



10TH International Conference on Sustainable Energy and Environmental Protection:

Hydrogen and Fuel Cells

(June 27TH - 30TH, 2017, Bled, Slovenia)

(Conference Proceedings)

Editors:

Emeritus Prof. dr. Jurij Krope
Prof. dr. Abdul Ghani Olabi
Prof. dr. Darko Goričanec
Prof. dr. Stanislav Božičnik



University of Maribor Press



University of Maribor Press



10TH International Conference on Sustainable Energy and Environmental Protection

Hydrogen and Fuel Cells

(June 27TH – 30TH, 2017, Bled, Slovenia)

(Conference Proceedings)

Editors:

Emeritus Prof. dr. Jurij Krope
Prof. dr. Abdul Ghani Olabi
Prof. dr. Darko Goričanec
Prof. dr. Stanislav Božičnik

June 2017

Title: 10TH International Conference on Sustainable Energy and Environmental Protection
(June 27TH – 30TH, 2017, Bled, Slovenia) (Conference Proceedings)

Subtitle: Hydrogen and Fuel Cells

Editors: Emeritus Prof. Jurij Krope, Ph.D. (University of Maribor, Slovenia),
Prof. Abdul Ghani Olabi, Ph.D. (University of the West of Scotland, UK),
Asso. Prof. Darko Goričanec, Ph.D. (University of Maribor, Slovenia),
Asso. Prof. Stanislav Božičnik (University of Maribor, Slovenia).

Review: Prof. Željko Knez, Ph.D. (University of Maribor, Slovenia),
Prof. Niko Samec, Ph.D. (University of Maribor, Slovenia).

Technical editors : Jan Perša (University of Maribor Press),
Armin Turanović (University of Maribor Press).

Design and layout: University of Maribor Press

Conference: 10TH International Conference on Sustainable Energy and Environmental Protection

Honorary Committee: Abdul Ghani Olabi, Ph.D. (Honorary President, University of the West of Scotland,
United Kingdom), Igor Tičar, Ph.D. (Rector of the University of Maribor, Slovenia),
Niko Samec Ph.D. (Pro-rector of University of Maribor, Slovenia), Zdravko
Kravanja, Ph.D. (Dean of the Faculty of Chemistry and Chemical Engineering,
University of Maribor, Slovenia).

Organising Committee: Jurij Krope, Ph.D. (University of Maribor, Slovenia), Darko Goričanec, Ph.D.
(University of Maribor, Slovenia), Stane Božičnik, Ph.D. (University of Maribor,
Slovenia), Peter Trop, Ph.D. (University of Maribor, Slovenia), Danijela Urbanč,
Ph.D. (University of Maribor, Slovenia), Sonja Roj (University of Maribor, Slovenia),
Željko Knez, Ph.D. (University of Maribor, Slovenia), Bojan Štumberger, Ph.D.
(University of Maribor, Slovenia), Franci Čuš, Ph.D. (University of Maribor,
Slovenia), Miloš Bogataj, Ph.D. (University of Maribor, Slovenia), Janez Žlak, Ph.D
(Mine Trbovlje Hrastnik, Slovenia), LL. M. Tina Žagar (Ministry of Economic
Development and Technology), Igor Ivanovski, MSc. (IVD Maribor, Slovenia), Nuša
Hojnik, Ph.D. (Health Center Maribor).

