Life time prediction of GRP piping systems

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ABSTRACT

Over the last 30 years GRP piping systems have been installed and operated to convey various fluids in process plant and equipment. In many cases, these systems are still in service. Engineers and asset owners are now facing the question of how long these piping systems can continue to operate reliably and safely, i.e. what is the remaining life time of the piping system. To determine the remaining lifetime, several aspects are important including the nature of the fluids in the pipe, temperature, condition of pipe supports, pressure excursions, installation procedures, pipe movement/settling, differences in the resin matrix of fittings and pipe (sometimes pipe and fittings have different curing agents). In some cases, pipes are made with epoxy compatible glass whereas others are not and some pipes have liners others have not.

The basis for a life time prediction is the regression line based on ASTM D 2992 using new pipe with appropriate materials properties. It is also possible to make a regression line from spools (pipes and fittings) which have been in service for several years and using appropriate materials and pressure test data for the regression line approach. However when a specimen is running at relatively low pressures then often no failure occur in a sensible time frame and the test is terminated. Analysis of the data can therefore results in a more conservative slope.

An alternative approach is to use low speed loading (LSL) tests where the pressure is ramped incrementally where failures of the specimen will occur within a practical timeframe. This paper presents a method to calculate remaining life using LSL curves and the conventional regression slope. Examples of previous test data will be presented and current developments will be discussed.

Content

1. Introduction

GRP pipes, pressure equipment and components have been in Oil and Gas service within the Middle East region since the 1980's and possibly earlier. Corrosion resistance, reduced weight and in some cases design flexibility and ease of installation are the primary business drivers leading to reduced life cycle costs and improved safety. In general, the in-service experience of using GRP has been mostly favourable although installation (and inspection issues) can still occasionally be problematic. As applications become more widespread and challenging, and as older systems reach the end of their original design lives, questions relating to their continuing structural integrity arise and validated inspection methods become increasingly important. Specific questions asked by asset owners, integrity specialists and regulators relate to continued fitness for service and the remaining lifetime before repair, refurbishment or replacement is required. Structural integrity is defined as the ability of a structure or component to perform its required service duty safely for the required design life, taking account of all reasonable loadings and potential degradation mechanisms to which it may be subjected. In order to address these questions an integrity assessment procedure needs to be developed and implemented.

The United Kingdom Health and Safety Executive Research Report RR509 on Plant Ageing [3] provides descriptions of the types of damage encountered in metallic components that can lead to incidents and loss of containment. Damage to metallic materials can be categorised into four main types:

- Wall thinning.
- Stress-driven damage, cracking and fracture.
- Physical deformation.
- Metallurgical / environmental damage.

Damage in non metallic materials, e.g. composites, is less clearly defined since composites do not corrode in the conventional sense but can be subject to a number of degradation mechanisms in-service including physical ageing, mechanical ageing and chemical ageing. The consequence of these effects can be a reduction of 20 - 40% (or greater) in the strength characteristics of the polymer during the lifetime of the component resulting from damage such as matrix cracking and delaminations. In service degradation is handled in design codes by use of regression curves based on short term and longer term tests to determine the qualification pressure for the component and the allowed operating pressure over the design life. However, there is some debate whether such methods of life assessment are sufficiently robust, given the increasing diversity of applications in which composites are applied.

2. Failure Modes

The most common failure mode of GRP pipes under pressure is by 'weepage' of the fluid through matrix micro cracks in the pipe wall. Other less common failure modes might be leakage at pipe joints (e.g. bell and spigot connections) or at locations subjected to third party impact damage or, if the pipe is buried, backfill damage. The fluid path through the pipe wall is a consequence of the coalescence of multiple transverse ply cracks resulting from debonding of the fibre-resin interface. The creation of micro-cracking and interfacial debonding can be accelerated by a number of factors including applied stress (or pressure), chemical species and temperature. The consequence of through-thickness matrix cracking is weepage and ultimately loss of integrity of the GRP pipe or vessel.

3. Mechanical Property

GRP pipes are usually constructed by filament winding of polyester, vinyl ester or epoxy resin impregnated glass fibres at [±55°] to the main pipe axis. At weepage, the fluid path through the pipe wall is a combination of mostly through-thickness matrix cracks running parallel to the fibres occasionally with some delaminations. During the pipe failure process the fibres usually do not break. The short term stress/strain behaviour of GRP pipes under internal pressure is linear elastic followed by a non-linear region to failure by weepage.

4. Prediction

Historical long term regression test data on GRP pipes has been collected by many pipe suppliers, including Flowtite (Member of the Amiantit Group) at its research centre in Norway, see [7] and figure 1 & 2. "*The samples date from the late 1970s to 2008. They comprise a variety of pipe designs, diameters, stiffness classes and pipe materials, from a number of Flowtite manufacturing facilities. All have in common that they represent certified products that have been, and are, in continuous use. A total of 645 samples are included in the analysis. The oldest sample (still running) is from October 1978 and the latest is from early 2008*".

Under conditions encountered in these tests, [7], many samples can last over 30 years and there is a tendency for all samples to exhibit a shallow slope on a log - log scale, referred to as the regression gradient, G. In general, the data which has been generated over a long time period show a reasonably consistent behaviour when looking at the trend line which appears to flatten out at long times and low applied strains. It may be inferred that using data in the first 3 to 4 decades for a regression curve to predict the long term performance that this approach can be seen as conservative.

