Associate prof. Lazarenko Oleksandr Ph.D., Loik Vasyl Ph.D.

Lviv State University of Life Safety, Ukraine

RESEARCH FIRE HAZARD OF SUPPLY POWER ELEMENTS IN ACCUMULATOR BATTERY OF ELECTRIC CARS

ИССЛЕДОВАНИЯ ПОЖАРНОЙ ОПАСНОСТИ ЭЛЕМЕНТОВ ПИТАНИЯ АККУМУЛЯТОРНЫХ БАТАРЕЙ ЭЛЕКТРОМОБИЛЕЙ

NIEBEZPIECZEŃSTWO POŻARU BADANIA ELEMENTÓW SILNIKÓW ELEKTRYCZNYCH ZASILAJĄCYCH ZASILACZA

**ABSTRACT**

**Goal:** Carry out an analysis of the latest research in the field of fire hazard lithium-ion cells, which used in accumulator batteries of electric cars. Proceeding from the obtained results of the research, to determine the direction of the subsequent research in the field of fire safety of lithium-ion accumulator batteries of electric cars.

**Methods:** This work based on the fundamental research of scientists from the US, China and other countries of the world, the results of which were presented in a variety of world scientific journals, conferences and national reports.

Results: An analysis of literature sources has shown that research in the field of fire safety of lithium-ion batteries is carried out around the world, as this technical device is constantly being modified and improved, which dictated by today's realities.

The obtained research results show that the elementary lithium-ion cell during combustion contributes to the production of 6 to 10 kW of energy and a rather large number of dangerous combustion products, especially HF, POF3. Furthermore, the shown research results unequivocally confirm that the amount of energy released by the lithium-ion battery depends on the degree of its charge. Based on the results of full-scale experiments, the average amount of water necessary to extinguish the battery of an electric car varies from 2500 to 6000 litres, which can exceed the amount of water carried by a single fire truck.

**Conclusions:** Subsequent work to research the fire safety of electric car accumulators and their supply elements can be devoted to conducting full-scale experiments on the extinguishing of real consumer electric cars. Followed by an assessment of the problems of access to batteries and the difficulty of their extinguishing, the risk of electric shock from the battery of an electric car, possibility of using various extinguishing media. It is also very urgent to develop a mathematical model for the heating of a lithium-ion battery that takes into account the geometric shape of the element and its chemical composition.

**Keywords:** lithium-ion battery, electric car battery, electric car fire hazard, extinguishing of electric car

**Article type:** overview

**АННОТАЦИЯ**

**Цель:** Провести анализ последних исследований в области пожарной опасности литий-ионных элементов питания, которые используются в аккумуляторных батареях электрокаров. Исходя из полученных результатов исследований определить направления последующих исследований в области пожарной безопасности литий-ионных элементов питания и аккумуляторных батарей электрокаров.

**Методы:** Данная работа основывались на фундаментальных исследованиях ученых США, Китая и других стран мира, результаты которых были представлены в разнообразных мировых научных журналах, конференциях и национальных докладах.

Результаты: Проведенный анализ литературных источников показал, что исследования в области пожарной безопасности литий-ионных элементов питания проводятся по всему миру, поскольку данное техническое приспособление постоянно модифицируется и усовершенствуется, что по большее мере продиктовано сегодняшними реалиями.

Полученные результаты исследований показывают, что элементарный литий-ионный элемент питания вовремя горения способен продуцировать от 6 до 10 кВт энергии и довольно большое количество опасных продуктов горения, особенно HF, POF3. Также показанные результаты исследований однозначно подтверждают, что количество выделяемой энергии литий-ионным элементом питания напрямую зависит от степени его заряда. Исходя из результатов полномасштабных экспериментов среднее количество воды необходимое для тушения аккумуляторной батареи электрокара колеблется от 2500 до 6000 л, что может превышать объем вывозимой воды одним пожарным автомобилем.