Programme Committee: Prof. Abdul Ghani Olabi (UK), Emeritus Prof. Jurij Krope (Slovenia), Prof. Henrik
Lund (Denmark), Prof. Brian Norton (Ireland), Prof. Noam Lior (USA), Prof.
Zdravko Kravanja (Slovenia), Prof. Jiri Jaromir Klemes (Hungary), Prof. Stane
Božičnik (Slovenia), Prof. Bojan Štumberger (Slovenia), Prof. Soteris Kalogirou
(Cyprus), Prof. Stefano Cordiner (Italy), Prof. Jinyue Yan (Sweden), Prof. Umberto
Desideri (Italy), Prof. M.S.J. Hashmi (Ireland), Prof. Michele Dassisti (Italy), Prof.
Michele Gambino (Italy), Prof. S. Orhan Akansu (Turkey), Dr. David Timoney
(Ireland), Prof. David Kennedy (Ireland), Prof. Bekir Sami Yilbas (Saudi Arabia), Dr.
Brid Quilty (Ireland), Prof. B. AbuHijleh (UAE), Prof. Vincenc Butala (Slovenia),
Prof. Jim McGovern (Ireland), Prof. Socrates Kaplanis (Greece), Dr. Hussam Jouhara
(UK), Prof. Igor Tičar (Slovenia), Prof. Darko Goričanec (Slovenia), Dr. Joseph
Stokes (Ireland), Prof. Antonio Valero (Spain), Prof. Aristide F. Massardo (Italy),
Prof. Ashwani Gupta (USA), Dr. Aoife Foley (UK), Dr. Athanasios Megartis (UK),
Prof. Francesco Di Maria (Italy), Prof. George Tsatsaronis (Germany), Prof. Luis M.
Serra (Spain), Prof. Savvas Tassou (UK), Prof. Luigi Alloca (Italy), Prof. Faek Diko
(Germany), Dr. F. Al-Mansour (Slovenia), Dr. Artur Grunwald (Germany), Dr. Peter
Trop (Slovenia), Prof. Philippe Knauth (France), Prof. Paul Borza (Romania), Prof.
Roy Douglas (UK), Prof. Dieter Meissner (Austria), Dr. Danijela Urbanč (Slovenia),
Prof. Daniel Favrat (Switzerland), Prof. Erik Dahlquist (Sweden), Prof. Eric
Leonhardt (USA), Prof. GianLuca Rospì (Italy), Prof. Giuseppe Casalino (Italy), Prof.
J. Dawson (USA), Dr. José Simoes (Portugal), Prof. Kadir Aydin (Turkey), Dr.
Khaled Benyounis (Ireland), Prof. Laszlo Garbai (Hungary), Prof. Mariano Martin
(Spain), Prof. Masahiro Ishida (Japan), Prof. Michael Seal (USA), Prof. Marco
Spinedi (Italy), Prof. Michio Kitano (Japan), Prof. Milovan Jotanović (BiH), Prof.
Nafiz Kahraman (Turkey), Prof. Na Zhang (China), Prof. Naotake Fujita (Japan),
Prof. Niko Samec (Slovenia), Prof. Oleksandr Zaporozhets (Ukraine), Prof. Osama
Al-Hawaj (Kuwait), Prof. Petar Varbanov (Hungary), Prof. Peter Goethals (Belgium),

Prof. Qi Zhang (China), Prof. Rik Baert (The Netherlands), Prof. Rolf Ritz (USA), Dr. Stephen Glover (UK), Prof. Signe Kjelstrup (Norway), Dr. Sumsun Naheer (UK), Prof. Sven Andersson (Sweden), Dr. Salah Ibrahim (UK), Prof. Sebahattin Unalan (Turkey), Prof. Sabah Abdul-Wahab Sulaiman (Oman), Prof. Somrat Kerdsuwan (Thailand), Prof. T. Hikmet Karakoç (Turkey), Prof. Tahir Yavuz (Turkey), Prof. Hon Loong Lam (Thailand), LL.M. Tina Žagar (Slovenia), Prof. A.M.Hamoda (Qatar), Prof. Gu Hongchen (China), Prof. Haşmet Turkoglu (Turkey), Dr. Hussam Achour (Ireland), Dr. James Carton (Ireland), Dr. Eivind Johannes (Norway), Prof. Elvis Ahmetović (BiH), Prof. D.G.Simeonov (Bulgaria), Prof. Abdelakder Outzourhit (Morocco), Prof. Bilge Albayrak Çeper (Turkey), Prof. Bekir Zühtü Uysal (Turkey), Prof. D. Bradley (UK), Dr. Silvia Tedesco (UK), Dr. Valentin Ivanov (Germany), Dr. Vincent Lawlor (Austria), Prof. Yonghua Cheng (Belgium), Prof. Yasufumi Yoshimoto (Japan), Prof. Yahya Erkan Akansu (Turkey), Prof. Yunus Ali Çengel (Turkey), Prof. Zeljko Knez (Slovenia), Prof. Zoltan Magyar (Hungary), Dr. William Smith (Ireland), Dr. Abed Alaswad (UK).

First published in 2017 by
University of Maribor Press
Slomškovo trg 15, 2000 Maribor, Slovenia
tel. +386 2 250 42 42, fax +386 2 252 32 45
<http://press.um.si>, zalozba@um.si

Co-published by
University of Maribor, Faculty of Chemistry and Chemical Engineering
Smetanova ulica 17, 2000 Maribor, Slovenia
tel. +386 (0)2 22 94 400, faks + 386 (0)2 25 27 774
<http://www.fkkt.um.si>, fkkt@um.si

Published: XX, june 2017

© **University of Maribor Press**

All rights reserved. No part of this book may be reprinted or reproduced or utilized in any form or by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying and recording, or in any information storage or retrieval system, without permission in writing from the publisher.

CIP - Kataložni zapis o publikaciji
Univerzitetna knjižnica Maribor

ISBN 978-961-286-054-7

DOI: <https://doi.org/10.18690/978-961-286-054-7>

Price: Free copy

For publisher: Prof. Igor Tičar, Ph.D., rector (University of Maribor)

Preface

The 10th International Conference on Sustainable Energy and environmental Protection – SEEP 2017 was organised on June 27th – 30th 2017 in Bled, Slovenia, by:

- Faculty of Chemistry and Chemical Engineering, University of Maribor, Slovenia,
- University of the West of Scotland, School of Engineering and

The aim of SEEP2017 is to bring together the researches within the field of sustainable energy and environmental protection from all over the world.

