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The safety paradigm in lithium and sodium-ion cell logistics: A comparative analysis of thermal runaway risk, evolution of ADR regulations, and operational recommendations

Paradygmat bezpieczeństwa w logistyce ogniw litowych i sodowych. Analiza porównawcza ryzyka thermal runaway, ewolucja przepisów ADR i rekomendacje operacyjne

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Abstract

This article evaluates the adequacy of current transport regulations (ADR) concerning the specific hazards posed by lithium-ion (LIB) and sodium-ion (SIB) technologies, and to formulate new safety standards for the road transport of dangerous goods. The study employs a methodology based on a critical literature review in fire safety engineering and materials chemistry, case study analysis of transport incidents, and a formal-legal analysis of international transport regulations. The analysis reveals that SIB technology does not eliminate the risk of thermal runaway. Despite the logistical advantage of transport in a deeply discharged state (0 V), sodium cells exhibit faster initiation of self-heating processes and toxic gas emissions (SO_2). Furthermore, it was determined that current ADR requirements, which rely on packaging classification, along with traditional firefighting methods, are insufficient against the autocatalytic nature of battery fires. In response to the identified regulatory gaps, an integrated operational safety model is proposed. It encompasses prevention (mandatory SoC < 30% verification and a strict ban on co-loading batteries with Class 1.4S explosives), monitoring (off-gas detection), and intervention (the Flood & Cool tactic). Shifting the safety paradigm from passive packaging assessment to proactive control of the cargo's energetic state is essential for effective risk mitigation.

Keywords: lithium-ion batteries, sodium-ion batteries, ADR agreement, thermal runaway

Streszczenie

Celem artykułu jest ocena adekwatności obecnych regulacji transportowych (ADR) wobec specyfiki zagrożeń stwarzanych przez technologie litowo-jonowe (LIB) i sodowo-jonowe (SIB) oraz sformułowanie nowych standardów bezpieczeństwa w drogowym przewozie towarów niebezpiecznych. Zastosowano metodykę opartą na krytycznym przeglądzie literatury z zakresu inżynierii pożarowej i chemii materiałów, analizie studiów przypadków incydentów transportowych oraz analizie formalno-prawnej międzynarodowych przepisów przewozowych. Badania wykazały, że technologia SIB nie eliminuje ryzyka ucieczki termicznej (thermal runaway). Mimo możliwości transportu w stanie głębokiego rozładowania (0 V), ogniwa sodowe charakteryzują się szybszą inicjacją procesu samonagrzewania oraz emisją toksycznych gazów (SO_2). Ustalono również, że obecne, opierające się na klasyfikacji opakowań wymogi ADR oraz tradycyjne metody gaśnicze są niewystarczające wobec autokatalitycznego charakteru pożarów baterii. W odpowiedzi na zidentyfikowane luki regulacyjne zaproponowano zintegrowany model bezpieczeństwa operacyjnego. Obejmuje on prewencję (obligatoryjna weryfikacja SoC < 30% oraz bezwzględny zakaz wspólnego transportu baterii z materiałami wybuchowymi podklasy 1.4S), monitoring (detekcja gazów typu off-gas) oraz interwencję (taktyka Flood & Cool). Zmiana paradygmatu bezpieczeństwa z biernej oceny opakowania na proaktywną kontrolę stanu energetycznego ładunku jest niezbędna dla skutecznej mitygacji ryzyka.

Słowa kluczowe: baterie litowo-jonowe, baterie sodowo-jonowe, umowa ADR, ucieczka termiczna

Introduction

The energy transformation of the global economy, driven by the dynamic development of electromobility and Battery Energy Storage Systems (BESS), is redefining the structure of supply chains. Galvanic cells, once a niche cargo in the transport of dangerous goods, have now become one of the dominant logistical volumes. However, this technological revolution brings a new spectrum of hazards that elude traditional risk assessment methods used within the framework of the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

The current safety paradigm in logistics has relied primarily on substance classification and packaging selection. Yet, a series of catastrophic incidents in air and maritime transport, as well as failures of land-based infrastructure, have exposed the insufficiency of this approach in the face of the thermal runaway phenomenon. The specificity of battery fires – characterized by rapid kinetics, the emission of toxic gases, and the ability to self-sustain reactions without atmospheric oxygen – requires the implementation of new preventive and intervention strategies.

