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Assessment of production factors in the manufacturing of lithium-ion batteries: case study of Gelon LIB equipment

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Abstract. The production of lithium-ion batteries (LIBs) is associated with a complex of hazardous factors at all technological stages. Existing studies are often fragmented and do not offer a holistic risk management system, which highlights the need to develop a comprehensive approach to ensuring safety and efficiency. The aim of this work is a systematic analysis of production risks at all stages of LIB manufacturing and the development of practical recommendations for creating an effective safety system, including technical, organizational, and personnel aspects. The research is based on a systematic analysis of the LIB production technological process. Methods of risk analysis, comparative assessment of manual and automated operations, and analysis of the technical characteristics of specialized equipment were used. The results are structured in the form of detailed risk assessment tables for each stage. Key hazards were identified and ranked: toxicity of chemical components (especially $LiPF_6$-based electrolyte), fire and explosion risks, nanoparticle exposure, and mechanical injuries. It has been established that the most hazardous operations involve the electrolyte, ultrasonic welding, and drying. A significant reduction in the risk of injuries and production defects during the transition from manual to automated assembly has been proven. Specific protective measures have been developed and systematized: engineering solutions (ventilation, interlocks), personal protective equipment (PPE) requirements, microclimate parameters, training programs, and the need for real-time monitoring systems. This article proposes a holistic, step-by-step approach to risk management in LIB production. The main conclusion is that safety and economic efficiency are achieved through a systematic combination of maximum automation of critical operations, implementation of multi-level monitoring, and comprehensive personnel protection. The presented recommendations form a ready-made basis for designing safe production lines.

Keywords: production risks; automation of production; labor protection; toxicology

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original draft preparation. *E.Yu. Evshchik* — data administration, scientific supervision of the research, manuscript writing. All authors have read and approved the final version of the manuscript.

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Оценка производственных факторов при изготовлении литий-ионных аккумуляторов на примере оборудования фирмы Gelon LIB

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Аннотация. Производство литий-ионных аккумуляторов (ЛИА) сопряжено с комплексом опасных факторов на всех технологических этапах. Существующие исследования часто фрагментарны и не предлагают целостной системы управления рисками, что актуализирует разработку комплексного подхода к обеспечению безопасности и эффективности. Цель исследования — системный анализ производственных рисков на всех этапах изготовления ЛИА, а также разработка практических рекомендаций по созданию эффективной системы безопасности, включающей технические, организационные и кадровые аспекты. Исследование основано на системном анализе технологического процесса производства ЛИА. Использованы методы анализа рисков, сравнительная оценка ручных и автоматизированных операций, анализ технических характеристик специализированного оборудования. Результаты структурированы в виде детализированных таблиц оценки рисков для каждого этапа. Выявлены и ранжированы ключевые опасности: токсичность химических компонентов (особенно электролита на основе $LiPF_6$), пожаро-взрывные риски, воздействие наночастиц и механические травмы. Установлено, что наиболее опасными являются операции с электролитом, ультразвуковой сваркой и сушкой. Доказано значительное снижение риска травматизма и производственного брака при переходе от ручной к автоматизированной сборке. Разработаны и систематизированы конкретные защитные меры: инженерные решения (вентиляция, блокировки), требования к СИЗ, параметры микроклимата, программы обучения и необходимость внедрения систем реального времени. Предложен целостный, поэтапный подход к управлению рисками в производстве ЛИА. Основной вывод заключается в том, что безопасность и экономическая эффективность достигаются через системную комбинацию максимальной автоматизации критических операций, внедрения многоуровневого мониторинга и комплексной защиты персонала. Представленные рекомендации формируют готовую основу для проектирования безопасных производственных линий.

Ключевые слова: производственные риски; автоматизация производства; охрана труда; токсикология

Вклад авторов. *Ахтямов Р.Г.* — концептуализация, разработка методологии исследования, написание рукописи. *Шиховцева А.В., Калугин Л.Е.* — курирование данных, написание и подготовка черновика рукописи. *Евщик Е.Ю.* — администрирование данных, научное руководство исследованием, написание рукописи. Все авторы ознакомлены с окончательной версией статьи и одобрили ее.

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Introduction

Modern lithium-ion batteries (LIB) are a key component of next generation energy systems [1]. Optimizing the LIB production process in terms of safety [4], cost-effectiveness [5] and environmental sustainability [6] is particularly important, requiring a comprehensive and detailed analysis of each step [7]. The production of LIB is a multi-stage process with risks: chemical hazard of components, fire and explosion hazards, mechanical injuries, exposure to nanoparticles [4, 8–13].

