- Gas-loaded accumulators –
A guide to applying the guarantee factor method to standard EN 14359 -

J.Lallement[a] ,A.Guillard[b] ,A.Houssais[c], P.Bonnet[d],

[a] CETIM
[b] UNITOP
[c] Chairman of UNM 31 committee
[d] I-Comète

Abstract Within the context of works under European Standard EN 14359 relating to gas-loaded accumulators for fluid power applications, the manufacturers have to verify by testing the in-service fatigue reliability of their accumulators. The aim of this paper is to help manufacturers to apply this testing methodology by assessing the required industrial data and conditions. An application is developed with a focus on how to provide reasonable estimates, using theoretical and statistical analysis of a fatigue strength variation coefficient level extracted from experimental results. It is concluded that the method can be applied to accumulators with some restrictions.

1 INTRODUCTION

A gas-loaded accumulator is a part of hydraulic transmission system allowing to store energy by compression of a gas. Hence, it is like a thin shell with gas inside, under a pressure of several megapascals (MPa). Through recent requirements of customers, accumulators manufacturers have to demonstrate the level of fatigue reliability of their accumulators according to given operating pressure ranges.

To answer their customers, gas-loaded accumulator manufacturers (ETNA Industrie, Hydro Leduc, OLAER Industries) have asked the CETIM, UNITOP and I-Comete to assess the requirements of the guarantee factor reliability approach [1] to demonstrate the level of fatigue reliability required, which is one of the two experimental methods proposed by the European Standard EN 14359[2] relating to gas-loaded accumulators. This method is described in paragraph 7.6.7 of the standard. In the following, after a quick summary of the probabilistic background of the method, the requirements for applying this approach to an industrial mechanical component are introduced. In the last part, an example of application performed on an operating accumulator using theoretical, experimental and a statistical approach is shown.

2 GENERAL PRINCIPLE OF THE GUARANTEE FACTOR METHOD

This method allows the verification of the fatigue behaviour of accumulators, to withstand a large number of what are called "unlimited" cycles. Its principle is based on verifying the ratio between the characteristic strength of the accumulator and the characteristic stress according to its intended function.

This method includes a probabilistic analysis phase and an experimental phase (fig.1)

- The probabilistic analysis phase corresponds to the Stress / Strength theory [3][4]. This approach, in some conditions, permits a reliability assessment to estimate the level of the part mean strength required to achieve the in service reliability target under in service pressure stress profile. The ratio between the mean fatigue strength and the mean operating pressure range defines **the guarantee factor**.

- The experimental phase validates the guarantee factor. The testing method proposed by the standard [1] corresponds to the **no failure test method:** from 3 to 5 **accumulators are tested** on a single pressure range ΔP_{Test}

corresponding to the component mean strength estimated and for a cycle number greater than or equal to 2.10^6 cycles.

