MONTE-CARLO-ANALYSIS OF MINIMUM BURST REQUIREMENTS FOR COMPOSITE CYLINDERS FOR HYDROGEN SERVICE

Mair, G.W.[1,], Bock, R.[2] Günzel, St.[3] and Gesell, St.[4]
[1,2,3] Division 3.5 Safety of Gas Storage Systems,
BAM Federal Institute for Materials Research and Testing,
Unter den Eichen 44-46, 12203 Berlin, Germany,
[1] Georg.Mair@bam.de
[2] Robert.Bock@bam.de
[3] Stephan.Guenzel@bamde
[4] Division 5.2 Experimental and Model Based Mechanical Behaviour of Materials,
BAM Federal Institute for Materials Research and Testing
Unter den Eichen 44-46, 12203 Berlin, Germany,
[4] Stephan.Gesell@bam.de

ABSTRACT

For achieving Net Zero-aims hydrogen is an indispensable component, probably the main component. For the usage of hydrogen, a wide acceptance is necessary, which requires trust in hydrogen based on absence of major incidents resulting from a high safety level.

Burst tests stand for a type of testing that is used in every test standard and regulation as one of the key issues for ensuring safety in use. The central role of burst and proof test is grown to historical reasons for steam engines and steel vessels but - with respect for composite pressure vessels (CPVs) - not due an extraordinary depth of outcomes. Its importance results from the relatively simple test process with relatively low costs and gets its importance by running of the different test variations in parallel.

In relevant test und production standards (as e. g. ECE R134) the burst test is used in at least 4 different meanings. There is the burst test on a) new CPVs and some others b) for determining the residual strength subsequent to various simulations of ageing effects. Both are performed during the approval process on a pre-series. Then there is c) the batch testing during the CPVs production and finally d) the 100% proof testing, which means to stop the burst test at a certain pressure level.

These different aspects of burst tests are analysed and compared with respect to its importance for the resulting safety of the populations of CPVs in service based on experienced test results and Monte-Carlo simulations. As main criterial for this the expected failure rate in a probabilistic meaning is used. This finally ends up with recommendations for relevant RC&S especially with respect to GTR 13.

1. INTRODUCTION

There are several regulations and standards available for composite pressure vessels whether for stationary application [1], transport of hydrogen of gases [2, 3, 4] or for the onboard storage of hydrogen [5]. There are differences e.g. with respect to safety margins and service-related aspects. But there are some common aspects of these regulations, codes and standards (RCS) in their approach for ensuring safety: burst tests with the criterion of minimum burst pressure and load cycle tests with the criterion of a determined number of minimum load cycles. The minimum burst pressure is in some cases expressed as "burst ratios" in other cases as "stress ratios". The link between those minimum criteria and the intended safety level is the available experience with safety testing and ageing during service.

It is realistic to expect a general market ramp-up of hydrogen technologies that will lead to a variety of hydrogen equipment and to an amount of hydrogen far beyond our available experience. Exemplarily a ramp-up and its influence on safety is schematically displayed in Figure 1.

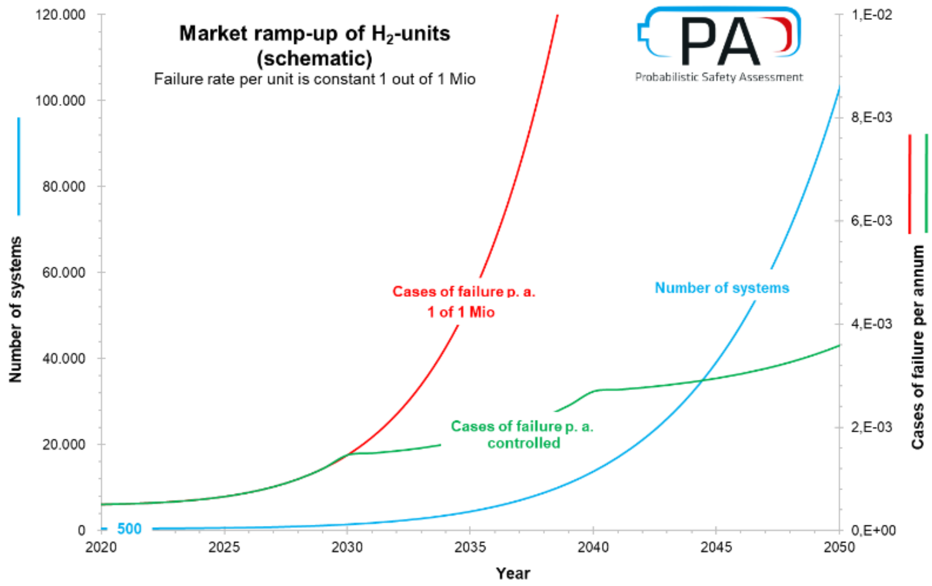

Figure 1: Schematic concept of controlling safety during the market ramp-up of hydrogen technologies

On the one hand there is an accelerating grow of the number of individual systems. In the case of a constant failure rate that stands for current experience the likelihood of facing failures increases significantly. For avoiding critical number of failures, it might be necessary to control the failure rate in a way that despite the increasing number of systems the number of failures will not increase critically.

Therefore, improved RCS are necessary, improved in way that ensures reliably safety based on a significantly reduced level of experience. For achieving such improvements new tools for the optimisation of RCS are necessary and discussed in the following. Special focus is set on the burst test and the optimization of burst test related requirements. This optimization can be done by running Monte-Carlo simulations to various extends.

2. GENERAL ASPECTS OF SIMULATING STRENGTH PROPERTIES BY MONTE-CARLO-SIMULATION

The Monte-Carlo-simulation (MCS) intends to create randomly a defined amount of individual values that follows an intended distribution function, e.g. the GAUSSian normal distribution (NV) [6, 7, 8, 9]. Thus, the “Monte-Carlo Simulation” stands for a broad class of different computational algorithms generating a large amount of random basic populations, which in most cases are sampled to groups of test samples for the approximation of statistical problems [10, 11, 12] of real test procedures.

