70 years of experience with PVC pipes

Thomas Hülsmann, European Vinyl Corporation (Deutschland) GmbH
Reinhard E. Nowack, ALPHACAN Omniplast GmbH

The demand for PVC has increased continuously in line with social development. Today, worldwide consumption is approaching 30 million tonnes per annum [1] and global growth is expected to be more than 4 % per annum. A significant proportion of this growth will be in PVC pipes, which make up about 27% of the market for PVC in Europe [2].

PVC pipes are used in a wide variety of applications, such as sewage, potable water, drainage and gas. In these areas plastics pipes often replace traditional materials. PVC continues to dominate the global plastics pipes market. In Europe, PVC use in pipes was 1.5 million tonnes, in 2002.

The roots of industrial PVC pipe production date back to the 1930`s. The first pipes were produced in 1934 in the Bitterfeld-Wolfen chemical industry area. These pipes were used for different applications such as potable water pipes, transparent food contact pipes (brewery applications) as well as industrial pipes (chemical laboratory and plant applications). The annual pipe production capacity reached about 480 to 600 tonnes in 1941 [3].

In parallel to the increasing production volumes the first standards for plastic pipes were developed and products were made to meet them.

Although the plastics industry is a relatively young materials segment, the production of industrial volumes of PVC polymer and PVC-U pipes is now about 70 years old, which is close to the predicted service lifetime of 100 years for PVC pipe applications.

After the reunification of East and West Germany in 1989 and the involvement of Omniplast with pipe production in Bitterfeld, it was possible to excavate and test PVC-U pipes from the early production years, as they were still in use in 1992/3.

A comprehensive series of tests on several of these old pipes and pipes produced in Troisdorf in the 1930´s and 1950´s was carried out, and the results compared against the current norms. The results provide an excellent basis on which to compare the data from the original long term pressure tests with actual results from 60 year old pipes.

This is not only an interesting reflection of the history of PVC pipe production and application as well as a confirmation of the long term performance predicted 60 years ago, but it is also an important contribution to future PVC pipe developments.

1. **History of PVC and PVC pipes** [3, 4]

The history of PVC started in 1835 when Regnault discovered vinyl chloride (VC) in the Liebig laboratory. But it took almost 100 years before first industrial production of PVC was started in 1928 in USA and 1930 in Rheinfelden, Germany.

Table 1 shows some important milestones in PVC history [5, 6].

1835	Liebig and Regnault discovered VC
1878	Baumann observed the light-induced polymerization of VC
1912	Zacharias and Klatte obtained VC by the addition of HCl to acetylene
1913	Klatte polymerized VC with organic peroxides and described the processing of PVC as a substitute for horn and for films, fibers and lacquers
1926	Griesheim-Elektron allowed the PVC patents to lapse; this opened the door for other companies
1928	Union Carbide and DuPont copolymerized VC and vinyl acetate
1930	IG-Ludwigshafen copolymerized VC and vinyl ethers and acrylic esters. VC was emulsion-polymerized. PVC was stabilized with alkali salts. PVC was characterized by its K value (Fikentscher).
1932	PVC was chlorinated (IG-Bitterfeld)
1933	Semon used phthalates and phosphates as plasticizers for PVC
1934	VC was suspension-polymerized (Wacker). The capacity in 1945 was 35,000 tons. A PVC pilot plant was opened in Bitterfeld (600 tons/year). Frazier Groff (Union Carbide) discovered alkaline earth soaps, and Carbide & Carbon Chemicals used lead salts as heat stabilizer for PVC.
1936	PVC was manufactured by Union Carbide and Goodrich. Dialkyl tin soaps were used as stabilizers by Carbide & Carbon Chemicals.
1947	Barium, cadmium, calcium, and zinc soaps were synergistically combined
1962	VC was bulk-polymerized in a two-stage reactor (in 1975, a one-stage reactor was used) by St. Gobain and Pechiney (Rhone-Poulenc).