Выводы: Последующие работы по исследованию пожарной безопасности аккумуляторных батарей электрокаров и элементов их питания могут быть посвящены проведению полномасштабных экспериментов пожаротушения реальных потребительских электрокаров с последующей оценкой проблем доступа к аккумуляторным батареям и сложности их тушения водой, опасности поражения личного состава электрическим током от аккумуляторной батареи электрокара, эффективности тушения аккумуляторных батарей с использованием различных огнетушащих средств. Также весьма актуальной остается задача разработки математической модели процесса нагрева литий-ионного элемента питания которая учитывала бы геометрическую форму элемента питания и его химический состав.

**Ключевые слова:** литий-ионный элемент питания, аккумуляторная батарея электрокара, пожарная опасность электромобиля, тушения электромобиля

**Вид статьи:** обзорная

**ABSTRACT**

**Cel:** Przeprowadzenie analizy najnowszych badań w zakresie akumulatorów litowo-jonowych pożarowych, stosowanych w akumulatorach samochodowych. Na podstawie uzyskanych wyników badań ustalono kierunek dalszych badań w zakresie bezpieczeństwa przeciwpożarowego akumulatorów litowo-jonowych i akumulatorów samochodowych.

**Metody:** Praca została oparta na podstawowych badaniach naukowców z USA, Chin i innych krajów świata, których wyniki zostały przedstawione w różnych światowych czasopismach naukowych, konferencjach i raportach krajowych.

**Wyniki:** Analiza literatury wskazuje, że badania w zakresie bezpieczeństwa pożarowego akumulatory litowo-jonowe odbywają się na całym świecie, jak to urządzenie techniczne jest stale modyfikowane i doskonalone, co najwyżej jest podyktowana realiami dzisiejszego.

Uzyskane wyniki badań pokazują, że elementarna bateria litowo-jonowa może wytwarzać od 6 do 10 kW energii i dość dużą ilość niebezpiecznych produktów spalania, zwłaszcza HF, POF3, podczas spalania. Ponadto przedstawione wyniki badań jednoznacznie potwierdzają, że ilość energii uwalnianej przez baterię litowo-jonową zależy bezpośrednio od stopnia jej naładowania. Opierając się na wynikach badań w pełnej skali, średnia ilość wody potrzebnej do gaszenia baterii akumulatora elektrycznego waha się od 2500 do 6000 litrów, który może przekroczyć ilości wody eksportowane jednym pożarze samochodu.

**Wnioski:** Dalsze prace nad studium baterii bezpieczeństwa pożarowego samochodów elektrycznych i elementów ich mocy, mogą być dedykowane do eksperymentów na pełną skalę gaśniczych pojazdów elektrycznych prawdziwy konsumenckich, a następnie oceny problemów związanych z dostępem do baterii i złożoności ich wody gaśniczej, ryzyko personelu prądu elektrycznego z baterii akumulatorów pojazdów elektrycznych, skuteczność gaszenia akumulatorów za pomocą różnych środków gaśniczych. Jest również bardzo pilne opracowanie modelu matematycznego do ogrzewania akumulatora litowo-jonowego, który uwzględnia kształt geometryczny elementu i jego skład chemiczny.

**Słowa kluczowe:** bateria litowo-jonowa, akumulator samochodowy elektryczny, zagrożenie pożarowe samochodu elektrycznego, gaszenie pojazdów elektrycznych

**Rodzaj artykułu:** przegląd

Introduction

The development of modern technologies provides great advantages to humanity even if we consider a short time span of 10 to 20 years, which, as a rule, make our world better and perfect. However, very often novelties of technical progress fail, especially at the primary stages of operation, which may entail a series of problems and dangers threatening the emergence of emergencies.

Recently, humankind began to think about alternative sources of energy that can replace hydrocarbon fuels. One of such striking examples is the rapid growth and development of electric and hybrid electric vehicles, which in the near future must replace cars on internal combustion engines [1]. Simultaneously with the advent of new technologies, the number of threats and dangers to which emergency rescue units should respond are also grows. Electric vehicles represent a similar danger today. Constant changes in the configuration of the placement of batteries in cars, the chemical composition of batteries and their capacity dictate the specifics of conducting firefighting tactics and carrying out emergency rescue operations in electric vehicles [2, 3]. The safety of firefighters and other emergency services depends on understanding and proper management of these hazards through proper training and learning.

