Composite Gas Cylinders
– Probabilistic Analysis of Minimum Load Cycle Requirements

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ABSTRACT

Gas cylinders made from composite materials receive growing popularity in applications where light weight is advantageous.

Current standards base safety determination mainly on the demonstration of minimum amounts of endured load cycles and minimum burst pressure of a small number of specimens. This paper investigates the possibilities of a probabilistic strength assessment for safety improvements and cost and weight savings. The probabilistic assessment is based on destructive testing of small samples. The influence of sample size on uncertainty of the assessment is analysed. Also methods for assessment of ageing in service (degradation) are discussed and displayed in performance charts.

1. INTRODUCTION

Gas cylinders made of continuous fibre reinforced plastics (composites) do have weight advantages over those made of metal. This makes them suitable for mobile use e.g., as storage unit in breathing apparatus for emergency services, fuel storage for gas powered vehicles or hydrogen transportation in battery vehicles or tube trailers. Weight advantages are most significant when carbon fibre material (CF) is used.
Unfortunately these gas cylinders also suffer from high production costs, particularly if they are made from CF. Compared to metal cylinders the determination of safety and reliability of composite cylinders is more complex, which increases the effort during approval process and for manufacturing quality control. The strength properties of composite gas cylinders are known to depend on a larger variety of design and production influences than the properties of cylinders made of metal. Also, composite material degradation is more complex, because of different failure mechanisms, which are mainly dependent on time and temperature.

Acknowledging this, methods for safety determination are becoming more sophisticated. The aim to lower material consumption and production cost can justify extended efforts in this field. The minimum burst pressure as a safety criterion is criticized for keeping costs unnecessarily high, at least since the completion of the EU-project StorHy [1] in 2008. The principle of safety assessment for type approval is still the same today. According to current standards, there are varying boundary conditions and required burst pressure, depending on the application. For this reason, 10 years after author's first international paper on the probabilistic approach in RC&S at the first ICHS conference 2005 [2], details on fatigue aspects are illustrated here. In the following it is shown how the current specifications according to regulations, codes and standards (RC&S) can be evaluated regarding a required reliability incorporating scatter of load cycle strength. This assessment results from experience as competent authority and as project partner in EU-projects like StorHy [1], HyCube [3] and HyComp [4]. Employing the methods introduced for evaluation of burst tests during the EHEC 2014 [5], the safety level resulting from current standards as well as a potential reduction of current minimum requirements can be derived. The safety concerning load cycling can be analysed in a very similar manner to the assessment of safety for quasi-static load tests as shown in [5]. According to [6], the most critical strength criterion (load cycle or static strength) depends on the design of the cylinders: High burst pressure does not guarantee high load cycle strength, particularly for gas cylinders with metal liner and vice-versa. For this reason, always both criteria have to be investigated.

This paper is based on [5], which refers to the criterion of burst strength. Burst strength is considered the main benchmark if a design type reliably withstands more than 50,000 load cycles [7]. Minimum burst strength is also employed to investigate the safety level resulting from current standards. In [8, 9] the slow burst test procedure and a performance chart for the statistical assessment of burst test results has been introduced. The sample performance chart shows the mean value of strength over the scatter of strength. Based on this, current requirements on minimum burst strength can be given [5]. In the following it will be shown how deterministic and probabilistic criteria can be compared with respect to load cycle strength. The background of analyses concerning burst and load cycle criteria is explained in detail in [10].

The nomenclature used in the following is:

CF	carbon fibre
CFRP	carbon fibre reinforced plastic
cyfas	cycle fatigue sensitive (design)
non-cyfas	non-cycle fatigue sensitive (design)
FC	fuel or filling cycle in service
LBB	leak before break (leakage without rupture)
LC	load cycle (at hydraulic or gaseous testing)
LCT	load cycle test
LND	log-normal distribution
ND	normal distribution
SBT	slow burst test: burst test with a constant pressure rate of not more than 20% of PH/h
SPC	sample performance chart
TDG	transport of dangerous goods
WD	WEIBULL distribution

m_{logN}	mean value of logarithmic values of load cycle sample testing		[-]
$p_{50\%}$	mean value or median of the burst pressure of a sample		[MPa]
s_{logN}	standard deviation of logarithmic values of load cycle sample testing		[-]
MSP	maximum service pressure*		[MPa]
			** MSP for general service can be interpreted as PH*
N	residual load cycles to failure of a specimen		[-]
$N_{50\%}$	mean value or median of the number of LCs to failure of a sample		[-]
N_s	Scatter of number of LCs (based on standard deviation)		[-]
NWP	nominal working pressure		[MPa]
PH	test pressure; equals 150 % of nominal working pressure		[MPa]
SR	survival rate of a sample or the whole population		[-]
T_N	spread of distribution of LCs: “Streuspanne”	$T_N = N_{90\%}/N_{10\%}$	[-]
Ψ	relative scatter value of burst pressure of a sample:	$\Psi \equiv \Omega_{10\%} - \Omega_{90\%}$	[-]
Ω	relative value of burst pressure of a sample:	$\Omega \equiv p/MSP^*$	[-]
$\Omega_{50\%}$	relative mean value of burst pressure of a sample:	$\Omega \equiv p_{50\%}/MSP^*$	[-] (see Ω)

2. THE PERFORMANCE CHART FOR THE PROBABILISTIC ASSESSMENT OF CYCLE FATIGUE STRENGTH

To qualify the results of cycle tests for a statistical assessment, the test procedure has to be described very precisely. This guarantees reproducible test results without significant fluctuations out of the experimental setup and procedure. Variations out of the experimental setup would blur a probabilistic assessment. Also, there should be a unified system for assessments of such results. This would permit a reliability analysis of strength values of specimens from a single test sample and as well a system for comparing various samples of one design type or even from different design types.

A sufficient precise description of a cycle test procedure is established in [11]. This procedure is much more detailed and permits a much closer range of parameters than various relevant standards like EN 12245 [12], EN ISO 11119-3 [13] or EN ISO 11439 [14] do. As a main difference to standard cycle procedures, the temperature in the test chamber and of the medium is described in a smaller range of variability.

