Fire Safety of Rechargeable Battery Energy Storage Systems: Present and Future Prospects

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ABSTRACT

The fire safety of the elements is determined by the various testing methods and procedures, which simulate the real world scenarios. Battery energy storage systems (BESS) continue to be developed and increased in size due to user demand. Simultaneously, European and global testing standards use test methods are not harmonized and use methodology of dubious accuracy and repeatability. In consequence, general concept of the fire safety in terms of battery energy storage systems can be advanced, especially under the circumstances the BESS fires are known for their high intensity, heat release, and inability to be efficiently doused. With exponentially increasing stock of the BESS in recent and upcoming years, the focus on the fire safety should be expanded. This paper aims to present the current state of testing methods in the field of fire resistance and mechanical failure of the BESS. The analysis will envelop multiple markets around the world and the major differences between them due to lack of harmonization, as well as evaluate the accuracy and repeatability of the selected method. Consequently, the article will present the future prospects and what can be done to ensure fire safety of the BESS using standardization.

INTRODUCTION

The battery energy storage systems (BESS) based on lithium ion batteries are largely used in the nowadays devices, since they offer numerous advantages compared to other battery technologies. These benefits include such characteristics as long life span (number of cycles), high energy and quick charge times. This advantages make the lithium-ion battery technology alluring for consumer products and power train applications [1, 2]. Simultaneously, Li-ion batteries are constructed from highly flammable and reactive compounds, thus with increasing popularity and size a safety concerns have been presented [3, 4].

BESS is required to tested before it can be sold to the end user. The regulations

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involve testing mechanical strength (e.g. resistance to vibrations, mechanical shock), electrical abuse (e.g. overcharge and overdischarge protection, short circuit), weathering tests (e.g. immersion under water, thermal shock cycling) and thermal abuse (e.g. resistance to external fire, thermal propagation) [5–15]. The main objective of this work is the investigation and model assessment of the BESS standards around the world in regards to fire resistance and mechanical shock failure. Subsequently, the paper presents the outlook for the future developments.

THE THERMAL ABUSE TEST METHODS

Testing standards and regulations for the thermal abuse were analysed for the largest BESS markets - United States: SAND2017-6925, SAE J2464, UL 1973-2022, China: GB 31467, GB 38031 and Europe: R100.03, ISO 6469-1, ISO 18243. The procedure comparison was made for the thermal abuse test methods, which are divided into 'exposure to fire' and 'thermal runaway propagation'. Testing methods were analysed in terms of their prerequisites to carry out the test (state of charge, specimen preparation) and exposure conditions - temperature, duration of the test, source of heat.

Exposure to fire or fuel fire test shown in SAND2017-6925, ISO 6469-1, ISO 18243, R100.03, GB 31467 and GB 38031 have the sample procedure consisting of four phases. The first is ignition of the gasoline 3 m away from the specimen and pre-heating it for 60 s, the second is placement of the specimen over the burning gasoline for 70 s, the third is covering the gasoline burning pool with refractory perforated board and indirectly burn the specimen for another 60 s and lastly the specimen is removed from the ignited gasoline (which is subsequently doused) and observed for up to 3 h for signs of explosion. The temperature above the gasoline pool fire was found to be between 400-900°C [16] without the specimen and with the specimen an average of 714° was recorded at the bottom surface [17, 18]. The procedures do not describe any requirements for the minimum or maximum temperature during the test. UL 19730-2022 also uses gasoline pool fire, however, with a duration time of exposition of 20 min. No temperature tolerances are required as well. SAND2017-6925 and SAE J2464 also provides alternative procedure with a specimen fixed inside a radiative heat chamber for 10 min. and exposed to a temperature of 890°C reached within 90 s. The required tolerance for the temperature is 5% (44.5°C). As for the acceptance criterion, the only defined in ISO 6469-1, ISO 18243, R100.03, UL 19730-2022, GB 31467 and GB 38031 is the specimen may not exhibit signs of explosion, that is defined as *"a sudden release of energy sufficient to cause pressure waves and/or projectiles that may cause structural and/or physical damage to the surrounding of the Tested-Device"*.