For displaying the statistical behaviour of a basic population, of a test sample or for a comparison of different samples a special chart has been developed, which is called sample performance chart (SPC), see Figure 2 [13]. The basic concept is to have the x-axis represent the scatter value of normalized strength and the y-axis to represent the mean value of normalized strength property of a given group of specimens. Usually the reference value for normalization is the maximum expected service load, to which it should be designed.

In the context of pressure vessels, the burst strength as the essential ultimate strength property is of high interest. When operating MCS on the burst pressure of pressure vessels and displaying the result in a

SPC a cloud of dots is created, displayed in Figure 2. The cloud stands for a basic population addressing its properties (yellow dot in the centre).

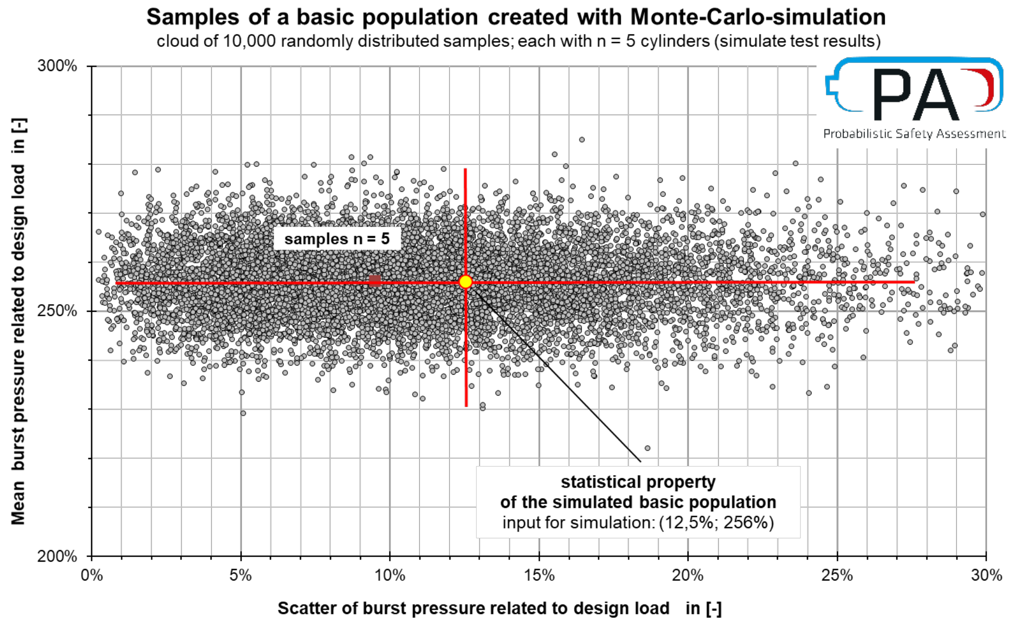

Figure 2: Cloud of a basic population sampled in groups of 5 individuals per sample displayed in the SPC

Figure 3 is an example for how a deterministic criterion is considered in a MCS simulations. It shows the values 26 samples of 3 individuals per sample and the related mean value of the triplet. While the mean value of the population is 2.6 the minimum requirement for each individual is 2.3 (here). Hereby, all values are related to the maximum service pressure (MSP). If one or more individuals of a sample are below the criterion (red dots) the whole sample (red beam) has failed. Thus, there are 7 samples in Figure 3, that have at least one CPV that failed the criterion. The other individuals (blue dots) of the remaining 19 samples (blue beams) met the minimum requirement.

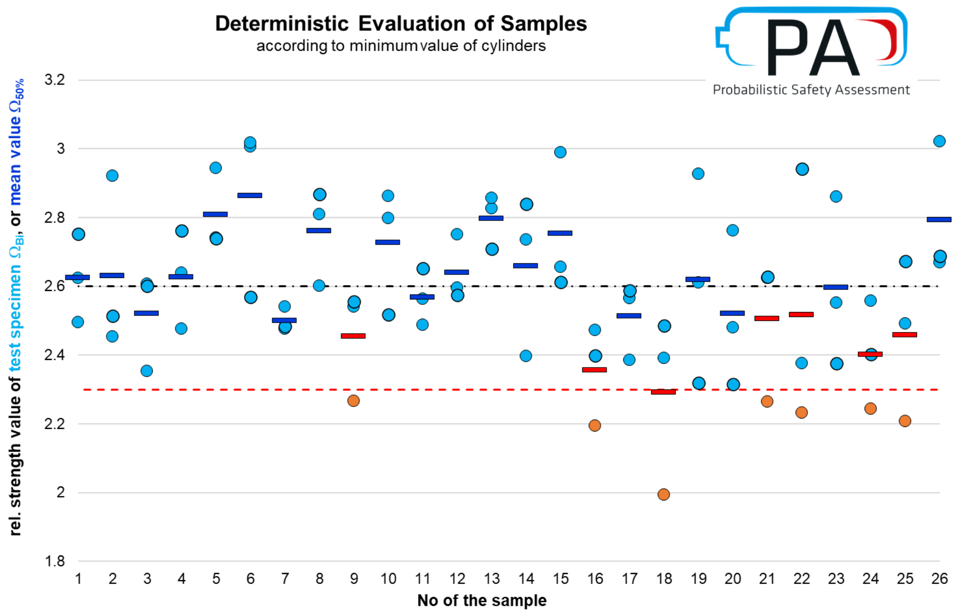

Figure 3: Examples for the handling of samples for deterministic acceptance criteria (see [10])

The result of this analysis of individual strength values can be displayed in a SPC. While the relative mean strength remains on the y-axis, the information concerning scatter provided by the individual dots is displayed in Figure 4 as normalised values of the x-axis. Just the information about the number of individuals not passing the requirement has been lost. Figure 4 provides just 26 samples but in principle, the shown beams built a cloud as already shown in Figure 2 for a cloud of dots. Again, each red beam stands for a sample that includes at least one individuum of insufficient burst strength.