5. Superposition

When the regression gradient is known and is a true description of long term performance then intermittent loads can be summed in the following way:

The regression line states that after t_i hours the pipe fails at pressure P_i and after t_j hours the pipe fails at pressure P_j. At $(0.5t_i + 0.5t_i)$ hours the pipe fails at P_i and at $(0.5t_j + 0.5t_j)$ hours the pipe fails at P_j. The assumed relationship between pressure and time, where G is the gradient of the regression line and A is a constant, as defined in ASTM D2992 is:

$$\log(P_i) = A - G \times \log(t_i) \tag{1}$$

$$\log(P_j) = A - G \times \log(t_j) \tag{2}$$

$$\log(P_i) - \log(P_j) = -G \times \log(t_i) + G \times \log(t_j) \tag{3}$$

$$\frac{\log(P_i)-\log(P_j)}{G} = \log(t_j) - \log(t_i) \tag{4}$$

$$t_j = t_i \times 10^{\frac{\log(P_i)-\log(P_j)}{G}} \tag{5}$$

Multiply the following two formulas with a 0.5 and assume that $P_i \neq P_m$:

$$t_j = t_i \times 10^{\frac{\log(P_i)-\log(P_j)}{G}} \tag{6}$$

$$t_j = t_m \times 10^{\frac{\log(P_m)-\log(P_j)}{G}} \tag{7}$$

$$0.5 \times t_j = 0.5 \times t_i \times 10^{\frac{\log(P_i)-\log(P_j)}{G}} \tag{8}$$

$$0.5 \times t_j = 0.5 \times t_m \times 10^{\frac{\log(P_m)-\log(P_j)}{G}} \tag{9}$$

When adding 8 and 9:

$$0.5 \times t_j + 0.5 \times t_j = 0.5 \times t_i \times 10^{\frac{\log(P_i)-\log(P_j)}{G}} + 0.5 \times t_m \times 10^{\frac{\log(P_m)-\log(P_j)}{G}} \tag{10}$$

Gives finally:

$$t_j = 0.5 \times t_i \times 10^{\frac{\log(P_i)-\log(P_j)}{G}} + 0.5 \times t_m \times 10^{\frac{\log(P_m)-\log(P_j)}{G}} \tag{11}$$

It is clear that this can be done for multiple increments Δt_i as well. This approach of multiple increments Δt_i , results in Equation (15 & 16) relating the time step at a particular pressure to an equivalent reference pressure and time, as shown below. A time step at a constant pressure results in an equivalent reference pressure with a reference time step. By summing all reference times, a total reference time can be calculated at a specified reference pressure an equivalent approach as described in [6]. By using an appropriate safety factor for the reference pressure, a prediction of the remaining lifetime of the pipe system can be generated. It can be seen in example 1 that the highest pressure contributes the largest reference time, which is intuitive.

$$\log(P_{ref}) = A - G \times \log(\Delta T_{TIME\_REF}) \tag{12}$$

$$\log(P_i) = A - G \times \log(\Delta T_{TIME\_i}) \tag{13}$$

Subtract and rewrite:

$$\Delta T_{TIME\_REF} = \Delta T_{TIME\_i} \times 10^{[(\log(P_i)-\log(P_{REF})]/G} \tag{14}$$

Sum of increments gives:

$$T_{TIME\_REF} = \sum_{i=1}^{n} \Delta T_{TIME\_i} \times 10^{[(\log(P_i)-\log(P_{REF})]/G} \quad (15)$$

From which A can be calculated:

$$A = \log(P_{REF}) + G \times \log(T_{TIME\_REF}) \quad (16)$$

For two different pressure-time relations up to failure say P_i and P_j then:

$$T_{TIME_{REF},i} = \sum_{i=1}^{n} \Delta T_{TIME\_i} \times 10^{[(\log(P_i)-\log(P_{REF})]/G} \quad (17)$$

$$T_{TIME_{REF},j} = \sum_{j=1}^{m} \Delta T_{TIME\_j} \times 10^{[(\log(P_j)-\log(P_{REF})]/G} \quad (18)$$

There will be a value for G so that : $T_{TIME_{REF},i} = T_{TIME_{REF},j}$

With numerical analysis G can be calculated and hence A can be calculated:

$$A = \log(P_{REF}) + G \times \log(T_{TIME\_REF}) \quad (19)$$

Suppose now that there are k different pressure-time relations up to failure say P_i, P_j, ..., P_k then:

$$T_{TIME_{REF},i} = \sum_{i=1}^{n} \Delta T_{TIME\_i} \times 10^{[(\log(P_i)-\log(P_{REF})]/G} \quad (17)$$

$$T_{TIME_{REF},j} = \sum_{j=1}^{m} \Delta T_{TIME\_j} \times 10^{[(\log(P_j)-\log(P_{REF})]/G} \quad (18)$$

$$T_{TIME_{REF},k} = \sum_{k=1}^{o} \Delta T_{TIME\_k} \times 10^{[(\log(P_k)-\log(P_{REF})]/G} \quad (19)$$