In terms of methodology, this study is based on a critical analysis of literature in the fields of fire safety engineering and materials chemistry, supplemented by case studies of selected disasters in air, sea, and land transport. Furthermore, a comparative analysis of the physicochemical properties of lithium and sodium cells was conducted, alongside a formal and legal analysis of current international regulations (ADR, IATA DGR). This article not only synthesizes the current state of knowledge but, above all, formulates original operational recommendations and proposals for changes in transport practice (*de lege ferenda*).

Analysis of safety incidents involving lithium-ion cells in transport and storage

The increasing ubiquity of lithium-ion technologies in supply chains and consumer applications generates new challenges for transport and storage safety. A review of recent incidents – ranging from aviation accidents to land-based infrastructure fires and maritime disasters – provides empirical evidence for the necessity of implementing appropriate preventive procedures. It is worth noting that, to date, no major large-scale failures involving sodium-ion cells have been recorded; however, this does not exempt the industry from a proactive and preventive approach to this emerging technology.

A critical example of risk in passenger transport is the incident involving an Air Busan Airbus A321, which occurred in January 2025 at Gimhae Airport in South Korea. The investigation revealed that the source of the fire, which led to the destruction of part of the fuselage, was a portable power bank located in an overhead locker. The ignition was caused by damage to the internal insulation of a cell, leading to a short circuit. This event became a direct catalyst for the revision of safety procedures by international carriers (e.g., Singapore Airlines, Thai Airways). South Korean authorities introduced a mandatory requirement for passengers to carry such devices on their person, aiming to enable faster detection of potential ignition and facilitate firefighting efforts, which are significantly more difficult in enclosed cargo or baggage spaces (Butler, 2025; Hogan, 2025).

The risk associated with Li-ion technology is not limited to aviation and also concerns land infrastructure. In April 2024, an explosion and fire occurred at a containerized energy storage facility in Trzebinia, Poland. This event highlighted the dynamics of thermal phenomena occurring within the cells, where a rapid temperature increase, exceeding the system's heat dissipation capacity, leads to an uncontrollable chain reaction. This case underscores that Battery Energy Storage Systems (BESS) must be treated as high-explosion-risk facilities, and rescue procedures must account for the specific nature of chemical fires (*Pożar kontenera z akumulatorami w Trzebini*, 2024).

The greatest scale of hazards is observed in maritime transport, where environmental factors (storms, salinity) and cargo securing errors can lead to catastrophic consequences. For instance, the National Transportation Safety Board (NTSB) report regarding the fire on the Genius Star XI (December 2023, North Pacific) pointed to a mechanical cause of ignition. Improper selection of securing equipment (undersized belt hooks relative to the lashing rings) led to their failure in harsh weather conditions. The unrestrained BESS units (weighing 9.5 tonnes each) suffered mechanical deformation, which initiated a fire within the battery packs. Although carbon dioxide-based fire suppression systems operate within a very limited range – as battery components can release oxygen for a self-sustaining combustion reaction, discussed later in this article – in this specific case, its application allowed for the situation to be brought under control (*Lithium-ion Battery Fires aboard Cargo Vessel Genius Star XI*, 2024; Howard, 2025).

A starkly different outcome followed the June 2025 incident involving the car carrier Morning Midas. The fire, which broke out on a deck carrying approximately 3,000 vehicles (including a significant number of electric and hybrid vehicles), proved impossible for the crew to contain. As a result of thermal damage and challenging hydrometeorological conditions, the vessel sank in the Pacific. This case illustrates the limited capabilities of conventional firefighting systems when facing a fire involving a large number of electric vehicles on the high seas (*Cargo ship carrying new vehicles to Mexico sinks in the North Pacific weeks after catching fire*, 2025; Hand, 2025).