Table 1: Milestones in PVC History

The white PVC polymer from Rheinfelden production was called “Igelit” and could not be processed with machinery used for rubbers and Celluloid which where already processed at that time.

After understanding that PVC needs temperature and pressure to melt it, in 1934/35 the modification of existing rubber calenders and metal pipe ram extruders and the related processing conditions resulted in first calendered crepe which were further processed into sheets, pipes, rods and profiles. PVC production volumes grew in Bitterfeld from 2686 tonnes in 1939 to 9202 tonnes in 1941.

By reference to old documents the PVC polymer was manually mixed with additives (lubricants) than it is known that calendered for 20 to 25 minutes at 160°C on a 2 roll mill to a crepe. This crepe was than manually rolled to a coil (sausage) of about 180 mm diameter and a length of 500 mm. This hot (160-165°C coil) was fed into a hydraulic ram extruder with cylinder temperatures of 160/165°C and die-temperatures of about 200 – 230°C. These first discontinuously extruded pipes had lengths of 150 cm and 420 cm and were air cooled. This ram extrusion processes developed for making pipes in Bitterfeld in 1935 was transferred to two other production sites in Troisdorf and Eilenburg.

In Bitterfeld pipes of 5 to120 mm diameter were produced during the early years. In 1941 it was possible to extrude PVC-U pipes up to 160 mm diameter and pipe production capacitiy increased in the three plants up to 600 t/year.

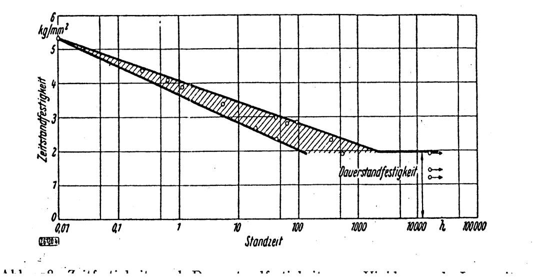

Figure 1: Long term creep strength of early Vinidur pipes

The PVC-U pipes were marketed under the trade name “Igelit” and “Vinidur” (Bitterfeld), “Mipolam” and “Trovidur” (Troisdorf) and “Decetith” (Eilenburg).

From 1942 to 1945 the extrusion process was developed further and the first continuous single screw extrusion was used to convert PVC-granules into pipes. The development of counter-rotating twin screw extruders started some years later.

At the same time as PVC pipe production started, the properties of the pipes were investigated and different application areas for the first pipes were selected. The following properties were tested regularly: density, tensile strength, elongation at break and impact strength/ductility.

Official reports characterized the PVC-U pipes as follows:

“PVC-U pipes have a specific weight of 1.4 g/cm³, a softening temperature of 80 to 85°C, a tensile strength of 500kg/cm² (= 50N/mm²) and an elongation at break of 15 to 20%. The product is physiologically blameless, resistant against acids, alkalis and sodium hydroxide, alcohols and benzene.

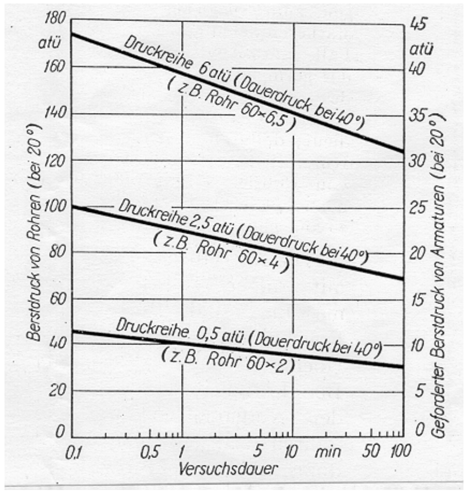

Figure 2: Short term hydrostatic burst pressure of early Vinidur pipes (left axis) and fittings (right axis) at 20°C

It is inflammable, a good electrical insulator and a poor thermal conductor."
On the basis of the first technical characterization the PVC-U pipes were, in 1935/36, directly used in different applications: the first water pressure pipes were layed in the cities of Bitterfeld and Salzgitter, pipes were used in the chemical industry for corrosive liquids and they were used for in-house potable water pipes as well as for food contact applications such as brewery pipes. Transparency and resistance against encrustrations made it a successful product in food contact applications.