Then there must be a value for G that Dist is minimum:

$$\text{Average}(T_{TIME_{REF}}) = \frac{Log(T_{TIME_{REF},i}) + \log(T_{TIME_{REF},j}) + \ \ldots\ldots \ + \log(T_{TIME_{REF},k})}{total\ number\ of\ functions} \quad (20)$$

$$\text{Average}(T_{TIME_{REF}}) = V \quad (21)$$

$$\sqrt{\{(V-\log(T_{TIME_{REF},i}))^2 + (V-\log(T_{TIME_{REF},j}))^2 + \cdots + (V-\log(T_{TIME_{REF},k}))^2} = Dist \quad (22)$$

Subsequently A can be calculated.

$$\text{With } A = \log(P_{REF}) + G \times V\ ) \quad (23)$$

This means that if a piping system can be seen as a series of black boxes then you can determine a set of these black boxes, using low speed loading (LSL) stepped pressure tests and a calculated regression gradient. For a reliable prediction at least 6 data points are required in a minimum of 3 decades as acc.

ASTM D 2992. It is evident that with this regression gradient the lifetime of the system can be predicted.

6. Examples

6.1. Example 1 (Stepwise pressure increase)

A test on a spool is conducted according to Table 1. Figure 3 gives the pressure as a function of time. Using Equation 4, the failure time can be calculated for a pressure of 50 bar, assuming the gradient G is 0.1. In this example, the spool fails after 1200 h once the pressure is raised to 85 bar. The reference time at the reference pressure of 50 bar is calculated and the spool is expected to fail when exposed to 50 bar after 13.4 years (the sum of all reference times). The example excludes safety factors which would be applied in practice. Table 1 shows the results of applying Equation (15) for calculating the reference time of one pressure step, see also Figure 2.

6.2. Example 2 (1000 h stepwise test pressures)

Another example is when performing a 1000 h test according to ASTM D 1598 . The design pressure of the spool is assumed to be 20 bar and the 1000 h test pressure is initially set to 50 bar. In the case where the spool does not fail after 1000 h, it is recommended to increase the pressure incrementally from 50 to 62.5 bar and a second time from 62.5 to 75 bar as shown in Figure 4 (Example 2) . In this example G = 0.08 and the reference pressure is 75 bar. Using Equation (14) for calculating the reference times the results are presented in Table 2. The results show that the influence of the 1000h test at 50 and 62.5 bar is almost negligible to the test at 75 bar and therefore the decision can be made to proceed to the next higher pressure level.

6.3. Example 3 (increasing and decreasing pressures)

In this example the same total pressure loadings are applied but for increasing and decreasing pressure sequences plotted on a log-log scale including the regression line see Table 3&4. Both approaches give the same reference time but they do not both intercept the regression line, see Figures 5&6.

6.4. Example 4 (Case study TPR Fiberdur piping system)

This example [5] is a DN 100 mm Fibercast pipe produced by TPR Fiberdur, Germany, shown in Figures 7&8. The structural wall of the pipe is 4.7 mm, the liner 2.0 mm. The fluid medium was salty water. The pressure during the 25 years service was 12 bar at a design pressure of 16 bar. The line was in service for 25 years until 1991. Four samples were taken from the pipeline and tested according to ASTM D1598 [4] at a temperature of 110°C, Table 5.

The low number of samples tested do not allow for a statistically significant evaluation see Figure 9. The calculated regression line based on four data points is $\log(\mathrm{P}) = 2.0719 - 0.1472 \times \log(\mathrm{t})$. The predicted lifetime for this system with a safety of two and by substituting for P, 2 times 12 bar, and then solve for t gives a predicted lifetime of 5.7 years. The variable t in the formula has the dimension hours.

6.5. Example 5 (transferring LSL data into a regression line)

A remaining lifetime prediction can be achieved by obtaining representative samples from the existing pipeline system and carrying out either a constant or stepwise increase (sometimes referred to as low speed loading, LSL) pressure test in line with ASTM D1598. Figure 10 shows four different loading rate LSL tests. The stepwise increase of pressure has some advantages over the constant pressure method particularly when time is limited. If the constant pressure chosen is too low then failure may take several months or years, whereas the stepwise LSL test can usually be done within 1000-2000 hours (6 to 12 weeks).

Procedure determination for regression gradient G:.

As G is unknown one can calculate for every LSL curve with the values for G: G=0.001 + n*0.001 (so for G= 0.001, G=0.002,…., G=0.001 + n*0.001) and use for instance for P_{ref}= 23 Bar, the equivalent time at P_{ref} see table 6. The result is called Sum_i . The next step is to calculate the average value of all Sum_i :

$$\frac{\sum_{i=1}^{N} Sum_i}{N} = Average$$

.Calculate now for every G value (is G= 0.001, G=0.002,…., G=0.001 + n*0.001)

$$\sum_{i=1}^{N} (Average - Sum_i\ )^2 = St$$

Be aware that Sum_i changes when G changes

Search now for that G value which gives you the smallest St.
Now you can derive a line namely you now the point (Average time, 23 bar) and you have a slope. Final remark: Instead of 23 bar one can take any pressure.