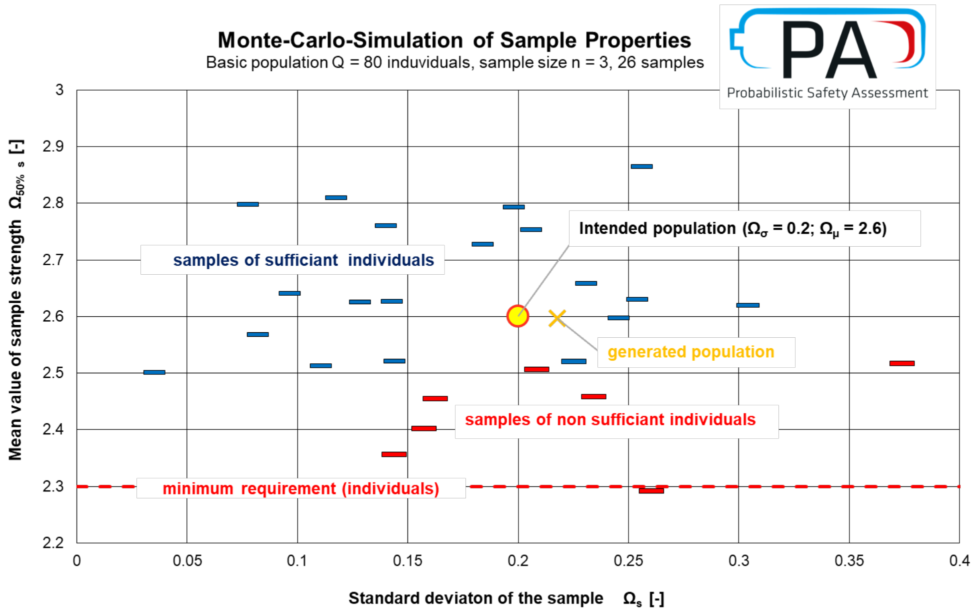

Figure 4: The 26 samples from Figure 3 displayed in a SPC

The number of accepted samples (blue beams) related to the total number of samples stands for the likelihood of accepting a sample out of the simulated basic population, which is here 19 of 26 (i.e. acceptance rate AR = 73%). In case of a relatively small number of simulated samples the property of the simulated basic population seems always to differ from the intended population properties. Nevertheless, it is always recommended to check the character of generated (or tested) strength results concerning their distribution function as soon as the number of individuals is sufficient (e.g. more than 40 results).

3. MINIMUM BURST PRESSURE REQUIRED FOR DESIGN TYPE TESTING

The most raised question of the last two decades was the question for the acceptable minimum burst criteria during design type testing. In principle, this question can be answered by evaluating the failure rate FR or the survival rate SR (i.e. reliability level) of the relevant basic population. Since the basic population of a product – as shown in Figure 2 - is always unknown the safety level of a population can just be determined based on sample properties.

Thus, on the one hand a systematic evaluation of minimum strength criteria – like the minimum burst strength – can performed by a systematic evaluation of the likelihood passing a minimum test criterion. On the other hand, the FR of the relevant basic population must be known. For this purpose, the sample performance chart SPC can be used to show the set of dots representing the basic populations with borderline populations, This is displayed in Figure 5 (see chapter 3.4.2 and 5.2.1 of [13]) by the red line representing all combinations of mean and scatter value with a FR of 1 of 1 Mio. The figure shows both axes referenced to the maximum service pressure MSP, which depends on the gas and the maximum temperature.

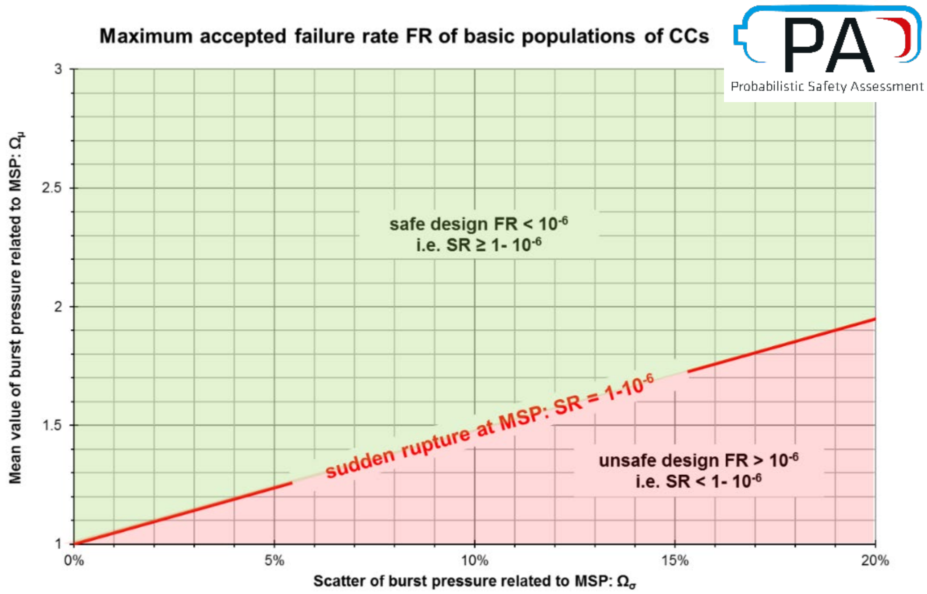

Figure 5: The SPC for burst tests with a determined failure rate FR of 1 of 1 Mio (see 5.2.1 of [13])

When evaluating the acceptance rate of basic populations according the description of Figures 3 and 4 along the red line in Figure 5 the Figure 6 is the result.