Existing studies are often fragmented and do not offer a holistic risk management system for all technological stages [14–19]. The introduction of automatisation to minimize the human factor is of particular importance [20].

However, the approaches proposed in most existing papers often focus either on a limited list of technological stages [4, 8–13], or on individual safety aspects [14–19], without integration into a single multi-level management system. The paper [21] describes a risk management system for all stages of the process but does not include a detailed analysis of each stage in the production of a lithium-ion battery taking into account all possible risk factors. Thus, unlike the published papers, this study offers a cross-sectional step-by-step analysis of the entire supply chain, which allows for the identification of interlinkages between risks at different stages and the development of measures to minimize them. This work thus fills the gap between fragmentary hazard assessments and a comprehensive risk management system that is suitable for direct implementation in real-world battery production.

The aim of the study is to provide a comprehensive analysis of production risks at all stages of LIB manufacturing and to develop practical recommendations for creating an effective safety system.

Research methods

The methodology is based on a systematic analysis of the technological process of LIB production. Methods of risk analysis, comparative assessment of manual and automated operations, analysis of technical characteristics of specialized equipment on the example of Gelon LIB equipment were used. The process included key steps: preparation of the electrode mixtures, manufacture of the electrode, stack assembly and battery. Detailed description of the stages of production of LIB is provided in additional materials.

Results

The greatest risks during the preparation of an electrical mixture are dust and chemical factors, as well as the risk of mechanical injury (Table 1).

Based on the results of the evaluation, risk reduction measures have been developed, including local ventilation systems, PPE (respirators FFP2/FFP3, chemically resistant gloves), earthing, locking, parameter control. Ensuring a safe working environment requires strict individual and collective protection measures, monitoring of the operating environment and regular training of staff. Implementation of the proposed recommendations will minimize professional risks, reduce the likelihood of accidents and ensure stable quality of products.

In the electrode manufacturing phase, the greatest risks are mechanical injuries caused by rolling and cutting devices, thermal burns during drying (~120°C), exposure to solvent evaporation (Table 2). Proposed key protection measures include safety fences and locks, ventilation, heat-resistant gloves and FFP3 respirators, and vibration insulation.

The electrode manufacturing process is thus characterized by a complex of hazardous factors, among which mechanical and thermal risks as well as exposure to harmful substances are the most significant. Special attention should be paid to collective protection equipment and the provision of quality personal protective equipment for workers. Regular monitoring of equipment and training activities for personnel are mandatory conditions to maintain a safe production process.

Table 1. **The electrode mixture preparation: results of the production factor assessment and risk mitigation measures**

Risk factor	Source	Possible consequences	Risk reduction measures
Weighing of components (scales)			
Air dustiness	Graphite, acetylene black, mixed lithium oxides	Irritation to respiratory tract, risk of explosion (soot)	Use of exhaust ventilation, PPE (respirator, gloves)
Skin contact	CMC, SBR, PVDF, NMP	Skin irritation, allergic reactions	Use of special clothing and gloves
Static electricity	Dry powders (graphite, soot)	Sparking, risk of fire	Equipment grounding, antistatic treatment
Loading components into the mixer (planetary vacuum mixer GN-PM-5L)			
Mechanical injury	Working with a mixer	Pinching, hands caught in moving parts	Locking the lid during operation, training, instructions
Dust emission	Filling with dry components	Air pollution, explosion hazard	Vacuum dust removal, local ventilation
Stirring for several hours			
Noise	Mixer operation	Hearing impairment with prolonged exposure	Using noise-canceling headphones
Vibration	Movement of mixer mechanisms	Discomfort, operator fatigue	Equipment condition monitoring, vibration isolation
Heating the mixture	Friction of components	Change in reagent properties, risk of overheating	Temperature control, mixing time limitation
Control of the viscosity of the electrode mixture (viscometer)			
Contact with chemicals	Mixture samples	Irritation of skin and/or mucous membranes	Use of gloves and glasses
Measurement errors	Incorrect calibration	Product defect	Regular inspection of equipment

Source: compiled by R.G. Akhtyamov, A.V. Shikhovtseva, L.E. Kalugin, E.Yu. Evshchik.