7. Conclusions

A semi-empirical approach for remaining lifetime prediction and assessment of structural integrity such as ageing has been presented, where the ageing process has been limited to matrix cracking resulting in weepage. The approach is based on transferring LSL test data into ‘traditional’ regression gradients. The LSL test can be any function and is not necessarily linear. Further developments and case study experience may be required to enable more generic assessments of physical and chemical ageing effects and ageing pipe systems removed from service and could form the basis of future work.

8. References

1. ISO 14692 Petroleum and natural gas industries - Glass-reinforced plastics (GRP) piping. Parts 1 to 4.
2. ASTM D 2992 Standard practice for obtaining hydrostatic or pressure design basis for Glass Fibre Reinforced Thermosetting Resin Pipe and Fittings.

3. HSE Research Report RR509, Plant Ageing – Management of equipment containing hazardous fluids or pressure, 2006.
4. ASTM D 1598 Standard test method for time-to-failure of plastic pipe under constant internal pressure.
5. Long term stressing and behaviour of glass fibre plastic (GRP) pipeline, H.K. Focke, B. Schlehőfer, AVK-Tagung Berlin, 1991.
6. J. Steen, W. J. Aben and K. E. D. Wapenaar, “Optimization of the Vulcanization Process of Rubber Products,” Polymer Engineering and. Science, 1993.
7. Högni Jónsson, Chemical Resistance of GRP pipes measured over 30 years. Flowtite Technology – Amiantit Group, Norway, Sewerage and Drainage Pipe Conference in Cologne, Germany, October 2009

FIGURES

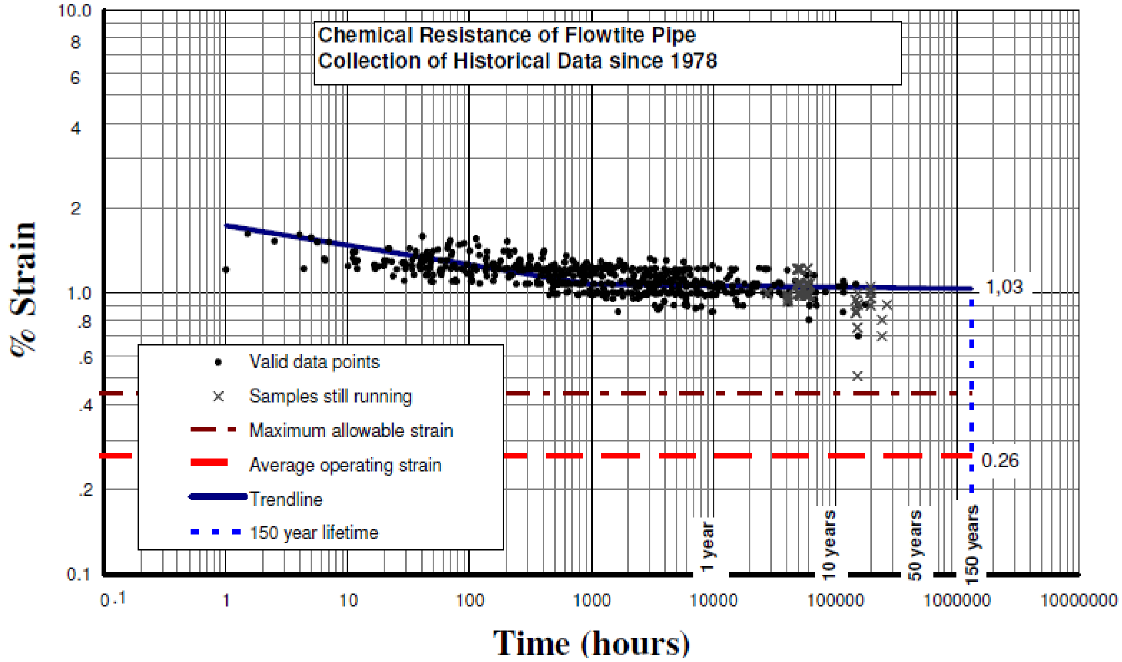

Figure 1. Test results: 30 years of regression testing (Courtesy: Flowtite, Amiantit Group, Norway).

Figure 2. Overview test samples (Courtesy: Flowtite, Amiantit Group, Norway).

