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Measurement Chamber Design for Testing Batteries of the Electric Vehicles

Crucial factors with respect to modern autonomous vehicles include reliability and design. Researchers and engineers strive to increase the number of vehicles over the latest possibilities both in industrial and in military applications. A number of modern batteries are available on the market for the electric autonomous vehicles. The authors suggest the use of test chambers to investigate optimal battery use and performance in vehicles. The results of the theoretical research suggest that the use of test chambers during battery management system development is necessary.

Keywords: *test, measurement chambers, autonomous vehicles, unmanned aerial vehicles, battery management systems*

Tesztkamrák tervezése elektromos járművek akkumulátorainak teszteléséhez

A modern autonóm járművek megbízhatósági kérdései elsődleges fontosságú tervezési faktorok. Ezen járművek a kutatóknak és mérnököknek köszönhetően egyre nagyobb számban jelennek meg ipari és haditechnikai alkalmazásokban. Kereskedelmi forgalomban már elérhetőek modern akkumulátorrendszerek autonóm elektromos járművek számára. A szerzők a tesztkamrák használatát javasolják az akkumulátorok optimális használatának és teljesítményének meghatározásához. A kutatás elméleti eredményei alátámasztják azon hipotézist, miszerint a tesztkamrák használata szükséges az akkumulátorrendszerek fejlesztési fázisában is.

Kulcsszavak: *teszt, mérőkamrák, autonóm járművek, pilóta nélküli autonóm járművek, akkumulátorfelügyeleti rendszerek*

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1. Introduction

Nature created cutting-edge, complex and efficient systems in billions of years. Modern and intelligent life is among the results. Consequently, mankind strives to either replicate or learn from nature to develop technological systems that are vital to improve social welfare.

In addition to the physical existence of manufactured goods or products and processed designs, the virtual world also gains benefits and tries to replicate the best creation of nature. The aim of AI, for example, is to gain the best of what computing power has to offer with the capabilities of human intelligence and experience. By human intelligence, one refers to the combination of abilities such as learning, communication through language, reasoning, dealing with data, and abstract thinking.

AI systems are varying the way industry manufactures goods and services, as well as the organisation of the market. The innovation and maintenance management are directly impacted by the rise of automated, autonomous or smart technologies and artificial intelligence. The trend is that the technical system landscape is rapidly changing; companies and users must adapt to these dynamically developing machines.

New markets are emerging and vanishing at a significant rate due to such advanced technologies as AI and robotisation. Now, faster than ever, the technology is changing the topography of vehicles on a global scale. According to recent studies, AI can open more ways in improving efficiency of electric vehicles and robots. There is a dilemma; current batteries would not operate under the right efficiency and safety. Therefore, a new technique in battery management systems is vital. Nevertheless, in the first step the engineers and scientists must make tests on the batteries. Due to the safety risk, the test chambers are a necessary part of the modern test engineering life.

The battery safety testing processes provide the right safety and reliability of the batteries, which are used in dynamically growing areas such as transportation, renewable energy, grid storage, grid balancing, backup applications and uninterruptible power supplies (UPS). The safety and reliability of batteries are a critical aspect of electric cars (passenger and logistic), railway, marine and aerospace applications. The safety, reliability and, consequently, the quality of your battery provide multiple benefits for manufacturers in the business. The battery manufacturers must stay ahead of the development of the battery cells. The battery testing laboratories need to be fully equipped to support various tests. The most important tests are the following:[4]

- performance testing;
- abuse testing;
- environmental tests;
- special environmental test;
- transport tests.

The authors aim at introducing the application of test chambers in diagnostics of the battery technical status and to segment technical parameters of the batteries often measured and available for further analysis.

[4] 'Battery Safety Testing – Development and validation testing to current and emerging standards,' TÜV SÜD.

This article summarises the most popular batteries in the drive chains applied in both military and non-military vehicles and robots. It introduces possible applications of test chambers in safety and security sciences.

2. Related works and preliminaries

An Unmanned Ground Vehicle (UGV) runs while contacting the ground without any onboard human control or driver. From another point of view, the UGV is a special ground-based mechanical robot/vehicle that can sense and interact with its environment. UGVs have several fields of use where a human operator may be dangerous or difficult to use. The vehicle has a lot of different sensors and actuators to check the environment and they can make decisions autonomously about its behavior or forward the information to a human operator. The operator can control the vehicle through a teleoperation system. The unmanned robotics area is rapidly growing in military and non-military fields, too.[5]

- battery charging;
- battery swap;
- automatic and opportunity charging;[6]
- automatic battery swap.