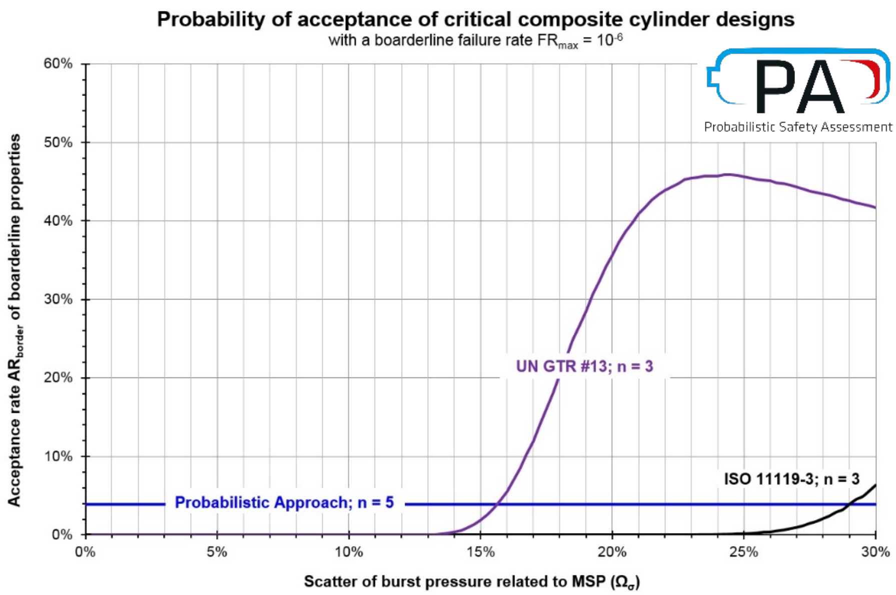

Figure 6: The acceptance rate AR along the 1 of 1 Mio-borderline depending from the relevant minimum criteria for burst pressure. (see 5.2.1 of [13])

It shows a comparison of the ECE R 134 [14] (based on GTR 13) with ISO 11119-3 [4] and the pure probabilistic approach provided in [13] by displaying the acceptance rate versus the scatter, which is traceably linked to the mean strength (see Figure 5) of the basic population. The probabilistic approach provides a constant acceptance rate AR of about 4%. This reflects the original requirement of meeting a confidence level of at least 95%. Due to the high level of minimum burst ratio of 300% NWP as a fixed requirement the line for the ISO 11119-3 stays at low scatter at zero. Then when the red line approaches the area of minimum requirements the AR increases up to 100 % beyond a scatter value of 30%, which is very high (and not displayed in the figure). That is because of acceptance of highly scattering basic populations without any reflection of the scatter. In this case, the level of safety, defined as the survival rate of 1-10^{-6} for an unknown population on a confidence level of at least 95%, is organised by a systematic overdesign, which could be reduced by an approach like UN GTR 13 (Phase 1). This set of requirements askes for a much lower level of minimum burst pressure as indicated by the much lower value when the curve goes up in Figure 6. This curve does not increase to 100% AR in case of high scatter because of a limitation of the accepted scatter in design type testing. Nevertheless, a maximum AR of critical design types on a level of 40% is much too high for an essential safety criterion. Therefore, some effort for optimizing these requirements was made in TAHYA ([15]; see deliverable D 08.03), addressing an essential safety criterion by a targeted level of safety with a survival rate of 1-10^{-6} for an unknown population on a confidence level of at least 95%.

The whole process of determining the acceptance rate is described in the flow chart represented in Figure 7. This figure is taken from a deliverable D08.01 of the H2020-project TAHYA.