Second thermal abuse test carried out for BESS is thermal propagation test. During thermal propagation one cell of the module or pack is put in thermal runaway state either by mechanical short circuit (e.g. nail penetration), thermal (heated until the separator is melted) or electrical (single cell overcharge) [19,20]. SAE J2464 presents thermal propagation with thermal short circuit, where a single cell is heated up to 400°C. The specimen is observed then for 1 h in order to record whether thermal event will not propagate to adjacent cells. The specimen is required to be charged to 100% SOC and the BESS should be heated to the maximum operating temperature prior to the thermal runaway event. SAND2017-6925 has same procedure for thermal propagation as SAE J2464 with an exception of additional observation period that should last until the last thermal runaway event is recorded. UL 19730-2022 does not specify the thermal runaway start method and allows for continuous observation until the propagation has finished. R100.03 and GB 38031 allow for all three mentioned above thermal runaway initiation methods and require from the specimen to signal the alarm 5 min. before the propagation is started.

THE MECHANICAL SHOCK TEST METHODS

The mechanical shock testing procedures were under investigation from following standards and regulations - United States: SAE J2464, UL 2580-2020, China: GB 38031 and Europe: R100.03, ISO 6469-1, ISO 18243. Mechanical shock test is aimed to produce a force replicating a rapid deceleration of the BESS in case of accident, while not being directly in the crumple zone [21].

Analysed procedures define following parameters of the test: required acceleration, duration and form of the pulse, and number of shocks dependent on the axis of force. A comparison was made in Table I to represent the differences in test methods.

TABLE I. Comparison table of the mechanical shock parameters [6, 8, 9, 11, 12, 14].

	Acceleration	**Pulse duration**	**Pulse waveform**	**Axes**	**Total number of shocks**	**Criteria**
UL 2580-2020	25 g	15 ms	half-sine	3	18	No explosion or fire
SAE J2464	25 g	15 ms	half-sine	3	18	-
GB 38032-2020	7g	6 ms	half-sine	1	12	No explosion or fire
ISO 6469-1:2019	Z: 70, X: 50, Y: 30, m/s2	6 ms	half-sine	3	36	No explosion, fire, leakage or rupture
ISO 18243:2017	15g	6 ms	half-sine	3	18	No explosion, fire, leakage or rupture
R100.03	Up to 28g (curve based)	Up to 120 ms (curve based)	-	2	2	No explosion, fire or leakage

The mechanical shock methods can be differentiated mainly by the two parameters of the impulse - acceleration and duration. The highest acceleration can be found in the R100.03 test method, where the upper limit is defined by the 28 g (average shock of 24 g), seconded with UL 2580 and SAE J2464 with 25 g. The duration of the pulse is the longest in R100.03 (120 ms), followed by the UL 2580 and SAE J2464 (15 ms). For the all of the procedures except for R100.03, half-sine pulse waveform is required. R100.03 provides the minimum and maximum tolerances instead, where an acceleration peak is at 28 g, however, a half sine waveform is also fitting for given tolerances.

DISCUSSION AND COMPARISON OF THE THERMAL ABUSE TEST METHODS AND THE MECHANICAL SHOCK

Pool burning fires presented in SAND2017-6925, ISO 6469-1, ISO 18243, R100.03, GB 31467 and GB 38031 were evaluated with the following equation:

$$\dot{Q} = \dot{Q}_r + \dot{Q}_c - \dot{Q}_{rr} - \dot{Q}_{misc} \tag{1}$$

where $\dot{Q}_r$ is radiant flux, $\dot{Q}_c$ is a heat absorbed by convective means, $\dot{Q}_{rr}$ is re-radiant heat loss, as surface of the pool is at high temperatures and ultimately, $\dot{Q}_{misc}$ defines any other losses (i.e. conduction of the walls, stochastic terms). In this particular situation, it was assumed that dominant heat transfer was convective [22].

