Assessment of the Residual Strength Thresholds of Composite Pressure Receptacles – Criteria for Hydraulic Load Cycle Testing

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Composite materials are subjected to particular service-related changes of their safety and reliability characteristics. According to a previous publication [1], there is a need to implement procedures for determination of the residual strength in order to survey a population of pressure receptacles or fuel gas storage cylinder made of composite materials. The expression “pressure receptacles” represents an umbrella term in the regulations for the transport of dangerous goods that covers cylinders, tubes, pressure drums, bundles of cylinders, closed cryogenic receptacles and salvage pressure receptacles.

Such a procedure to determine the residual strength has been published previously [2] and is used by BAM as basis for safety assessment when determining the periods of periodic inspection and retesting of pressure receptacles made of composite materials.

The described procedure [2] considers the safety of composite pressure receptacles over their entire life cycle, including failure/survival probability through to the end of life. In this contribution, the respective relevant criteria [2] are described more detailed and comprehensively. As shown previously [1, 3], this can only take place by inclusion of test specimens used for many years and not solely on the basis of design type test (and therefore new test specimens). However, an economically viable in-process assessment of samples only enables an estimate of the behaviour of a population rather than giving a precise description [4]. This alone opens up a new dimension in the assessment of the operational safety of composite pressure receptacles.

Still missing for a complete understanding of the procedure [2] is a bridge from the fundamental principles [1] via the results described elsewhere [3] through to a consideration of criteria for the definition of minimum residual strengths.

As also shown previously [1, 5], it makes sense to assess the design types initially in terms of their different material-related behaviours according to the criterion of their fatigue susceptibility and to treat them differently. Here, the fatigue susceptibility is...
assessed based on the occurrence of significant damage in the load cycle test.

As shown previously [6], the abstinence from classification of a design type with respect to the property of fatigue cycle sensitivity can, or even must, lead to a critical misjudgement of operational strength. Reference has been given initially [6] and further on [1] to the slow burst test for non-load-cycle-sensitive design types (no leak before 50,000 hydraulic load cycles) in contrast to load-cycle-sensitive design types. Even though the burst test represents the historical basis of all tests, it is emphasized that in terms of operational strength this must always remain something of a less than ideal solution. It allows an assessment of primary operational failure based on structural/mechanical considerations only where strength degradation similar to fatigue is also to be expected under static load.

The burst test is in no way meaningful [2, 5, 6], if an elastic-plastic material is combined with a material considered as elastic as it is the case in types II and III composite pressure receptacles. In the case of load-cycle-sensitive design types, which are typically design types with a metal liner and/or with load-bearing glass fibre materials, the quantification of residual strengths by means of hydraulic load cycle tests has proved as effective [2].

Based on this, the aim in the following passages is to describe how these values can be used and interpreted for safety assessments in the context of previous results [2].

Degradation of fibre composites describes the reduction of the material properties over time. More generally, it is also used for the ageing behaviour of components. Regarding this contribution, the term degradation is also used to describe an empirically ascertainable ageing behaviour in the sense of the loss of required and measurable safety characteristics. This means that the decrease in the probability of survival, i.e. reliability against failure during use [1], is also an aspect of degradation. Here, the probability of survival (survival rate SR), which decreases over the life time, because of the dominance of time periods with a low probability of survival, is relatively well described by the smallest value at the end of life.

Figure 1 [1] shows how linear idealized “isoasfatias” (lines of constant values of survival rate [7]) change over time according to load. In principle, this figure should be seen as a cross-section through the three-dimensional plane of characteristics consisting of survival probability, load and time.

It has also been outlined [1] how a definition of protection goals using statistical aspects might look like. The basis is the definition of a threshold value for accepted failure probability as a social/political responsibility. As detailed in a previous publication [8], there is a relationship between the permitted threshold value for prospective failure probability (or retrospective failure frequency) and the aspect of risk that includes both, the consequence of an event and the probability of occurrence of this event. The consequence of this kind of events and their influence on the acceptance of the occurrence probability are discussed in relation to pressure receptacles against the background of accepted risks [9, 10].

Regarding the social issue of defining tolerable risks, engineering can only provide some support. For instance, an engineering support may be the assessment of pressure receptacles that are approved according to statistical criteria today and describe them comparatively in terms of safety and economic efficiency.