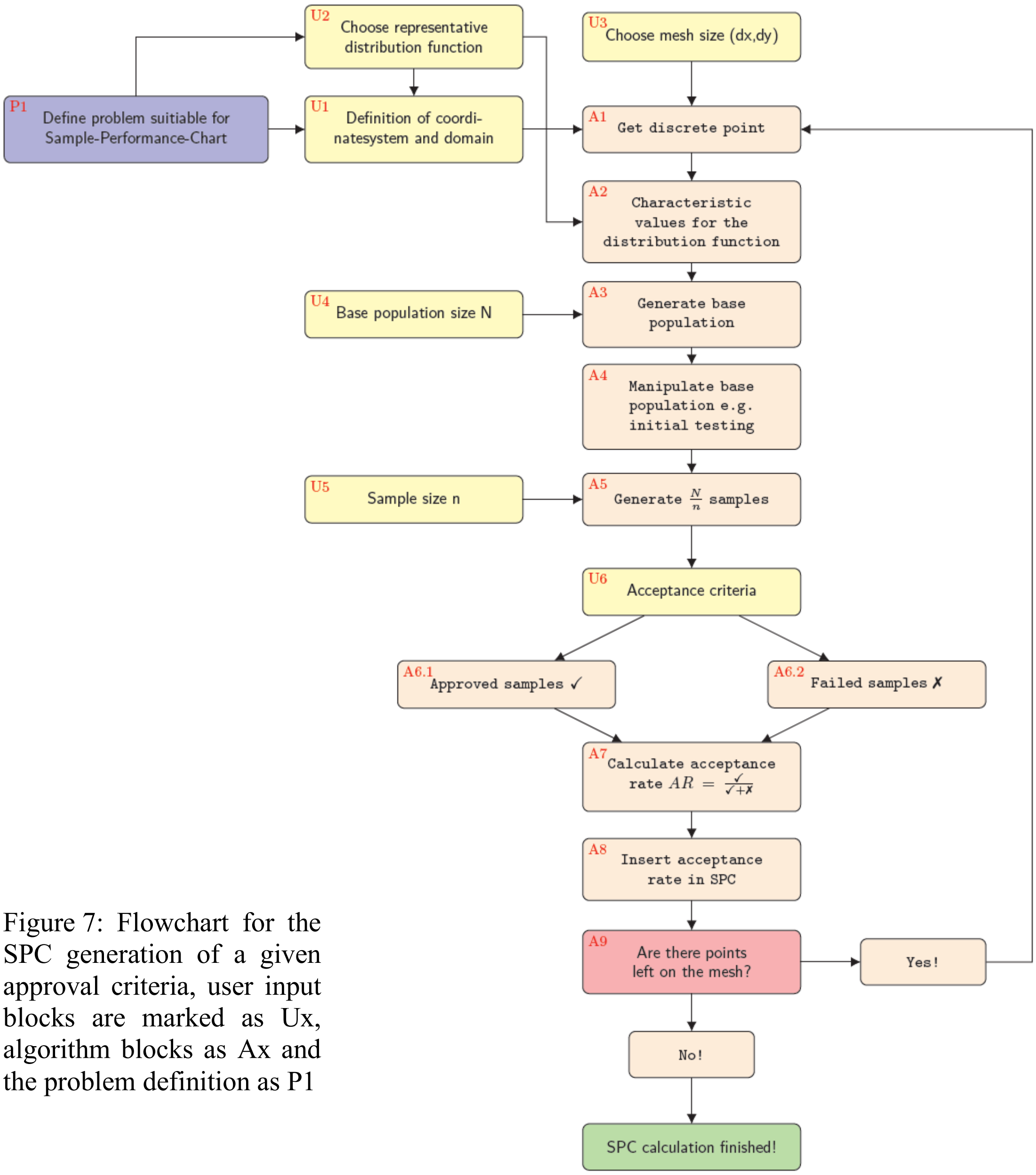

Figure 7: Flowchart for the SPC generation of a given approval criteria, user input blocks are marked as Ux, algorithm blocks as Ax and the problem definition as P1

This procedure enables to easily check variations of minimum acceptance criteria concerning burst strength. While doing so, the interaction of minimum burst pressure and maximum acceptable scatter becomes obvious and should be introduced in relevant standards and regulations.

4. MINIMUM BURSTPRESSURE REQUIRED FOR BATCH TESTING

The second minimum requirement for composite pressure vessels (CVP) that is based on burst testing is the so-called batch testing. There, according to most standards, each 200+1 CPVs of an ongoing and unchanged production are collected to one batch. Before a manufactured batch can be released one CPV of the batch of 201 must be tested destructively. This is called rupture or burst test and means to pressurize the randomly picked CPV hydraulically until burst.

A) This currently mandatory requirement for approving each production batch of CPVs is to demonstrate a burst test result above the minimum burst pressure that is even requested for design type testing. If the test fails, the manufacturer should search for the reason and if then the reason for the insufficient test result can be traced back to one or several individuum the manufacturer may repeat the test and ship the remaining production batch (of max. 199) to the customer, if the repeated test meets the minimum requirement.
   The regulation for the approval of Hydrogen vehicles ECE R 134 [16] is based on the GTR 13 [14] but completed by additional batch test requirements as follows:
   a) the burst pressure must be above BP_{min}, which is 200% NWP and
   b) the mean value of the last 10 results shall surpass 0.9 times the BP_O. The BP_O is the estimated mean value of the production population, which the manufacturer does based on design type testing.

When looking on the cloud of samples related to a basic population in Figure 2 it is obvious that such an effect of not passing the test may just be a pure statistical effect In combination with the Figure3 and 4 it is even clear that due to statistical effects a tendency of decreasing strength in a production is not indicated immediately. Without the checks concerning outliers and the character of the distribution , it may just create an increasing likelihood of insufficient batch results but cannot traced back to a deficit. Therefore, this genuine idea of batch testing should be re-thought.

When following this mandatory procedure of batch testing the ongoing process of production creates an increasing amount of strength data, which describes properties of the growing basic population. When looking on the value of having available statistical data and the potential of using this value by running statistical assessments, there are three further aspects to be discussed.

B) The first aspect is to use the knowledge about the produced population for its deeper statistical description and understanding. The available data should be collected to a pair of data (scatter and mean values) describing the overall strength of the basic population as it is indicated by the yellow dot in the centre of Figure 2. This provides a good reference for comparison of batch test results with the basic population that has been manufactured before. But this will just work if the produced batches really belong to the same basic population that has initially been described by the burst strength data out of the design type testing. This shows the main problem of running approval tests in a pre-series of CPVs.

C) Another aspect is the surveillance of high-volume production by evaluating batch test results of defined periods of production (e.g. production of the year or month) as samples and displaying the position of the relevant dots around the dot of the basic population in the SPC. Thus, long term tendencies can be allocated, traced back and unknown influences on the production may get indicated.

D) Finally, the intention of recognising manufacture faults can be improved. On the one hand, production failures that may just occur at a single individuum cannot be covered by destructive testing because 1 out or 201 makes it very unlikely to take just the defect one. Therefore, NDT and other production surveillance methods are available and should be used for the detection of faulty individuum. On the other hand, it is necessary to recognise deviations in production or even tendencies as soon as possible for avoiding costly actions that otherwise may become necessary later. Since the following concepts are better than the idea of a minimum burst pressure it may even work when accepting (seldom) test results below the minimum burst pressure:

i. It is possible to compare the test result for each individually manufactured batch with the already available values of the previous basic population. That means to check the position of the new test result (new dot) in the order of older results (dots) according the usual ranking of test results including its visualisation in the relevant probability net (see e.g. Fig. 3.37 or Fig. 4.37 from [13]). This should get completed by running outlier tests, e.g. Grubbs-tests as specified in DIN ISO 5725-2:2020-12 chapter 7.3.4.

ii. An additional approach can be introduced now on the basis of a systematic analysis of procedures for assessing batch test results (extracted from deliverable D8.3 [15]). It promises more significant decisions in addition or instead of the idea of demonstrating a minimum burst strength: This is the idea of observing the production by focussing on the mean strength of the ongoing last 5 burst test results.

The idea lastly mentioned here can be used for generating much more information than current regulations do. Therefore, it has become part of a German national accepted technical rule named “ATR D 01/21” [17] for CPVs fixed mounted on e.g. tube trailer vehicles. How the effect of ongoing last 5 test results (5 batches equalling 1000 individual CPVs) works is indicated in Figure 8.

