MONTE-CARLO-ANALYSIS OF MINIMUM LOAD CYCLE REQUIREMENTS FOR COMPOSITE CYLINDERS FOR HYDROGEN

Becker, B.[1] and Mair, G.W.[2]
[1] Tanks for Dangerous Goods and Accident Mechanics, BAM, Unter den Eichen 44-46, Berlin, 12203, Germany, ben.becker@bam.de
[2] Tanks for Dangerous Goods and Accident Mechanics, BAM, Unter den Eichen 44-46, Berlin, 12203, Germany, georg.mair@bam.de

ABSTRACT

Existing regulations and standards for the approval of composite cylinders in hydrogen service are currently based on deterministic criteria (ISO 11119-3, UN GTR No. 13). This paper provides a systematic analysis of the load cycle properties resulting from these regulations and standards. Their characteristics are compared with the probabilistic approach of the BAM. Based on Monte-Carlo simulations the available design range of all concepts is compared. In addition, the probability of acceptance for potentially unsafe design types is determined.

1. INTRODUCTION

Relevant assessment criteria for approval and definition of retest periods of composite cylinders are intended to ensure a safe use over its entire service life. The overall aim is to avoid a critical failure during service. The risk of such a failure can never be completely eliminated but have to be reduced to a broadly accepted level. In this case, the residual risk is accepted as a function of consequence.

The usual methods for the approval of composite cylinders for compressed hydrogen (CGH_2) are based on determined minimum performance criteria. They follow the concept of a deterministic approach, i.e. the proof of minimum values with regards to burst pressure and load cycle strength.

The approval of composite cylinder as CGH_2 storage systems for vehicle needs to follow the criteria from the UN GTR No. 13 [1]. In regards to burst pressure, the UN GTR No. 13 is based on an extended semi-probabilistic approach. This means, there is a specific minimum burst pressure as usual. But in addition to that the maximum scatter of the single burst test results is also limited. In regards to load cycle strength it is required to demonstrate a minimum number of load cycles without failure by testing just 3 specimens resisting.

The BAM (Bundesanstalt für Materialforschung und -prüfung) has developed a probabilistic approach (PA) that could be developed to an alternative to the GTR 13. The BAM-PA [2], [3] is based on sample testing and statistical assessment in combination with reliability criteria. Sample means here always a group of nominal identically manufactured and used composite cylinders. The approach is currently used by the BAM to determine retest periods for composite cylinders according to ADR / RID P200 (9) [4] and for service life tests for UN composite cylinders according to section 6.2.2.1.1 of IMDG Code [5] and ADR / RID.

The comparison of these different assessment methods leads to the question: Which level of safety do they ensure and how much potential do they offer for further optimization of composite cylinders?

2. REQUIREMENTS FOR CGH_2 COMPOSITE CYLINDERS

The GTR 13 defines the approval requirements for CGH_2 composite cylinders. These requirements include specific performances test and criteria for initial burst pressure, initial load cycle strength and as well performance durability and expected on-road performance.

The semi-probabilistic criterion for burst test results was already discussed in [6]. It was shown that the burst criterion from the GTR 13 is basically suitable to identify unsafe cylinder populations.

However, there are deficits in the safety assessment, especially in case of burst properties with a high scatter value.

The requirements for initial load cycle strength from the GTR 13 are based on a deterministic minimum value for the number of hydraulic load cycles (LC) without leakage. The defined limits are 11,000 LC; 7,500 LC or 5,500 LC. The chosen minimum value need to be demonstrated by 3 load cycle tests. The aim of this requirement is to ensure a certain number of safe filling cycles over lifetime. The limit of 11,000 LC corresponds to 15 years with up to 2 filling cycles per day. The expected maximum number of filling cycles in practical service would be around 5,500 even under heavy use (e.g. Taxi usage).

The BAM-PA for the evaluation of load cycle test results is based on a statistical assessment of samples with at least five individual test results. The aim of this probabilistic approach is to ensure a sufficient residual reliability against critical failure of aged and new composite cylinders. A sample is described by its mean load cycle strength $N_{50\%}$ and its scatter N_s. These two parameters result from the residual load cycle strength N_i of n individual test results by using a Log-Normal distribution:

$$m_{log} = \frac{1}{n}\sum_{i=1}^{n} \log_{10}(N_i) \quad (1)$$

$$s_{log} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\log_{10}(N_i) - m_{log}\right)^2} \quad (2)$$

$$N_{50\%} = 10^{m_{log}} \quad (3)$$

$$N_s = 10^{s_{log}} \quad (4)$$

The parameters $N_{50\%}$ and N_s can be assessed by lines of constant reliability (isoasfalia). Figure 1 shows the Sample Performance Sheet (SPC) with the requirements (blue lines) for samples with a sample size of n = 5 and n = 10 in comparison to the deterministic minimum values of the GTR 13.