The contributed papers are grouped in 18 sessions in order to provide access to readers out of 300 contributions prepared by authors from 52 countries.

We thank the distinguished plenary and keynote speakers and chairs who have kindly consented to participate at this conference. We are also grateful to all the authors for their papers and to all committee members.

We believe that scientific results and professional debates shall not only be an incentive for development, but also for making new friendships and possible future scientific development projects.

General chair
Emeritus Prof. dr. Jurij Krope



Table of Contents

CONFERENCE PROCEEDINGS

Composite Storage Systems for Compressed Hydrogen - Systematic Improvement of Regulations for More Attractive Storage Units	1
Georg W. Mair, Ben Becker, Sebastian John & Eric Duffner	
Development of Pr₂-XCaxNiO₄ Cathode Materials for It-Sofcs Based on Oxygen-Ion and Proton-Conducting Solid State Electrolytes	11
Elena Pikalova, Nina Bogdanovich, Alexander Kolchugin, Dmitry Medvedev, Larisa Vedmid', Sergey Pikalov & Sergey Plaksin	
Experimental Study of Operational Parameters on the Performance of PEMFCS in Dead end Mode	25
Tabbi Wilberforce, Fawwad Nisar Khatib, Ogungbemi Emmanuel, Oluwatosin Ijeaodola, A. Abdulrahman, Ahmed Al Makky Ahmad Baroutaji & Abdul Ghani Olabi	
Characterisation of Proton Exchange Membrane (PEMFC) Fuel Cell Through Design of Experiment (DOE)	37
Tabbi Wilberforce, Fawwad Nisar Khatib, Ahmed Al Makky, Ahmad Baroutaji & Abdul Ghani Olabi	
Cu/CGO Cermet Based Electrodes for Symmetric and Reversible Solid Oxide Fuel Cells	53
Giovanni Carollo, Alberto Garbujo, Davide Ferri, Marta Maria Natile & Antonella Glisenti	
Improvement of a Hybrid Serpentine-Interdigitated Flow Field by Adjusting Numbers of Inlet and Outlet of Gas Flow Channels	65
Nuttapol Limjeerajarus & Thatphong Santiprasertkul	
Concept of an Integrated Thermally Self-Sustained Methanol Steam Reformer – High-Temperature PEM Fuel Cell Stack Manportable System	75
Andrej Lotrič, Mihael Sekavčnik, Andrej Pohar, Blaž Likozar & Stanko Hočevar	

Transport Properties of Ca-Doped Ln₂NiO₄	87
Vladislav A. Sadykov, Elena Yu. Pikalova, Alexander A. Kolchugin, Nikita F. Ereemeev, Nina M. Bogdanovich, Azat F. Khasanov, Pavel I. Skriabin, Alexey V. Krasnov, Ekaterina M. Sadovskaya, Alexander N. Shmakov, Zakhar S. Vinokurov, Arcady V. Ishchenko, Sergey M. Pikalov & Elena A. Filonova	
Novel Nanocomposite Materials for Oxygen Separation Membranes	97
Vladislav A. Sadykov, Alexey V. Krasnov, Yulia E. Fedorova, Anton I. Lukashevich, Nikita F. Ereemeev, Pavel I. Skriabin, Konstantin R. Valeev & Oleg L. Smorygo	
Electrochemical Resistance Reduction by Acid Treatment of Coal in Direct Carbon Fuel Cell	105
Seongyong Eom, Seongyool Ahn, Gyungmin Choi & Duckjool Kim	
Rapid Synthesis of Co/CeO₂ Nanoparticles for Selective Oxidation of Carbon Monoxide in H₂-Rich Stream	117
Liping Zhong, Dingkai Chen, Kezhen Chen, Jichang Lu, Jing Wang, Caiyun Han & Yongming Luo	
The Effect of Chloride Ions in Sn Doped CuO-CeO₂ Catalysts for Co Preferential Oxidation (CO-PROX) in H₂-Rich Stream	129
Kezhen Chen, Liping Zhong, Jichang Lu, Gengping Wan & Yongming Luo	
Design and Testing of a Single-Cell PEM Electrolyser for Small-Scale Hydrogen Production Under Mild Conditions	141
Antonio L. Tomas-Garcia, Mojtaba Mirzaeian, Greig Chisholm & Abdul G. Olabi	
European-Wide Field Trials for Residential Fuel Cell Micro-CHP	151
Tadej Auer & Mike Small	
Exploring the Profit Potential of Energy Storage in a Car Park Using Electrolysis, Hydrogen Storage and Fuel Cell Electric Vehicles	161
Reinier van der Veen, Remco Verzijlbergh, Zofia Lukszo & Ad van Wijk	
Investigation on the Coupling of Fuel Cell with Photovoltaic and Parabolic Trough Solar Systems	173