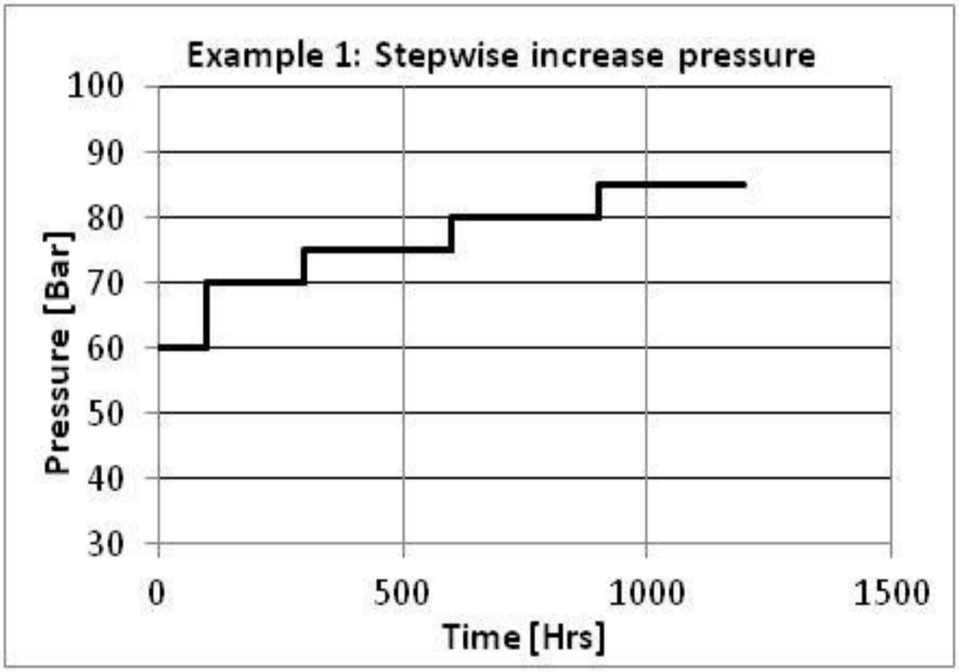

Figure 3. Example 1 stepwise increase pressure.

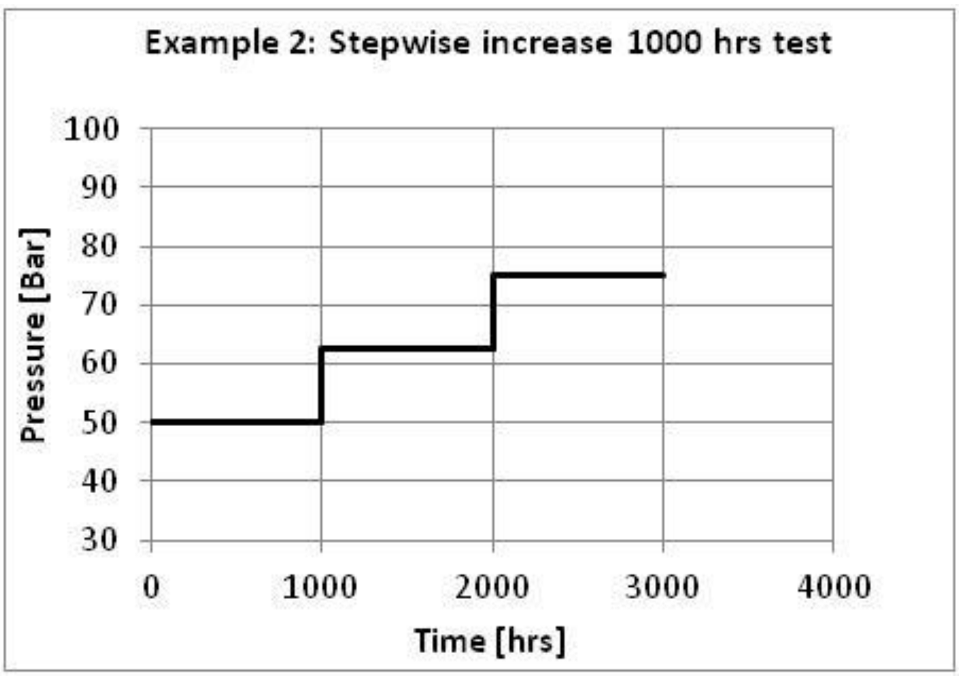

Figure 4. Example 2 step wise increase in pressure.

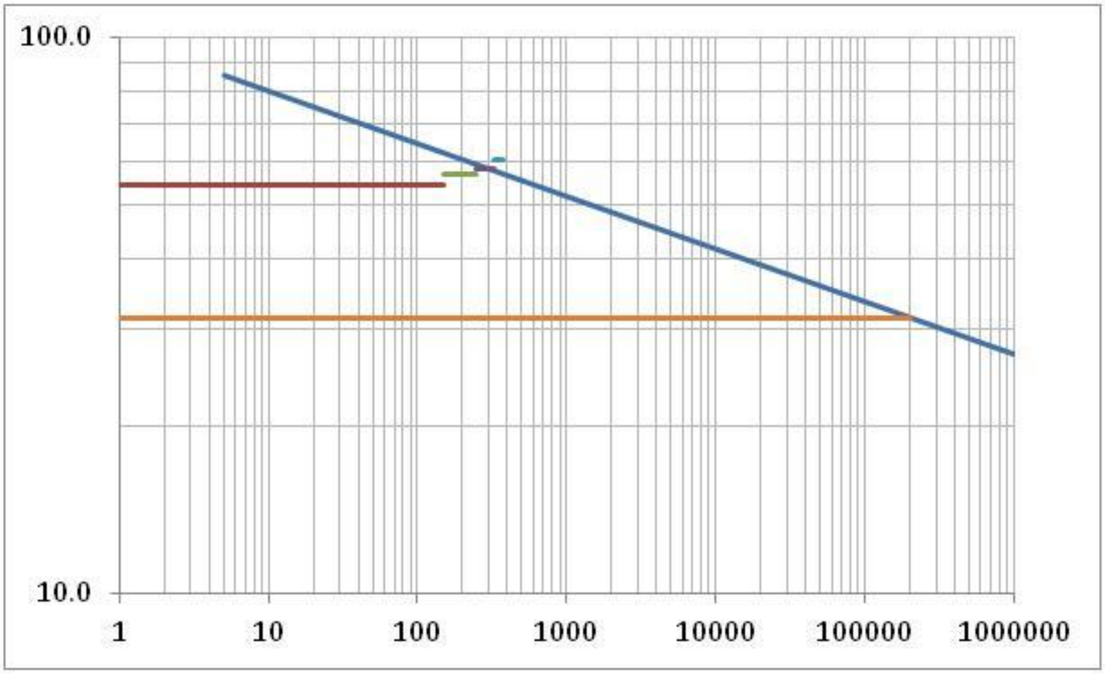

Figure 5. Example 3 – Pressure increasing sequence.