An isoasfalia represents a reliability or survival rate (SR) of e.g. 99.9999% ($1-10^{-6}$) against a failure due to leakage or sudden rupture for N = 1 additional load cycle. In some cases, the required reliability can be reduced to lower values e.g. 99.99% ($1-10^{-4}$) depending on application, consequence of failure and failure behaviour (leak before break) of a composite cylinder. In general, the required reliability is a function of the cylinder’s pressure volume product and therefore the consequence of a critical failure.

The required reliability for the BAM-PA is combined with a confidence level of 95%. A confidence level considers that a sample represents only a small part of a cylinder population. As shown in figure 1, an increase in sample size reduces the required mean load cycle strength and allows higher scatter values. A high sample size increases the amount of available information and reduces uncertainties about the true properties of an assessed cylinder population.

Figure 1 includes as well the isoasfalia for infinite n (red line). This lower reliability limit refers to the true properties of a cylinder population without any uncertainties. However, the true load cycle properties of a cylinder population can only be estimated by samples and are usually unknown in practice. This area represents cylinder populations which are statistical unsafe and should not be accepted by an approval criterion.

The scatter range of the SPC ends at $N_s = 2$. The usual scatter of load cycle test results from composite cylinders under new and aged conditions is in a range of $1.1 < N_s < 1.6$.

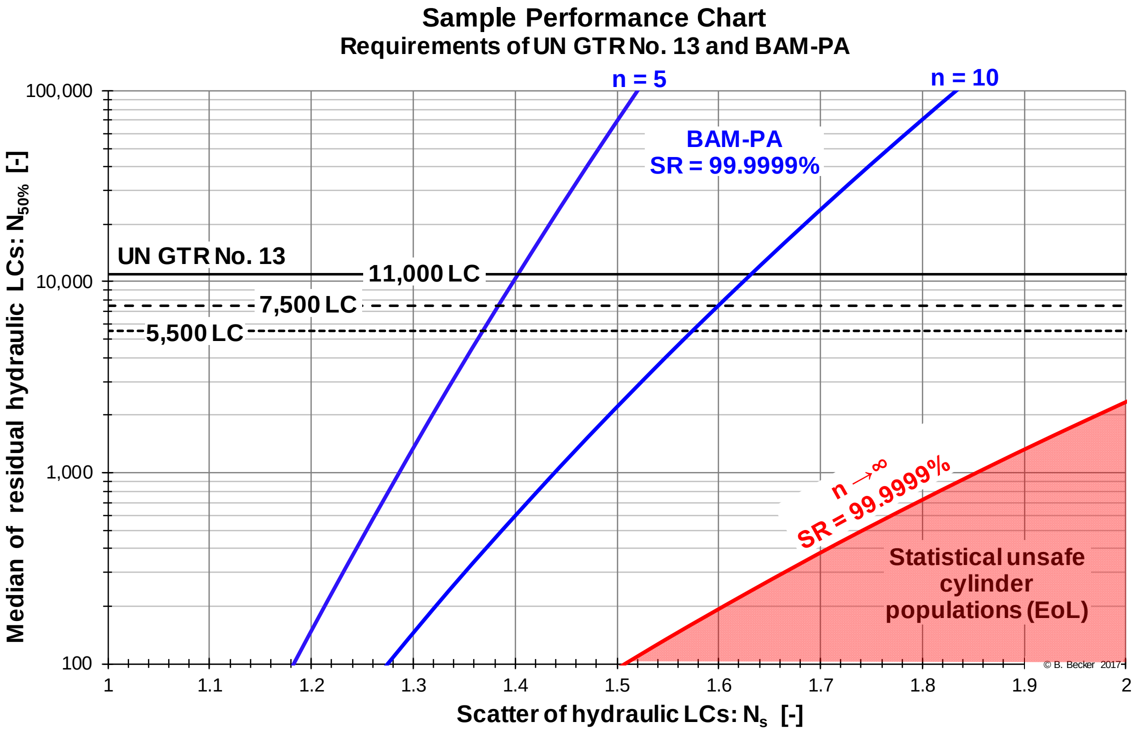

Figure 1. Requirements for load cycle strength from UN GTR No. 13 and BAM-PA

The comparison of requirements for load cycle test results in figure 1 shows a clear difference between the deterministic criterion from the GRT 13 and the BAM-PA. With an increasing scatter value, the probabilistic approach requires higher mean load cycle strength to achieve the same reliability. A deterministic criterion, does not consider any scatter effects. The specific behaviour of both approaches will be discussed the following chapters.

3. STATISTICAL DESCRIPTION OF LC TEST RESULTS

The statistical analysis of properties in general requires the definition of a suitable distribution function. A distribution function describes the probability of occurrence for certain values by a parametrized function. Such parameters are for example mean value and standard deviation in the case of Normal distribution or Log-Normal distribution.

A known distribution function allows extrapolating the probability of occurrence for very rare events or in this case performance values. This allows assessing effects which cannot be covered by practical experiments. However, such an extrapolation always includes uncertainties. Especially in case of extreme probabilities it is unknown if an assumed distribution function describes the real distribution of an assessed property. The usual solution to this problem is to use a suitable conservative approach.