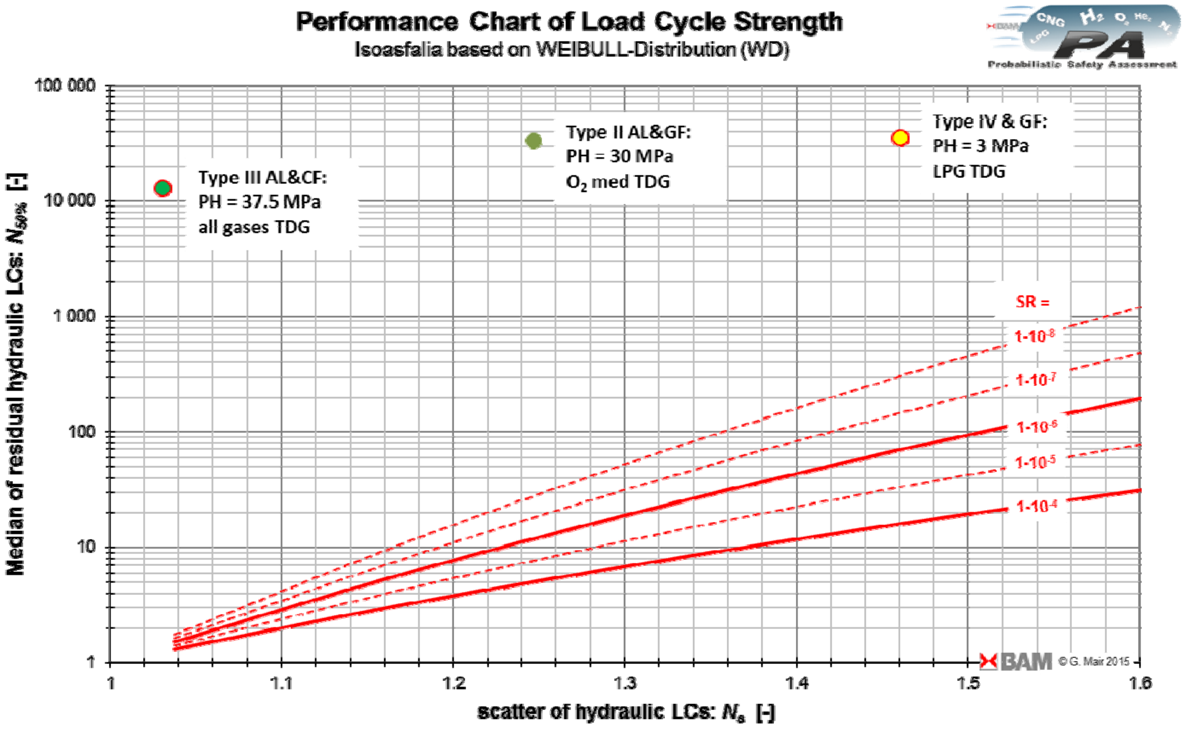

Figure 1 Performance chart with curves of constant survival rate

A sample performance chart (SPC) for the systematic assessment of sample tests has already been proposed in [5, 6] and [7] for slow burst tests (SBT) and in [7] for load cycle tests (LCT). The SPC is re-introduced in this paper. This diagram shows the number of load cycles to failure LC. It consists of an x-axis (abscissa), displaying scatter, and a y-axis (ordinate), representing the mean value (median) as shown in Fig. 1. In principle, this layout is applicable independently of the load case criteria load cycle or burst pressure. It visualizes safety limits as lines of constant survival rate (called “iso-asfalia”) against first failure. In case of LCT cycles shall be performed to maximum developed service pressure (MSP) or test pressure (PH). The shown red lines are valid for the assessment of the whole population. The influence of confidence of limited sample size is not shown here. Results of three tested samples are added.

The mean value of load cycle capability in the meaning of the median of the log-normal distribution (LND) is calculated as follows:

$$N_{50\%} = 10^{m_{\log N}} \quad \text{with} \quad m_{\log N} = \frac{1}{n} \sum_{i=1}^{n} \log_{10}(N_i) \qquad \text{[LC]} \qquad (1)$$

In case of hydraulic load cycle capability the standard deviation of the LND is:

$$s_{\log N} = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \left(\log_{10}\left(\frac{N_i}{N_{50\%}} \right) \right)^2} \;, \qquad \text{[-]} \qquad (2)$$

For load cycles this results in $N_s = 10^{s_{\log N}}$ or for those who are used to work with the scatter range T_N "Streuspanne" the relevant equation is:

$$1 : T_N \equiv \frac{N_{SR=10\%}}{N_{SR=90\%}} = 10^{2.57 \cdot s_{\log N}} = N_s^{2.57} \qquad \text{[LC]} \qquad (3)$$

In this paper, reliability of survival will be discussed as criterion for the safety of gas cylinders. It is often called survival rate (SR; complement to failure rate FR; SR = 1 - FR). When assessing composite gas cylinders, only extremely high survival rates ($SR \geq 1\text{-}10^{-6} = 99.9999\%$) are acceptable. With respect to explanations given in [7, 14] the WEIBULL distribution (WD) was introduced in [16] and [17].

3. REQUIREMENTS FROM CURRENT STANDARDS

There is a multitude of standards and regulations for pressure receptacles which are aiming at various applications (transport of dangerous goods, fuel storage in vehicles) and valid in various geographical limits (country, region, worldwide). All those regulations have more or less varying safety factors. Here, ISO 11119-2 [18] and European regulation ECE 406/2010 [18,19] are chosen as representative examples. ISO11119-2 is applicable worldwide for the transport of dangerous goods (TDG) in fully wrapped gas cylinders with load bearing liner, while ECE 406/2010 is the current code for fuel storage in hydrogen vehicles in the EU. Additionally, there are global technical regulations (GTR) for hydrogen vehicles [21]. Currently, these GTRs do not have legally binding status and are not implemented uniformly in most industrialized countries. For this reason, here they are considered unsuitable as a practical example. Regulations for hydrogen vehicles are preferred as an example over codes for natural gas vehicles, because current debates are centred on hydrogen applications.