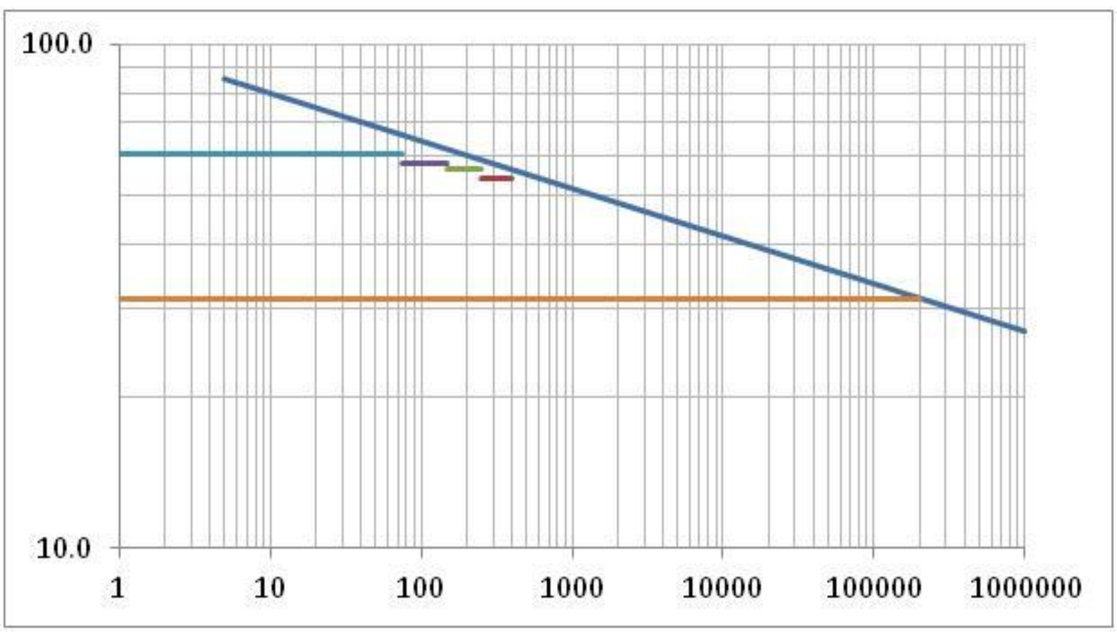

Figure 6. Example 3 – Pressure decreasing sequence.

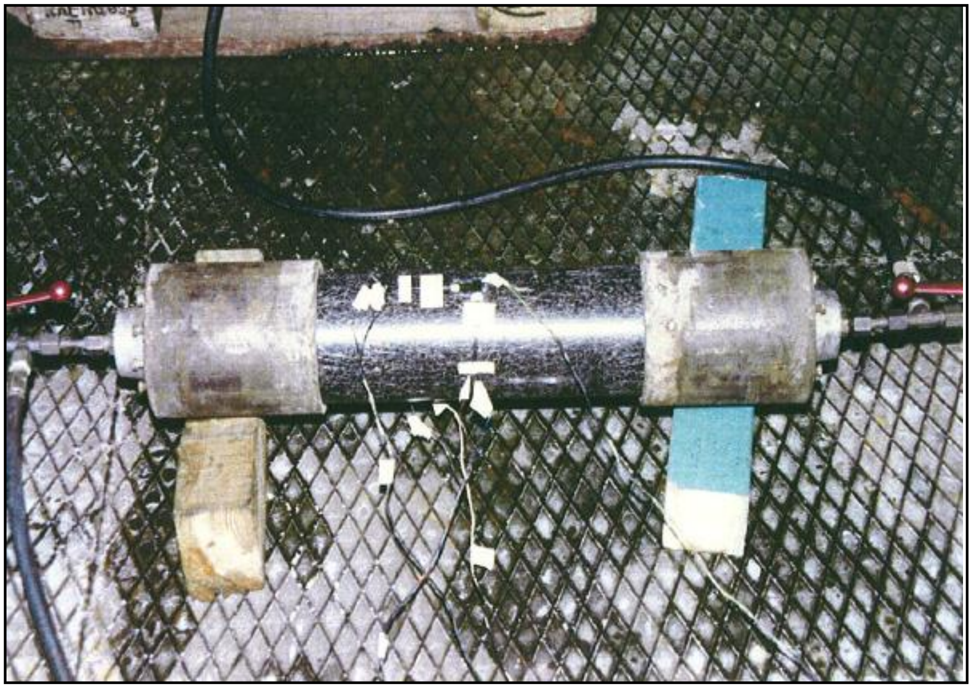

Figure 7. 25 year old test sample. (Courtesy TPR Fiberdur, Germany)