Beside the practical experience with the pipes from first production comprehensive systematic laboratory investigations had also been done. Buchmann [7] and Krannich [8] documented relevant properties, including creep strength, chemical resistance and welding performance. In 1941 the first diagrams from hydrostatic burst pressure tests and long term creep test were available (figures 1, 2) and the first PVC-U pipe DIN-standards were established (figures 3) [9, 10, 11].

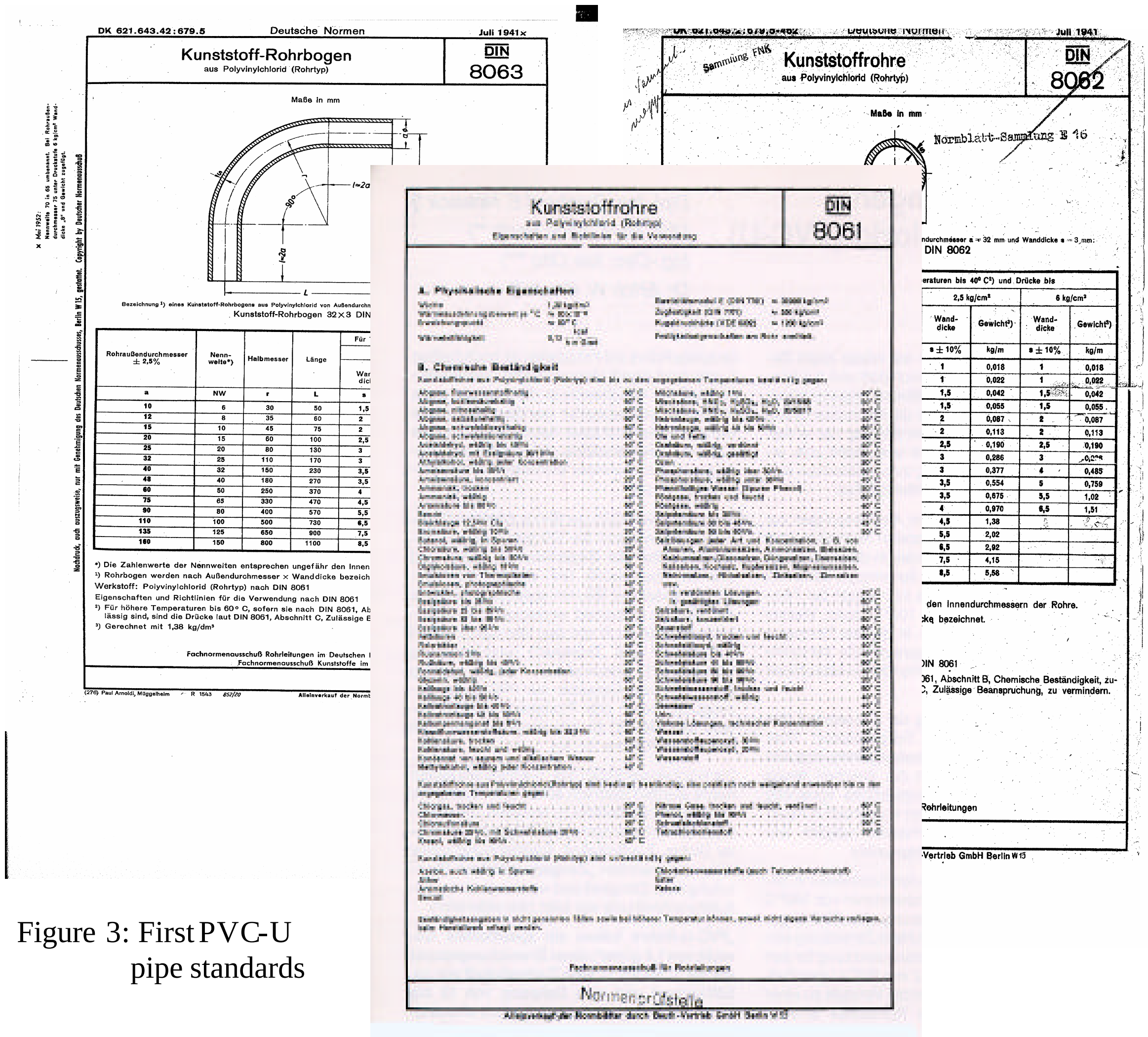

Figure 3: First PVC-U pipe standards

2. **Practical experience with PVC-U pipes** [3, 4]

2.1 Initial feedback from the early years

PVC-U pipes from the early production years (1935/36) were installed immediately and, after the first couple of years of experience with these pipes, the following reports from 1938 are documented:

- experience with 3.9 tonnes of pipes in the Merseburg ammoniac plant:
  "Igelit pipes were used with good success in contact with different acids, alkalis and gases (in particular sulfuric and chloric acid)"

- experience with 969 m of PVC-U pipes in the Wolfen film plant:
  "Igelit pipes are layed for 2 years in Inorganic Laboratory Wiss. Chemicals in contact with the pipes are: HCl of every concentration, NaOH up to 20%, $SiCl_4$, NaCl-solution, sea water, distilled water, formalin, vapors of chloric acid with alcohol. Until now the pipes have not caused any negative comment with regards to the chemical resistance. The laying is easy because of the simple processing."

- statement of the Berlin police president (department V):
  "There are no concerns about the use of the Mipolam tubes for the movable part of carbon dioxide pressure pipe system."

- statement from the Institute of Fermentation and Starch Production, Berlin 1940:
  "…contact of beer over 3 weeks with the Vinidur Pipes MP has not caused any change or deterioration of taste and smell or visible changes. Therefore these pipes can be used in beer tap equipment without any restrictions…"

- statement from the Institute of Fermentation and Starch Production, Berlin 1941:
  "… surprisingly, there are no noticeable changes neither on the Vinidur pipes nor on the brandy, or spirits of different concentrations which were in contact under rigorous testing conditions (contact time, large surface)…."

2.2 Results on PVC-U pipes from the early production years after long term use

PVC-U pipes from the first production years (1935-1941, hydraulic ram extrusion) have been installed in different regions in Germany mainly for potable water pressure pipe systems and sewer systems. About 400 flats in Bitterfeld have been installed with such pipes. Another example is a potable water pipe system in Steinfurth (Wolfen) which was operated at 3.5 to 6 bar and was still in use 1992. Also test pipeline systems had been installed in the first production years, e. g. in Leipzig, Dresden, Magdeburg, Berlin, Hamburg, Köln, Heidelberg and Wiesbaden. These pipelines were operated at pressures of up to 6 bar with pressure peaks up to 18 bar (at a frequency of 10 pressure changes per minute). All these pipelines have demonstrated good performance. A lot of them were destroyed in the Second-World-War, but some are still in use [4].

In 1961 two different Mipolan pipes (16 x 1.6 mm) which were installed in a house in Hamburg in 1937 were removed and tested after 23 years of use. Most of the properties would meet current specifications (table 2).

Properties of historical PVC-U pipes from different installation times/service lives				
Sample No. Pipe-dimensions (mm)	1 (A) * 16x1.6	2 (A) * 22x1.6	3 (B) * 20x2.5 – 49x5.5	4 (D) * -
Service life (years) Period installed	23 1937-1961	23 1937-1961	ca. 50 1935/40 – 1992	- -
Operating pressure (bar) Application medium	4 water	4 water	4 – 5 water	6 – 20 water
Operating temperature (°C) Trade name Tensile strength (N/mm^2)	ca. 16-18 Mipolam 54	ca. 16-18 Mipolam 48	ca. 12 – 20 Igelit 49 – 64	$\leq$ 20 Pressure Pipe 3 S 55 - 70
Elongation at break (%) Impact strength (kJ/m^2) at +23°C at $\pm$ 0°C (nb = no breaks)	45 10 nb 10 nb	14 10 nb 10 nb	13 – 19 31 – 58/ 2 b	20 - 40 10 nb
Impact strength notched (kJ/m^2)			3 – 17	3 – 4
Water absorption (%)	3.4	3.5	-	-
Vicat softening temperature VST/B/50 (°C)	83	82	79 – 82	83