Codes for TDG permit approvals for an unlimited life-time of gas cylinders. This means a cylinder can be used until it fails either the visual inspection before refilling or the mandatory retest after retest-period. To account for this, e.g. ISO 11119-2 demands demonstration of hydraulic load cycle testing of 2 test specimens up to 12,000 load cycles without leakage. Normally, the upper pressure level has to be test pressure PH. If cylinders need to be approved only for one gas, the respective MSP can be chosen as upper pressure level for load cycling. The required load cycle number stays the same (12,000). If pressure receptacles need to be approved for limited life, ISO 11119-2 has lower demands on load cycle resistance. 500 load cycles per annum of design life have to be achieved for approval. If "leak-before-burst" properties can be demonstrated, an even lower amount of 250 load cycles is sufficient. According to experience from the gas industry, approximately 4 refills per annum are representative for typical TDG usage. In some cases only 1 to 2 refills annually occur. According to recollection of the author on discussions in standardization boards during the 1990s, the maximum number of refills for a gas cylinder is expected to be around 1,000 during 50 years of service life in TDG. Gas cylinders in battery vehicles have to be excluded from these assumptions. Such cylinders can experience more than 300 refills annually.

Opposite to TDG, the automotive industry expects approximately 6,000 refills in 15 years of service life, which means 400 refills annually (see section A.5.1.1.2.b of the technical regulation (GTR) on hydrogen and fuel cell vehicles [21]). The European approval code EC 406/2010 accounts for 1,000 load cycles as a base value, with an additional 200 load cycle per year of design life, if electronic filling surveillance is part of the system. Life time cannot exceed 20 years. If no electronic filling surveillance is available, requirements for a life time of 20 years, which means 5,000 refills, have to be fulfilled. To demonstrate reliability against the corresponding load, there are requirements dependent on "leak-before-burst"-properties. If leak-before-burst is proven, the threefold of the expected refilling cycles has to be demonstrated in load cycle testing. In all other cases, the fuel storage cylinders have to endure 9-times the expected refilling cycles during hydraulic load cycle testing without failure. The upper pressure level for load cycle testing has to be 125% of the nominal working pressure NWP. In case of Hydrogen this represents the pressure developed after filling to NWP at 20°C and heating of the cylinder up to 85°C. In all cases, the actual number of load cycles until failure is not considered and not tested for. Commonly, load cycle tests are aborted after the required load cycle number is achieved.

For further explanation the demands of the current legally binding requirement for hydrogen vehicles (EC 406/2010) will be used. Another important point for the assessment of statistical aspects is the treatment of production batches. Various types of tests are required in all relevant pressure receptacle approvals for quality surveillance. Besides materials testing and initial pressure testing of each gas cylinder, samples from every production batch will be employed for destructive testing. EC 406/2010 demands load cycle testing of one cylinder out of every production batch. Only if 10 production batches have passed batch testing successfully, load cycle testing can be reduced to one cylinder per 5 production batches.
The size of production batches is limited to 200 cylinders plus cylinders for testing in EC-Regulation 406/2010. The described tests for quality assurance are commonly called "batch tests". If a tested cylinder does not fulfil the requirements, the reason for this failure has to be investigated. In a simplified way, the relevant regulations permit repetition of the test with a different cylinder, if a problem can be traced back to the individual failed cylinder. If the repeated test is a success, the production batch can be admitted for the market. If a systematic problem can be found for the whole production batch, the whole batch has to be discarded.

In current regulations total production volume is not limited and there is also no minimum production volume. For mass produced automotive fuel storage system, 10,000 is considered a minimum number (A), while 100,000 are a reasonable objective (B), and maybe even 1,000,000 are aspired. Production methods are assumed to permit maximum batch size in all cases. The scenarios are based on the assumption that the mentioned amount of critical individuals has either not been detected (only one of 10 batches is tested by LCT) or do not lead to the rejection of a batch. This is possible if further assessment on batch properties does not give hints on manufacturing defects in other cylinders in the batch. Passing batch tests is a question of statistics. For the following comparison it may be assumed, that all requirements of design type approval are fulfilled during the first attempt with a probability of 90% for A and 99% for B. For batch testing it is assumed for A, that every fifth batch fails a batch test just due to the scatter of properties. This means further without an actual production problem and without relevant hints on manufacturing defects. For scenario B it is assumed that only every 20th batch is accepted to be discarded after batch testing. These scenarios are summarised in the following Table 1.

Table 1 Scenarios for the statistical assessment of deterministic requirements

Criterion	On-board: EC-Regulation 406/2010; para 3.9.1.1 (CFRP; CGH2; types III and IV)	
Scenario	A	B
Design type testing	2 cylinders to LC-test	
N_{min} of LCs (based on expected fuel cycles FC)	FCs = 1 000LCs + 200LCs p.a. (max. 5000) no leakage before 3 x FCs no rupture before 9 x FCs	
Max. life time	20 years	
Size of batch	200 cylinders + specimen for batch testing	
LCT per batch	1 cyl/batch (1 of 200) to 10 batches; then 1 cyl per 5/10 batches (1 of 1000/2000)	
Total population	10 000 cyl	100 000 cyl
LC-Test	2 cyl. + 18 cyl.	2 cyl. + 108 cyl.
Rate of deficient batches	10%	1%
LCT total	20 cyl.	120 cyl.
Rejection rate	0 batch	0 batch

Overall, the probability to pass an approval or batch test depends on mean value and scatter of a population. Another influence is the “lucky hand” in picking the test specimens.

Fig. 2 shows the corresponding requirements for load-cycle-testing, based on a logarithmic scale. On the left of the diagram there is an area which represents unrealistically small scatter values.
The diagrams show an area between the lines „A“ and „B“ (EC-Regulation 406/2010) for the realistic range of statistical minimum requirements resulting from standards. Those are found above the lines representing the deterministic minimum requirements.