Figure 8. 25 year old pipe test sample. (Courtesy TPR Fiberdur, Germany)

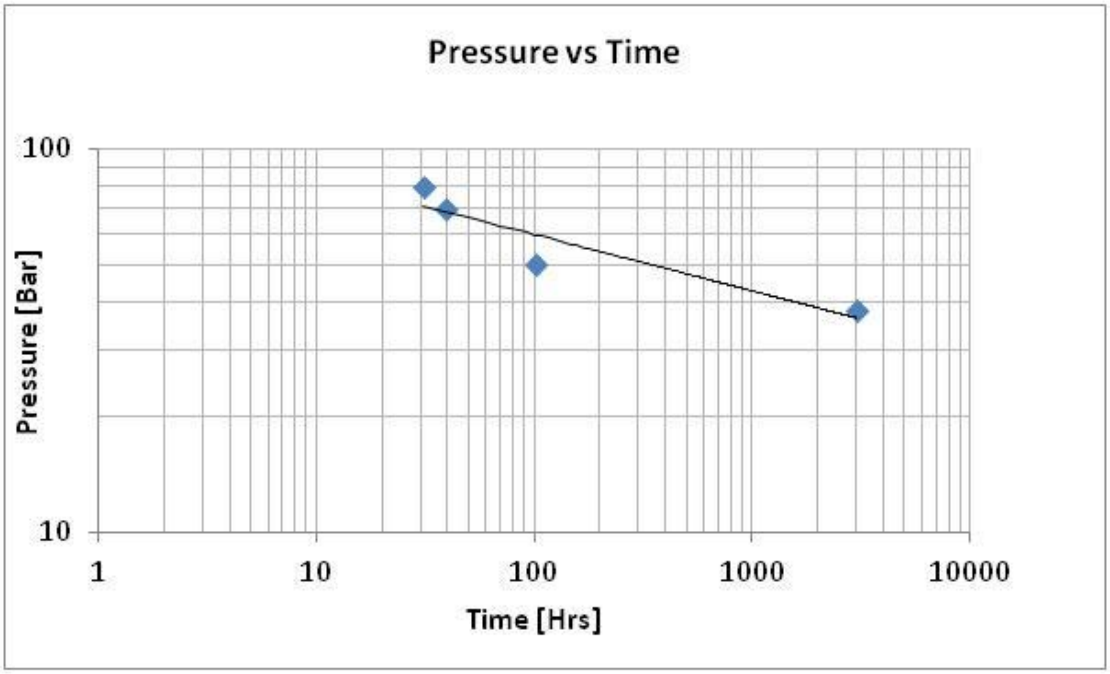

Figure 9. Regression curve for TPR Fiberdur pipe example.

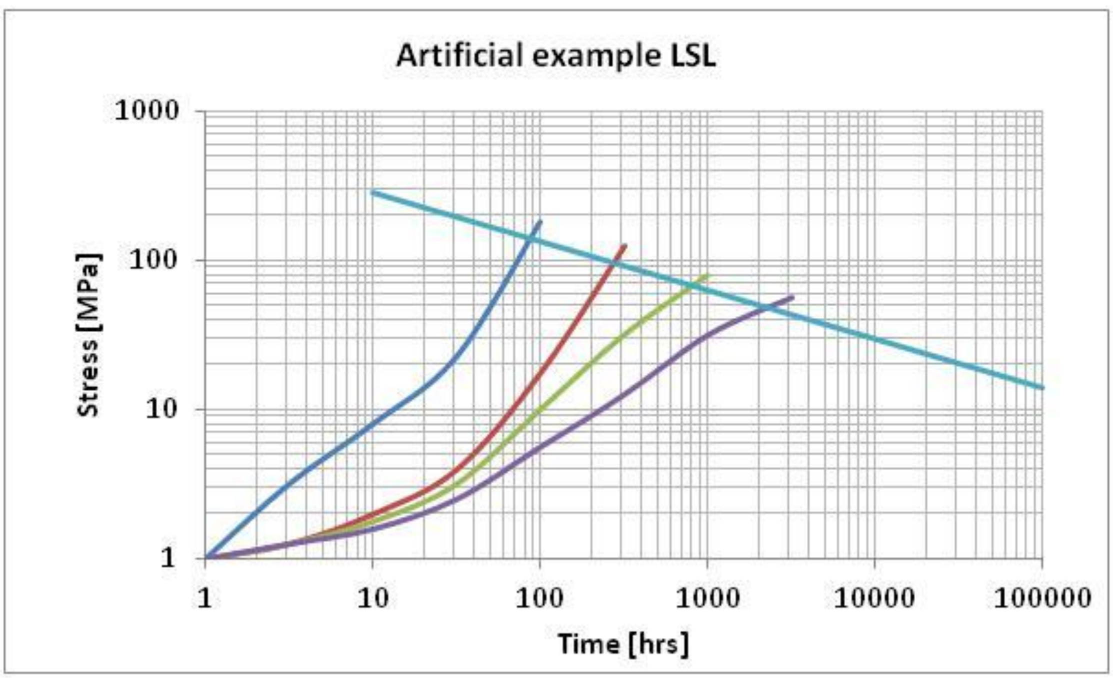

Figure 10. Low speed loading tests intercepting regression line.