Since, fortunately, there are very few accidents with critical consequences in this area and even fewer accidents that cannot be traced back to human error, the status quo cannot be described using (per se retrospective) damage statistics. Instead, residual strengths and failure probabilities (as described above) must be estimated probabilistically, i.e. prospectively, by means of test sequences.

| Recapitulation of Current Test Results |

An initiative has been undertaken towards a statistical description of the characteristics of cylinders which are approved today with respect to the residual lifetime and is displayed in the form of hydraulic load cycles at room temperature in Table 1 [3, 11].

The essential parameters calculated for the samples are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A I</th>
<th>A II</th>
<th>B II</th>
<th>C II</th>
</tr>
</thead>
<tbody>
<tr>
<td>size of sample n</td>
<td>8</td>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>average period of use t</td>
<td>16 months = 1.3 years</td>
<td>152 months = 12.7 years</td>
<td>182 months = 15.2 years</td>
<td>136 months = 11.3 years</td>
</tr>
<tr>
<td>average $N_{50%}$ of the residual load cycles</td>
<td>33,780</td>
<td>26,070</td>
<td>8,220</td>
<td>13,310</td>
</tr>
<tr>
<td>log_{10} standard deviation</td>
<td>0.096</td>
<td>0.134</td>
<td>0.089</td>
<td>0.079</td>
</tr>
<tr>
<td>scatter span of load cycles $T_k$</td>
<td>1 : 1.77</td>
<td>1 : 2.20</td>
<td>1 : 1.70</td>
<td>1 : 1.60</td>
</tr>
</tbody>
</table>
The average duration of use $t_i$ (equal or less than the age) of a sample of $n$ test specimens at the time of testing is determined on the basis of individual statements of age $t_i$ (precise number of months) by calculating the mean value:

$$t = \frac{1}{n} \sum_{i=1}^{n} t_i \quad \text{[month]} \quad (1)$$

The average load cycle capability is calculated by:

$$N_{50\%} = 10^m \quad \text{with}$$

$$m = \frac{1}{n} \sum_{i=1}^{n} \log_{10}(N_{\text{hydr},i}) \quad \text{[LC]} \quad (2)$$

The standard deviation of the logarithmic hydraulic load cycle capability is:

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\log_{10}(N_{\text{hydr},i}) - m)^2} \quad \text{[LC]} \quad (3)$$

The scatter width $T_N$ of load cycle capability is defined by the failure load cycle number with survival probabilities (rates) of 10% and 90%:

$$\frac{1}{T_N} = \frac{N_{10\%}}{N_{90\%}} \quad [-] \quad (4)$$

and can be calculated from the standard deviation:

$$\frac{1}{T_N} = 1:10^{2.57+s} \quad [-] \quad (5)$$

Although unfortunately only test specimens of design A were available and could be investigated in relevant age levels, the initial results are remarkable in comparison to the expected figures [5]. The values for scatter width in the meaning of Equation (4) of pressure receptacles are smaller than would have been expected here on the basis of test samples of the materials used in the tested pressure receptacles.

The display of the results from the series of tests in Table 1 is also taken from a previous publication [3] and is shown in Figure 2. Displays of this type are based on normal distribution (ND) since this normally represents the best compromise between accuracy of representation and effort within the range between 10% and 90% survival probability, even for known skewed distributions of characteristic values of the population. The situation for extremely small failure probabilities $P_A$ is somewhat different. The extreme values in load cycle capability analyses are normally described using Weibull distributions.

### Use of Normal Distribution for Extreme Values

To display the range between 10% and 90% failure probability and the extreme values together, there is a conflict between the options of symmetrical normal distribution (ND) and Weibull distribution (WD), which is relatively accurate for fatigue aspects with high survival probabilities.