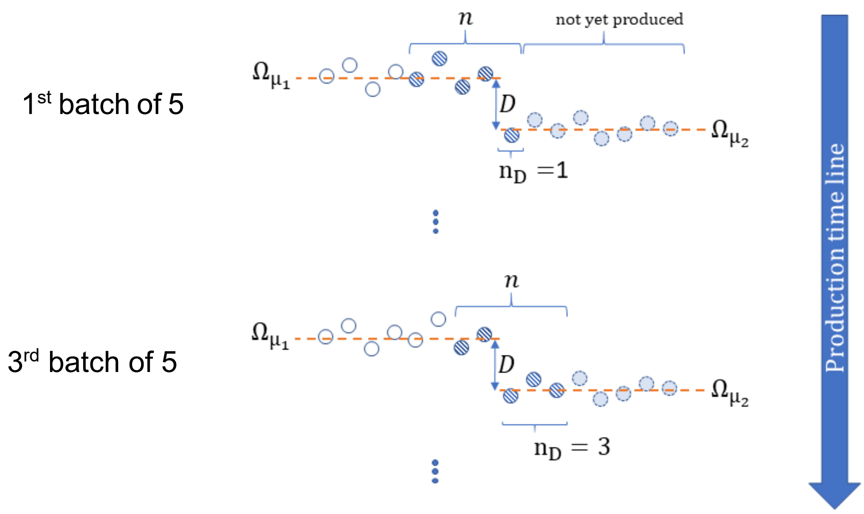

Figure 8: Schematic overview of sample composition, if a defect D is not found.

The scenarios in Figure 8 shows how samples contain individuals from the original population $(\Omega_{\mu_1}, \Omega_\sigma)$ and the population with a defect $(\Omega_{\mu_2}, \Omega_\sigma)$. Once the manufacturing defect occurs, the first batch test will only contain one burst test result from the population with a defect $(n_D = 1)$. The value n_D is the number of CPVs in the sample drawn from the lowered population. If the manufacturing fault is not found, the next batch will be produced with a lowered mean value. The next batch test will then have two individuals $(n_D = 2)$ from the population with decreased mean value. This continues until the mistake is eventually found. When now running MCS it can be shown by varying several parameters this concept is much more sensitive than the pure deterministic requirement of demonstrating minimum burst pressure but even better than the concept of the ECE R 134 [16].

But there are two other processes, which even require to pressurize CPVs hydraulically and can be used for the safety surveillance of the basic population during entire lifetime. These test procedures are nominally non-destructive and must therefore performed on each individual CPV. These are the initial proof testing and - in all areas besides the onboard storage systems - the proof testing during periodic inspection. Nevertheless, each loading of a composite above the maximum service pressure means an extraordinary damage on micro level and is therefore not really “non-destructive”.

5. QUASI-STATIC LOADING DURING INITIAL TESTING

As final item of the manufacture of pressure vessels each individual must undergo a final proof testing (initial proof test). This test means to increase the internal pressure continuously up to the test pressure (PH), to hold it constant for some seconds and then to depressurise again. Since the hydrogen in a pressure vessel filled to NWP (at 15°C) develops at the maximum temperature (65°C/85°C) to the maximum service pressure (MSP = 118% or 125% NWP), which is significantly below the test pressure (150% NWP). Thus, results to a pressure gap that means a special safety aspect: All individuals with an initial strength at begin of life (BoL) below the test pressure fail and are not part of the basic population anymore. This is shown in Figure 9 with the red area.

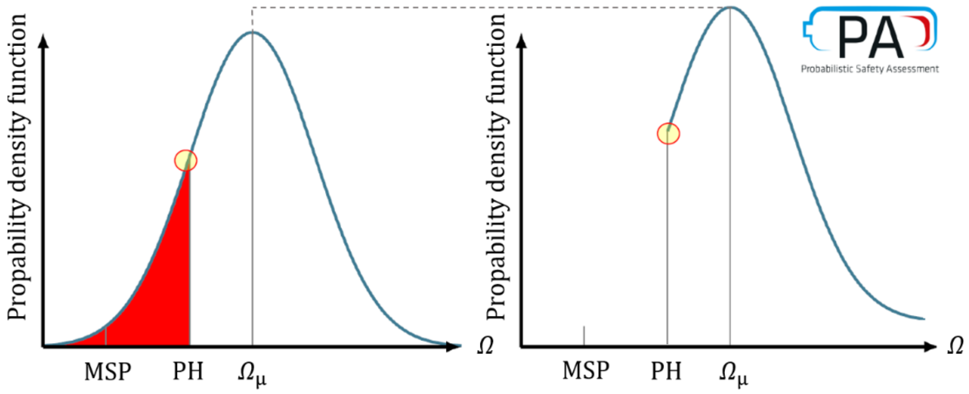

Figure 9: Trimming of the probability density function through initial proof testing

Unfortunately, this does not mean that none of the remaining individuals will fail during lifetime under normal service loads up to MSP. The ongoing service life means a degradation of strength properties by cyclic and even by static loads. Thus, it is just a question of time when the first individual of the basis population will fail. This effect of aging is exemplarily displayed in Figure 10 based on artificial ageing.

The background of the provided figure is a test series (see chapter 4.2.2 in [13]) operated on three samples of type-IV-cylinders from one production batch. The first sample stands for unloaded conditions at begin of live (BoL). The 2nd sample underwent 50,000 load cycles at 65°C up to test pressure PH while the 3rd sample experienced 100.000 LC at 65°C to PH. Subsequent to this artificial ageing, each individual was continuously pressurised until burst. Slow burst tests (SBT) acc. BAM-GGR 021 [18] were used. Slow burst test (SBT) means a test procedure at an extraordinary slow and accurately controlled rate of constant pressure increase until rupture occurs. The pressure rate is about 20% of the test pressure per hour. Either time to rupture or pressure at rupture can be evaluated as test result. This test is the preferred procedure for quantification of residual strength in case of design classified as non-cycle fatigue sensitive. As the test duration of a SBT is – dependent from the strength - about 8 to 12 hours, while a conventional burst test takes – mainly dependent from the pressure rate – usually about 2 to 15 minutes. The SBT is the appropriate test procedure for addressing potentially strengthening creep and relaxation effects. In addition, the comparison of results from virgin composite pressure vessels and from those after service provides a reliable value for ageing effects. The determined degradation shows a reduction of mean strength and an increase of scatter values. With increasing degradation, the loss of means strength slows down while the increase of scatter accelerates as described in Figure 10. The effect of aging can be analytical modelled for normal distributed burst pressures as described in [19] and be used in Monte-Carlo simulation.