For the alternative procedure shown in SAND2017-6925 and SAE J2464 and the radiant heat flux was calculated with simplified equation, due to the specimen being sheltered from the convective heat transfer of the burner:

$$\dot{Q} \approx \dot{Q}_r \approx \sigma \epsilon A T^4 \tag{2}$$

where $\dot{Q}_r$ is radiant flux, σ is Stefan-Boltzman constant, A is a surface of the area and T is absolute temperature.

Comparison results were presented in Table II below:

TABLE II. Comparison table on the BESS fire testing procedures [8, 9, 11–13]

	Open flame procedure
Documents	R100.03, ISO 6469-1:2019, ISO 18243:2017
Source of heat	Petrol
Main heat transfer	Radiative/Convective
Temperature range	250-900°C
Temperature tolerance	None
Heat flux range	25-50 kW/m^2
Test length	130 seconds
Heat amount range	3.25-6.5 MJ/m^2
Temperature deviation	260%
Heat flux deviation	100%
	Radiative source procedure
Documents	SAND2017-6925:2017, SAE J2464:2009
Source of heat	Hot plate
Main heat transfer	Radiative
Temperature range	890°C
Temperature tolerance	5% (890±44.5°C)
Heat flux range	56-77 kW/m^2
Test length	600 seconds
Heat amount range	33.6-46.2 MJ/m^2
Temperature deviation	5%
Heat flux deviation	38%

The open flame testing procedure contain large temperature deviation (up to 260%) and in consequence - large heat flux deviation (up to 100%). In comparison, in the radiative source procedures, temperature and heat flux deviations are respectively 5% and 38%. This may result in open flame methods having varying amount of heat absorbed by the tested specimen. Due to the fact the specimen is required to be tested once, the test may be carried out in non-comparable exposure conditions for different specimens. The open flame procedures should be again evaluated and tested for consistency of the exposure conditions. This coincides with the previous research results found for the open flame testing [17, 18, 23].

TABLE III. Comparison table on the BESS mechanical shock procedures.

	UL 2580-2020	**SAE J2464**	**GB 38032-2020**	**ISO 6469-1:2019**	**ISO 18243:2017**	**R100.03**
Area under curve	499.4	499.4	55.6	56.6	119.2	1933.3

The mechanical shock was compared on the basis of area under the pulse curve. The area under curve of the pulse was calculated according to following equation:

$$\dot{A} = \int_{t_0}^{t_1} a(t)dt \tag{3}$$

where A is area under curve, a is acceleration and t is time.

Mechanical shock test methods vary in the area under curve (Table III). The overall shock during R100.03 procedure is 35 times larger than one encountered in GB 38032. Although the value of shock is associated with the mass of the specimen, the differences are still significant and call for harmonisation among the globe.

CONCLUDING REMARKS

The main objective of this work was to compare thermal abuse and mechanical shock test methods of the battery energy storage systems in terms of their consistency, accuracy and level of the exposure conditions, as well as intensity of the pulse shock. For evaluation following procedures were analysed - United States: SAND2017-6925, SAE J2464, UL 1973-2022, China: GB 31467, GB 38031 and Europe: R100.03, ISO 6469-1, ISO 18243.

Thermal abuse test methods based on open flame show large deviations in terms of temperature and heat flux (deviations of respectively 260% and 100%). This may impact the overall consistency of the tests, especially when a single test is required to be performed on the given sample.

Mechanical shock test methods also present significant variance in terms of intensity of the pulse. The R100.03 is by far the most demanding test method. GB 38032 and ISO 6469-1:2019 had the lowest pulses in terms of intensity among the analysed. Despite the fact the mass of the specimen is differentiated between the procedures, a global harmonisation of the standards and requirements can result in safer BESS.

ACKNOWLEDGMENT

The research was carried out within the fourth edition of the Program of the Polish Ministry of Science and Higher Education entitled ”Doktorat wdrożeniowy” (Industrial Doctoral Program).

Computations were carried out using the licences of Centre of Informatics Tricity Academic Supercomputer & Network.