**Figure 2. Scatter of the most comprehensive year groups of test specimen [3]**

**Figure 3. Adaption of ND to WD by spreading [12]**

<table>
<thead>
<tr>
<th>survival probability (rate) $P_A$ = 1-$P_R$ (1-FA)</th>
<th>$P_C$</th>
<th>50%</th>
<th>90%</th>
<th>99%</th>
<th>99.9%</th>
<th>1-10⁻¹</th>
<th>1-10⁻²</th>
<th>1-10⁻³</th>
<th>1-10⁻⁴</th>
<th>1-10⁻⁵</th>
<th>1-10⁻⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>value of standardized deviation $x$ of normal distribution (ND)</td>
<td>$x$</td>
<td>0</td>
<td>1.29</td>
<td>2.33</td>
<td>3.10</td>
<td>3.72</td>
<td>4.27</td>
<td>4.76</td>
<td>5.20</td>
<td>5.67</td>
<td></td>
</tr>
<tr>
<td>adjustment factor $\chi$ for spreading to WD</td>
<td>$\chi$</td>
<td>-</td>
<td>-</td>
<td>1.53</td>
<td>1.79</td>
<td>2.01</td>
<td>2.21</td>
<td>2.29</td>
<td>2.56</td>
<td>2.72</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Adjustment factor $\chi$ for the point-by-point spread of ND to WD**
Comparing ND ($\chi = 1$) with this skewed WD extreme value distribution brings up considerable deviations as shown in Figure 3 [12]. The parameter $\xi = 0$ in Figure 3 indicates a two-parameter WD. As a conservative solution to the above-mentioned conflict, the normal distribution might be spread by the factor $\chi$, as shown in Figure 3, in such a way that the failure probability values of both distributions are brought point by point into congruence. This is applied using the values in Table 2 in order to consider the statements as general as possible under the (theoretical) assumption that the population is known.

### Influence of Volume on Safety Requirements

The ageing of a pressure receptacle will lead, as shown in principle in Figure 1, at some point in time to a status of unsafe service life. Before this relevant point in time can be determined, the question of what is the threshold value above it is considered as unsafe (in the meaning of danger in the context of risk analysis) needs to be addressed. Based on the procedure outlined previously [1], it is provisionally assumed, until completion of the social task of defining acceptable risk threshold values, that a rate of total failure (failure with major consequences probably resulting in fatality: bursting or emission of toxic gases) of more than “one in a million” pressure receptacles ($R = 1 \times 10^{-6}$) would not be permitted.

As used in ADR before restructuring [13], the product of pressure and volume of a cylinder or other pressure receptacles can be used as a criterion to describe the consequences of a failure. Ranges of consequences are defined here as classes without quantifying specifically the influence of the pressure-volume product in terms of consequence potential. The permitted probability of failure (failure rate FR = 1 – SR) can now be identified depending on this. It is therefore feasible that in the event that the geometric maximum volume of gas cylinders is exceeded, a survival probability (survival rate SR) one level of magnitude larger may be required.

By definition gas cylinders have a so-called water volume of up to 150 litres, but the majority is not larger than 50 litres. Based on pressure levels that are most common these days, i.e. working pressures (PW) of 200-300 bar and test pressures (PH) of 300-450 bar (30-45 MPa), a (test) pressure-volume product limit would be useful to differentiate between large cylinders (tubes) of more than 5,000 MPa litres and most common cylinders below this limit. In view of the fact that new pressure containments – so-called mega-tubes or composite gas tanks – with up to approx. 10,000 litres capacity and over 750 bar test pressure (750 000 MPa litres) are envisaged in future, it seems appropriate to require, in addition to the previously mentioned limit for large cylinders, a further increase in the permitted level of e.g. 50,000 MPa litres.

For this reason, previous table [1] has been expanded to Table 3 for upcoming discussions. The handling of flammable gases should correspond either to that for toxic or inert gases depending on transport conditions.

There are, however, other factors that indicate a deviation from a basic value for reliability would make sense. For instance, for pressure receptacles with reliable leak-before-break characteristics (fail-safe design [7]), failure rates of up to one in 10 000 pressure receptacles ($R = 1 \times 10^{-4}$) could be accepted, because of the less serious potential consequences in term of only relatively small amounts of inert gases escape and the reliability against bursting remains above $R = 1 \times 10^{-6}$. Cracks that have grown in metal liners may close again as a consequence of pressure loss, because of the composite pre-stressing, so that the leak rate is almost no longer measurable. However, the question here remains unresolved as to how reliability should be considered over the entire lifetime where there are different lengths of life and as to whether, in cases where failure probabilities are considered in yearly tranches, reliability R up to end of life should also be made dependent on the length of life.