The analysis of the above case studies – regardless of scale or location – points to a common failure mechanism: thermal runaway. This is an autocatalytic process in which an increase in cell temperature accelerates exothermic reactions, leading to further increases in temperature and pressure until the casing ruptures and ignition occurs. Understanding the thermodynamics of this phenomenon and the differences in its progression for various cell chemistries is crucial for developing effective prevention methods and fire protection strategies. These incidents serve as a direct impetus for shaping international transport law and recommendations related to best transport practices.

Lithium and sodium batteries and cells as dangerous goods under the ADR Agreement

Due to the complexity of multimodal regulations, further considerations in this article have been narrowed down to road transport, which constitutes a key link in the land supply chain. Contemporary logistics of energy materials is based on two key technological pillars: the widely used lithium and the increasingly important sodium. To correctly interpret the ADR regulations governing the transport of dangerous goods by road, one must first understand the fundamental distinction applied by the legislator – the division based on technology type (chemistry) and physical form (cell or battery).

The ADR Agreement precisely categorizes energy sources in Class 9 (miscellaneous dangerous substances and articles), assigning them dedicated UN numbers:

- Lithium technology: includes well-known entries such as lithium-ion batteries (UN 3480) and lithium-metal batteries (UN 3090);
- Sodium technology (new regulations): in response to market innovations, new entries have been introduced: UN 3551 (sodium-ion batteries with organic electrolyte) and UN 3552 (sodium-ion batteries contained in equipment).

Although chemistry defines the UN number, it is the physical form that determines the limits for utilizing exemptions from the regulations (e.g., the popular Special Provision 188). The ADR Agreement introduces a clear energy threshold (3.3.1):

- Cell: the basic electrochemical unit. Due to the lack of external protection (such as a BMS – Battery Management System), limits for individual cells are more restrictive. Partial exemption (SP 188) applies only to cells with an energy rating not exceeding 20 Wh;
- Battery: understood as a set of cells electrically connected. Since finished batteries typically possess a more robust casing and protective circuitry, the limit for them is higher, at 100 Wh.

This principle applies to both lithium and sodium technologies. Exceeding these values necessitates the application of full ADR procedures. Regardless of whether a single cell or a complex battery is being transported, the possibility of admission for transport is conditional upon successfully passing the tests described in the Manual of Tests and Criteria (Part III, subsection 38.3). Additionally, manufacturers of cells and batteries are obliged to implement a quality management program, aimed at eliminating manufacturing defects before the product enters the supply chain.

End-of-life cells pose a particular challenge in transport. The ADR Agreement provides for specific scenarios regulated by Special Provisions (3.3.1):

- Damaged/Defective (SP 376): If a battery is damaged or defective (e.g., cracked casing, leaks), it must be transported under special conditions. A critical assessment is required to determine if the damage is critical (risking rapid disassembly or fire). Packaging for such batteries must bear a clear marking indicating a damaged/defective lithium-ion or sodium-ion battery;

- Recycling (SP 377): Cells transported for disposal are subject to Special Provision 377. This allows for transport in collective packaging, provided they are durably marked with an inscription indicating they are for recycling.

It is worth noting that in the case of sodium-ion batteries transported as waste or for recycling, a total exemption from ADR regulations is possible, provided they are in a completely discharged state (no electrical energy), which constitutes a significant logistical advantage over lithium technology.

Understanding these regulations, however, requires a deeper look into the nature of the cargo itself. Why are regulations evolving towards the inclusion of sodium, and how does it differ from the dominant lithium from a physicochemical perspective?

Comparative analysis: lithium vs. sodium batteries

Over the last few decades, lithium-ion batteries (LIB) have become the undisputed kings of the market, powering everything from smartphones to electric vehicles and energy storage systems (Kamble, Walvekar, 2023: 1). Their dominance stems from high energy density and long cycle life, which have made them the standard in consumer electronics and electromobility (Farhan et al., 2025: 189).