Formulation of the problem

Considering the modern design of the electric vehicle, and based on research [4], it can be argued that the main danger both in terms of fire safety and safety of the rescue works, in this mode of transport, is in high-capacity batteries (about 24 to 85 kW/hours and more, depending on the model of the car).

The main manufacturers of electric cars (Nissan, Tesla, Mitsubishi, Ford, etc.), in the design of accumulator batteries, use lithium-ion supply power elements which differ only in the type of elements (Fig.1.) and their distribution in the accumulator battery itself.

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| *a) Example of 18650 cylindrical cells (18* х *65 мм)* | *b) Example of a hard case prismatic cell* | *c) Example of a soft-pouch polymer cell* |
| Figure.1. Example of supply power elements in accumulator batteries of electric cars | | |

In this case, it is worth to mention that the most common batteries today are cylindrical (Fig.1.a), which used, in particular, in Tesla's electric cars and soft-pouch polymer cell (Fig.1.c), which are widely used by other automakers, such as Nissan.

To obtain the required capacity of the electric car battery and protect the battery itself from the mechanical damage, the battery cells are placing in metal blocks. For example, the Nissan Leaf battery consists of 48 aluminium blocks (each has four packaged polymer batteries), and in the Tesla Model S, there are 16 blocks (444 elements of the 18650 type are installed in each). [5].

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| *a)* *accumulator battery of* *Nissan Leaf* | *b) accumulator battery of Tesla Model S* |
| Figure.2. Example of the distribution of supply power elements in accumulator battery of electric cars of different manufacturers | |

Lithium-ion batteries have a number of advantages, for example, long service life and the ability to quickly charge. However, along with the great advantages of lithium-ion batteries, there are numbers of drawbacks that carry a potential hazards risk both to the vehicle as well as to humans.

Since the electrolyte located in the middle of the cell is combustible, he can cause an irreversible thermal reaction, which subsequently leads to the release of flammable and toxic gases, and in some cases, the explosion of the battery [6, 9-15]. An irreversible thermal reaction can occur in the event of a disturbance of the stable mode of the battery mode of work and the next reasons can cause this:

1. Short circuit;
2. Overheating;
3. Overcharge;
4. Mechanical damage.

Accordingly, with the foregoing, the purpose of this paper is to analyze the current scientific results in the field of fire safety with respect to the supply power elements in accumulator battery of electric cars.

Main scientific results

In order for the lithium-ion battery to become a source of ignition, it is necessary to have three components: oxygen, ignition source and fuel.

In work [6], in detail was described the process during which, with temperatures of 170 °C and 74 °C, a positive electrode Li0,5CoO2 and a negative electrode Li0,86C6, respectively, decompose and release oxygen products and a large amount of exothermic heat which are contributed to the combustion triangle.

Additionally, on the basis of the theory of Semenov [7, 8], it was calculated by the authors that when the temperature of the cell is raised above 65.5 °C, there is an acceleration of the occurrence of thermochemical reactions which can lead to an irreversible ignition process. Upon reaching, a temperature of 75 °C there is a point of no return and the subsequent ignition of the battery happen. The general process of ignition and, as a consequence, the emergence of the chain reaction of the "domino effect", according to the authors this process could be described in following way Fig. 3.

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| Figure.3. Domino effect of lithium ion battery fire and explosion [5] |

During the course of the thermochemical reaction, a significant amount of thermal energy and hazardous combustion products released from the lithium-ion power element. These quantities were studied and measured in detail in the following research papers [9-16].

The authors of [9] investigated the order of nine different supply elements among which the greatest attention was paid to cylindrical cells 18650 and soft-pouch polymer cell. The experiment was conducted on the submitted power elements, in order to determine the amount of released energy using a calorimeter which operating on the principle of oxygen consumption. In these tests, the batteries were exposed to a radiant heat flux from 10 to 75 kW/m2. Batteries with different state of charge from 20 to 100% were tested, which also influenced the results of the research.