The new technologies may reduce the human factor in battery management. These technologies may provide better efficiency for technical systems, but the safety factor is very critical.[7] Crucial batteries include:[8]

- Lithium Ion Batteries;
- U-Charge Lithium Iron Magnesium Phosphate;
- VRLA lead-acid;
- Nickel–cadmium battery;
- Nickel Metal Hydride Battery;
- Lithium LiFeP04 battery;
- Lead Acid Battery.

Most of the hobby robotics batteries operate with lithium-based batteries and are marketed with C rating. This rating is a crucial multiplier used for the capacity of batteries to show the maximum continuous current discharge of the batteries.[9]

Other important power sources are depicted in the UGV Database[10] as:

- batteries 24 V;
- batteries 36 V DC;
- batteries 14.5 V;

[5] J. Carlson, R. Murphy and A. Nelson, 'Follow-up Analysis of Mobile Robot Failures,' IEEE International Conference on Robotics and Automation. Proceedings. ICRA '04. 2004.
[6] 'AGM Battery Guide,' Canbat.
[7] 'Battery Safety Standards – The Changing Requirements for Batteries,' Lithium Werks.
[8] 'AGM Battery Guide'; 'Large Lithium Ion Batteries for Material Handling Equipment and Automated Guided Vehicles (AGVs).' Lithium Werks.; 'Lead Acid Batteries,' Concordia University – Environmental Health and Safety.
[9] 'UGV System Design: A Practical Approach,' SuperDroid Robots.
[10] UGV Database, Michigan Technological University.

- batteries 48 V;
- 120 V AC or DC via tether;
- military batteries;
- lithium-polymer (LiPo) batteries.

3. Battery properties and measurements

The rising oil prices, the worldwide awareness of environmental crisis and in some cases the physical size of the vehicles increased the development of energy storage and special operation management systems. The batteries are the most popular energy sources for environment friendly vehicles and for robots. New modern batteries are less polluting, but their efficiency is still not acceptable, often and old combustion engine is a much better choice than an electric vehicle. The battery has the advantages of high working cell voltage, low pollution, low self-discharge rate, and high power density.[11]

The State of Charge (SOC) is a key challenge for battery use. The SOC can describe the remaining capacity of the batteries or battery cells. This capacity is an indispensable part of the battery control strategy. The SOC can represent the battery performance, which is an important property of the vehicle's drive chain system. The accurate SOC is not just a battery protection property, but it can avoid deep discharge and also improve the battery life. It is important to mention that batteries are chemical energy storage sources, and the chemical energy cannot be accessed directly, this can be a dangerous part of the batteries. This fact hinders the estimation of the SOC of a battery. The right estimation of the SOC is a very complex task. The implementation of the right SOC strategy is not so easy, because battery models are limited and there are parametric uncertainties.[12]

The definition of SOC covers lot of other issues. Generally, the SOC of the battery is defined as a rate of its instantaneous capacity $Q(t)$ to the nominal capacity (Q_n). The nominal capacity is provided by the manufacturer and shows the result of the maximum amount of charge stored in the battery. The SOC can be defined as follows:[13]

$$SOC(t) = \frac{Q(t)}{Q_n}. \qquad (1)$$

Other mathematical methods about this problem:[14]

- Direct Measurement;
- No Load Circuit Voltage Method:

$$V_{oc}(t) = a_1 \cdot SOC(t) + a_0, \qquad (2)$$

where a_1 is obtained from knowing the value of a_0 and $V_{oc}(t)$ at SOC = 100%, a_0 is the battery terminal voltage when the SOC is 0% and SOC(t) is the SOC of the battery at time t.

[11] W. Y. Chang, 'The State of Charge Estimating Methods for Battery: A Review,' *ISRN Applied Mathematics*, Volume 2013, pp. 1–7.; K. L. Man, C. Chen, T. O. Ting, T. Krilavičius, J. Chang and S. H. Poon, 'Artificial Intelligence Approach to SoC Estimation For Smart BMS.'; 'BU-903: How to Measure State-of-charge,' Battery University.

[12] Ibid.

[13] Ibid.

[14] Ibid.

- Terminal Voltage Method;
- Impedance Method;
- Impedance Spectroscopy Method;
- Book-Keeping Estimation;
- Coulomb Counting Method:

$$SOC(t) = SOC(t-1) + \frac{I(t)}{Q_n} \Delta t, \tag{3}$$

where $I(t)$ is the discharging current over time in order to estimate the SOC, Q_n is the nominal capacity, $SOC(t-1)$ is the previously estimated SOC value and Δt is the time change.