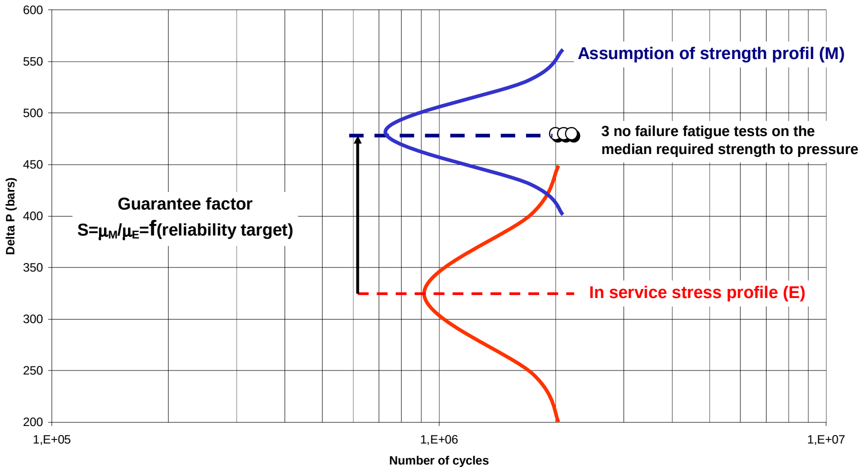

Fig.1 Illustration of guarantee factor S

3 REQUIREMENTS FOR APPLYING THE GUARANTEE FACTOR METHOD TO ACCUMULATORS

3.1 Definition of the guarantee factor using Stress / Strength probability approach

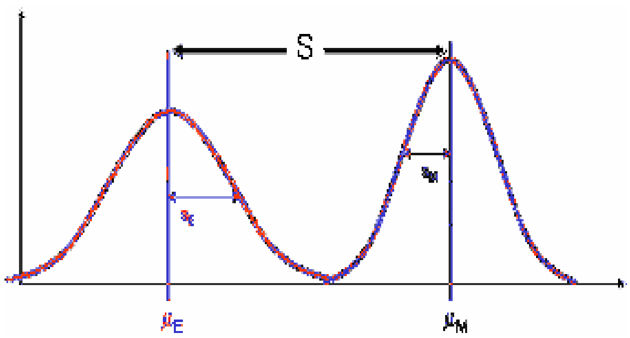

Fig.2 Illustration of the stress / strength probabilistic method.

In the most general case, the definition of the survival function of a structure depends on several random variables that can describe several failure modes.

In the case of the reliability assessment for a single mode of fatigue failure, it is always possible to reduce the definition of this function to an inequality between two main random variables of strength M to the failure mode and stress E generating this fatigue failure mode.

Given M and E, such that:

- M, mechanical component strength, average μ_M, standard deviation σ_M and coefficient of variation CVM = σ_M / μ_M
- E, stress on the component, random variable, average μ_E, standard deviation σ_E and coefficient of variation CVE = σ_E / μ_E

In the present industrial application, the random variables M and E are respectively the fatigue strength to the pressure range of a hydraulic accumulator and the equivalent pressure range at 2.10^6 cycles of an in-service pressure range spectrum.

A Log-normal distribution for the operating pressure range and the fatigue strength has been chosen according to the failure mode (Fatigue), the objective of cycles (2.10^6 cycles) and a reasonable target of reliability.

On the further hypothesis that the two random variables are statistically independent, the reliability R, relating to the fatigue strength distribution and operating pressure range distribution, is evaluated with the aid of the Normal distribution standardised deviate function Φ such that: $\mathbf{R = \Phi(-\beta)}$

β, the reliability index, in the case of log-normal distribution is given by:

$$\beta = \frac{Log(S) + Log\sqrt{\frac{1+CVE^2}{1+CVM^2}}}{\sqrt{Log\left((1+CVM^2)(1+CVE^2)\right)}} \qquad (1)$$

S is the guarantee factor defined as follows: $\frac{\mu_M}{\mu_E} = S$ (2)

Inversely, knowing the Reliability target defined by the reliability index, the S guarantee factor is perfectly determined as:

$$S = EXP\left(\beta.\sqrt{Log\left((1+CVM^2)(1+CVE^2)\right)} - Log\sqrt{\frac{1+CVE^2}{1+CVM^2}}\right) \qquad (3)$$

3.2 Estimation of the testing pressure range ΔP_{test} to demonstrate the reliability target at 2.10^6 cycles[1].

Given ΔPE such as the mean of the in service equivalent pressure range law at 2.10^6, the pressure range ΔP_{test} over which the no failure tests must be carried out is given by the expression:

$$\Delta P_{Test} = \frac{S}{e^{-a'\sqrt{\frac{Log(1+CVM^2)}{n}}}}.\Delta PE \qquad (4)$$

With:

- n is the number of parts tested successfully in terms of cycle objective (2.10^6 cycles).
- a' is the probability factor resulting from the one-sided confidence level used taking into account the experimental median fatigue strength to the pressure at 2.10^6 cycles, in accordance with the recommendations of the standard.