### Influence of Gas Type on Operational Safety

Since real operating cycles are not applied in the in-process tests [1] under discussion here, i.e. the residual strength that can only be determined hydraulically, it needs to be mentioned initially [3] that it is not possible to equate hydraulic load cycles with real filling cycles. With composite pressure receptacles, an age-related proportionality can be assumed that is described in the following context as specific filling sensitivity $\eta_{\text{fill}}$ as per [21]:

$$n_{\text{fill}}(t) = \frac{\Delta N_{\text{min}}(t)}{\Delta} = \frac{d_{LC}(t)}{n_{\text{fill}}} \geq 1 \quad [\text{month}^{-1}] \quad (6)$$

Here, the following equation applies for filling frequency (gas fillings over time):

$$n_{\text{fill}}(t) = \frac{\Delta N_{\text{min}}(t)}{\Delta} = \frac{d_{LC}(t)}{n_{\text{fill}}} \geq 1 \quad [\text{month}^{-1}] \quad (7)$$

and the following equation describes the average degradation rate $d_{LC}$ for the time period under consideration:

$$d_{LC}(t) = \frac{N_{\text{min}}(t)}{\Delta} = \frac{N_{\text{fill}}(t) - N_{\text{min}}(t)}{t_a - t_0} \quad [\text{month}^{-1}] \quad (8)$$

The specific filling sensitivity has a value of $\eta_{\text{fill}} = 170$ in the example of test specimen A and also has the same order of magnitude in other cases. Based on the presumed causal processes, it is expected (this should be checked for every test period) that the degradation rate, and therefore also the filling sensitivity, are dependent on the duration of use and decrease with

<table>
<thead>
<tr>
<th>Cylinder and gas characteristic test pressure-volume product</th>
<th>Leakage in safe leak-before-break behaviour (fail-safe design)</th>
<th>Bursting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inert gas</td>
<td>Toxic gas</td>
<td>(Independent)</td>
</tr>
<tr>
<td>Minimum reliability $R$ at end of life (EOL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\leq 5,000$ MPa litres</td>
<td>$R \geq 1 \times 10^{-4}$</td>
<td>$R \geq 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$&gt; 5,000$ MPa litres</td>
<td>$R \geq 1 \times 10^{-4}$</td>
<td>$R \geq 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\leq 30,000$ MPa litres</td>
<td>$R \geq 1 \times 10^{-6}$</td>
<td>$R \geq 1 \times 10^{-7}$</td>
</tr>
<tr>
<td>$&gt; 30,000$ MPa litres</td>
<td>$R \geq 1 \times 10^{-6}$</td>
<td>$R \geq 1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

Table 3. Minimum reliability as criterion for determining the end of safe use
increasing operational age. The calculated residual strength (number of load cycles) is therefore a measure for the degradation that cannot be interpreted absolutely, but only in comparison with values from test specimens with a different operational age.

Of importance for hydraulic comparison tests of this sort including extrapolation of the degradation line (Figure 1) is the definition of the load status upon which these comparison tests are based. In respect of gases frequently transported in composite pressure receptacles, Table 4 shows how the developed partial pressure and therefore the real load in the component depends on the gas characteristics. The figures are based on calculations made using the program IST: Thermophysical Properties of Fluid Systems © 2011 USA.

The right column of the table shows the maximum partial pressure at 65 °C in relation to the test pressure. This demonstrates clearly that the universal use of test pressure according to gas type is to a greater or lesser extent conservative in operation as well as in the hydraulic comparison test. Although it can be assumed, at least in Europe, that a temperature of more than 55 °C is very unlikely to be reached, because of the climatic conditions, the specified temperature of 65 °C can be reached more or less frequently in practice during the filling process depending on the system and may even be exceeded in certain cases locally in the pressure receptacle (e.g. with compressed air). In view of the (normally non-gas-specific) approval, the test pressure is normally used in the approval tests. This represents a simplification and time reduction in the hydraulic test as compared to dedicated assessments with real gas pressures.