As a result of the studies, the following data were obtained for batteries of the form 18650 Fig. 4.

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| *a) The HOC and PHRR vs. SOC for a lithium-ion 18650 at a heat flux of 50 kW/m2* | *b) Maximum surface temperatures of 18650 lithium-ion cell at failure vs. SOC* |
| Figure. 4. Results of studies to determine the dangers of lithium-ion batteries 18650 [9] | |

The results of studies for soft-pouch polymer cell were obtained only at a charge value of 50%, where the average value of the HRR was 6.1 kW.

In the studies [10], a number of experiments were carried out to determine the temperature of the batteries of type 18650, depending on the SOC and the type of power elements. For experiments, two options for stacking the batteries were chosen - vertical and horizontal (Fig.5.). In each of the stacking options, a single cell was placed and heated by connecting to an electrical transformer, and this served as a heat source for another active cell. The rest of the batteries were just an imitation, but at the same time, they were the closest thing to an active cell with built-in thermal sensors.

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| 1. *horizontal or hexagonal* | 1. *vertically* |
| **Figure. 5**. Example of placement of batteries type 18650 [10] | |

As mentioned, the experiment was also carried out at a different SOC of the active cell: 30%, 100% and more than 100%. The following results were obtained (Table 1), where: - the surface temperature of the active cell,  - the average temperature of the adjacent imitation cells.

Table 1

The results of research, depending on the SOC of the battery and their packing [10]

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| --- | --- | --- |
| SOC | Horizontal  placement of batteries | Vertically placement of batteries |
| 30% | = 126 0С  = 148-236 0С | = 127 0С  = 70-75 0С |
| 100% | = 130 0С  = 155-2310С – for elements 2, 3, 4;  = 250-4180С – for elements 1, 5. | = 129 0С  = 64-68 0С |
| > 100% | = 141 0С  = 114-259 0С | = 107 0С  = 805 0С – maximum temperature.  = 91-1090С – for element 1;  = 89-960С – for element 2. |

It worth to mention that when the charge of the active cell was 100% or more when critical temperatures were reached, abundant spark and gas emission were observed, which become a signal for completing the experiment.

In addition, worthy of attention is the paper [11] in which the authors carried out a series of experiments, similar to the previous work, with several power cells (5 pieces) of the 18650 type. During the experiment, the amount of heat, the type and amount of hazardous gases releasing during there burning depending on the state of their charge were determined.

The results of the experiment showed that the HRR depends directly on the SOC of the battery Fig.6.

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| Figure.6. The magnitude of the HRR for the five power elements, depending on their SOC (0% - 100%) [11] |

As mentioned, not only a significant amount of heat but also significant amounts of toxic combustion products were released in the result of combustion of lithium-ion batteries, among which the authors [11] isolated hydrogen fluoride (HF) and phosphorus oxyfluoride (POF3). However, because of the accuracy of equipment, the authors failed to measure the concentration and magnitude of POF3, and the production rate of HF depicted in Fig.7.

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| Figure.7. The production rate of hydrogen fluoride (HF) for five cells, depending on the SOC (0% - 100%) during their burning [11] |

It is important to note that the rate of HF release is much higher with SOC of a battery 50%, and at 100%, the indices are the least.

The results of the research presented above relate only to separate battery cells, but as mentioned earlier, the accumulator battery of the electric car consists of 192 - 7000 thousand such elements (depending on the car brand). Such a number of batteries cells, based on the results presented earlier, during the fire should allocate an extremely large amount of energy, and if we consider this type of fire from the tactics of its suppression, then a huge amount of fire extinguishing agent will be necessary for extinguishing.

As a result to the full-scale testing fire experiment [12, 13], which was aimed to determine the amount of heat released, during the combustion of a real battery and the tactics of its suppression, unique results are available to us.