Ahmad Haddad, Mahmoud Khaled, Mohamad Ramadan, Haitham
Ramadan & Mohamad Becherif

State-of-the-Art Manufacturing Technologies of PEMFC Components 189

Abdulrahman Alanazi, Emmanuel Ogungbemi, A. Wilberforce,
Oluwatosin S. Ijaodola, Parag Vichare & Abdul-Ghani Olabi

Design of a Polygeneration Plant Based on Solar Power and Solid Oxide Cells with Desalination Plant 199

Nicolás Cobos Ullvius & Masoud Rokni

Turbulent Burning Velocity of Mixture of Methane and a High Hydrogen Content Syngas 217

Arley Cardona Vargas, Alex M. García, Fabián E. Cano Ardila, Carlos
E. Arrieta, Hernando A. Yepes & Andrés A. Amell

Electrochemical Analysis of Experimental Output Voltage for PEMFC Based on the MVWT 227

Jonghoon Kim & Woonki Na

Composite Storage Systems for Compressed Hydrogen - Systematic Improvement of Regulations for More Attractive Storage Units

GEORG W. MAIR, BEN BECKER, SEBASTIAN JOHN & ERIC DUFFNER

Abstract Hydrogen is an attractive energy carrier that requires high effort for safe storage. For ensuring safety they have to undergo a challenging approval process. Relevant standards and regulations for composite cylinders used for the transport of for on-board storage of hydrogen are currently based on deterministic (e.g. ISO 11119-3) or semi-probabilistic (UN GTR No. 13) criteria. This paper analysis the properties of such methods in regards to the evaluation of load cycle strength. Their characteristics are compared with the probabilistic approach of the BAM. Based on Monte-Carlo simulations, the available design range (mean value and scatter of strength criteria) of current concepts were exemplarily estimated. The aspect of small sample sizes is analysed and discussed with respect to the evaluation procedures.

Keywords: • probabilistic • hydrogen • composite • cylinder • regulations •

CORRESPONDENCE ADDRESS: Georg W. Mair, Dr.-Ing., Bundesanstalt für Materialforschung- und prüfung BAM (Federal Institute for Materials Research and Testing), Unter den Eichen 44-46 12203 Berlin, Germany, e-mail: georg.mair@bam.de. Ben Becker, Dr.-Ing., Bundesanstalt für Materialforschung- und prüfung BAM, Unter den Eichen 44-46 12203 Berlin, Germany, e-mail: ben.becker@BAM.de. Sebastian John, Bundesanstalt für Materialforschung- und prüfung BAM, Unter den Eichen 44-46 12203 Berlin, Germany, e-mail: sebastian.john@BAM.de. Eric Duffner, Bundesanstalt für Materialforschung- und prüfung BAM, Unter den Eichen 44-46 12203 Berlin, Germany, e-mail: eric.duffner@BAM.de.

1 Introduction

Hydrogen is an attractive energy carrier that needs to be compressed (CGH₂) or liquefied (LH₂) for storage and transport. The high storage pressure bears a risk of rupture with high consequences. Therefore H₂-storage systems have to undergo an extensive approval process. Relevant assessment criteria for approval and definition of retest periods of composite cylinders are intended to ensure a safe use over its entire service life. The overall aim is to avoid a critical failure during service. The risk of such a failure can never be completely eliminated but have to be reduced to an broadly accepted level. In this case, the residual risk is accepted as a function of consequence.

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

The approval of composite cylinder for CGH₂ storage systems for vehicles needs to follow the criteria from the UN GTR No. 13 [1]. In regards to burst pressure, this GTR 13 is based on an extended semi-probabilistic approach. This means, there is a specific minimum burst pressure as usual. But in addition to that the maximum scatter of the single burst test results is also limited. In regards to load cycle strength it is required to demonstrate a minimum number of load cycles (e.g. 11,000) without failure by testing just 3 specimens resisting.

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

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

Concerning burst pressure, this has been already investigated in [6] by using Monte-Carlo simulation. In the following, the Monte-Carlo simulation is extended to the statistical analysis of test results created by cycle testing with respect to the GTR 13 and the BAM-PA.

2 Monte-Carlo Simulation

The concept of a Monte-Carlo simulation [7] is based on a large number of computer generated samples. These samples result from a basic population following an assumed distribution function with defined properties. Due to a limited sample size n , mean value and scatter of a single sample deviate from the true characteristics of the original basic population.

This concept can be adopted to burst pressure and load cycle strength of composite cylinders. Corresponding studies on the statistical distribution of both performance parameters are presented in [8] and [9].