(A)* Mipolam pipes from installation in Hamburg; produced in Troisdorf 1937
(B)* Typical values from 13 Igelit pipes from installation in Bitterfeld; produced in Bitterfeld in 1935 – 1940
(D)* Typical values from Omniplast pipe from 1993 production

Table 2: Properties of historical PVC-U pipes of different installation times and service lives

After the reunification of East and West Germany in 1989 and the involvement of Omniplast with pipe production in Bitterfeld, 23 pipe samples (figure 3) have been removed from different installations after more than 50 years of use. These pipe samples have also been tested and their properties compared to a pipe produced in 1993. The physical short term properties are similar to those of PVC-U pipes from current production (table 2).

Figure 3: Bitterfeld pipe samples, production 1935 - 1940

The “Bitterfeld” pipes were tested at DVGW Technologie Zentrum, Karlsruhe 1994 against the standard KTW drinking water recommendations and the results obtained demonstrate that the performance of these pipes is similar to PVC pipes made today [12].

Long term hydrostatic pressure tests have also been done on the PVC-U pipes from the first production years after 23 and about 50 years of use (“Hamburg” and “Bitterfeld” pipe respectively). Another two pipes from Bitterfeld have been tested and these were long enough to provide several test samples each, while the first series of “Bitterfeld pipes” were tested as individual pipes at different pressures (Table 3).

Sample(*)	Dimension (mm)	Test stress (N/mm^2)	Time to burst (h)	Comments
1.1	16x1.6	14	3.1	-
1.2	16x1.6	10	203	-
1.3	16x1.6	8.75	323	-
1.4	16x1.6	8.55	648	-
5.1	20x2.5	13.06	6.21	Brittle break (small crack
5.2	20x2.5	10.00	32.6	Brittle break
6	25x3.0	5.84	138.0	Brittle break
8	40x3.6	5.04	521.5	Weeping
9	40x5.1	8.01	383.0	Brittle break
10	48x4.6	7.72	477.0	Brittle break
11	32x3.8	7.83	203.6	Brittle break
12	32x3.8	5.98	16608.0	Brittle break
13	32x3.8	5.00	1063.0	Brittle break
14.1	32x3.7	6.94	562.6	Brittle break
14.2	32x3.7	6.14	624.5	Brittle break
14.3	32x3.7	5.06	961.3	Brittle break
15.1	32x3.6	6.96	163.2	Brittle break
15.2	32x3.6	6.06	0	Break at 15 bar g
15.3	32x3.6	5.06	425.5	Brittle break
24.1	32.5x3.8	10.00	3.8	Brittle break (ca. 2 cm longitude crack)
24.2	32.5x3.8	8.1	84	Brittle break (ca. 2 cm longitude crack)
24.3	32.5x3.8	6.0	>312	Brittle break (ca. 3 cm longitude crack)
24.4	32.5x3.8	5.0	>312	Brittle break (ca. 2,5 cm longitude crack)
25.1	25.2x2.9	9.0	27.6	Brittle break (ca. 1 cm longitude crack)
25.2	25.2x2.9	8.2	72.2	Brittle break (ca. 1 cm longitude crack)
25.3	25.2x2.9	7.0	11.1	Brittle break (ca. 5 cm longitude crack)
25.4	25.2x2.9	6.1	>312	Brittle break (ca. 2,5 cm longitude crack)
25.5	25.2x2.9	5.0	>312	Brittle break (ca. 2cm longitude crack)