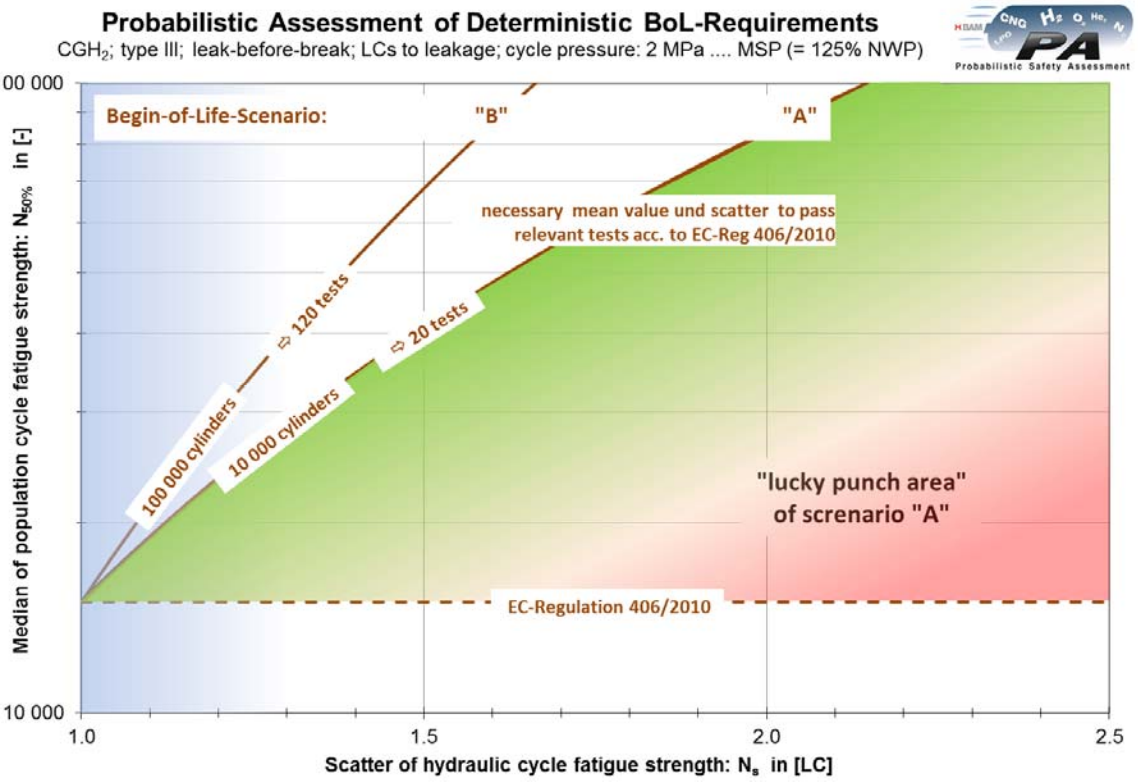

Figure 2 Description of ambient load cycle test requirements based on statistical properties

The area below the lines ”A“ does not exclude passing approval or batch test. But they require “accident” or “luck” additionally to the requirements found in Table 1. For this reason, the area up to a success rate of 50% of passing a batch or approval tests is called “lucky punch” area. This is marked in colour in the Fig. 2. Based on known properties of cylinder types (type III: fully wrapped; type IV without load sharing liner), there are application preferences. On the one hand, a CFRP-cylinder without metal liner commonly has no problem in fulfilling load cycle requirements, if burst requirements are achieved. On the other hand, cylinders with metallic liners usually fulfil burst requirements, if they surpass load cycle fatigue demands. For this reason, type II and III cylinders are very common in TDG, while type IV cylinders are mainly used in vehicle applications.

4. GRAPHICAL COMPARISON OF BOTH APPROACHES

Fig. 3 is taken from [5] and shows the areas of different conclusions of safety assessment based on burst strength. Although the burst test (BT) is not considered here, this reference allows explaining the principle of comparison briefly. There scatter is described by using the difference of the pressure values of 90% and of 10% reliability.

On the left side of Fig. 3, in the area from left to the centre (marked in green to yellow), design types can be found which could be approved according to the probabilistic approach. Due to their small

scatter, these pressure receptacles can be considered safe although their average strength does not comply with the safety margins demanded in current RC&S. On the very left of Fig. 3 a vertical area (marked blue) can be found, which indicates limits of unrealistically small scatter:
More towards the right side of Fig. 3, a sector can be found, marked in yellow to red, which shows design types most likely not passing tests according to EN 12245/ISO 11119-2. These gas cylinder designs below the line of minimum survival rate are also identified as unsafe by the probabilistic approach. Nevertheless, they could pass the standard tests if some randomly picked strong specimens of a production batch with a high scatter are tested ("Lucky Punch Area"). In these cases, unsafe gas cylinder designs and/or production batches could be approved for service by chance.