REFERENCES

1. Manthiram, A. 2017. “An outlook on lithium ion battery technology,” *ACS central science*, 3(10):1063–1069.
2. Li, M., J. Lu, Z. Chen, and K. Amine. 2018. “30 years of lithium-ion batteries,” *Advanced Materials*, 30(33):1800561.
3. Yang, Y., S. Bremner, C. Menictas, and M. Kay. 2018. “Battery energy storage system size determination in renewable energy systems: A review,” *Renewable and Sustainable Energy Reviews*, 91:109–125.
4. IEA. 2020. “Global EV Outlook 2020,” Report, International Energy Agency, [Online; accessed 14 February 2022].
5. 2015. “Lithium-ion traction battery pack and system for electric vehicles—Part 3:Safety requirements and test methods,” Standard, Standardization Administration of the People’s Republic of China, Shenzhen, CN.
6. 2020. “Electric vehicles traction battery safety requirement,” Standard, Standardization Administration of the People’s Republic of China, Shenzhen, CN.
7. 2016. “Secondary lithium-ion cells for the propulsion of electric road vehicles - Part 3: Safety requirements,” Standard, The International Electrotechnical Commission, Geneva, CH.
8. 2017. “Electrically propelled mopeds and motorcycles — Test specifications and safety requirements for lithium-ion battery systems,” Standard, International Organization for Standardization, Geneva, CH.
9. 2019. “Electrically propelled road vehicles — Safety specifications — Part 1: Rechargeable energy storage system (RESS),” Standard, International Organization for Standardization, Geneva, CH.
10. 2013. “Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train,” Regulation, European Union.
11. 2021. “Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train,” Regulation, European Union.
12. 2009. “Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing,” Standard, Society of Automotive Engineers, Warrendale, US.
13. 2017. “Recommended Practices for Abuse Testing Rechargeable Energy Storage Systems (RESSs),” Standard, Sandia National Laboratories, Albuquerque, US.
14. 2020. “Batteries for Use In Electric Vehicles,” Standard, Underwriters Laboratories, Northbrook, US.
15. 2022. “Batteries for Use in Stationary and Motive Auxiliary Power Applications,” Standard, Underwriters Laboratories, Northbrook, US.
16. for Europe of the United Nations, E. C. 2016. “Global Technical Regulation on the Electric Vehicle Safety (EVS),” Regulation.
17. Darnikowski, D., M. Mieloszyk, and M. Weryk. 2022. “Fire resistance of construction elements,” in *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2022*, SPIE, vol. 12046, pp. 203–218.
18. Darnikowski, D. and M. Mieloszyk. 2021. “Investigation into the Lithium-Ion Battery Fire Resistance Testing Procedure for Commercial Use,” *Batteries*, 7(3), ISSN 2313-0105, doi: 10.3390/batteries7030044.
19. Feng, X., M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He. 2018. “Thermal runaway mechanism of lithium ion battery for electric vehicles: A review,” *Energy Storage Materials*, 10:246–267, ISSN 2405-8297, doi:https://doi.org/10.1016/j.ensm.2017.05.013.
20. Li, H., Q. Duan, C. Zhao, Z. Huang, and Q. Wang. 2019. “Experimental investigation

on the thermal runaway and its propagation in the large format battery module with Li (Ni1/3Co1/3Mn1/3) O2 as cathode," *Journal of hazardous materials*, 375:241–254.

21. Zhao, Z., H. Hu, Z. He, H. Zhu, P. Davari, and F. Blaabjerg. 2023. "Advanced solid-state lithium battery and its safety," *CPSS Transactions on Power Electronics and Applications*.
22. Heskestad, G. 2002. "Fire Plumes, Flame Height and Air Entrainment," in P. DiNenno and C. Beyler, eds., *SFPE Handbook of Fire Protection Engineering*, NFPA, pp. 2–1–2–17.
23. Darnikowski, D. 2022. "Fire resistance test methods of battery energy storage systems (BESS): analysis, comparison and prospects," in M. Mieloszyk and T. Ochrymiuk, eds., *Selected Problems in Mechanical Engineering 2022*, Wydawnictwo Instytutu Maszyn Przepływowych PAN, Gdansk, Poland, 1 edn., ISBN 978-83-66928-09-1.