Thus, the strength performances of the accumulators to be attained in terms of mean strength are perfectly described. The expression of the guarantee factor has direct consequences on the industrial feedback knowledge required to apply the method to accumulators manufacturing.

3.3 Requirements for applying the guarantee factor method to accumulators

Following the expressions given by the equations (3) and (4), the requirement for applying the guarantee factor method to accumulators is the knowledge of the following data:

- **ΔPE**: mean of the in-service equivalent pressure range distribution (in-service profile) at 2.10^6 cycles
- **CVE**: coefficient of variation of the in-service equivalent pressure range distribution (in-service profile) at 2.10^6 cycles

- **CVM**: coefficient of variation of the fatigue strength distribution to the pressure range at 2.10^6 cycles
- **β**: reliability index=f(reliability target)
- **n**: number of items successful in terms of cycle objective (2.10^6 cycles).
- **a'** : probability factor=f(confidence level)

3.3.1 In service profile (ΔPE and CVE)

Not all accumulators operate in the same way: annual number of hours in service, cycle number, proportion of cycles at maximum load, can vary greatly from one application to another. A reliable definition of load thus requires using multi-year feedback from pressure measurements on an exhaustive and representative sample of in-service accumulators.

3.3.2 CVM

If the no failure test method allows assessing the median accumulator strength at 2.10^6 cycles, this method does not allow estimating the standard deviation and the associated coefficient of variation of the fatigue strength (CVM).

It therefore requires involvement from the manufacturer on CVM. This plainly means that this method should normally only be implemented once database results from previous destructive testing, analysis of feedback on the accumulator, and the process for obtaining it are available from the manufacturer.

If this knowledge of CVM on similar accumulator is missing (geometry, material and process), the CVM level must be estimated in advance by an experimental approach as proposed in §4.

3.3.3 Reliability target

This fundamental datum of the method is the manufacturer's choice. This choice is most often the consequence of a failure on human safety and its resulting economic cost but also depends on the maintenance policy (e.g. the possibility of an inspection detecting cracks in service). Decision aids for choosing acceptable industrial risk levels are offered in literature [5][6]. The Reliability target mentioned in the standard is of R>99.9%.

3.3.4 Size of experimental sample and testing methodology

A minimum of 3 parts to test, without a single failure being recorded, is proposed for the standard.

It should be noted that the experimental method is non-destructive. In this sense, the failure mode is not verified. The manufacturers will therefore have to look at the relationship between the designed fatigue failure mode (e.g., the component and the fatigue failure area produced by analytical calculation or by finite elements analysis) and the experimental reality. For example, if according to the design the most likely point of cracking is on the envelope and the destructive test results show cracking on one of the other components subjected to pressure cycles, the non-destructive test method would not fit **because CVM is not the same.**

By consequence, it is strongly advised to test at least one of the accumulators to failure by cumulative fatigue approach to verify the failure mode [3].

It should be also noted that the demonstration of the mean strength to pressure is performed with only no failure items. However, the binomial analysis of k=0 failure items for n=3 tested items allows to estimate a level of reliability of 79% for a median level of confidence. In this way, the non failure testing methodology is quite conservative to demonstrate with three unfailed items a level of reliability of 50%.

3.3.5 Confidence level

In all cases, the number of test parts is low. It is therefore rightly proposed in the standard to apply a correction factor to the safety factor, the purpose of which is to take into account a confidence interval **only for the median strength of the accumulator**. This probabilistic choice is not surprising according to the fact that to apply the method requires a previous knowledge of the accumulator fatigue strength coefficient of variation. For accumulators application, the minimum two-sided confidence interval advised is of 90%.

Following these precisions of requirement, it is imperative to note that, to fully use this method, each manufacturer must know the failure modes, the CVM(s) and particularly the operating pressure range distribution (ΔPE and CVE).