- Modified Coulomb Counting Method:

$$I_c(t) = k_2 I(t)^2 + k_1 I(t) + k_0, \tag{4}$$

$$SOC(t) = SOC(t-1) + \frac{I_c(t)}{Q_n} \Delta t, \tag{5}$$

where k_2, k_1 and k_0 are constant values obtained from the practical experimental data, and finally, is the nominal capacity of the battery provided by the manufacturer.

One of the significant users of the LiPo batteries are the unmanned aerial vehicles (UAVs). The electric propulsion and the onboard systems are normally supplied with energy using batteries. The UAV/UAS conceptual design and some aspects of the UAV airworthiness validation are thoroughly analysed and shown by Róbert Szabolcsi.[15] The design of the UAV/UAS systems have an important criteria, which is often called 'minimum energy problem.' Szabolcsi outlined basic theoretical and practical issues for the design of the UAV automatic flight control systems based on LQR design methodology, and introduced several design examples for small UAVs.[16]

4. Failures affecting the technical status of the batteries

Failures can be classified into several classes. Physical failures are further classified into sensor, control system, power and communication failures, while human failures are design and interaction problems. We can find two sub-categories in interaction, which are the short failures and slips.[17]

15 R. Szabolcsi, *UAV/UAS rendszerek koncepcionális és előzetes tervezése, vizsgálata* (Budapest: Óbudai Egyetem, 2020).

16 R. Szabolcsi, *Pilóta nélküli légi járművek automatikus repülésszabályozó rendszerei: Rendszertervezés és rendszervizsgálat* (Budapest: Óbudai Egyetem, 2020).

17 Carlson, Murphy and Nelson, 'Follow-up'; Jeffrey A. Kramer and Robin R. Murphy, 'UGV Acceptance Testing,' Proceedings of SPIE – The International Society for Optical Engineering, Vol. 6230 I, Unmanned Systems Technology VIII, 62300P (2006).

Table 1
Types of failures. Source: Carlson, Murphy and Nelson, 'Follow-up.'

Failures				
Physical	***Human***		***Impact***	***Reparability***
effector sensor control system power communications	*Design*	*Interaction* Mistakes slips	non – terminal / terminal	field – repairable / non-field – repairable

- Control system: A robot subsystem including on-board computer, software by the manufacturer, and any remote operator control units (OCU).
- Effector: A device that performs actuation and any connections in connection with those components.
- Mistakes: human failures by fallacies in conscious processing.
- Slips: human failures by fallacies in unconscious processing.
- Power Failure.[18]

5. Test chambers

The undercharging, overcharging, overheating or damage in the separating membrane are common errors of lithium ion batteries that can generate safety problems. The safety risks associated with any of these errors range wide, and are specific to the product under test and/or development.[19]

Dozens of standards, UL and IEC specifications are available for testing batteries to ensure the survival of their daily operation including the use of environmental chambers to subject batteries to low and high temperature (often during charging and discharging process, too). Figure 1 represents some interesting information about the temperature and voltage connection of the batteries.[20]

The temperature, charge/discharge rates and the depth of discharge have paramount importance in the life cycle of the battery cells. Depending on the aim of the tests, the temperature and the DOD should be controlled at a pre-defined reference level to have repeatable results, which can be compared with the standards.[21]

18 Carlson, Murphy and Nelson, 'Follow-up'; Jeffrey A. Kramer and Robin R. Murphy, 'UGV Acceptance Testing.'
19 Mark Chrusciel and Wayne Diener, 'Mitigating Risks of Battery Testing in Environmental Chambers.'; 'Electric Vehicle Battery Test Laboratory,' Proventia.; 'Battery Testing Chambers,' Cincinnati Sub-Zero.; 'Environmental Chambers for Battery Testing,' Cincinnati Sub-Zero.
20 Ibid.
21 Ibid.

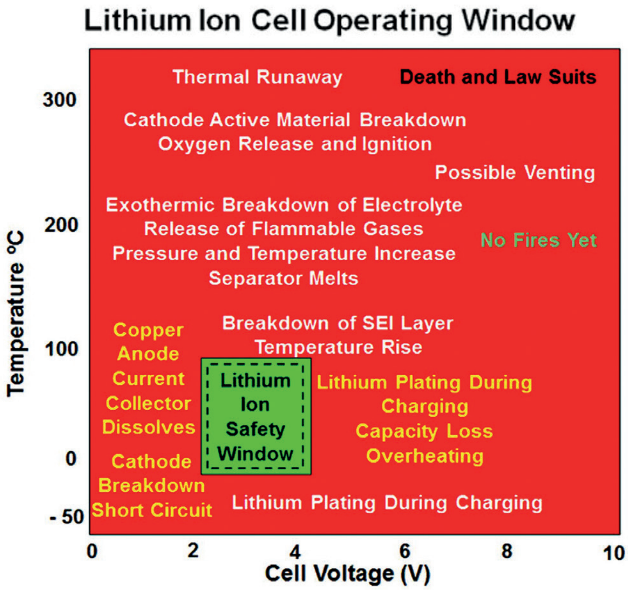

Figure 1
Lithium Ion Cell Operating Window. Source: Chrusciel and Diener, 'Mitigating risks.'