TABLES

Table 1. Results calculation reference time at reference pressure 50 bar.

Pressure (Bar)	Time (hours)	$\Delta T_{TIME_i} \times 10^{[\frac{(\log(P_i)-\log(P_{REF}))]}{0.1}} =$	Ref Time (hours)
60	100	$100 \times 10^{[\frac{(\log(60)-\log(50))]}{0.1}} =$	619
70	200	$200 \times 10^{[\frac{(\log(70)-\log(50))]}{0.1}} =$	5785
75	300	$300 \times 10^{[\frac{(\log(75)-\log(50))]}{0.1}} =$	17300
80	300	$300 \times 10^{[\frac{(\log(80)-\log(50))]}{0.1}} =$	32985
85	300	$300 \times 10^{[\frac{(\log(85)-\log(50))]}{0.1}} =$	60480
Total hours	1200 h		117169 h =13.4 Years

Table 2. Step-wise pressure increments during 1000hrs tests.

Pressure (Bar)	Time (hours)	$\Delta T_{TIME_i} \times 10^{[\frac{(\log(P_i)-\log(P_{REF}))]}{0.08}} =$	Ref Time (hours)
50	1000	$1000 \times 10^{[\frac{(\log(75)-\log(50))]}{0.08}} =$	6
62.5	1000	$1000 \times 10^{[\frac{(\log(75)-\log(62.5))]}{0.08}} =$	102
75	1000	$1000 \times 10^{[\frac{(\log(75)-\log(75))]}{0.08}} =$	1000

Table 3. Pressure increasing sequence.

Time	Pressure
0-150	54.5
150-250	56.6
250-325	58.2
325-400	60.5
Reference time	**Reference pressure**
0-200000	31.4

Table 4. Pressure decreasing sequence.

Time	Pressure
0-75	60.5
75-150	58.2
150-250	56.6
250-400	54.5
Reference time	**Reference pressure**
0-200000	31.4

Table 5 Pressure – Time relationship for Fiberdur pipe.

Sample nr.	Pressure bar	Time hours
1	80	31
2	70	39
3	50	101
4	38	3003

Table 6. Equivalent time at reference pressure for different LSL curves.

Curve 1

Time	Pressure	$\Delta T_{TIME_i} \times 10^{[\frac{(\log(P_i)-\log(P_{REF})]}{G}}$
0	$P_{1,0}$	
$T_{1,1}$	$P_{1,1}$	$T_{1,1}$*10^(((Log($P_{1,1}$)-log(23))/G)
$T_{1,126}$	$P_{1,126}$	$T_{1,126}$*10^(((Log($P_{1,126}$)-log(23))/G)
$T_{1, 127}$	$P_{1,127}$	$T_{1,127}$*10^(((Log($P_{1,127}$)-log(23))/G)
$T_{1,128}$	$P_{1,128}$	$T_{1,128}$*10^(((Log($P_{1,128}$)-log(23))/G)
$T_{1,129}$	$P_{1,129}$	$T_{1,129}$*10^(((Log($P_{1,129}$)-log(23))/G)
etc	etc	Etc
		Total Sum= SUM_1

Curve 2

Time	Pressure	$\Delta T_{TIME_i} \times 10^{[\frac{(\log(P_i)-\log(P_{REF})]}{G}}$
0	$P_{2,0}$	
$T_{2,1}$	$P_{2,1}$	$T_{2,1}$*10^(((Log($P_{2,1}$)-log(23))/G)
$T_{2,126}$	$P_{2,126}$	$T_{2,126}$*10^(((Log($P_{2,126}$)-log(23))/G)
$T_{2, 127}$	$P_{2,127}$	$T_{2,127}$*10^(((Log($P_{2,127}$)-log(23))/G)
$T_{2,128}$	$P_{2,128}$	$T_{2,128}$*10^(((Log($P_{2,128}$)-log(23))/G)
$T_{2,129}$	$P_{2,129}$	$T_{2,129}$*10^(((Log($P_{2,129}$)-log(23))/G)
etc	etc	Etc
		Total Sum= SUM_2

Curve n

Time	Pressure	$\Delta T_{TIME_i} \times 10^{[\frac{(\log(P_i)-\log(P_{REF})]}{G}}$
0	$P_{n,0}$	
$T_{n,1}$	$P_{n,1}$	$T_{n,1}$*10^(((Log($P_{n,1}$)-log(23))/G)
$T_{n,126}$	$P_{n,126}$	$T_{n,126}$*10^(((Log($P_{n,126}$)-log(23))/G)
$T_{n, 127}$	$P_{n,127}$	$T_{n,127}$*10^(((Log($P_{n,127}$)-log(23))/G)
$T_{n,128}$	$P_{n,128}$	$T_{n,128}$*10^(((Log($P_{n,128}$)-log(23))/G)
$T_{n,129}$	$P_{n,129}$	$T_{n,129}$*10^(((Log($P_{n,129}$)-log(23))/G)
etc	etc	Etc
		Total Sum= SUM_n