Due to the recent nature of this type of approach by the accumulator manufacturers, it can be assumed that this feedback is not always available.

Concerning the operating pressure range distribution, it has not been yet possible to obtain robust data. For this reason and at present time, it is therefore advised to restrict reliability commitments to an experimental level pressure range associated with an experimental reliability target demonstrated on a fatigue bench. This is the way which has been chosen to verify the conditions of application of the methodology on accumulators. Hence, the target in terms of pressure is not an operating profile but a single pressure range ΔPE (CVE=0).

Concerning assessment of failure modes and CVM, the estimation of its type and its order of magnitude have required to collaborate with the manufacturers agreeing to supply components for fatigue bench testing. **70 accumulators from three different technologies have been tested on the CETIM fatigue bench allowing test under repeated pressure range up to 650 bar with a possibility of testing 15 parts simultaneously.**

The following paragraph shows an example of the methodology and results obtained on one of the three technologies.

4 RESULTS OF EXPERIMENTAL AND SIMULATION APPROACH TO DEFINE THE FAILURE MODES AND TO ESTIMATE THE CVM OF ACCUMULATOR

The S-N curve method [7][8][9][10] has been carried out on a homogeneous sample of 15 accumulators distributed over 3 pressure levels and tested at the pressure ratio R =0 (lower pressure of 0). The results obtained are shown in the graph below:

4.1 Estimation of the CVM of the sample (CVMexp)

- The failure modes obtained are a fatigue crack located on the accumulator shell and on the fluid end component (both steel components).

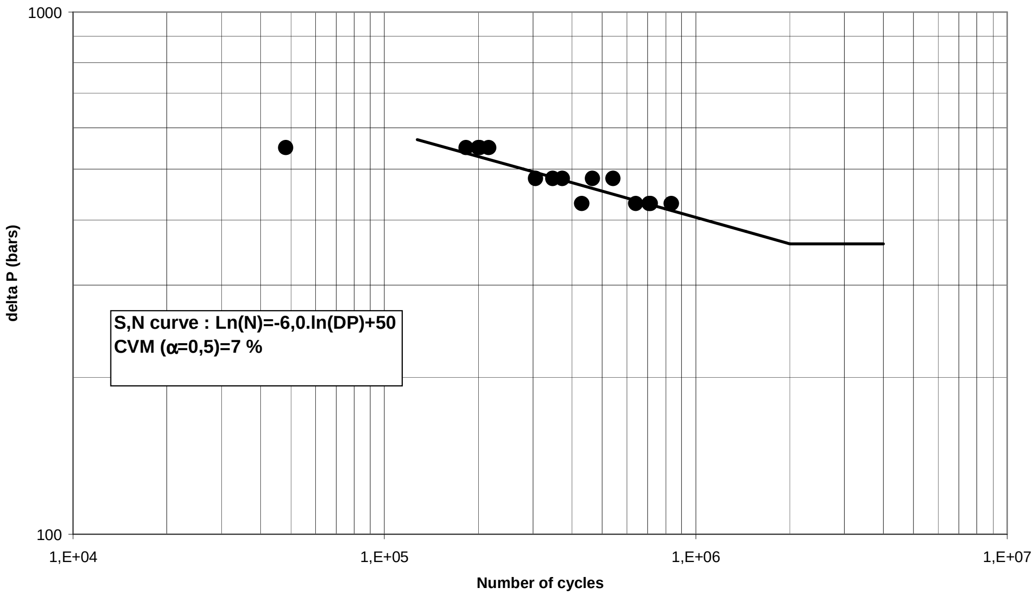

Fig.3 Fatigue strength result on accumulator.

- The fatigue life N for a given pressure range ΔP is presupposed Log-normally distributed [9][10]. To confirm those assumptions, the Log-normal distribution by level has been statistically tested at 0,2 p-value significance level [11].