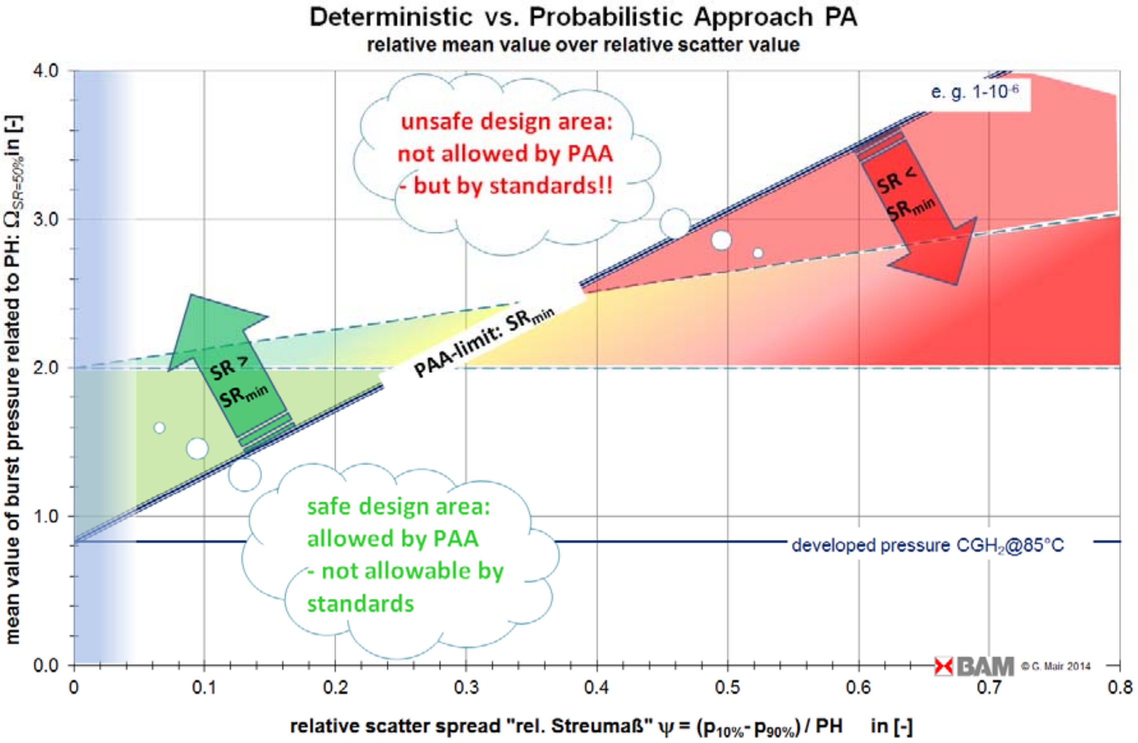

Figure 3 Areas of diverging assessment results

Highest attention should be paid to the upper part of the red area on the right side of Fig. 3. This area below the line of minimum acceptable survival rate represents design types, which are insufficiently reliable according to the probabilistic assessment. But according to current RC&S only a minimum burst pressure is required which would result in these design types being approved regardless. Such an approval is conditionally probable in the case of properties described by the "lucky punch" area or is achievable more or less easily above this area.

Automotive applications and transport of dangerous goods (gas suppliers) each have dedicated standards for composite gas cylinders, which mainly differ in the numerical aspect of the requirements. Different burst ratios or numbers of load cycles are demanded. The structure of the requirements is always very similar to what is described above. Scatter of the (few) test results is usually not assessed. One exception is UNECE GTR [21], which imposes further demands if burst pressure of three initial test specimens differs more than 25%. This does permit extremely high scatter without further demands. Also, three test results are not considered acceptable for statistical assessment by the authors. As found in [7, 16], test samples should at least consist of 5 specimens. Particularly if scatter is not proven to be small for a specific design type, single tests are of limited significance.

Some relevant regulations for automotive use are EN ISO 11439 [14] and (EC) No. 79/2009 [19] in connection with (EU) Nr. 406/2010 [20]. The UNECE GTR [21] is not directly compulsive in the legal sense. For use it has to be implemented by national law. As an example, [18] is discussed here. It applies to hydrogen vehicles with pressurized gas fuel storage systems. A burst ratio of the computed stress level of 2.25 of nominal working pressure NWP or 1.5 PH is demanded for carbon fibre gas cylinders. The hydrogen pressure developed at 85°C is only 84% PH, so an "effective safety margin" of 1.8 results. Justifications for comparably low safety margins in automotive application are commonly the fixed and protected mounting of the cylinders. This results in no manual handling and prevents impact damages in most cases. Also, service life time of these gas cylinders is limited to a maximum of 20 years.

5. IMPROVED SAFETY ASSESSMENT

Current RC&S are based mainly on experiments with cylinders right of the production line. Artificial aging effects are only investigated with the approach of reducing mandatory strength when testing single pre-conditioned specimens. Currently no probabilistic analysis about the development of degradation is performed or required by relevant RC&S. First attempts in doing so have been presented in [5]. It is known that fatigue in composite gas cylinders is not only dependent on the number of load cycles, but also on the time under load and the temperature. The correlations are not yet fully understood and proven. Additionally there are some service conditions improving the burst strength properties in the first years of service. Criteria useful for the determination of safety towards the end of service life (EoL) of composite pressure receptacles with respect to burst strength are discussed in [5]. The topic of artificial aging, employed for the simulation of service life degradation, is even discussed briefly in [5].

A comparison of statistical and deterministic requirements with respect to load cycle strength is shown in the following. Major differences in comparison to the results as shown in [5] are based on the way of describing cycle strength. On the one hand, a burst tests result is a maximum pressure while the number of cycles is fixed (pressure increase equals = 1/2 cycle). On the other hand, the cycles test results in a number of maximum endured cycles while the pressure level (pressure peak and minimum pressure) is a test parameter. Therefore a degradation of burst strength results in a reduction of burst pressure in relation to maximum service pressure while degradation of cycle strength leads to a reduction of residual number of cycles. As expressed in [5] the critical point in the degradation of safety is the reliability at end of life (EoL). The often made conclusion of degradation resistant carbon fibres is not discussed here. But it has been demonstrated several times (e. g. [6], [15], [22]) that multi-layer CFRPs are sensitive to cycle and to sustained loads. In terms of load cycles safety at end of life deems to be sufficient if one (the very last) filling cycle can be withstood with the required survival rate of for example $1\text{-}10^{-6}$. This assumption may sound strange but it equals with the request to withstand the MSP in a burst test with an adequate survival rate. Since the degradation of metal liners in composite cylinders per filling cycle is higher than the one by one hydraulic cycle the issue of the very last cycle may be discussed for different design types in a different, more conservative manner. But this does not change the principle of the analysis shown here: It is assumed that degradation caused by one FC correspond to degradation by one LC.

The load cycle requirement at end of life refers to the last safe refill. For this reason, the set of lines representing the requirements for the last refill (red) in Fig. 4 crosses the lines representing the regulation 406/2010 far outside the realistic scatter range. Respectively, the most important issue is the validation of expectable degradation.

Two aspects are open to describe the potential for cost and weight reduction by probabilistic safety assessment of a whole cylinder population: Aging, respectively degradation, and sample size. To handle those issues, at first aging should be estimated. Unfortunately, no reliable conservative assumption is available. But for now, one refill shall be represented by one hydraulic load cycle. Assuming the described boundary conditions and load assumptions, black lines in Fig. 4 results for new cylinders. The distance between the black set of begin-of-life-curves (BoL) and the red set of EoL-curves of constant survival rate represents the allowable degradation during service (yellow areas).