Figure 4 illustrates the effect of this practice on the expected number of load cycles. It uses the values in the right column of Table 4 and shows what these pressure differences would mean for the fatigue strength of a steel cylinder. Due to the stress in the liner which is mainly dependent on temperature and pre-stressing such an assessment can only be done for composite cylinders on a design specific basis and not generally. This makes it necessary to switch to example analysis; e.g. of a steel cylinder for the universal illustration in Figure 4.

The example values shown in Figure 4 for the numbers of load cycles are based on the following parameters: the material data of a steel cylinder of 34CrMo4 is analyzed for leakage at 12 000 LC (LC: load cycles) with SR = 99.99 % [7, 12].

The permitted amplitude is therefore defined to resist the test pressure under the assumption of a constant residual pressure of 10% PH for 12 000 LCs. This gives the displayed individual number of load cycles before leakage for the upper stress limit, dependent on the maximum gas pressure developing at 65 °C assuming a residual pressure/lower stress limit of 10% (load ratio R = 0.1).

It is clear that the degradation of a design type with approval for multiple gases may be considerably greater when using methane than compressed air. The above mentioned proportionality between the real filling cycles and the loss of hydraulically tested residual load cycles itself therefore depends on the filling gas where other conditions are identical. Ultimately, this means that the scatter of relevant characteristics for a population of a design type may increase significantly with its use for storing several gases compared to new test specimens. Obligatory differentiation by type of gas in the case of destructive retesting of specimens with general approval is for reasons of traceability only viewed as feasible in individual cases. This seems to be a dilemma: if safety is deduced from determined survival rate tests should be exact as possible and if they are not traceable, uncertainty of the results is increasing. It is left to the operator to decide for differentiated testing to increase the certainty of results and respective demonstrated safety margins.

<table>
<thead>
<tr>
<th>gas</th>
<th>test pressure PH MPa</th>
<th>working pressure WP MPa</th>
<th>filling ratio [%]</th>
<th>real pressure of gases as function of temperature</th>
<th>gas pressure at 65 °C related to PH</th>
</tr>
</thead>
<tbody>
<tr>
<td>compr. air</td>
<td>30</td>
<td>20</td>
<td>-</td>
<td>14.40 16.44 20.00 24.03 25.03</td>
<td>83.4%</td>
</tr>
<tr>
<td>UN 1002</td>
<td>45</td>
<td>30</td>
<td></td>
<td>20.86 24.20 30.00 36.55 38.17</td>
<td>84.8%</td>
</tr>
<tr>
<td>hydrogen</td>
<td>30</td>
<td>20</td>
<td>-</td>
<td>16.03 17.48 20.00 22.87 23.58</td>
<td>78.6%</td>
</tr>
<tr>
<td>UN 49</td>
<td>45</td>
<td>30</td>
<td></td>
<td>24.00 26.19 30.00 34.32 35.40</td>
<td>78.7%</td>
</tr>
<tr>
<td>methane</td>
<td>30</td>
<td>20</td>
<td>-</td>
<td>39.97 43.64 50.00 57.19 58.98</td>
<td>78.6%</td>
</tr>
<tr>
<td>UN 1971</td>
<td>45</td>
<td>30</td>
<td></td>
<td>56.06 61.16 70.00 79.95 82.42</td>
<td>78.5%</td>
</tr>
<tr>
<td>oxygen</td>
<td>30</td>
<td>20</td>
<td>-</td>
<td>11.26 14.44 20.00 26.31 27.88</td>
<td>92.9%</td>
</tr>
<tr>
<td>UN 1072</td>
<td>45</td>
<td>30</td>
<td></td>
<td>15.61 20.84 30.00 40.38 42.96</td>
<td>95.5%</td>
</tr>
<tr>
<td>butane</td>
<td>1</td>
<td>-</td>
<td>0.017 0.045 0.176 0.564 0.720</td>
<td>72.0%</td>
<td></td>
</tr>
<tr>
<td>UN 1072</td>
<td>3</td>
<td>-</td>
<td>0.111 0.245 0.732 1.907 2.343</td>
<td>78.1%</td>
<td></td>
</tr>
</tbody>
</table>

Tabel 4. Application of the work diagram (Figure 4) to the test results from Table 1