Due to the smallest observation in the sample, the upper pressure level does not fit strictly a Log-normal distribution. The practical signification of this result is that the failure mode of the first item could be different from the other and could give some precious information on the homogeneity of the material-process couple. However, this item has been integrated in the CVM assessment. The variations of the standard deviation of Log(N) with the pressure range are homogeneous with respect to Fisher-Snedecor statistical test at 0,05 p-value significance level.

- Following these results, a median curve of Basquin model is verified for the cycles between 10^5 and 10^6 cycles : $Log(N) = -m.Log(\Delta P) + LogA$

- The slope and the intercept of the model are of m=6,0 ($C.I._{0,90}$=[4;8] ; LogA=50.

- Calculation of standard deviation:

    - $s_{LogM} = s_{LogN} / m = 0.068$
    - ν, degrees of freedom number associated with standard deviation = 13.

- The coefficient of variation of the strength associated with the accumulators tested is thus estimated as:

$$\mathbf{CVM_{exp} = \sqrt{\exp\left(s^2_{LogM}\right) - 1} = 6.8\% \approx s_{LogM}} \quad (10)$$

4.2 Estimation of the coefficient of variation of the population of accumulator (CVM)

4.2.1 Estimation of the CVM by theoretical approach

As the CVMexp is obtained from small test samples, they must be considered as only spot estimates of the variation coefficient of the population produced. In this sense, it is strongly recommended that the variation coefficient of the population is estimated by confidence interval. However it should be noticed that the calculation is not in standard EN 14359 regardless of the verification methods. The only recommendation here is to integrate the confidence level into the median strength estimate.

Confidence interval for the median and the standard deviation of a normal distribution are clearly defined in the literature [12]. However, the confidence interval for the coefficient of variation has to be built through the distribution of the mean and of the standard deviation.

In the case of a log-normal distribution of the strength M to pressure, Log(M) fits a normal distribution. In this sense, it is admited [12][13] to estimate the confidence interval limits of the standard deviation σ_{LogM} of the population by the following expression:

$$\mathbf{Prob\left(s_{LogM} \times \sqrt{\frac{\nu}{\chi^{\nu}_{\frac{\alpha}{2}}}} < \sigma_{LogM} < s_{LogM} \times \sqrt{\frac{\nu}{\chi^{\nu}_{1-\frac{\alpha}{2}}}}\right) = 1 - \alpha} \quad (10)$$

- ν: number of degrees of freedom associated with the determination of the CVM of the sample
- $\chi^{\nu}_{1-\frac{\alpha}{2}}$: value of the function KHI-2 to ν degrees of freedom having the probability $1-\alpha/2$ of being exceeded.

Following equation (10), confidence limits of the coefficient of variation CVM of the production could be defined as:

$$\mathbf{Prob\left(\sqrt{EXP\left(s^2_{LogM} \cdot \frac{\nu}{\chi^{\nu}_{\frac{\alpha}{2}}}\right) - 1} < CVM < \sqrt{EXP\left(s^2_{LogM} \cdot \frac{\nu}{\chi^{\nu}_{1-\frac{\alpha}{2}}}\right) - 1}\right) = 1 - \alpha} \quad (11)$$

As the standard deviation of the strength Log-normal distribution is small, the theoretical estimation of the lower and upper confidence limits of the CVM of the population is given by:

$$\mathbf{LCU(CVM) = CVM_{Exp} \times \sqrt{\frac{\nu}{\chi^{\nu}_{1-\frac{\alpha}{2}}}}}$$
$$\mathbf{LCL(CVM) = CVM_{exp} \times \sqrt{\frac{\nu}{\chi^{\nu}_{\frac{\alpha}{2}}}}} \qquad (12)$$

N.A.:
- $\nu=13$
- $\alpha=0.1$ (two-sided risk)

⇒ Prob (5% < CVM <10%) ≈ 0,9

In our case, the theoretical factor to obtain the value of the 0.95 one-sided confidence level of CVM is about k_{theo} = LSU(CVM)/CVM_{exp}=1.5

4.2.2 Estimation of the CVM by simulation approach

It is also possible to estimate confidence interval using a MONTE CARLO [14] simulation.