Figure 1 shows for example the variety of sample properties from burst tests according to GTR 13. Mean value and scatter of the samples are distributed around the true (but unknown) characteristics of the basic population. Each individual point in Figure 1 was generated by a Monte-Carlo simulation and represents burst values of a sample of 3 cylinders. The comparatively small sample size of $n = 3$ creates a wide range of possible sample properties out of the same basic population. The challenge of an approval requirement is to identify potentially unsafe design types despite the high variability of the test results.

Figure 1 uses the sample performance chart (SPC) developed and applied by the BAM since 2012. The combined representation of mean value and scatter in relation to the test pressure PH enables the display of both properties relevant for a safety assessment. The shown scatter of sample properties results from the basic population with a mean burst pressure $\Omega_{50\%}$ of 2.6 PH and a scatter Ω_s of 10% of PH .

When these generated samples are combined with an assessment criterion, they can be divided into two groups: Samples that meet the criterion (black) and those, which do not meet it (red). Figure 1 is based on the criterion according to GTR 13. Each of the three burst pressure values within a sample must exceed the test pressure PH by 1.5 times, i.e. the nominal working pressure (NWP) by 2.25 times. Additionally, each burst pressure needs to be within a range of $\pm 10\%$ of the mean value $\Omega_{50\%}$.

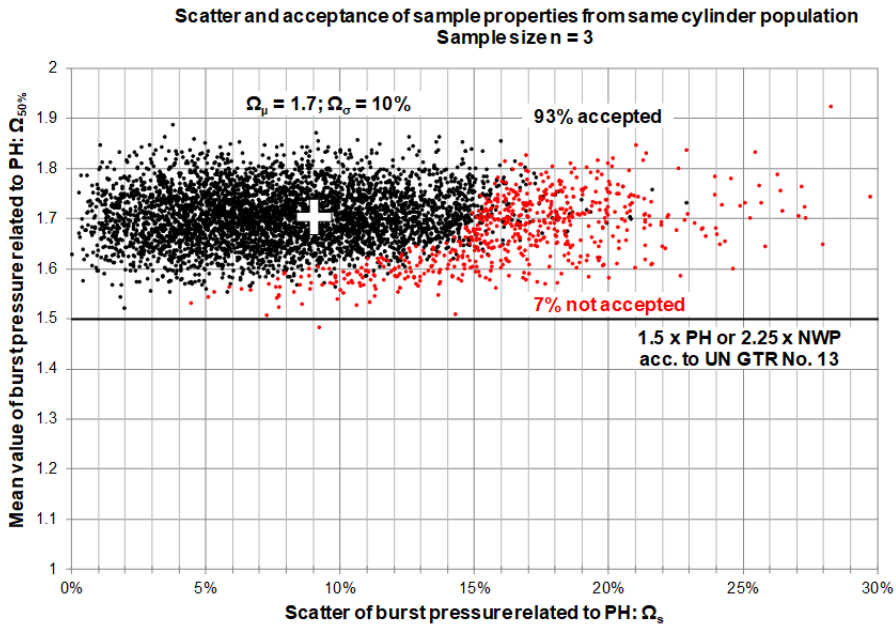


Figure 1. Monte-Carlo simulation of sample properties for a cylinder population $\Omega_{50\%} = 2.6$ PH; $\Omega_s = 10\%$ PH, assessed by UN GTR No. 13.

As shown in Figure 2, around 93% of the generated samples include adequate test results and fulfill the burst criterion of the GTR 13. That means that the underlying basic population of composite cylinders would be accepted with a probability 93%. This probability is called Acceptance Rate (AR). Conversely, the basic population would not meet the criterion with a probability of about 7%.

The example shows that the evaluation of a small sample with $n = 3$ leads to considerable uncertainties. These uncertainties are always present and are usually covered by appropriate safety margins and additional tests. However, the decisive point of an assessment criterion should be the risk that an unsafe design type could be accepted - or even not.

To evaluate this it is necessary to clearly define the term “unsafe” respectively “safe”. In the case of burst pressure, “safe” can be defined by the reliability or survival rate (SR) against a sudden rupture at a certain pressure [3], [4], [8]. A comparable criterion for load cycle strength can be defined based on the reliability against a leakage or sudden rupture after N further additional load cycles. In case of a composite cylinder at its end of service life N corresponds to just one (the very last) residual load cycle.

3 Evaluation of un GTR 13

The adoption of Monte-Carlo simulation to generate load cycle values requires a suitable assumption of the distribution function for the load cycle strength of composite cylinders. The average load cycle strength $N_{50\%}$ and scatter N_s are obtained by a combination of Log-Normal and Weibull distribution [9] as shown in an adapted sample performance chart in Figure 2.

A high number of Monte-Carlo simulations for different combinations of $N_{50\%}$ and N_s allows to calculate acceptance rates (AR) over the entire range of the SPC. Points from basic populations (N_s ; $N_{50\%}$), with same AR are linked together to isolines of a constant acceptance rate.