Figure 4. Developed gas pressure at 65 °C and its relative effect on the fatigue strength of a 34CrMo4 steel cylinder
In the relevant design and testing standards mandatory for design type approvals it is permitted to perform the hydraulic load cycle test with the gas pressure developing at 65 °C when approving the design for a specific gas exclusively. This option is also feasible in this concept. However, it must be kept in mind that termination of such tests without failure is then only possible after an adequate cycle loading. That means an increased number of load cycles of at least 250,000 load cycles, i.e. it is more time-consuming. Also, it is unlikely there will be no much change in the final result as the specific filling sensitivity \( \eta_{\text{fill}} \) according to Equation 6 will become larger, as shown by the relationships in Figure 4. It is therefore recommended that one should work as far as possible solely with cycles up to the test pressure for the determination of the residual load cycle number [2]. Under no circumstances can results based on different pressure or temperature values be compared with each other.

With the required reliability at end of life and the load level (using test pressure) now specified, it still needs to be defined how high the minimum number of residual load cycles shall be in relation to the minimum survival probability.

### Criteria for Minimum Number of Residual Load Cycles

As a residual strength criterion the last filling must be withstood safely, i.e. with the required level of reliability. According to Equation 6, the last filling is, however, not the same as the last hydraulic load cycle and the general uncertainties of the estimate shown here are not negligible. Accordingly, it would not be acceptable to go to the limit of the very last hydraulic cycle. Therefore in Figure 5 isoasfalias are shown as an array of lines for the last 10 load (hydraulic or gaseous) cycles in relation to the scatter of component characteristics.

Here, the array of lines of different SRs is based on the assumption that the aforementioned 10 cycles must always be achieved with a survival probability (survival rate SR) of 99,9999 % irrespective of the scatter. It can also be seen from the diagram that the normally required 12,000 load cycles do not represent a measurement of safety, if the scatter and specific fill sensitivity \( \eta_{\text{fill}} \) are not known. But even without the negative influence of the fill sensitivity, one can imagine circumstances at scatters of 1:5 or above where although the required sample of two prototypes pass the test up to 12,000 load cycles in accordance with the relevant standards for characteristics, sufficient reliability can still not be guaranteed. This means that these two tests with termination at 12,000 load cycles have no significance in terms of the safety of a composite design type, if one does not know the spread.

If one further modifies this type of representation and structures in the chart in a way that only the average values of the required number of gaseous filling cycles \( \Lambda \) of a sample are queried so as to obtain a specific survival probability, the isoasfalias (lines of equal reliability) in Figure 6 can be obtained [2].

Figure 6 represents a working diagram in order to be able to assess test results and extrapolate empirical values from multiple samples with differing existing operational damage. However, it is vital for any interpretation using this diagram that, as well as the comparison of samples with differing histories of operational stress (periods of usage), the specific filling sensitivity \( \eta_{\text{fill}} \) is also known. Only with this value the number of gaseous filling cycles may be related to the hydraulically determined residual load cycles.

If the scatter according to Equation 4 is applied to the abscissa in this work diagram, the minimum residual strength \( \Lambda \) is required as an average value at any point in time up to end of life for the last operational filling process can be taken at the ordinate as a parameter in relation to the...
required reliability R. In the first step a general assumption of $R = 1 \times 10^{-6}$ is made:

$$
\Lambda_{50\%} \left( \frac{1}{T_N} \right) = N_{\text{resid}50\%}
$$

from $\Lambda$ - work diagramm $["LC"]$ (9)

This opens the perspective to check whether the degradation is likely to stay non-critical up to end of life or to an earlier point in time of a repeat test. This is deemed to be fulfilled if the average number of residual load cycles extrapolated to the point in time under consideration remains larger than the value (calculated with the aid of Figure 5) for the average minimum residual strength $\Lambda$ multiplied by the specific filling sensitivity $\eta$. The following condition must be fulfilled:

$$
\frac{N_{\text{resid}50\%}(t)}{\eta_{\text{fill}}} \geq \max \left[ 10; \Lambda_{50\%} \left( \frac{1}{T_N} \right) \right] ["LC"] (10)
$$