In [7] was already discussed which distribution functions are suitable to describe the load cycle strength of composite cylinders. It was shown that the distribution function of load cycle strength changes over service life time. The assumption of a Log-Normal distribution is especially suitable for new cylinder populations. Population at their end of service life can be described by the conservative approach of a 2-parameter Weibull distribution. A Log-Normal distribution would tend to overestimate the residual reliability of aged composite cylinders while a Weibull distribution generally underestimates the reliability of cylinders in new condition.

The BAM-PA is based on a Weibull distribution, since the approach aims on a sufficient safety at end of service life. The Weibull distribution is used as a conservative assumption for the calculation of the isoasfalia in figure 1. A Weibull distribution is described by the parameters characteristic lifetime T and form parameter b:

$$SR(N) = e^{-\left(\frac{N}{T}\right)^{b}} \tag{5}$$

In combination with the SPC the Weibull parameters can be transformed to parameters of a Log-Normal distribution according to [8]:

$$T = N_{50\%} \cdot N_s^{0.48416} \tag{6}$$

$$b = 1.02743 / \left(2 \cdot \log_{10}(N_s)\right) \tag{7}$$

The equations 6 and 7 allow a simplified representation of a Weibull distribution by parameters of a Log-Normal distribution according to equation 1 to 4. The following chapters are mainly based on the assumption of conservative Weibull distribution. In some cases, the results are compared with the corresponding results of a Log-Normal distribution to consider the properties of cylinder populations in new condition.

4. MONTE-CARLO SIMULATION OF LC TEST RESULTS

A way to analyse criteria from different standards is the Monte-Carlo simulation [9]. A Monte-Carlo simulation is based on computer generated test results. In this case, the generated values for load cycle strength are following a Weibull distribution with the parameters $N_{50\%}$ and N_s.

A Monte-Carlo simulation allows creating a high number of random samples out of a defined population within in a very short time. These samples can be compared with the respective criterion from the GTR 13 or the BAM-PA.

The properties of a single sample differ from the properties of the original cylinder population. The smaller the sample size the higher is the deviation between sample properties and the true properties of a cylinder population. Figure 2 shows the variability of sample properties in the SPC using a Weibull distribution with the parameters $N_{50\%}$ = 15,000 LC and N_s = 1.2. The result is a cloud of possible sample properties derived from the same cylinder population.

Each dot in figure 2 represents a sample out of 3 computer generated load cycle test results and was assessed by a minimum number of 11,000 LC according to the GTR 13. That means each individual test result within a sample need to be higher than 11,000 LC. This assessment divides the cloud into two groups. A part of the possible samples would lead to an acceptance of the cylinder population (black dots), another part would be rejected (red dots). The ratio of these two groups is the acceptance rate AR.

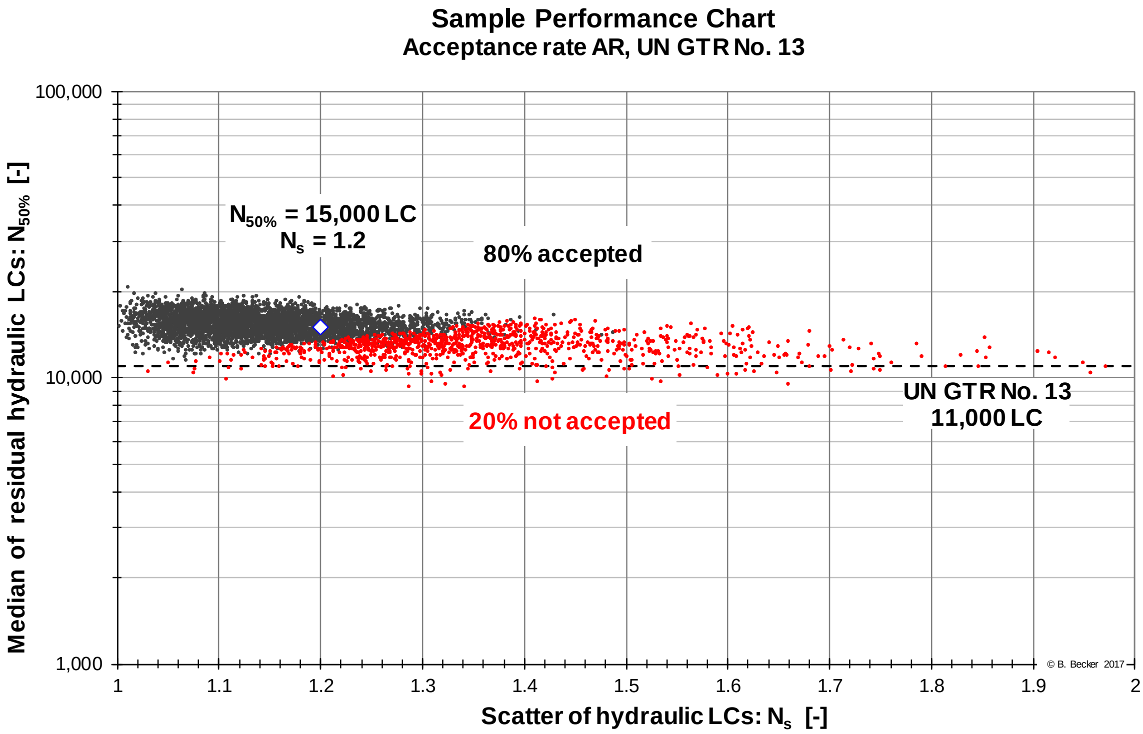

Figure 2. Monte-Carlo Simulation of samples from load cycle test with n = 3 and their acceptance according to UN GTR No. 13

Figure 2 shows that a lot of the samples are rejected despite a mean value of $N_{50\%}$ > 11,000 LC. This is related to individual values within the respective sample which are below the criterion of 11,000 LC.