Some other tests contain humidity or vibration analysis about the battery cells. Common specifications for testing lithium ion cells are listed below:[22]

- UL 1642 – General safety testing of Li-Ion Batteries;
- IEC 61960 – Safety standards for secondary lithium ion batteries;
- SAE J2464 – General guidelines for rechargeable energy storage;
- UN/DOT 38.3 – Standards for shipping lithium batteries;
- IEC 62281 – Safety of primary cells during shipment;
- UL 2580 – Batteries for use in Electric Vehicles;
- IEC 62660-2 – Reliability and abuse testing of secondary cells;
- IEC 62133 – Testing of secondary cells.

The right selection of the proper environmental test chamber is an important question for test engineers and the manufacturers. When the product being tested is a Li-Ion battery, there is a huge amount of information to consider. Significant considerations should be targeted at the level of safety required for the application by the end user. The manufacturers and test engineers must follow a lot of strict safety rules and regulations. The Li-Ion battery manufacturers have a proprietary chemistry and packaging which in turn carries its own risk during testing. These materials and process are very dangerous ones.[23]

There are several hazard levels in connection with Li-ion batteries. One of the most important safety features incorporated into environmental test chambers for testing of

[22] Chrusciel and Diener, 'Mitigating risks.'
[23] Chrusciel and Diener, 'Mitigating risks'; 'Electric Vehicle'; 'Battery Testing Chambers'; 'Environmental Chambers.'

batteries include temperature limited sheath heaters. Some heaters on environmental test chambers are Ni-Chrome (Ni-Cr) wire heaters. The surface temperature of these chambers is over 500 °C. These preventative measures include, but are not limited to, non-sparking fan blades and/or blower wheels, intrinsically safe barriers on all sensors (both temperature and humidity) to prevent the potential of high voltage pulses into the chamber through wires, and the removal of any internal chamber lights.[24]

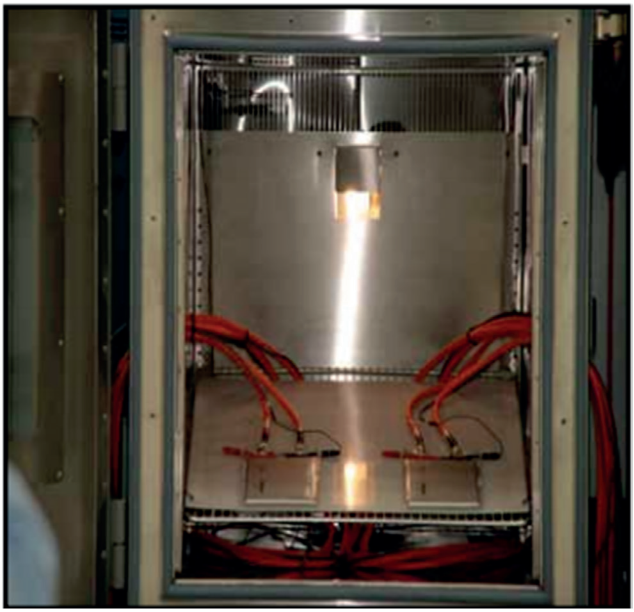

Figure 2
Battery Cell testing chamber (inside view). Source: 'Environmental Chambers.'

Another issue to consider is pressure compensation inside the chamber. The pressure at which gases are released from the battery during failure depends not only on the chemistry of the batteries. Most of the chamber manufactures have a standard pressure relief port on the chambers. This port allows the chamber to "breathe" to the environment for the expansion and contraction of the air within the conditioned workspace.[25]

These gases are toxic, noxious or at the very least have an offensive smell and should be vented to the exhaust system. These are only some of the most important safety features. The different hazard levels define the list of special features that may be used during the tests. The test systems must include fire detection systems, gas monitors, door safety interlock switches, and a flushing system of N_2 or CO_2 to minimise fire if this is necessary.

[24] Ibid.
[25] Ibid.