This process is shown in grey in Figure 7. In both figures, a minimum value of 10 in-service filling cycles is always assumed to cover any possible uncertainties. As experienced up today, this corresponds to a reliability of at least 99% for a number of hydraulic load cycles within the range of scatter ($T_N < 1:6$). The values from sample tests on design type A as well as the other values from Table 1 and Figure 2 for design types B and C are shown in Figure 7. It is also shown for sample A II (Table 1) how the required number of filling cycles $A$ is translated to the required number of load cycles using the specific filling sensitivity $\eta_{\text{fill}}$. It can clearly be seen that it cannot be assumed that a high number of hydraulic load cycles for composite pressure receptacles provides a reliable statement about operational safety. Only taking into account the specific filling sensitivity $\eta_{\text{fill}}$ makes reliable assessments possible. Only the difference in duration of use between the two samples of design type A (11.4 years) enables an assessment of the load cycles as indicator of residual strength of pressure receptacles. This residual strength shows an approximation to threshold values. Such increasing approximation is shown by the loss of residual strength as well as by the increase in scatter, indicated in the diagram by a shift to the right over the 11.4 years. With the assumption of linear degradation it can therefore roughly be estimated that approximately 10 years to 15 years would again be permis-

For completeness, it should be mentioned that even for steel cylinders higher scatters of hydraulic load cycle resulting in leakage are assumed than those found here for metal liners in composite cylinders, the aspects detailed here would be transferable to steel. This is particularly the case, because steel cylinders are not subjected to degradation in the sense of damage from static load provided relevant conditions concerning corrosion and materials' compatibility are taken into account. This means that the described proportionality of gas filling cycles and hydraulic load cycles is significantly better for steel cylinders and $\eta_{\text{fill}}$ may approach 1.

In conclusion, the validity significance of load cycle test for the design type approval up to 12 000 load cycles for steel cylinders is much better than for composite pressure receptacles. In the latter case of metal liner composite cylinders there is no direct correlation between hydraulic load cycles and safe filling cycles. Again: the residual load cycle capability assessment does not necessarily have to be based on the test pressure. It is permissible for design types having an approval for only one gas can also be tested with the developed gas pressure at 65 °C, as permitted by the standard (Table 3). However, it is vital that two conditions are met here:

1. All tests to determine residual strength are performed with the same pressure.
2. The test may not be terminated before 5 times the number of load cycles [2] (250 000 cycles).

**Figure 7. Application of the work diagram (Figure 6) to the test results from Table 1**

**Figure 8. Threshold value of number of residual load cycles and extrapolation to end of life at 20 years (240 months)**
Extrapolation and Forecast

The extrapolation is shown in principle in Figure 8, similarly to Figures 1 and 2. However, the threshold value of Figure 6 appears here as a minimum value for the average number of hydraulic residual load cycles. Here, the value $A$ of Figure 6 is multiplied by the specific filling sensitivity $\eta_{init}$ in order to obtain the average minimum number of load cycles from a residual strength test using hydraulic load cycles. The aim though remains to assess whether the last filling cycle can still be adequately be represented (Figure 7).

A further aspect of Figures 2 and 8 is the extrapolation to a remaining residual strength at a point in time positioned in the future $t_1 > t_0 > t_2$. Here, the average degradation rate $d_{LC}$ according to Equation 8 is used. Thus, the following condition applies:

\[ N_{ resid \ frac{up}(t_1)} = N_{ resid \ frac{up}(t_0)} - d_{LC} (t_1 - t_0) \]  

In addition, for a forecast of the status, e.g. at end of life, the increase in scatter must also be estimated by extrapolation of the scatter into the future $t_2$:

\[ \frac{1}{N_{ resid \ frac{up}(t_1)}} = \left( \frac{1}{N_{ resid \ frac{up}(t_0)}} \right)^{t_1/t_0} \cdot 1 - \left( \frac{1}{N_{ resid \ frac{up}(t_2)}} \right)^{t_1/t_2} \]  

With the results from Equations (11), (12) and (6), a forecast status for the duration of use $t_1$ can then also be assessed with the aid of Figure 6 as a work diagram.

Character of Degradation

As already mentioned, the degradation of cycle fatigue strength may be linear versus time and by this is probably also linear to the number of fillings (as it is assumed) for fatigue behaviour of metals and is expressed by linear damage accumulation hypothesis, and means a constant loss of residual load cycles.