The given example shows that the acceptance rate of the defined cylinder population is AR = 80%. This demonstrates that acceptance or rejection of a cylinder population is always associated with a probability even in case of a deterministic criterion.

5. ACCEPTANCE RATES FOR GTR 13 AND BAM-PA

In chapter 4 was shown that the acceptance rate AR of a cylinder population results from the variability of the sample properties. However, a comprehensive analysis of the behaviour of an approval criterion requires much more information. It is required to calculate the distribution of acceptance rates for all cylinder populations within the SPC.

The described method from chapter 3 and 4 allows such an analysis with sufficient accuracy and acceptable computing effort. The calculation of acceptance rates for all cylinder populations results into combinations of mean value $N_{50\%}$ and scatter N_s with same acceptance rates. These populations can be connected to iso-lines of a constant AR (AR-isoasfalia). Figure 3 shows on the example of the GTR 13, the AR-isoasfalia for AR = 5%; 50% and 95% for a deterministic minimum load cycle strength of 11,000 LC. Additionally, figure 3 includes the safety criterion for cylinder populations at end of service life (red line).

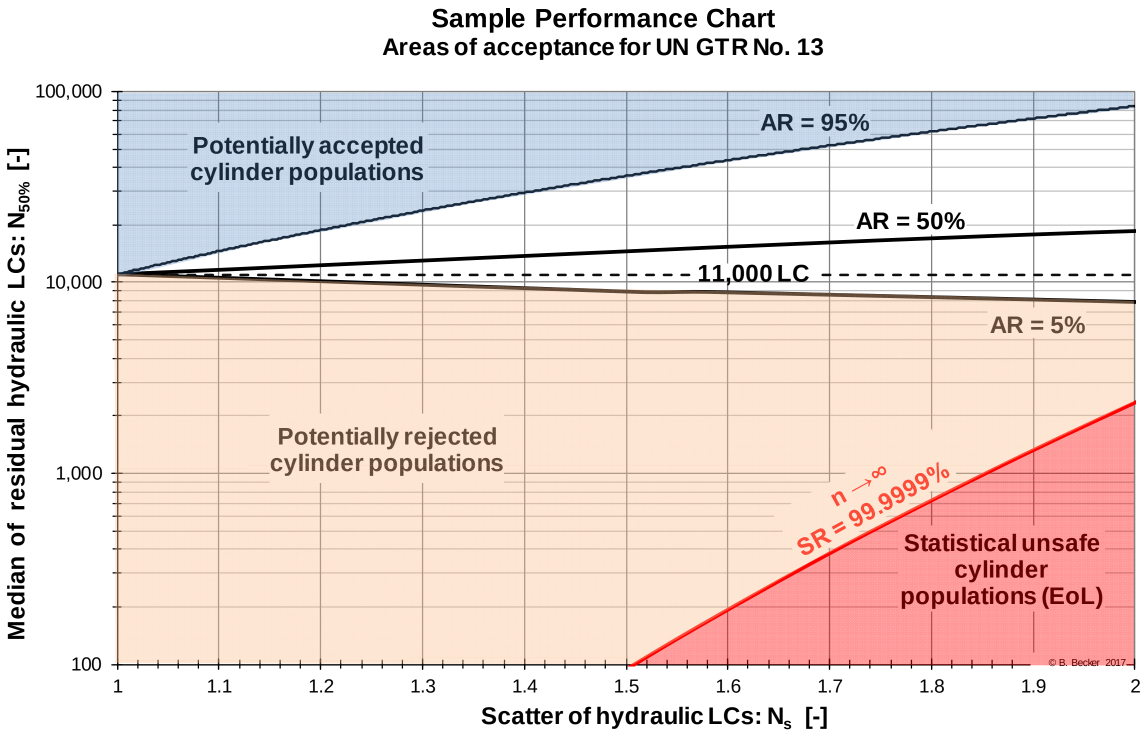

Figure 3. Areas of acceptance for cylinder populations according to the GTR 13

Figure 3 shows the statistical analysis of a deterministic criterion. For better understanding, a sample out of a cylinder population whose properties are corresponding e.g. with the AR-isoasfalion for AR = 50% would fulfil the load cycle criterion of the GTR 13 with a probability of 50%. In this context, the AR-isoasfalia for AR = 5% and AR = 95% are of particular relevance for the behaviour of a criterion.