Two types of batteries were taken for the experiment. The battery "A" intended for hybrid cars, which contains sealed lithium-ion rechargeable batteries. The accumulator battery with a capacity of 4.4 kWh enclosed in a metal case and rigidly mounting at the bottom of the rear cargo area behind the rear seat, Fig. 7a. The metal case is isolated from high voltage, hidden and separated from the passenger compartment by a moulded plastic cover with carpet covering. The electrolyte used in lithium-ion batteries is a flammable organic electrolyte.

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| a) Accumulator battery type "A" | b) Accumulator battery type "B" |
| Figure. 7. An example of accumulator batteries for carrying out full-scale fire experiments [12] | |

The battery "B" intended for electric cars with a capacity of 16 kWh and enclosed in a casing made of fibreglass. The T-shaped form of the battery covers almost the entire length of the vehicle from the rear axle to the front axle and rigidly mounting under the car's pallet. Fig. 7 b.

The first stage of the experiment was aimed to determine, the amount of heat that the battery "B" released, the battery was pre-heated from a third-party heat source (propane burners) with a capacity of approximately 400 kW.

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| Figure.8. The results of experiments to determine the amount of heat during the combustion of an accumulator battery type"B" [13] |

Temperature and heat flux measurements were recorded on the outer and inner sides of the battery, as well as at a distance of 1.5 and 3 meters from the battery. Gas samples were collected for analysis for toxic or corrosive compounds. The experiment was considered complete after a complete burnout of the battery without assistance.

The maximum value of the HRR was 300 kW (when the propane burner power was subtracted) with a test time of 17 minutes and 30 seconds, and the case temperature from 684 to 1155 °C. The maximum temperature at a distance of 1.5 and 3 meters from the battery was 94 - 110 °C and 41 - 52 °C, respectively. At the same time, the maximum value of thermal radiation at a similar distance was from 17.1 to 18 kW/m2 and 3.7 to 4.7 kW/m2.

After the burners were switched off, approximately 20 minutes later the values of the thermal radiation gradually decreased, after the 36-minute mark, the flame decreased significantly, and the value of the thermal radiation was practically zero.

Small local fires on the battery continued for about another hour. When the apparent burning stopped, the external maximum temperature of the battery was approximately 400 °C. After another three hours, the maximum temperature was about 155 °C.

Moreover, during the first stage of the study, fourteen samples of combustion products using Tedlar bags were taken. Sampling was carried out every 5 minutes, starting with 5 minutes of testing. The bags were analyzed for HCl, HF, HBr, HCN, CO2, CO, NOx, SO2, acrolein and formaldehyde using an infrared Fourier transform spectrometer. The results showed only the presence of CO and CO2. Each spectrum was directly examined for the presence of HCN and HF, but they were not detected. However, the authors acknowledge that during the tests there could be some error that affected the final results.

In the second stage of the research, full-scale studies were carried out whose main task was to determine the amount of time and the extinguishing agent (water) which will be necessary for suppression fire in the batteries "A" and "B". At the same time, the conditions for placing the batteries were as close as possible to the real ones:

• the battery was placed in the body of the car;

• the battery was additionally covered with a metal protective sheet;

• the interior of the car was additionally fitted with decorative elements.

The results of the tests presented in Table 2.

Table 2

The total results of the amount of water expended during the extinguishing of the batteries in the car [13]

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| --- | --- | --- | --- | --- |
| Battery type / test series | Operation Time, minutes | Water flow time, minutes | Total water flow, litres | Comments |
| А1 | 5.88 | 2.20 | 1040 | Battery only |
| А2 | 36.60 | 3.53 | 1673 | Battery only |
| А3 | 49.67 | 9.77 | 4012 | Battery + Interior Components |
| В1 | 26.52 | 14.03 | 6639 | Battery only |
| В2 | 37.60 | 21.37 | 9989 | Battery only |
| В3\* | 13.88 | 9.32 | 4410 | Battery + Interior Components |

\* Suppression times and water flow times influenced by the previous experience of one of the firefighters, who extinguished the Test B2 battery fire the previous day. This firefighter acknowledged that he had gained knowledge on the best and most appropriate way to access the battery below the floor pan during the previous test.