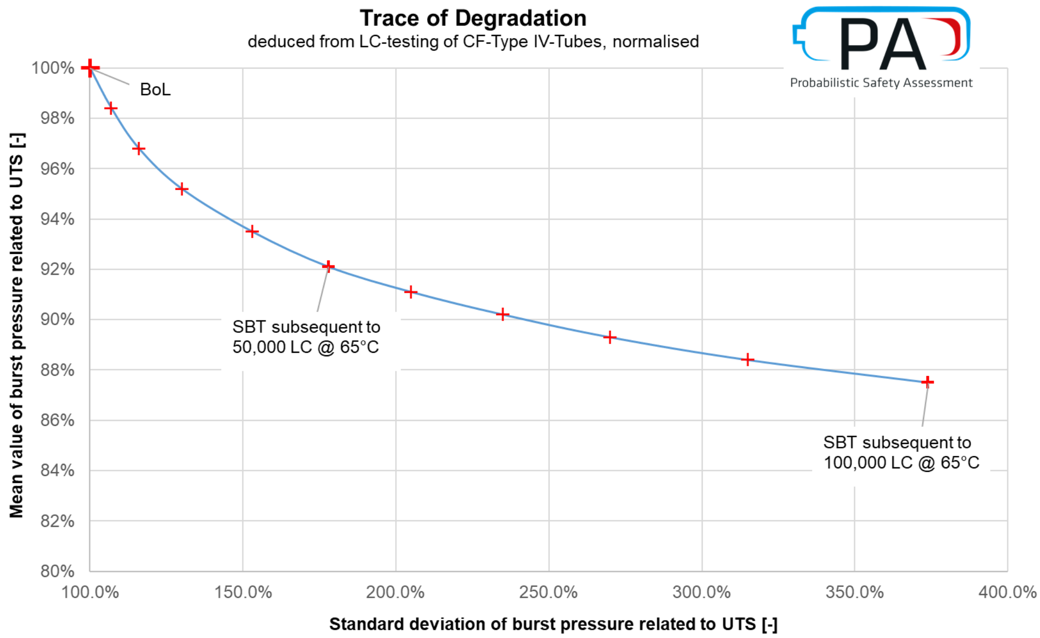

Figure 10: SPC showing ageing effects of a CPV design through cycling at 65°C

For displaying the interaction between the initial proof testing and the degradation the Monte-Carlo Simulation (MSC) can be used. The result of this simulation is presented in Figure 11 on the basis of deliverable D08.02 of [15]. Here for every combination of Ω_μ and Ω_σ, the amount of load cycles is determined until the first of 1 Mio CPVs has a strength $\Omega \leq$ MSP, representing a failure rate of 1of 1 Mio.

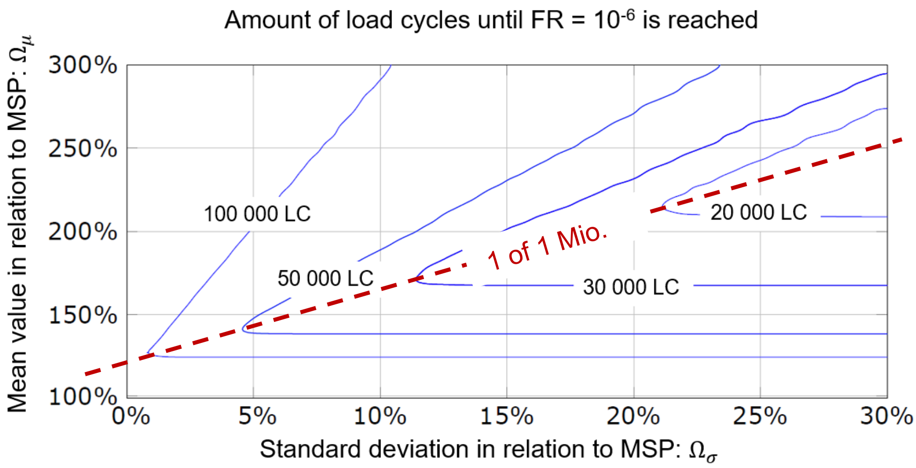

Figure 11: Amount of load cycles until the failure rate increased to a value of 10^{6} s; simulated by MCS

The lines of constant survival rates (isoasfalia) for the respectively given amount of load cycles form triangles in the SPC. Each line separates CPVs with a higher survival rate than 1-10^{-6} (left/below) from designs with a lower SR (right/above). Above the tips linked by the broken line, the isoasfalia demand higher mean values for higher scatter values, a typical behaviour. The lower scatter levels, the higher is the number of LCs (amount of degradation) that is necessary to degrade the weakest CPVs of the population subsequent to initial proof testing down to a FR or 1 of 1 Mio. On the one hand the higher the mean value strength the lower is the number of individual CPVs is rejected by initial testing at PH. On the other hand, the effect of degradation is the higher the bigger the distance from the mean value is.

This results into a high total amount of CPVs with a high tendency of rapid degradation.
The area below the conjunction line of all triangle tips stands for all basic populations that have an initial FR of higher than 1 of 1 Mio at PH. Thus, no further degradation is necessary for meeting the criteria of a FR of 1 of 1 Mio. For checking the duration of the failure free time, it is necessary to know the real scatter und mean values of the basic population.

The basic problem of trusting in this prediction of degradation is the uncertainty of artificial ageing in relation to the real degradation during service. In opposite to metal materials composite degrades not exclusively under cyclic load it even loose significant strength under sustained load.

6. QUASI-STATIC LOADING DURING RETESTING

This uncertainty about the degradation during service is even a key issue for the surveillance of safety until end of life. Due to the diversification of usage of pressure vessels the relevant regulations have developed into different directions: While the onboard storage is dominated by the idea of a safe life design the areas of transport of dangerous goods and stationary applications do usually not design to determined end of life. There, the idea of a safe service until the periodic inspection will reject individually each individuum rules the world.