The 5% AR-isoasfalion represents the lower limit of basic populations who could pass the criterion. It is very likely that such a population would get negative attention in case of retesting or following batch tests.

The analysis of the GTR 13 shows that it is possible to approve a cylinder population with mean load cycle strength of $N_{50\%} < 11{,}000$ LC. This results from the already discussed variability of sample properties as shown in chapter 4. A cylinder population with a very high scatter of $N_s = 2$ could be even get an approval at $N_{50\%} = 8{,}000$ LC.

However, figure 3 shows as well a significant gap between the 5% AR-isoasfalion and the area of statistical unsafe cylinder populations with a reliability of SR < $1\text{-}10^{-6}$ against failure. A cylinder population which is statistically unsafe in respect to the reliability at end of service life could not pass the criterion of the GTR 13. This is discussed in detail in chapter 6.

The AR-isoasfalion of AR = 95% represents a more realistic attempted based on economic considerations by a manufacturer of composite cylinders. A smaller acceptance rate than 95% lead to increased rejection rates in production due to batch tests and is therefore not economically efficient.

Figure 3 shows that the 95% AR-isoasfalion is above the criterion of 11,000 LC. That means an economic acceptance rate of AR = 95% for the approval criterion forces a manufacturer to achieve higher mean load cycle strength, depending on the expected scatter. This result is based on a assumed Weibull distribution as shown in chapter 3. This conservative assumption refers to a cylinder population at their end of service life. Under the assumption of a Log-Normal distribution for composite cylinders in new conditions the 95% iso-line would be at a slightly lower level than shown in figure 3.

The analyses of acceptance rates for the probabilistic approach of the BAM is shown in figure 4 for a sample size of n = 5 and a reliability of SR = $1\text{-}10^{-6}$ against failure. Since the BAM-PA is not limited to a specific sample size, the 95% AR-isoasfalion for n = 10 (dotted line) is as well shown in figure 4.

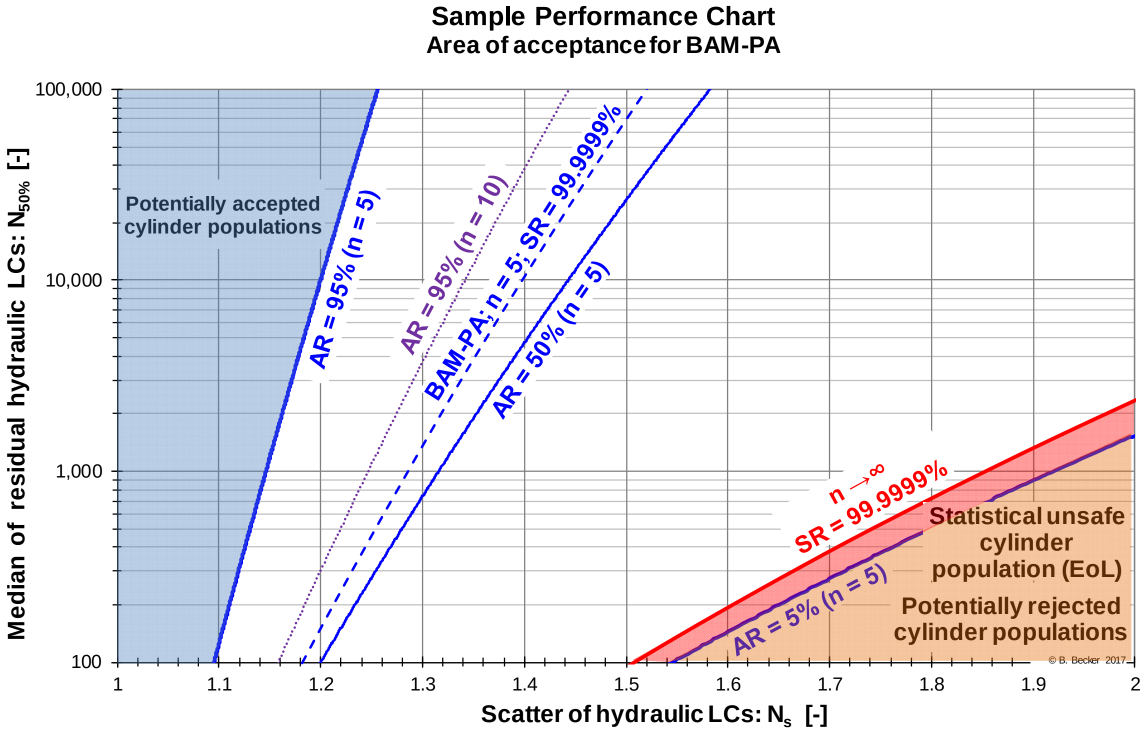

Figure 4. Areas of acceptance for cylinder populations according to the BAM-PA

The aim of the BAM-PA is to identify potentially unsafe cylinder population after a certain part of their service life time. Therefore, the 5% AR-isoasfalion is close to the reliability criterion of SR = $1\text{-}10^{-6}$. The isoasfalia for the statistical unsafe area corresponds to a constant acceptance rate of around 6%. This results from the defined confidence level of 95%. The confidence level limits the probability of a positive false decision to 5%. The difference of 1% between the acceptance rate of the reliability criterion for end of life and the 5% AR-isoasfalion results from the simplification to transform the Weibull parameters into parameters from a Log-Normal distribution as described in chapter 3.