Table 2. **The electrode manufacturing: results of the assessment of production factors and risk mitigation measures**

Risk factor	Source	Possible consequences	Risk reduction measures
Installing a foil roll into the electrode mixture application machine (GN-C300 electrode mixture application and drying device)			
Mechanical injury	Working with foil rolls	Cuts, pinched fingers	Use of protective gloves, training in handling materials
Static electricity	Dry foil	Sparking, risk of fire	Equipment grounding, antistatic coatings
Roll centering error	Incorrect installation	Foil breakage, equipment downtime	Loading control, automatic guides
Application of electrode mixture to foil and drying (GN-C300)			
Exposure to high temperatures	Drying at 120°C	Burns, equipment overheating	Furnace thermal insulation, temperature control, PPE (heat-resistant gloves)
Solvent evaporation	Drying the electrode mixture	Respiratory tract irritation, toxic effects	Exhaust ventilation, respirators (class A1 or A2)
Contact of the mixture with skin	Application of electrode paste	Skin irritation, allergic reactions	Protective gloves, workwear
Rolling of electrode rolls on rollers (Rollers GN-HR-200)			
Mechanical injury	Drawing into rolls	Severe limb injuries	Access lock during operation, emergency stop buttons
Noise and vibration	Operation of the rollers	Hearing loss, fatigue	Noise-canceling headphones (SNR ≥ 25 dB), vibration isolation
Deformation of electrodes	Uneven pressure	Defective products	Roller gap adjustment, quality control
Cutting electrode rolls into sheets (GN-S 200P electrode cutting machine)			
Cuts and injuries	Sharp edges of foil	Hand injuries	Use of protective gloves, automatic material feed
Cutting errors	Material displacement	Product defect	Positioning control, precision sensors
Cutting sheets into electrodes of the required size (GN-S500 electrode cutting device)			
Contact with moving blades	Operation of a guillotine cutter	Finger injuries	Protective covers, two-button switch
Formation of metal dust	Cutting foil	Respiratory tract irritation	Dust collection system, respirators

Source: compiled by R.G. Akhtyamov, A.V. Shikhovtseva, L.E. Kalugin, E.Yu. Evshchik.

During the battery stack assembly phase, significant differences in risk levels between manual and semi-automated production methods were identified (Table 3). Manual assembly implies high risk of injury, electrostatic discharge, defect due to human factor. Switching to semi-automatic assembly (GN-DP200S) reduces the risks of injury, defect and electrostatic effects but adds the risk of automation failures and noise.

Table 3. **The stack assembly: results of the assessment of production factors and risk mitigation measures**

Risk factor	Source	Possible consequences	Risk reduction measures
Manual assembly of a stack (form made of plexiglass)			
Mechanical damage	Sharp edges of electrodes, improper handling of foil	Cuts, minor finger injuries	Use of protective gloves (nitrile/antistatic), training in work safety rules
Static electricity	Dry materials (separator, electrodes)	Sparking, risk of damage to sensitive components	Workplace grounding, antistatic wristbands
Assembly errors	Incorrect placement of electrodes and separator	Short circuit, product defect	Visual control, use of templates
Exposure to dust/ particles	Metal and polymer particles	Irritation of skin and respiratory tract	Work in a clean area, use a respirator (FFP1)
Semi-automatic stacking machine (semi-automatic stacking machine GN-DP200S)			
Mechanical injury	Working with moving parts of the device	Pinched fingers, injuries	Access lock during operation, two-hand control
Automation errors	Electrode/separator supply failure	Incorrect assembly, defective	Position control sensors, periodic equipment testing
Electrostatic discharges	Automatic stacking of dry materials	Damage to electronics, risk of fire	Anti-static coating of equipment, humidity control (no more than 10%)
Noise	Operation of the device mechanisms	Increased operator fatigue	Using headphones (SNR ≥ 20 dB)

Source: compiled by R.G. Akhtyamov, A.V. Shikhovtseva, L.E. Kalugin, E.Yu. Evshchik.

The risk analysis carried out shows the clear advantage of semi-automated assembly method both in terms of production safety and product quality stability (Table 4). However, even with the use of automated equipment, there is still a need for strict safety measures and regular monitoring of the condition of the machine. The manual assembly method should be considered as a temporary or fallback solution, which is acceptable only if automated lines cannot be used and enhanced security measures are in place.

Table 4. **Comparative risk assessment for two assembly options**

Criterion	Manual assembly	Semi-automatic assembly
Risk of injury	High (contact with sharp edges)	Medium (restricted access to hazardous areas)
Risk of defects	High (human factor)	Low (automated control)
Electrostatic risks	Medium	Low (best control)
Performance	Low	High
Operator dependency	Critical	Minimum

Source: compiled by R.G. Akhtyamov, A.V. Shikhovtseva, L.E. Kalugin, E.Yu. Evshchik.

Implementation of the proposed recommendations would significantly reduce occupational risks, reduce the number of industrial marriages and create safe working conditions regardless of the chosen method of assembly. Particular attention should be paid to the gradual transition from manual operations to automated processes, which is the most effective way to improve both safety and overall productivity in an enterprise.