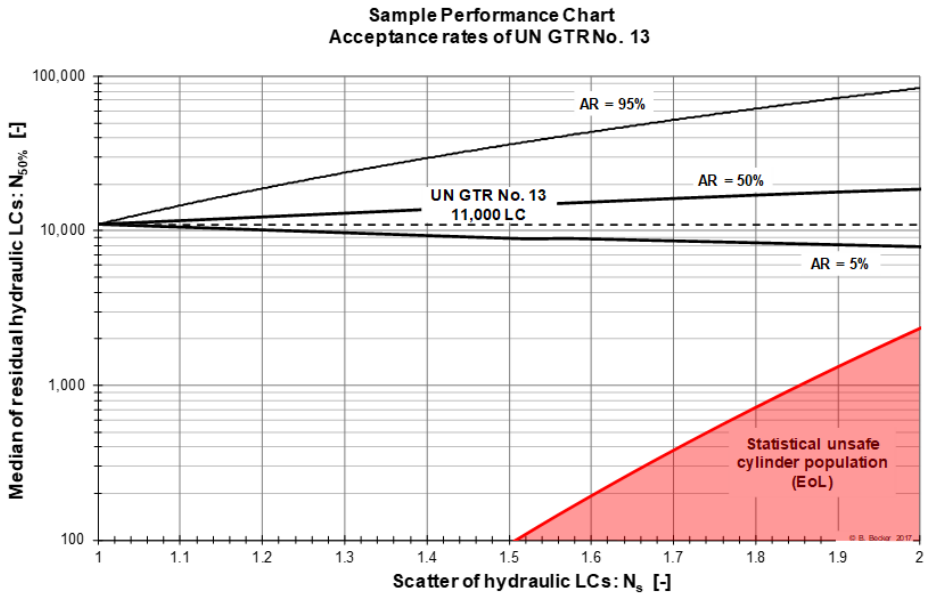


Figure 2. Iso-lines of acceptance rates for GTR 13 in comparison to statistically unsafe cylinder populations.

Figure 2 shows the distribution of AR for the load cycle criterion of GTR 13. For a better understanding: if the properties of a basic population of composite cylinders are located e.g. on the iso-line AR = 50%, there will be a probability of 50% that this basic population meets the requirement of GTR 13. Figure 2 combines the calculated isolines for AR with the safety criterion of a reliability of $1-10^{-6}$ (99.9999%) against failure at the next load cycle (red line).

Two main questions arise in this context:

1. What is the acceptance rate for a potentially unsafe population of composite cylinders?
2. Which range of $N_{50\%}$ and N_s can be used for designing composite cylinders acc. to GTR?

Concerning the first question, Figure 2 shows at very high scatter values of $N_s = 2$ the general possibility to accept a basic population with a mean load cycle strength of $N_{50\%} < 11.000$ LC. The probability to accept a potentially unsafe cylinder population below the red line is less than 5% and consequently practically irrelevant.

For the second question, it can be assumed that an acceptance rate of above $AR = 50\%$ should be relevant in practice. Otherwise a design type would be conspicuous due to too many rejected batch tests and becomes therefore uneconomical. Acceptance rate of $AR = 95\%$ appears to be realistic from experience. The range between the line of $AR = 95\%$ and the red line of minimum reliability can be considered as a range of permissible reduction in load cycle strength during service life.

4 Evaluation of BAM-PA

A similar application of the Monte-Carlo simulation to the BAM-PA for the probabilistic assessment of load cycle strength is shown in Figure 3.

A cylinder population with reliability of less than $1 \cdot 10^{-6}$ against failure (red line, compare [3], [6], [10]) is regarded as unsafe for further use. The already explained uncertainty of sample testing is covered in the PA by operating a confidence level of 95%. Therefore, a sample needs to demonstrate at least an average strength for load cycles and a scatter value above the dotted line. Aim of this approach is to ensure that the acceptance rate of a potentially unsafe cylinder population is not significantly higher than 5%. The shown example is based on a sample size of $n = 5$ test results.

Figure 3 shows that in case of a cylinder population which is located on the line of the minimum requirement, a sample would be accepted by slightly more than 50%.

The isoline of $AR = 95\%$ limits the range of the de facto required properties for a cylinder population as otherwise the requirement would not be fulfilled very often.

5 GTR 13 compared with BAM-PA

Figure 4 shows the AR iso-lines for the GTR 13 and the BAM-PA. For the BAM-PA with $n = 5$ the scatter N_s of a cylinder population should be lower than 1.25 for reaching an acceptance rate of $AR = 95\%$. In comparison, the GTR 13 allows to accept cylinder populations with a much higher scatter value. On the other hand, the BAM-PA allows accepting cylinder populations with very low mean load cycle strength in case of a scatter

$N_s < 1.2$. A low scatter value of load cycle strength leads to an increased reliability against failure. This is considered in the BAM-PA and demonstrates the general potential of weight and cost savings by probabilistic assessment criteria. A high production quality ensures a high reliability against failure even at lower mean load cycle strength.