Similarly, with the first stage during the second stage, the value of the thermal radiation was measured at a distance of 1.5 meters and thus amounted to 2.1-3.7 kW/m2 (during the burning of one battery) and 8.1-11.9 kW/m2 (during the burning of the battery with decor elements).

After the termination of each variant of the extinguishing of storage batteries, water samples for the subsequent analysis for the presence of harmful substances were taken. Samples of water collected during the tests indicate the presence of chloride and fluoride (probably in the form of HF and hydrogen chloride HCl). However, the chloride concentration in the solution was only 2-3 times higher than the normal detection levels, while the fluoride concentration was more than 100 times higher. No other corrosive or toxic compounds were found in water samples.

Discussion of the results

The results of researches concerning lithium-ion cells of accumulator batteries received to date, give us a clear understanding that this technical device, simultaneously with a positive effect, is a great danger for humanity.

The obtained research results show that the elementary lithium-ion cell can produce from 6 to 10 kW of energy and a rather large amount of dangerous combustion products, especially HF, POF3, during the combustion, although the latter statement requires further studies. Additionally, the shown research results unequivocally confirm that the amount of energy and hazard gases released by the lithium-ion battery depends directly on the degree of its charge.

Full-scale testing results on the investigation of the tactics of extinguishing electric car batteries showed unexpected result regarding the amount of water necessary to extinguish such a fire. Based on the results of the experiment, the average amount of water needed to extinguish such ignition varies from 2,500 to 6,000 litres, which may exceed the volume of water taken by one fire truck. Thus, there will be an urgent need to improve the tactics of extinguishing such fires and training personnel.

In connection with the continuous development and improvement of technologies, the results presented will differ from new types of batteries [16-18], therefore, there will always be a need to conduct additional studies in this direction.

Conclusions

Based on the above research results, it is possible to outline the following topics of work in this direction:

• Conduct a full-scale firefighting test of real consumer electric cars to assess the problems of access to batteries and the complexity of their water quenching;

• Carry out a full-scale firefighting test of real consumer electric cars to assess the risk of electric shock to personnel from the electric car battery;

• Carry out full-scale testing of firefighting of real consumer electric cars with batteries of other types, for example, 18650;

• To develop alternative versions of fire barrels for extinguishing electric car batteries;

• assess the efficiency of extinguishing the batteries using other extinguishing agents.

It is also very urgent to develop a mathematical model for the heating of a lithium-ion battery that takes into account the geometric shape of the element and its chemical composition. The development of such a mathematical model would later enable the calculations to be made to determine the necessary temperature and heat quantity, without the need for costly experiments and for a variety of new battery options.

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LIST OF ACRONYMS

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| --- | --- |
| HOC | Heat of combustion |
| HRR | Heat release rate |
| PHRR | Peak heat release rate |
| SOC | State of charge |

BIOGRAPHIC INFORMATION ABOUT AUTHORS:

Lazarenko Oleksandr – Associate Professor of the Department of Fire Tactics and Emergency Rescue Operations of the Lviv State University for Safety of Life, Ph.D, Associate Professor. Sphere of scientific interests: development of methods for extinguishing fires at various sites, methods for training firefighters, studying heat and mass transfer processes during a fire and protection against thermal radiation.

Department of Fire Tactics and Rescue Works

Lviv State University of Life Safety

Kleparivska str., 35, Lviv, Ukraine, 79007

Contact tel.: 098-575-96-43

E-mail: [lazarenkoolexandr@gmail.com](mailto:lazarenkoolexandr@gmail.com)

Loik Vasyl – Associate Professor of the Department of Fire Tactics and Emergency Rescue Operations of the Lviv State University for Safety of Life, Ph.D. Sphere of scientific interests: development of techniques for emergency rescue operations during the elimination of man-made accidents, development of mathematical models for heat and mass transfer during a fire, development of substances to protect building structures from exposure to high temperatures during a fire.

Department of Fire Tactics and Rescue Works

Lviv State University of Life Safety

Kleparivska str., 35, Lviv, Ukraine, 79007

Contact tel.: 067-994-58-48

E-mail: [v.loik1984@gmail.com](mailto:v.loik1984@gmail.com)