* Samples A 1.1 – 1.4 Mipolam pipe from installation in Hamburg; produced in Troisdorf 1937, tested 1961
* Samples B 5.1 – 15.3 Values from 10 different Igelit pipes from installation in Bitterfeld; produced in Bitterfeld in 1935 – 1940, tested 1992/93
* Samples C 24.1 – 25.5 Values from 2 different Igelit pipes from installation in Bitterfeld, produced in Bitterfeld 1938, tested 1994

Table 3: 60°C Hydrostatic burst pressure test of used PVC-U pipes from production 1935 - 1940

Although the “Bitterfeld pipes” from 1935 to1940 are all different and were used in different areas, the variation in results is very similar to variation seen in the FNK round robin tests done in 1966 on one production batch; these also showed a variation of 3 decades in the burst pressure test [3]. Therefore the results of all single pipes from the Bitterfeld production have been compiled in one hydrostatic pressure test diagram (figure 4).

A comparison of the data from the pressure test with the requirements of the first standards (DIN 8061 and 8062) from 1941 indicate that even pipes from the first production years met these long term requirements although the results are below today’s requirements and typical contemporary data (figure 4, line DIN 8061).

An extrapolation of the regression data from the early pipes results in data at 10^5 h and burst stresses of 5 N/mm^2 and 4 N/mm^2 for the mean and lower confidence limit respectively. Even if the data are extrapolated to 10^6 h (ca. 114 years) it results in minimum burst stress of 4.5 N/mm^2 and 3.5 N/mm^2 respectively. This indicates that, for example, pipe sample No. 14 at a safety factor of 1.5 and operating conditions of 11 bar and 40°C would last for more than 100 years. But this pipe has already been in use since 1938, i. e. for about 53 years, therefore the remaining lifetime is at a minimum another 50 years, based on the extrapolated 60°C-data. Under realistic conditions in Bitterfeld of 12 to 20°C and 4 to 5 bar it may be assumed that another 100 years of safe operation could be expected.

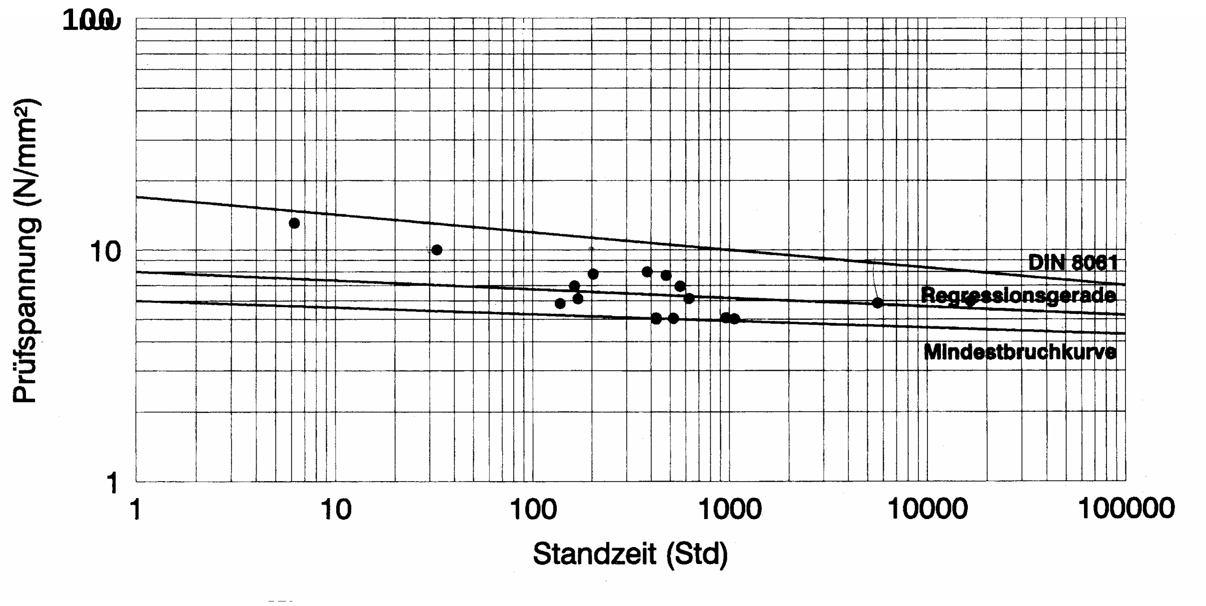

Figure 4: 60°C long term hydrostatic burst pressure test of 10 Bitterfeld pipes (samples B: 5.1 – 15.3)