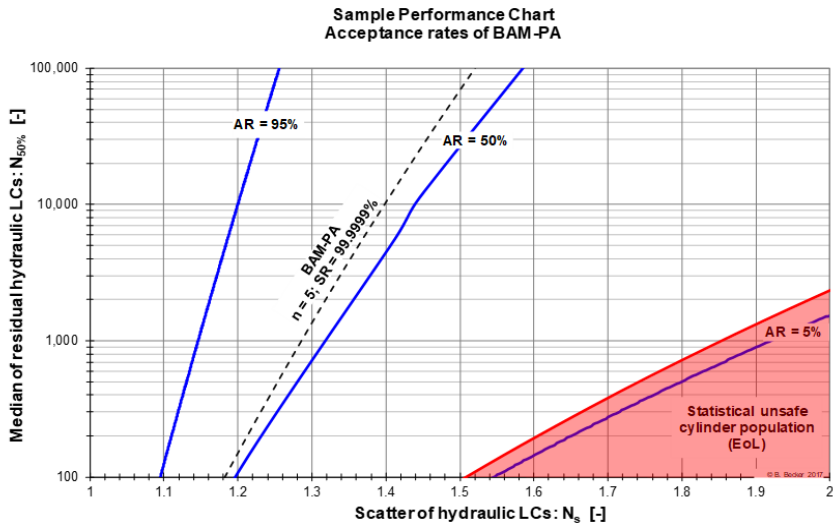


Figure 3. Isolines of acceptance rates for BAM-PA in comparison to statistical unsafe cylinder populations.

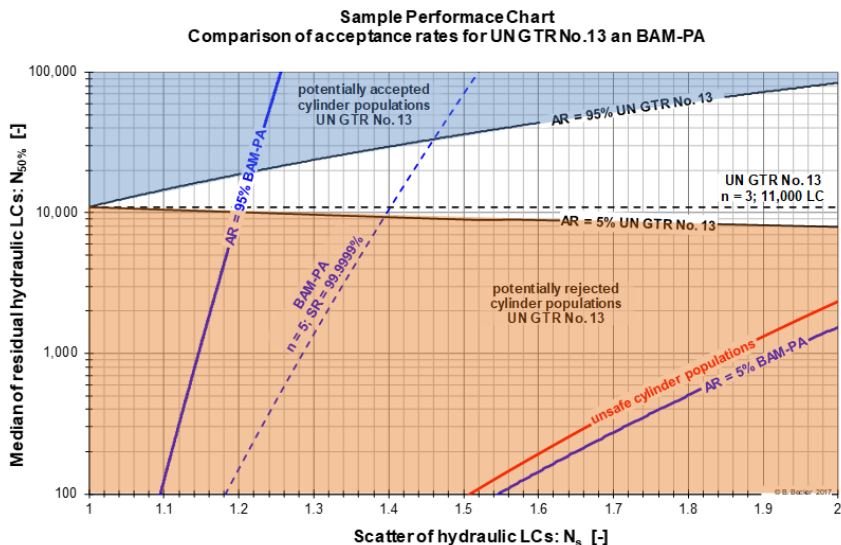


Figure 4. Requirements and of areas of acceptance for GTR 13 and BAM-PA.

ven if the iso-line $AR = 95\%$ of the BAM-PA seems to reduce the scatter to a relatively small range this requirement is far less limiting the freedom for design in practical terms. In contrast to the GTR 13 and other standards based on deterministic requirements, a probabilistic assessment does not require fixed minimum values. It is important to look at the characteristics of the entire sample.

Therefore, it is possible within the BAM-PA to increase the sample size if necessary. This offers additional and more accurate information about a cylinder population. In practical use of the BAM-PA, an increased sample size often proves that the minimum requirement for the sample is met despite a critical first impression.

An increased sample size reduces the statistical uncertainty. Regarding Figure 3, this means that the dotted black line moves further right and allows higher scatter values.

The dependencies between sample size n , scatter N_s and mean load cycle strength $N_{50\%}$ are shown in Figure 5 for an acceptance rate of $AR = 95\%$.

The required load cycle strength which ensures a minimum reliability against failure for a sample scatter of $N_s = 1.2$ is reduced from 10,000 LC ($n = 5$) to 300 LC ($n = 10$). This effect is directly related to reduced statistical uncertainties in case of a sample size of 10 test specimens versus a sample size of only 5 test specimens with otherwise similar properties.