For CPVs, both approaches are leading into a dead end. On the one hand the degradation mechanisms of composites are much more complex and not as well experienced like for metals. On the other hand, the methods for detecting critical defects prior at periodic inspection are not as far developed and open safety gaps. This brought Germany to develop an approach for the survey of degradation by destructive tests in parallel to operation (s. BAM-rule for dangerous goods BAM-GGR 022) [20]). With the national accepted regulation ATR D 4/10 [21] this approach is in charge for more than 10 years and provides good and in some cases surprising results. Even when the far aim is to manage the individual residual strength assessment by non-destructive testing there is a clear recommendation for the current practise: set focus on the test that is the best for the relevant design type to determine the residual strength. In the case of CPVs with plastic liner und CFRP this is the slow burst test, in other cases with cycle fatigue sensitive materials like glass fibre or metal liner this is the ambient cycle test. This approach closes the loop of discussing the slow burst test for design type testing and for batch testing as introduced above. If the data from design type testing and especially batch testing are available, A set of data deduced from experience of a real design type is presented in Figure 12.

Figure 12 shows the light (yellow) dot representing the small sample tested during design type testing, the different (dark blue) dots for the batches collected to annual production data and the (red) cross for the collection of all BoL-data. This cross stands for the compilation of all knowledge about the basic population. Finally, it presents a cloud of Monte-Carlo generated samples that fit with the cross.

This is completed by two lines for safety assessment. The lower (red) line stands for the minimum survival rate out of Figure 5, while the (blue) isoasfalia indicates the requirement for a sample size of n = 5 on a confidence level of 95%. Thus, a sample of 5 CPVs must lie above the blue line for demonstrating sufficient safety. Nevertheless, the sum of test results in the context of the (blue) cloud shows that some test results from production would lead to the rejection of individual samples. When comparing this with the shown cloud, this expresses a lack of data, when testing a sample of 5 CPVs, and not of safety. Even the dot in the far right is part of the cloud and stands for a sufficient safety, since the (red) cross is far above the minimum requirement for the basic population (red line). It stands for the borderline position of the basic population represented by the red cross with a failure rate of 1 of 1 Mio.

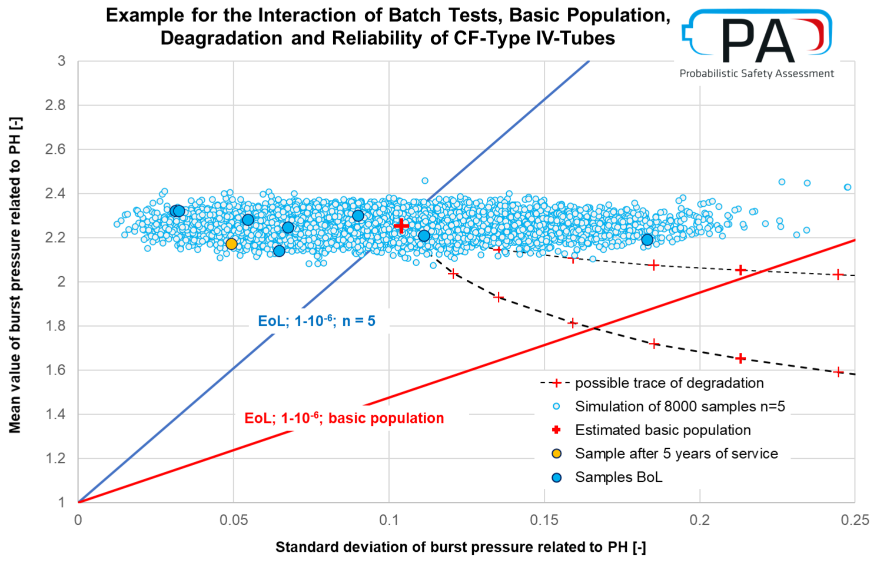

Figure 12: Results from SBT-testing in their related clouds from MCS in comparison with a SR-value of 10^{6}

A critical safety status means a failure rate of 1 of 1 Mio, which means the centre of the cloud (red cross) has moved on or below the red line. The size of the simulated cloud is described by the scatter value.

The difference between (red) cross describing BoL and (red) borderline is the range that can be consumed safely by the degradation processes until end of life (EoL). The degradation in accordance with Figure 10 is added by two (black) broken line with small crosses. While the upper line equals the values of Figure 10, shows the lower line a potentially higher degradation. Up to now experience shows that neither the amount of degradation (distance of crosses) nor the character of degradation (shape of the line) can be described universally valid. The degradation is a property of the individual design types and may differ enormously across the range of designs. Furthermore, the transfer of artificial aging behaviour to aging under service conditions is still unknown.

It is important to understand the behaviour of the basic population towards the end of life. Unfortunately, there are no data from CPVs taken out of service available yet, to an extend that is comparable with the data from batch testing and allowing the simulation of a comparably reliable cloud. This is an item of future work.

7. CONCLUSIONS

It has been shown that a systematic usage of Monte-Carlo-experiments enables simulating how requirements makes effect on safety level and influence the acceptance rate of more or less safe design types. This is valid for all variations of burst tests, whether it is design type testing or the batch testing. Monte-Carlo simulation can help to improve the effect of minimum requirements in the approval standards and regulations on the safety level of produced basic populations.

In addition, it has been presented how results from tested samples and its statistical evaluation improve the understanding of initial safety and degradation of safety. This is on the one hand a good rational for modifying the testing procedures a little bit for enabling statistical evaluation. On the other hand, it has been demonstrated that a statistical evaluation of available sample test results needs no significant effort but helps to optimise the evaluation process of available test results for maximizing the safety level.

Due to the mandatory proof testing to a pressure above the maximum service pressure the basic population following an original distribution function is cut for the weakest, which means a kind of failure free time. The duration of this failure free time cannot be evaluated without detailed knowledge about the design type specific degradation of strength. This request reliable laboratory tests representing service degradation and – what is much more reliable – the recuring check of degradation during service by destructive tests for the moment and by NDT in future. Both outcomes can be visualised by the usage of Monte-Carlo simulations and help to understand what test data stands for.

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