The both 95% AR-isoasfalia for n = 5 and n = 10 are showing that the area of potentially accepted cylinder populations strongly depends on sample size n. A high sample size leads to a significant reduction of uncertainties about the true properties of a cylinder population. Another important factor is the required reliability SR against failure. These two parameters allow a flexible adoption of the BAM-PA depending on expected failure consequences and operating conditions.

6. RESULTING SAFETY OF THE GTR 13

The previous chapter showed the general behaviour of acceptance rates for the deterministic load cycle criterion of the GTR 13 and the probabilistic approach of the BAM. Following questions need to be answered:

- How high is the probability to accept a potentially unsafe cylinder population?

- Which level of load cycle strength can be ensured for the planned service life time?
- Does a statistical analysis offer additional options to optimize existing approval criteria?

In regards to the acceptance of potentially unsafe cylinder populations, figure 5 shows the acceptance rates of a cylinder population with a marginal reliability of SR = $1\text{-}10^{-6}$ against failure depending on scatter N_s.

As already explained, the BAM-PA results a in constant level of acceptance rate AR of about 6%. The corresponding lines for the GTR 13 are separately shown for the minimum requirements of 11,000 LC; 7,500 LC and 5,500 LC. All three criteria show a sharp increase in the acceptance rate at a scatter level of $N_s > 2$. For $N_s < 2$, the acceptance rate is close to zero. Therefore, all variants of the GTR 13 exclude the acceptance of cylinder population with critical reliability against failure at one additional load cycle N = 1.

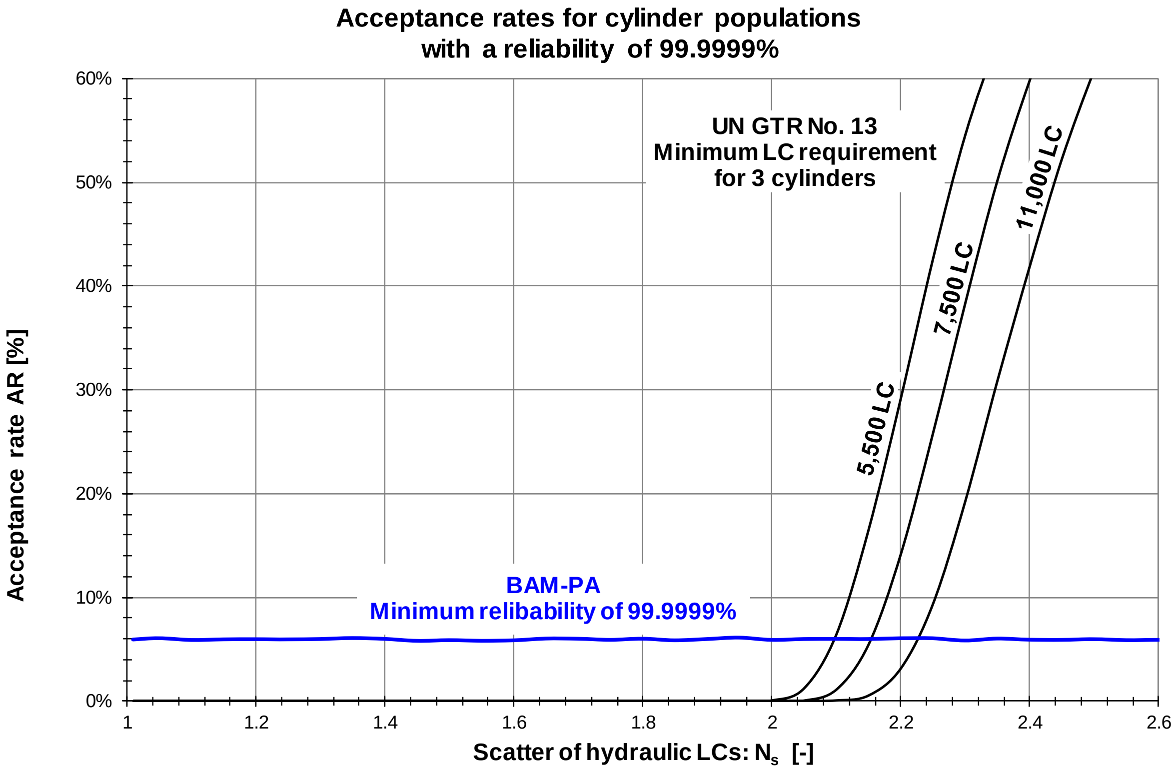

Figure 5. Acceptance rates of cylinder population with a critical reliability of 99.9999% against failure at the next load cycle

However, figure 5 does not show the actual aim of a deterministic criterion such as the GTR 13. The aim is not to ensure a sufficient safety against failure at N = 1. The GTR 13 tries to ensure certain load cycle strength for the whole service life time.