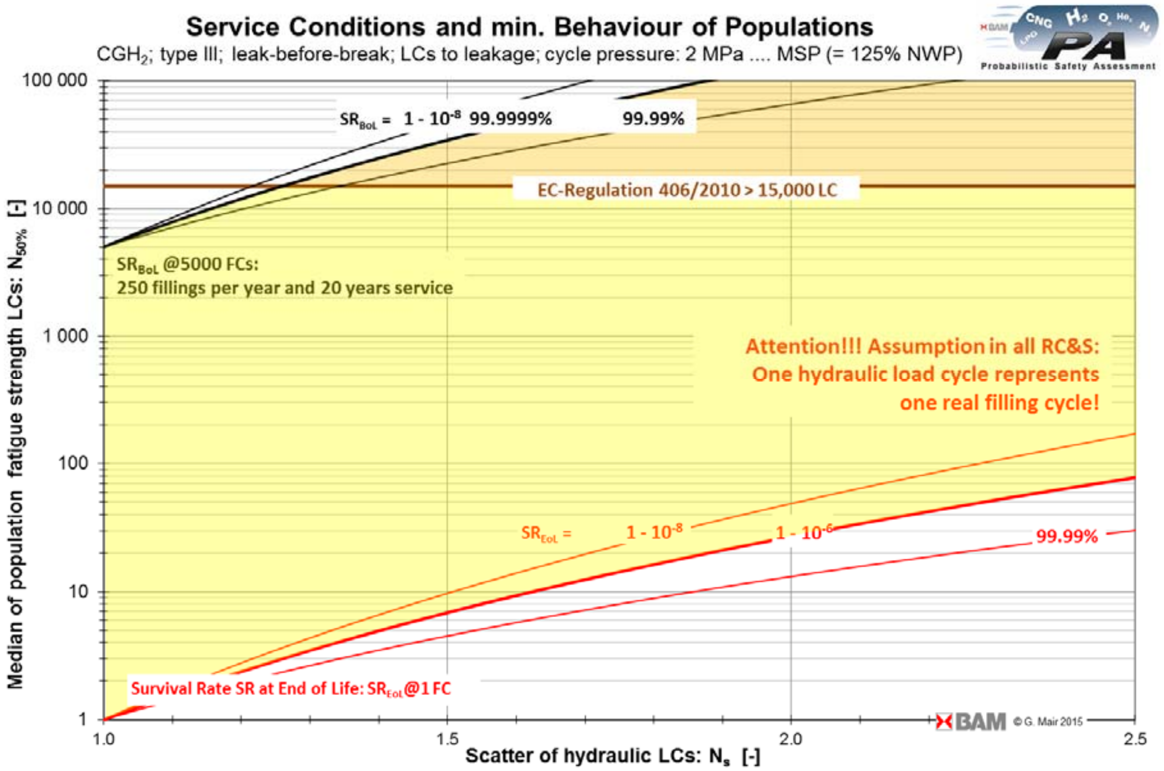

Figure 4 Initial minimum load cycle strength and EoL-requirements (red)

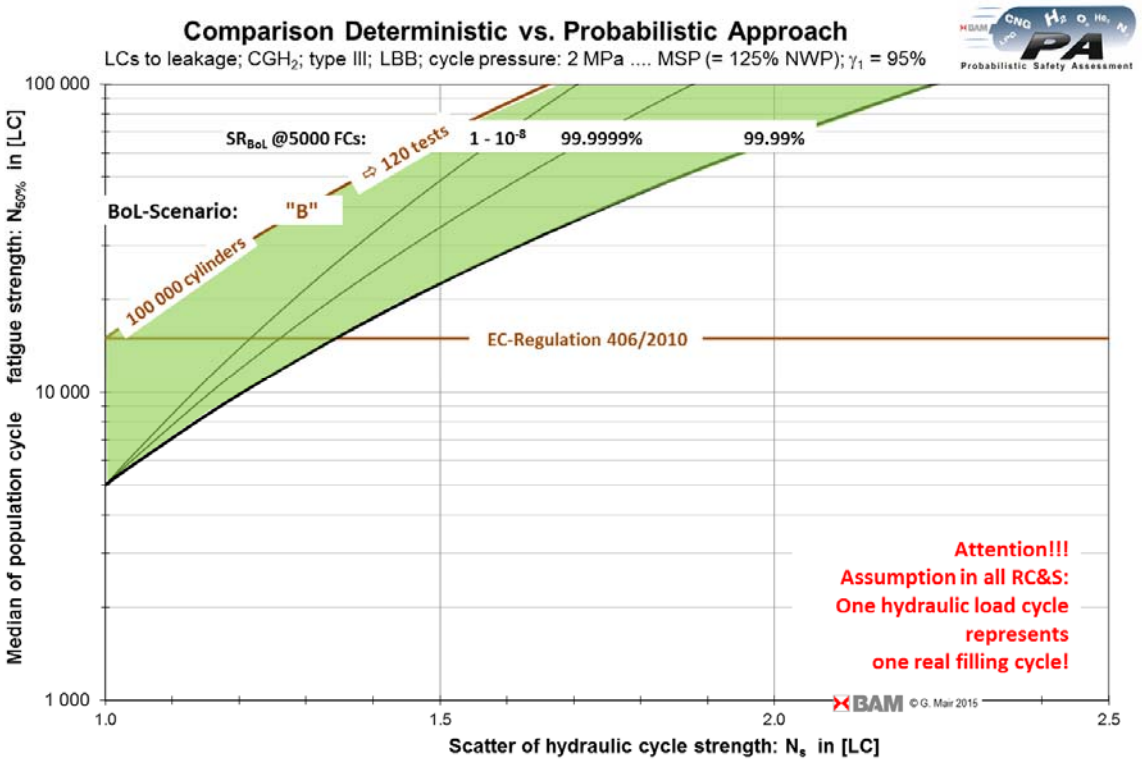

Figure 5 Areas usable for further optimisation

The nominal load assumption (5000 filling cycles) is higher than the experienced number of fillings during real service in most cases and the real properties are usually much higher than the minimum requirements (15,000 LCs in case of leak before break. It has to be mentioned that there is an actually larger degradation per refill of a type III cylinder. First experience on this is shown in [15]. Nevertheless, the assumption of one load-cycle representing one refill non-conservative is continued to be used here, so this needs to be mentioned. Eventually, the black set of curves meets the area representing minimum requirements according to standards as shown in Fig. 5. Similar to Fig. 3 areas usable for probabilistic optimisation are coloured green in Fig. 5.

