is still a gap between these products and the impact modified products mentioned above.

If a material were to be developed to fill this gap for application in water pressure pipes, the emphasis would be on toughness over long time scales rather than impact. Once pipes are safely buried, it is highly unlikely that they will fail due to sharp impacts. What is necessary is a PVC material that will stem the growth of cracks from defects especially when the localised stresses are enhanced by point loads.

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