To evaluate this, it is necessary to consider the reliability against a specific minimum number of load cycles N > 1 LC. That means, for example that 99.9999% of all cylinders into a population need to withstand at least N load cycles. In the SPC this leads to a shift of the safety criterion by N load cycles. Figure 6 shows this on the example of N = 1,000 LC.

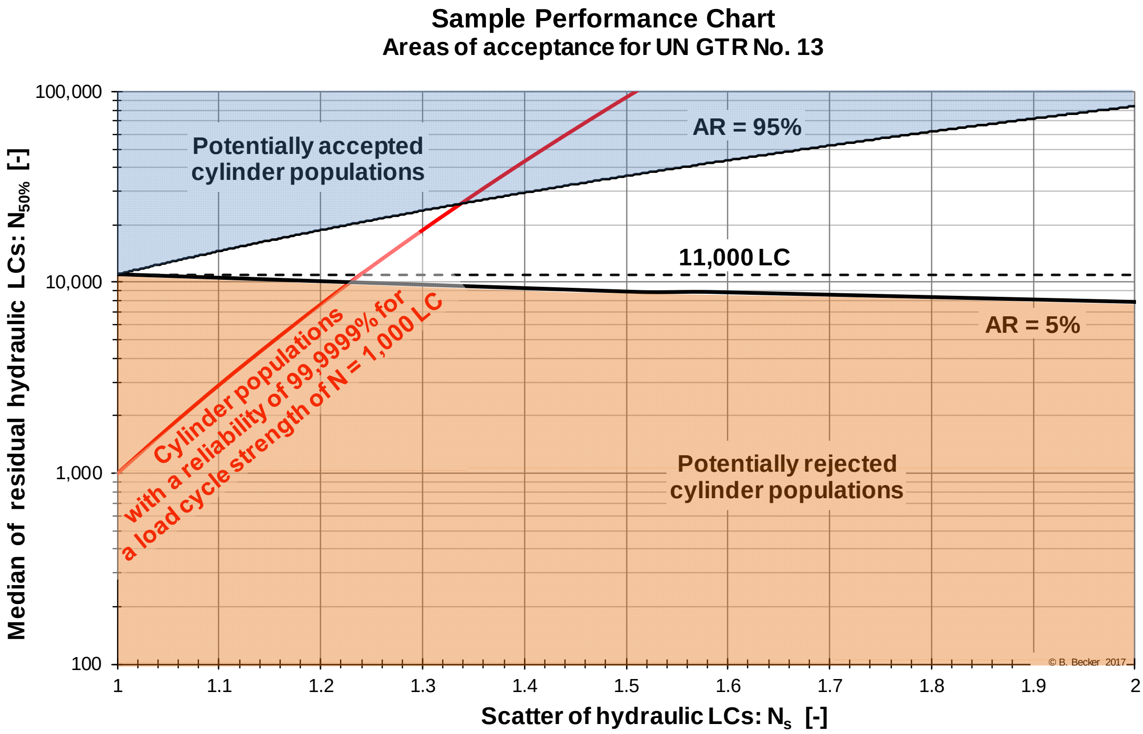

Figure 6. Areas of acceptance for the UN GTR No. 13 in comparison to cylinder populations with a reliability of 99.9999% for N = 1,000 LC

The red line in figure 6 represents all cylinder populations with a reliability of SR = $1\text{-}10^{-6}$ to withstand N = 1,000 LC. According to the results of the analysis such a cylinder population would be rejected by the GTR 13 below a scatter of $N_s < 1.24$. However, above a scatter level of $N_s > 1.34$ these cylinder populations would be probably accepted.

This means that cylinder population where one of a million cylinders has load cycle strength of N < 1,000 LC can be approved by the GTR 13. This is in contrasts with the aim of the GTR 13 to ensure 11,000 LC. In general, a deterministic criterion that is based on 3 single tests cannot ensure the defined criterion for a whole population.

This leads to the question: How many load cycles can be ensured? Under the assumption that a manufacturer follows the isoasfalion of AR = 95%, figure 7 shows the number of ensured load cycles in dependence of scatter N_s. The results in figure 7 are based on a Weibull distribution and a Log-Normal distribution. As already explained in chapter 3, a Log-Normal distribution is a more suitable description for the load cycle strength of composite cylinders in new conditions.