It has to be noted: A smaller area for optimisation indicates a danger for over-estimation of design types with large scatter by standards. This leaves open the issue of sample size, aiming at a meaningful estimation and assuming validation of degradation during service.

6. INFLUENCE OF SAMPLE SIZE

A major limitation is the uncertainty of gas cylinder properties, which can currently only be determined by destructive testing. Obviously, such a property (for example load cycle strength) cannot be determined for each specimen of the whole population while leaving usable gas cylinders. This leads to the necessity of deriving the properties of a cylinder population from a group of cylinders (test sample). Initially, the results from approval and batch testing can be employed for this. Later during service life of a design type, samples of cylinders should be tested, which have "lived" parts of, or even their whole, design life. There remains an uncertainty, which is represented by the confidence level γ [7]. Increasing the sample size creates more confidence in the results. An additional source of uncertainty is found in production variations, particularly at the beginning of production. Independent from an actual improvement of properties this creates scatter.

The most important influence of sample size is the resulting minimum test requirement for demonstrating certain reliability.

It becomes clear, that not the whole theoretical area from Fig 3 or Fig. 5 can be used for optimisation. Also, for a population with somewhat large, but actually still acceptable scatter, sample size has to be larger than for cylinders with small scatter to ensure safety. Another result of this consideration is the indirect correlation between the safety achieved from minimum requirements from standards and sample size. For small scatter, the deterministic approach results in unnecessary high mean values. For large scatter, deterministic minimum burst requirements potentially result in unsafe gas cylinders being approved.

Some of the relevant standards permit reduced burst pressures for aged pressure cylinders. More important regarding aging and degradation are load cycle requirements. The assumption that one load cycle represents one refill, which is made for composites cylinder, is actually based on experience with metals and corresponding cumulative damage theories [23]. A safety margin is added, which is supposed to cover uncertainties from load assumption and production scatter. The resulting relation between expected refills and demanded load cycles is comparably large. With respect to [15] a factor of 250 times the number of filling cycles seems to be realistic for the very first years in some cases. While Fig. 4 combines BoL-requirements with EoL-requirements, Fig. 5 shows the demands for demonstrating minimum BoL-load cycle strength. Unfortunately the real degradation of load cycle strength cannot be considered as predictable as assumed in standards. For this reason, the requirements for EoL as shown above have to be compared to the requirements from current standards as shown in Fig. 2 under consideration of sample size. The result is displayed in Fig. 6. There the influence of sample size is shown for the automotive scenario (5,000 filling cycles), assuming leak-before-burst-properties. Areas of contradicting approval decisions are shown for both approval approaches, assuming a total production of 100,000 cylinders (deterministic scenario "B" with 5,000 load cycles) and sample size n=7 with 99.99% probability (blue lines). Conversely, larger sample size (n=27) would increase the green area and reduce the red area. The procedure is described in [7].

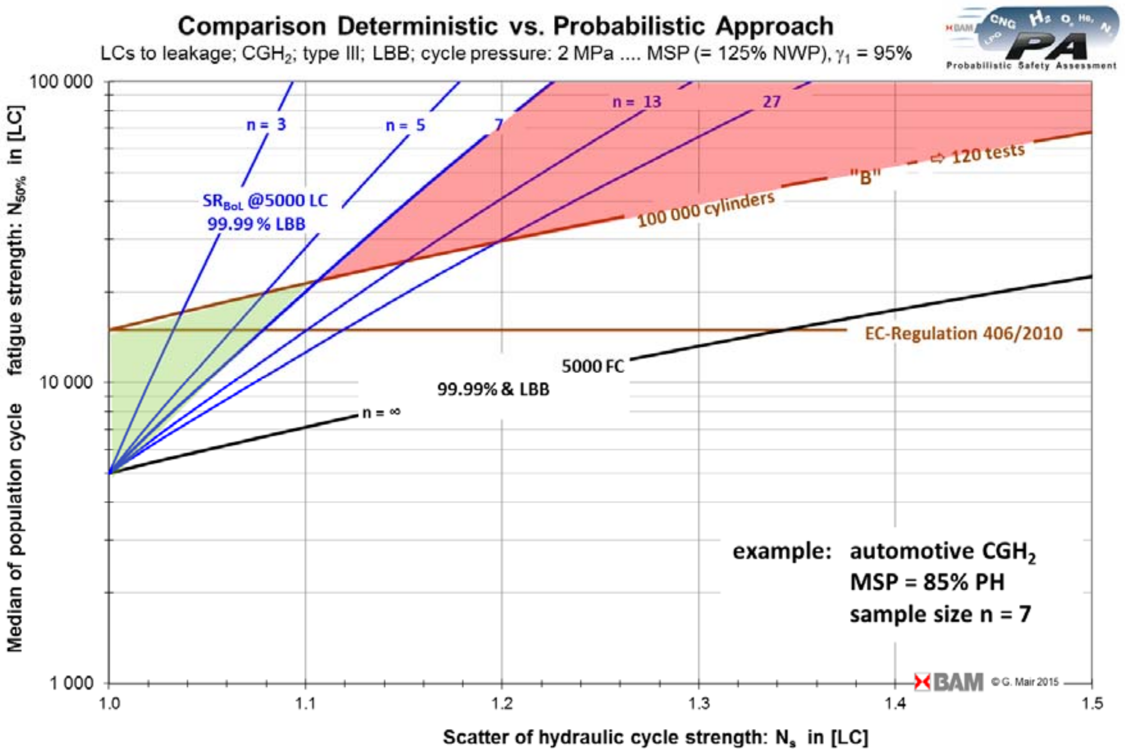

Figure 6 Areas of load cycle strength usable for further optimisation dependent from sample size