However, the success of lithium has become its own problem. This element is relatively rare in the Earth's crust (accounting for only about 0.0065%), and its resources are unevenly distributed geographically (mainly South America, Australia, and China) (Hua, 2023: 234). This leads to geopolitical risks, price volatility, and environmental issues associated with its extraction (Farhan et al., 2025: 189).

These phenomena have led to the search for alternative elements that could serve as a sustainable successor to lithium. Attention has focused on sodium (Na). It is the sixth most abundant element in the Earth's crust (approx. 2.73%), and its resources – unlike lithium – are virtually unlimited and widely available, for instance in seawater (Hua, 2023: 234; Farhan et al., 2025: 189). It is this abundance of raw material and the potential for lower production costs that make sodium-ion (SIB) technology perceived as a key complement, and in some areas a successor, to lithium technology (Kamble, Walvekar, 2023: 1).

Although lithium and sodium belong to the same group of alkali metals and exhibit similar chemical properties, they differ in a crucial aspect – size and mass. Lithium ions ($Li+$) are small and light. Sodium ions ($Na+$) are significantly larger and heavier (Farhan et al., 2025: 190). This physical difference is fundamental to battery parameters – lithium has a more negative redox potential (-3.04 V) compared to sodium (-2.71 V). This means that lithium batteries naturally offer higher cell voltage and higher energy density, which is crucial in mobile applications where every minute of device operation counts (Farhan et al., 2025: 190). Despite the differences in ion size, both technologies operate on the same "rocking chair" principle. Ions move between the cathode and the anode through the electrolyte, “rocking” back and forth during charge and discharge cycles (Hua, 2023: 233).

Sodium technology introduces a significant innovation in cell construction that translates into costs and ecology. In lithium batteries, the anode (most often graphite) requires the use of a copper current collector because lithium reacts with cheaper aluminum (these are not dangerous reactions; they merely lead to the formation of intermetallic compounds). In the case of sodium batteries, this problem does not occur – sodium does not alloy with aluminum. This makes it possible to use aluminum foil of appropriate chemical purity instead of expensive and heavy copper on both the cathode and the anode (Hua, 2023: 237; Farhan et al., 2025: 190).

The elimination of copper not only lowers costs but also reduces the negative environmental impact of battery production, as copper is one of the materials with the highest potential for environmental damage in Life Cycle Assessments (LCA) (Degen, Mitterfellner, Kampker, 2025: 124). It is also worth noting the difference in anode material. While graphite is the standard for lithium, “hard carbon” is used for sodium ions (which are too large to efficiently intercalate into graphite structures) (Rehm et al., 2025: 2).

In terms of performance parameters, both technologies have their strengths and weaknesses:

- Energy density: lithium cells still lead. However, the latest sodium cells (e.g., from CATL) already achieve energy densities of around 160 Wh/kg, which is significantly better than lead-acid batteries and close to older generations of lithium cells (Hua, 2023: 236);
- Temperature behavior: sodium batteries show promising performance across a wide temperature range (-40°C to 80°C) (Hua, 2023: 236). However, it should be noted that at very low temperatures and low states of charge (SOC < 30%), their internal resistance increases significantly, which may limit their energy efficiency in specific conditions (Rehm et al., 2025: 7);
- Transport and storage: a unique advantage of sodium batteries is the possibility of discharging them completely to 0 V for transport. This is impossible for lithium batteries (which would most likely be damaged by such action) and constitutes a huge asset from the perspective of logistical safety (Rehm et al., 2025: 2).

In summary, it can be stated that sodium batteries are seen as a safer and cheaper alternative to lithium technology, especially in stationary applications where battery weight is not critical (Kamble, Walvekar, 2023: 3). However, although sodium technology is characterized by higher thermal stability compared to lithium (Kamble, Walvekar, 2023: 3), it is not entirely free from risks. In the case of both lithium and sodium cells, extreme operating conditions, mechanical damage, or errors in charging management can lead to one of the most dangerous phenomena in the transport of dangerous goods – thermal runaway. This mechanism, common to both technologies, requires detailed discussion, as its progression determines firefighting strategies and emergency procedures.