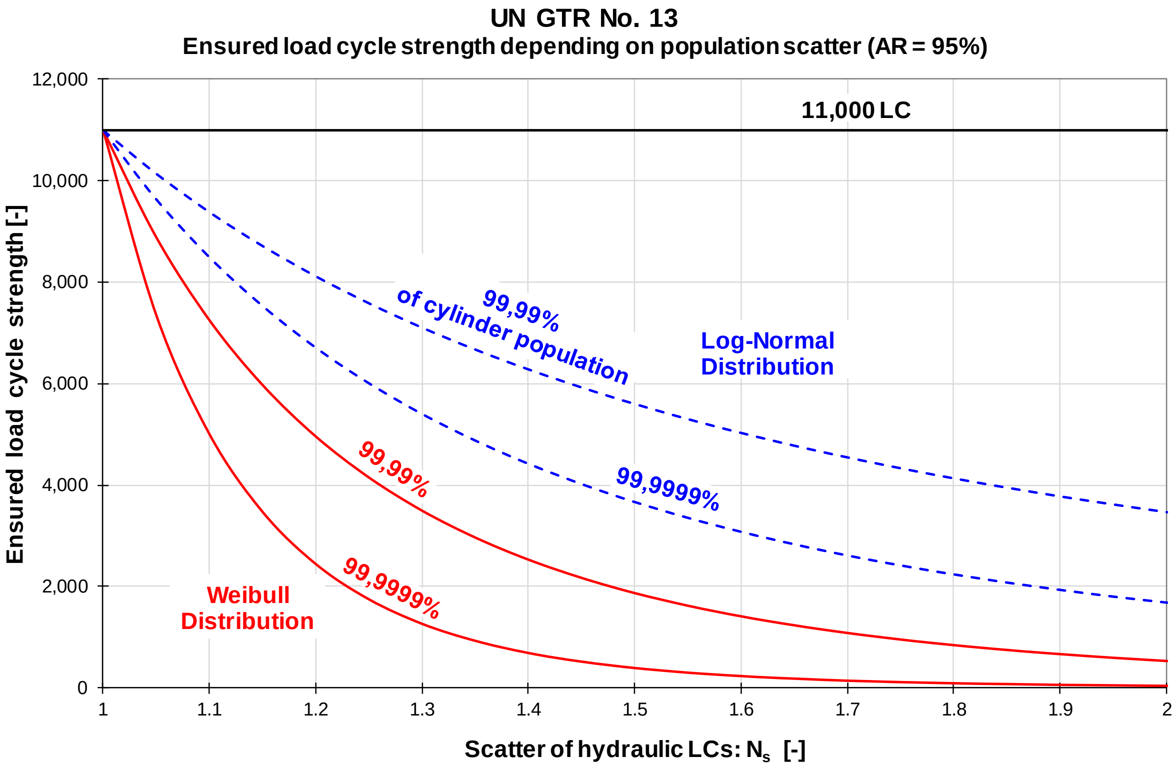

Figure 7. Ensured load cycle strength for cylinder populations with an acceptance rate of 95% for UN GTR No. 13

Figure 7 shows a drop in the number of ensured load cycle strength with increasing scatter of the cylinder population. In case of a typical scatter value of N_s = 1.4, a load resistance of at least 6,000 LC can be ensured under the assumption of a Log-Normal distribution for 99.99% of the cylinders. A minimum strength of 4,000 LC can be ensured for 99.9999% of the cylinder population. Under the conservative assumption of a Weibull distribution, these values are reduced to approximately 2,500 LC and 700 LC.

The analysis shows that a deterministic criterion as the GTR 13 ensures a significantly lower load-cycle strength than the criterion itself. This behaviour could result into a problem in case that a manufacturer uses the available design range as assumed and if a cylinder with poor load cycle properties is used for applications with a very high number of filling cycles.

In case of composite cylinders, it must be also considered that a hydraulic load cycle cannot be transferred one to one to a filling cycle. Composite materials in general are sensitive to load cycles and constant loads. Both type of stress results into an accumulation of micro-damages and an increasingly weakening of the structure. Additionally, the polymer matrix underlays chemical aging and shows higher temperature sensitivity compared to metallic materials. The influence of these factors is usually not covered by hydraulic load cycle tests.

In [10] was demonstrated that the ratio between filling cycles and the loss of hydraulic load cycle strength can be up to 250 LC for 1 filling cycle. The composite cylinder in this example was approved according to ISO 11119: 3 and was used for a stationary application with around 4 filling cycles per year. These operating conditions led to a loss of around 1,000 LC of mean load cycle strength per service year. However, the ratio of hydraulic load cycles to filling cycles strongly depends on operating conditions and cylinder design; it cannot be generalized by tools available today.

7. CONCLUSIONS

The analysis showed the behaviour of two different approaches for an assessment of load cycle tests results. Both approaches are based on different methods and are following different objectives. The GTR 13 uses a deterministic criterion with the aim to ensure minimum load cycle strength for new cylinders. The BAM-PA is based on a probabilistic method to assess residual reliabilities of aged cylinder populations for further use.

The BAM-PA does not contain any definition of minimum load cycles. However, this method is very sensitive to high scatter values. A high scatter of load cycle strength can be an indicator for quality problems or aging effects.

The analysis of the GTR 13 shows that a potentially unsafe cylinder design with a risk of failure against one additional load cycle cannot be approved. But the ensured load cycle strength is clearly below the target of 11,000 LC. The number of ensure load cycles drops with an increasing scatter of a cylinder population. This demonstrates a general weakness of deterministic criteria.

The aim should be an assessment criterion which ensures both, sufficient minimum load cycle strength and a high reliability against failure. The GTR 13 already contains a semi-probabilistic criterion to assess burst test results. It is recommended to add corresponding measures to limit the scatter of load cycle strength for approved cylinder populations within the GTR 13.

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