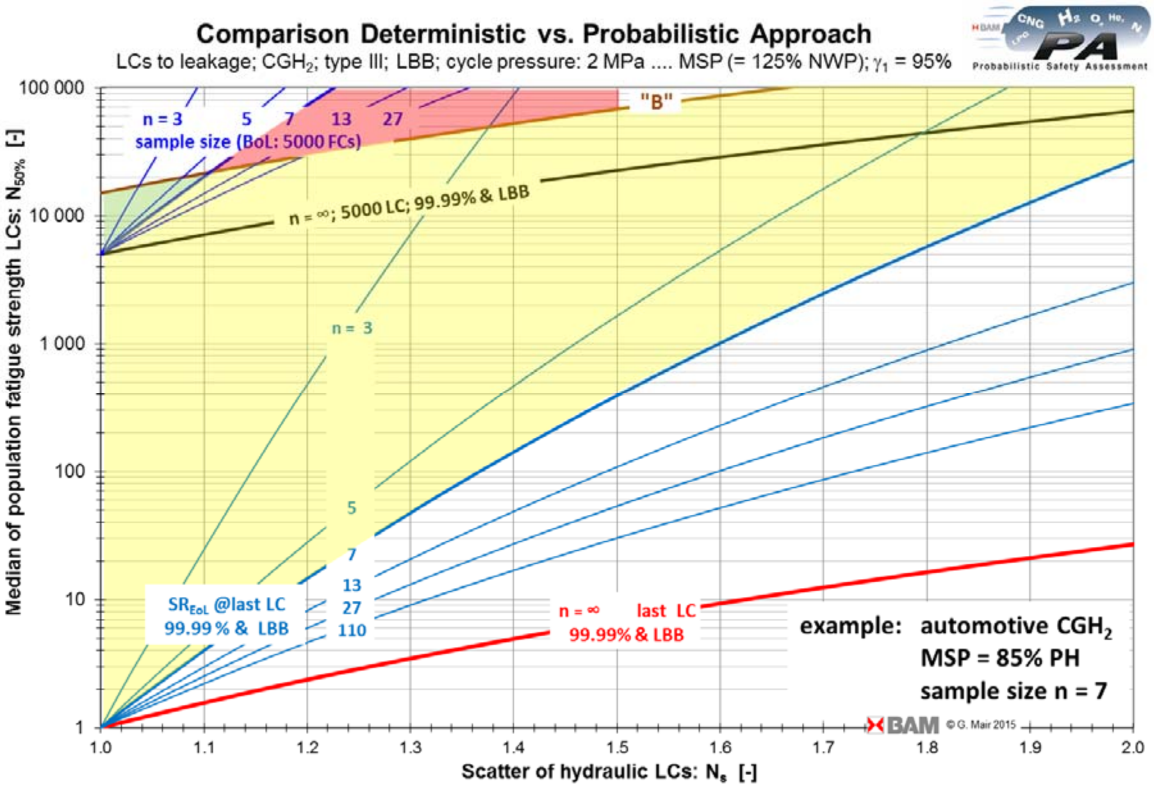

Figure 7 Areas of load cycle strength usable for further optimisation dependent from sample size

This means, for example, that a point of (N_s; $N_{50\%}$) = (1.1; 20,000) is sufficient if based on a sample size n = 7 for demonstrating a survival rate of not less than 0.01% on a unilateral level of confidence of 95%. But even a mean value of just $N_{50\%}$ = 10,000 LCs is sufficient in the case of a scatter not higher then N_s = 1.05. If sample size is reduced to n=3, the same properties are barely suitable to demonstrate the minimum requirements at BoL.
Fig. 7 includes all details from Fig. 6. Both figures show the influence of sample size on properties required for "safe" gas cylinders. The set of curves representing required reliability for the very last load cycle (EoL; SR = 1-10-4; leak-before-break LBB-property) is added. The area between is marked with yellow, as introduced in Fig. 4. It becomes clear on the one hand, that prediction of safety of a population during service is heavily depending on sample size. On the other hand, the area for optimisation below deterministic minimum requirements can be large, if enough data is available. The most difficult and critical aspect is the prediction of degradation, which is necessary for designing the properties at beginning of life (aiming at the green area) to still guarantee sufficient properties at the end of life (at least not leaving the yellow area).

As an example, a representative sample of the cylinder population can be in the green area at BoL and a sample taken later during service life may end up in the yellow area. Once a sample demonstrates properties leaving the yellow area, the population has ended its safe service life. If the EoL-properties of a population of cylinders go beyond the yellow area, it becomes an unsafe design – independent from its virgin properties. The population is not expected to meet the requested survival rate any more.

6. CONCLUSIONS

During the next years the first composite pressure cylinders from the "early years" will experience the end of their service life. If no catastrophic failures occur until then, this endorses the standards which were valid at the time of those cylinder's approvals to a certain degree. It must be considered though, that the very first design types, which entered the market, were largely overdesigned relative to the standards and compared to "modern" designs, mainly because of limited experience with the materials. There might also be temptations to reduce safety margins in future standards. Regarding such an advance the author wants to refer to the results of the "StorHy" project [1]. It was found, that such a reduction of safety margins should only be considered together with probabilistic validation. Such a validation has been shown here. It was pointed out that the deterministic approach may permit approval of cylinders with critical reliability. This shall not be discussed further here. It must be pointed out though, that the safety margins for fuel storage systems against aging and residual strength are already relatively small – in comparison with the margins of the transport of dangerous goods. Nevertheless there are areas for further weight and cost reduction. Since the degradation by real life cannot be predicted in the necessary depth the surveillance of degradation becomes the most important point. It has to be ensured that degradation is not underestimated. The safety level for end of life has to stay above the margins of cycle and burst strength that demonstrates the requested reliability level. The best way to do so is the use of probabilistic assessment of mean value and scatter as explained here.

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