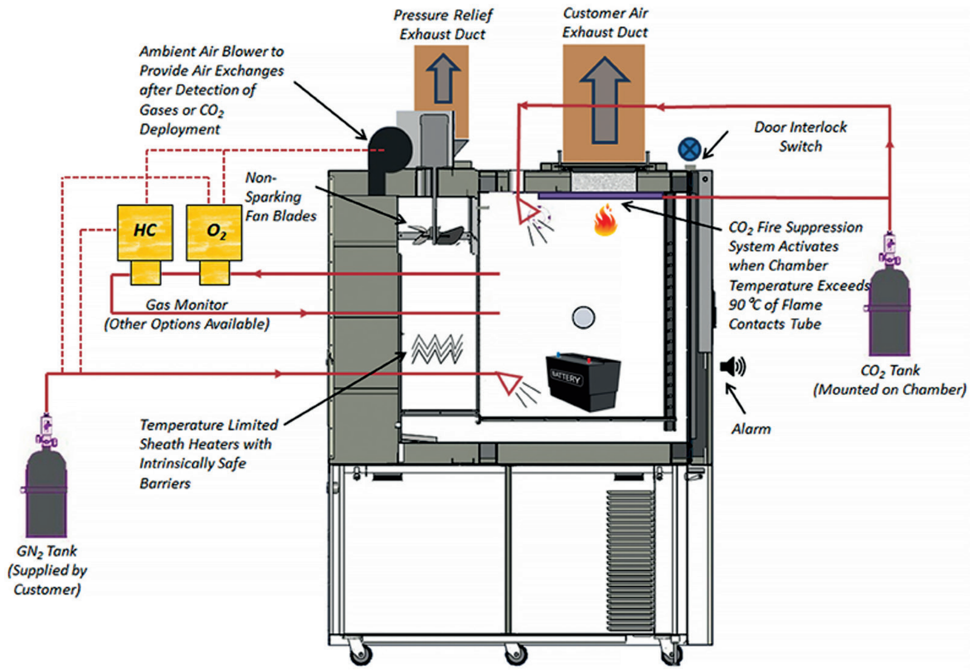

Figure 3
Battery Cell testing chamber features and options. Source: 'Environmental Chambers.'

Besides mitigating the safety risks, there are several other factors that should be considered in the selection of the right environmental test chamber. The questions are: "What type of control system will one need, and will it integrate with other equipment (like your cyclers)?"; and "What type of refrigeration system will be required?" A compressor system that controls the temperature down to –54 °C may be preferred over cascade systems due to energy savings. Also, make sure that your system is sized well to handle your extra heat load. The humidity requirements are also a key point of the chambers. The users must make sure it is included up front. During the test, engineers must be sure that the points of temperature and humidity are obtainable.[26]

It is a crucial aspect that in case of each battery, the manufacturer of the battery components evaluates their individual risks and failure modes (DFMEA or PFMEA). If the risk is unknown or difficult/impossible to define, it is necessary to design for the 'worst case' scenario. Based on this information the engineers can work with a chamber manufacturer to determine the proper safety requirements necessary in their application. The test engineers can provide feedbacks to the test chamber designers about the weakest or critical points of the chambers. Due to this continuous improvement, the reliability of the chambers can

[26] Ibid.

improve. In these years (2019), there are no available safety equipments, tools and battery chambers, as the risk may vary considerably by product design, build and battery chemistry.[27]

Both the design of the mechanical part of the measurement chamber design and the charge and discharge processes can be modelled and simulated using reference,[28] whilst the measurement environment (i.e. temperature, pressure, gas presence and its concentrate) inside the measurement chamber can be simulated using reference.[29]

6. Discussion and future work

The paper described the most important battery types of UGV and AGV systems. It introduced the most important battery properties, and gave a picture about the possibilities of State of Charge estimation. Regarding maintenance and management, a new operation management system is emerging, where more solution forms increase technical reliability. The developers and producers must provide opportunities to real time measuring systems and special test chambers.

The article introduces the most important standards about battery testing chambers and the most important risk aspects.

The latest or the best solution for developing and testing electric vehicle battery packs, cells and modules used in hybrid (HEV), plug-in hybrid (PHEV) and battery electric vehicles (BEV) is the modular EV battery test laboratory. The design of climatic battery test chamber meets all the requirements of module and full-size battery pack.[30]

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[27] Ibid.

[28] R. Szabolcsi, *Szabályozáselmélet* (Budapest: Óbudai Egyetem, 2019).

[29] R. Szabolcsi, *Irányítástechnikai rendszerek tervezése és vizsgálata MATLAB környezetben* (Budapest: Óbudai Egyetem, 2020).

[30] ‘Electric Vehicle.’

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