Additional tests to increase the sample size for a statistical assessment cannot be compared with the very questionable praxis of retesting individual results in deterministic procedures. In case of a statistical assessment all previous test results are still part of the sample. In contrast, retests procedures for deterministic requirements are ignoring previous test results.

5 Conclusions

It was shown that deterministic and probabilistic requirements are very different in terms of the acceptance of samples with high scatter values and potentially unsafe cylinder populations.

The used method of operating the Monte-Carlo simulation offers detailed analyses of approval criteria. Monte-Carlo simulation can be used to identify under which conditions minimum requirements could be reduced or changed without critical safety losses.

Especially probabilistic approval requirements would allow considerable improvements regarding the avoidance of critical cylinder populations. A probabilistic safety assessment offers a high potential for future optimization of cylinders designs. The consideration of scatter values provides additional information about production quality

and reliability and an optional increase of sample size allows immediate reactions on potential problems, too.

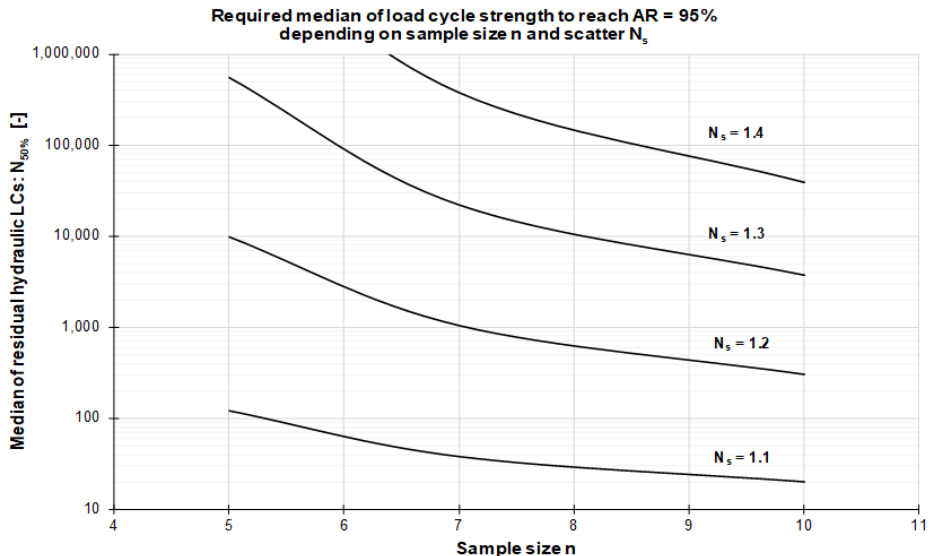


Figure 5. Required load cycle strength for BAM-PA to achieve an acceptance rate of 95% for specific scatter values of basic populations.

References

- [1] UN GTR No. 13 – Global Technical Regulation Concerning the Hydrogen and Fuel Cell Vehicles, 2013.
- [2] BAM – Official Publications: Dangerous Goods Containments – Composite Pressure Receptacles, Berlin, Germany, 2016. http://www.tes.bam.de/en/regelwerke/amtliche_mitteilungen/index.htm
- [3] G.W. Mair, *Sicherheitsbewertung von Composite-Druckgasbehältern - Potential statistischer Methoden jenseits aktueller Vorschriften*, Springer-Verlag, Berlin 2016
- [4] ADR/RID 2017, Technical annexes to the European agreements concerning the international carriage of dangerous goods.
- [5] International Maritime Code for Dangerous Goods (IMDG Code), Amendment 37-14, International Maritime Organization, London, UK, 2014.
- [6] B. Becker, G.W. Mair, “Statistical analysis of burst requirements from regulations for composite cylinders in hydrogen transport”, *Materials Testing*, vol. 59, pp. 226-232, Mar. 2017.
- [7] E. Zio, *The Monte Carlo Simulation Method for System Reliability and Risk Analysis*, London, 2013.
- [8] B. Becker, G. W. Mair, F. Scherer, “Burst strength of composite cylinders – assessment of the type of statistical distribution” *Materials Testing*, vol. 56, pp. 642 – 648, Sep. 2014.

- 10 | 10TH INTERNATIONAL CONFERENCE ON SUSTAINABLE ENERGY AND ENVIRONMENTAL PROTECTION (JUNE 27TH– 30TH, 2017, BLED, SLOVENIA), HYDROGEN AND FUEL CELLS
G. W. Mair, B. Becker, S. John & E. Duffner: Composite Storage Systems for Compressed Hydrogen - Systematic Improvement of Regulations for More Attractive Storage Units
- [9] G.W. Mair, B. Becker, I. Scholz, “Assessment of the type of statistical distribution concerning strength properties of composite cylinders”, 20th ICCM, Copenhagen, 2015.
- [10] B. Becker, G. W. Mair, “Risks and safety level of composite cylinders”, Proceedings of WHEC 2016, pp. 34-35, Saragossa, 2016.