In the final stage of battery manufacturing, the most dangerous are electrolyte operations ($LiPF_6$), which require work in an argon box due to the risk of producing toxic HF (Table 5). Also critical: noise and burns during ultrasonic welding, overheating during vacuum drying, risks of short circuit in testing.

Proposed measures include sound-absorbing skins, electrolyte injection robotization, multi-level thermal control, and a complete set of PPEs.

Table 5. **The battery manufacturing: results of the assessment of production factors and risk mitigation measures**

Risk factor	Source	Possible consequences	Risk reduction measures
Preparing a laminated aluminum case (GN-S230F case forming machine)			
Mechanical damage	Sharp edges of aluminum foil	Hand cuts while molding the body	Use of protective gloves (cut-resistant)
Deformation of the body	Incorrect device setting	Product defect	Control of molding parameters, equipment calibration
Ultrasonic welding of nickel terminals (ultrasonic welding GN-2500)			
Noise and vibration	Operation of an ultrasonic welding machine	Hearing damage, operator fatigue	Noise-canceling headphones (SNR ≥ 25 dB)
Thermal exposure	Heating the welding zone	Burns due to careless handling	Heat-resistant gloves, protective screens
Poor connection	Incorrect welding parameters	Reduced conductivity, defect	Welding quality control, regular equipment inspection
Vacuum drying of stack (vacuum drying oven)			
Overheating of components	High drying temperature	Degradation of electrodes, ignition	Temperature control, automatic shutdown when overheating
Vacuum depressurization	Cabinet malfunction	Moisture ingress, product defects	Regular equipment maintenance, vacuum control sensors
Sealing the housing (GN-HS200 sealing device)			
Thermal burns	Hot surfaces during sealing	Skin burns	Heat-resistant gloves, automatic pliers
Leaky seam	Incorrect sealing parameters	Electrolyte leakage, defective	Seam quality control, visual and instrumental control
Filling the argon box with electrolyte (argon box, GN-VS300 impregnation device)			
Electrolyte exposure	Contact with $LiPF_6$ and solvents	Chemical burns, toxic effects	Full set of PPEs (gloves, glasses, apron), exhaust ventilation

Table 5, ending

Risk factor	Source	Possible consequences	Risk reduction measures
Argon leak	Depressurization of the box	Suffocation, loss of inert atmosphere	Air composition monitoring sensors, emergency ventilation
Vacuuming and final sealing (GN-HS200V)			
Residual gases	Incomplete vacuum	Bulging of the case, decreased capacity	Vacuum degree control
Reheating the case	Sealing process	Deformation of the body	Precise temperature control
Electrochemical tests (Neware BTS4000-5V20A)			
Short circuit	Incorrect connection	Fire, equipment damage	Staff training, connection testing
Battery overheating	High testing currents	Thermal runaway, ignition	Temperature control, automatic shutdown

Source: compiled by R.G. Akhtyamov, A.V. Shikhovtseva, L.E. Kalugin, E.Yu. Evshchik.

Discussion

Analysis shows that the safety of LIB production cannot be ensured by precise measures. A systemic approach is required that integrates three key principles:

Maximum automation of critical hazardous operations (electrolyte work, welding) to prevent direct contact of personnel with hazards;

Implementation of multi-level monitoring of parameters (temperature, humidity, dust, air composition) in real time;

Comprehensive protection of personnel, combining modern engineering solutions (locking, ventilation), adequate PPE and continuous training.

The feature of this study is its phasing and practical orientation. In contrast to works that consider individual risks, here is proposed a holistic management system for the entire process chain, confirmed by a comparative analysis of the effectiveness of different assembly methods. Moving to automated lines is the most efficient way to simultaneously improve safety, quality and productivity.

Conclusion

The research allowed us to systematise key aspects of lithium-ion battery production, with particular attention to the analysis of production risks at each stage of the process. Electrolytes, ultrasonic welding and drying operations requiring special protection measures have been identified as the most safety-critical operations.

The results of the study demonstrate that modern approaches to organizing battery production should be based on three key principles: maximizing automation of critical hazardous operations, implementing multi-level monitoring systems of parameters and comprehensive protection of personnel. The combination of technical solutions and organizational measures proved particularly effective.

The practical significance of the work lies in the developed set of recommendations on optimization of technological processes from the point of view of safety, choice of means of individual and collective protection, as well as organization of quality control system and occupational safety. Implementation of the proposed measures would significantly improve safety and efficiency in the production of lithium-ion batteries while reducing production costs.

Generally, the study confirms that only a systemic approach that takes into account all aspects of production, from raw material selection to final testing, can ensure competitive and safe battery manufacturing.

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