- The assumption of the simulation is a production of accumulators characterized by a fatigue failure mode on a 42CD4 steel component. By experience, the slope of the Basquin curve for this kind of steel could be chosen at a value of 8. The CVM chosen is of 10%.

- S,N curve are simulated using 15 failed items on 3 fixed levels of pressure according to a median time to failure from 10^5 cycles to 10^6 cycles (see fig.4).

Following this assumption, a sample of 3000 curves is generated using MONTE CARLO simulation. For each simulated curve, the $\mathbf{CVM^{i}_{Sim.}}$ is processed as mentioned in §4.1.

By that way, each simulation supplies a sample of 3 000 $\mathbf{CVM^{i}_{Sim.}}$ in relation with 15 items extracted from a population of accumulators defined by a CVM and a Basquin slope of 8.

The simulated factor K_{sim} to obtain the value of the 0.95 one-sided confidence level of CVM is given by the average result of 10 simulations (3 000 curves each**). $K_{sim}$is of 1.65**.

The factors produced by simulation are larger than the theoretical factor. This first result has to be strengthened by design of experiments to take into account the set of influence parameters (slope, fatigue limit, standard deviation, …)

According to theoretical or simulation approaches, the estimation of the CVM for this family of accumulators with a 95% one-sided level of confidence is from CVM=6.8% x 1.5=10% to CVM=6.8% x 1.65=11%. That is in good accordance with the current industrial fatigue applications.

Following equation (4), ΔP_{test} computed for this accumulator with 3 no failure tests at 2.10^6 cycles and a'=1.64 is from 1.5ΔPE to 1.6ΔPE for a reliability of 99.9%. Without taking into account the confidence interval on the experimental CVM (6.8%), ΔP_{test} is about 1.3ΔPE.

5 CONCLUSION

The analysis of the guarantee factor reliability approach proposed by the European Standard EN 14359, relating to gas-loaded accumulators, to estimate the operating fatigue reliability of accumulators has allowed to classify this method as a probabilistic stress / strength approach. The experimental assessment of the mean fatigue strength is performed by a no failure methodology on a single level of pressure range at 2.10^6 cycles.

The main requirements linked to the use of this approach have been underlined for the accumulator manufacturers as:

- A good knowledge of the fatigue failure modes of the component,
- The fatigue strength influence parameters have to be under manufacturing control in order to fit with a well-known distribution of the fatigue strength (normal or log-normal distribution) and a level of variation in relation with fatigue operating applications.
- A strong feedback of the operating pressure range distribution stood by accumulator until target lifetime.

The fatigue tests performed for three manufacturer on three differents kind of accumulators have allowed to define the failure modes and the level of fatigue strength variation of a 15 items sample by the S,N curve approach. The estimation of the coefficient of variation of the production has been assessed by a 90% confidence interval established with theoretical approaches and MONTE CARLO statistical simulation in Excel.

The level of coefficient of variation in this example is estimated around 10% which is considered as an industrial standard limit for applications subjecting mechanical components to fatigue [15]. Values higher than this experience-based limit have been found on some batches. This could reflect a lack of design/process control without which it is illusory to apply any statistical method to determine a reliability level.

The future experimental results on fatigue strength to verify conditions of application of the qualification by similarity proposed by the standard, and the future in service measurements will build the data base and will fill in a part of the operating knowledge lake of.

Finally, when the operating data are not known by manufacturer, it is advised to limit the use of this method to demonstrate only experimental reliability target on a fatigue bench associated with a single and constant level of pressure range. The necessary condition to forecast operating reliability from experimental reliability will be to have pressure range data bases from pressure measurements on an exhaustive and representative sample of in-service accumulators.As a consequence, the guarantee factor method is not applicable to new developments, innovations or technological improvements.

6 REFERENCES

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