The two pipe samples from production and use in Bitterfeld (samples C 24.1 – 25.5) were in operation as potable water pipes in houses for 53 years at 4 to 5 bar operating pressure. These 9 pipe samples were used for hydrostatic burst pressure tests at 60°C (table 3). The regression line from the long term hydrostatic pressure diagram, extrapolated to 10^6 h indicates that a hoop stress of 2.8 N/mm^2 is predicted (figure 5). This demonstrates that these pipes would last another 100 years of operation even at 7 bar and 60°C operating conditions. If these data are plotted into an "Arrhenius diagram" then at temperatures between 20°C and 40°C, these pipes would last another 100 years operating at 9 to 14 bar with a safety factor of 1.5. This means that, even if the operating pressure was doubled to 8 or 10 bar this pipe would easily last the 100 years as a potable water pipe with a safety factor of 1.5.

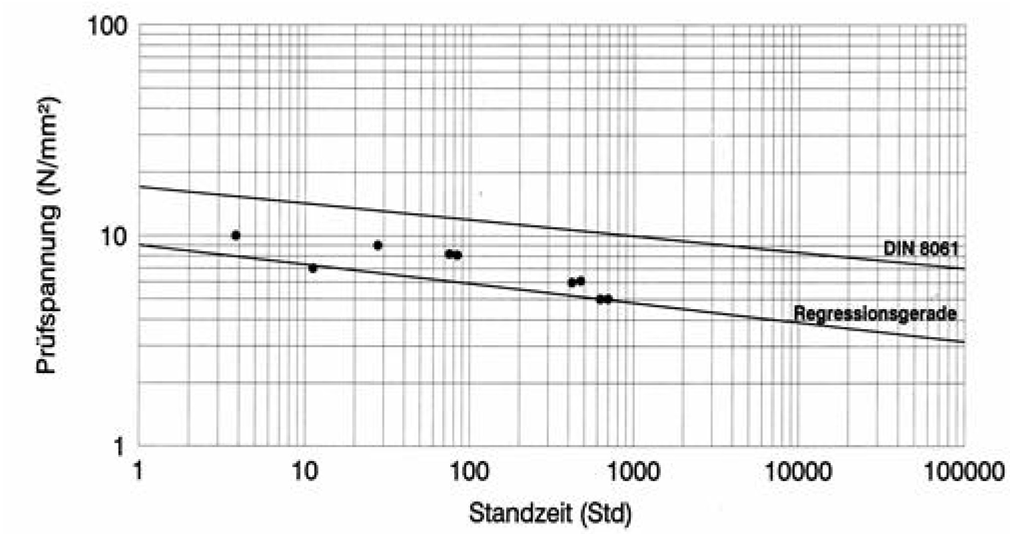

Figure 5: 60°C long term hydrostatic burst pressure test of 2 Bitterfeld pipes (samples C: 24.1 – 25.5)

3. Summary and outlook

All the results, even from the first produced PVC-U pipes which have a service life of about 50 years, demonstrate in an impressive way the excellent durability of these plastic pipes.

The development of PVC polymers, compound recipes and processing machinery for pipes production today results in much better long term performance of PVC-U pipes compared to the early PVC-U pipes, which is reflected also in the newer standards.

The best reflection of the positive experience and long term performance is the fact that, globally, PVC pipes are the most widely used plastics pipes.

For new developments in PVC-U pipes, such as new stabilizer types, this long term experience forms an excellent basis against which to compare and correlate performance data. This will ensure that the excellent durability demonstrated in practice by the old pipes will, in the future, equalled and even exceeded by newly developed PVC-U pipe products.

Acknowledgement:

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