On the other hand, it is even possible that degradation of composite pressure receptacles with metal liners is dominated by the degradation of the composites. It is assumed that the early degradation of cycle strength of a composite pressure receptacle is dominated by creep effects. That means that the sketched effect is mainly independent from the cycle number of loads and decreases with the duration of service.

The description of this behaviour needs at least two repetitions of residual strength test campaigns and the only field data currently available have been published previously [14]. It has been shown [14] that at least for the design type investigated here, i.e. with glass fibre, the average degradation of residual load cycles during the first six years in terms of specific filling sensitivity $\eta_{init}$ was more than 250 times the number of filling cycles. In contrast, the average degradation decreased to a $\eta_{init}$ of about 75 during a second period of six years. By such effect, the duration of service life is reduced and might exceed the ascertained value in the first year(s).

Nevertheless, the behaviour of a pressure receptacle with respect to these principles has to be quantified for each design type separately and should be checked after each repetition of residual strength tests. In principle, it is expected that the first estimation of the specific filling sensitivity is on the safe side for extrapolation.

Aspects of Restricted Sample Size

The overall feature of the assessment presented here is based on the ability to view the results from the sample test as characteristics of the total population. However, as stated earlier [3], this is not the case from a statistical viewpoint. Ideally, a sample size approaching the total population would have had to be used here. However, this would make the approach of in-service residual strength tests in vain.

In respect of non-limited life time in conjunction with a very limited sample of 2 specimens, evidence of 12 000 hydraulic load cycles is required according to the relevant standards. A test termination at 12 000 cycles is allowed and common. Here the criteria discussed above come into play in addition to the currently applicable requirements. Therefore it can be assumed that, despite the systemic weakness of the sample test, which for reasons of cost effectiveness is almost impossible to resolve, a level of ascertainment is achieved that has previously not been possible with the mandatory standards to be applied.

In this context, a further aspect of sample testing should be mentioned. Depending on the size of the sample, the significant majority of test results are within the calculated 10% to 90% scatter band of the sample. If this or other criteria do not apply for a specimen, one is quickly inclined to talk about an “outlier”. But, the safety of a pressure receptacle population is now determined without exception by all elements of a population being in service. It is of no interest here whether a pressure receptacle that has burst in a worst-case scenario may be designated as an “outlier”.

An outlier can only be defined within the framework of a sample test if it has been demonstrated that the cause of the low residual strength verifiably applies only to this specimen, e.g. as a result of incorrect test procedures or a testing system malfunction.

Since for financial reasons the size of sample for tests of this kind must normally be kept small (e.g. for cylinders from high volume production five to seven specimens per test), there is a relatively large degree of uncertainty regarding the significance of the sample in the context of the overall population. Therefore, the results of the sample should be checked to see whether any of the test results fall below the SR 90% value. If so, it is recommended that the size of samples is increased by at least two specimens or the worst individual value should be used as a 90% value for extrapolation of the scatter according to Equation (12). This should help to show whether it is in fact statistically a relatively poor value and therefore the entire sample may be over/underestimated. Such outliers may, however, also be an indication that other damage mechanisms were involved in older test specimens than would be expected based on the characteristics of new test specimens and therefore the in-service test campaign has primarily led to this discovery.

Summary

The method presented here and being used by BAM on composite pressure receptacles when a test period of more than five years is desired, represents something new in terms of its approach without abandoning other knowledge-providing methods. Despite the inevitable statistical uncertainty, this method makes a significant contribution to improve the safety assessment of populations of load cycle-sensitive composite pressure receptacles. In addition to the safety assessment at a particular point in time, it also allows the performance of an extrapolation to end of life. This method therefore offers for the first time an operator-oriented system that enables the approved lifetime of load cycle-sensitive composite pressure receptacles to be individually tested in probabilistic terms on the basis of operational stress.
Abstract


You will find the article and additional material by entering the document number MPI10413 on our website at www.materials-testing.de.

Outlook

It is shown here how load cycle sensitive design types of composite pressure receptacles can be assessed with respect to their service life time. However, it is still not solved what should be done [1, 2] if the necessary expense for the quantification of fatigue strength under cyclic loads exceeds accepted limits, because of very low load cycle sensitivity. As a provisioanl measure, slow and very controlled burst tests might be applied [6]. The advantages and disadvantages of this procedure are to be discussed in a further contribution based on even more comprehensive test results.

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