Thermal runaway phenomenon – mechanism and specificity for different cell chemistries

In the world of hazardous materials logistics, the term that raises the most concern is “thermal runaway”. This phenomenon is the primary reason why lithium batteries (and recently also sodium batteries) are subject to such strict supervision under dangerous goods regulations.

Thermal runaway is a self-accelerating exothermic process. In simple terms: an increase in temperature inside the cell initiates chemical reactions that generate even more heat. This heat accelerates the reactions, leading to an avalanche-like increase in temperature, resulting in fire, the emission of toxic gases, or an explosion. This process typically occurs in three increasingly dramatic stages (Boozula et al., 2025: 3):

- **Stage I:** Decomposition of the SEI (Solid Electrolyte Interphase) layer. As the cell temperature rises (e.g., due to an external fire or an internal short circuit), the first victim is the passive layer on the anode. Its breakdown exposes the reactive material of the anode to the electrolyte, generating the initial heat.
- **Stage II:** Melting of the separator. A further increase in temperature leads to the melting of the separator (usually a polymer membrane separating the positive and negative terminals). Once this occurs, a massive internal short circuit ensues, causing a sudden spike in temperature.
- **Stage III:** Ignition of the cathode and electrolyte. At extreme temperatures, the cathode begins to decompose, releasing oxygen. Oxygen, combined with the flammable electrolyte and high temperature, creates ideal conditions for an uncontrolled fire (Boozula et al., 2025: 4).

Although both technology types (lithium and sodium) exhibit a similar ignition mechanism, the cell chemistry itself is crucial to the course of the disaster. Comparative studies bring fascinating and sometimes counterintuitive conclusions.

In the world of lithium batteries, there are two safety poles. The first is LFP (LiFePO4), which is considered a “safe haven”. Research shows that even with high heating power (500~W), LFP cells rarely undergo spontaneous ignition without an external fire source, and their maximum temperature during failure is approximately 478°C (Li et al., 2025: 851). Furthermore, LFP has the highest self-heating onset temperature (approx. 124°C), which means it is the most difficult to “trigger” the process associated with uncontrolled degradation leading to catastrophic consequences (Boozula et al., 2025: 6). The second is NCM (Nickel-Cobalt-Manganese), which is considered a higher-risk technology. These cells can reach temperatures of around 871°C and are prone to rapid ignition (jet fire) even without an external spark (Li et al. 2025: 851).

Regarding sodium technology, it ranks exactly in the middle. In calorimetric tests, sodium cells (with layered cathodes) reached maximum temperatures of around 794°C – significantly more than the safe LFP, but still less than the extreme NCM (Li et al. 2025: 851).

However, it is worth noting that despite sodium being recognized as a safer raw material, sodium cells begin the self-heating process much faster than lithium cells – at just 94°C (compared to 124°C for LFP) (Boozula et al., 2025: 6). This results from the lower stability of the SEI layer on hard carbon anodes, which begins to degrade at lower temperatures (Boozula et al., 2025: 14).

An extremely interesting phenomenon observed in sodium batteries is their fire specificity. During tests at high heating power (500~W), sodium cells generated a rapid stream of gases and flames (jet fire), similar to lithium NCM. However, due to the very high rate of gas production, the gas stream was capable of "blowing out" the flame, leading to a self-extinguishing phenomenon after just a few seconds (Li et al., 2025: 844). This does not mean they are entirely safe – the emission of toxic gases is still immense – but the risk of open fire spreading may be different than in the case of lithium.

In the context of urban fleets (e-bikes, scooters), the problem is not just a single cell, but their dense packing in a battery module. The phenomenon of thermal propagation (fire spreading from cell to cell) is crucial here. Research indicates that in densely packed e-bike batteries, the thermal runaway of one cell almost guarantees a chain reaction (Kociemba, 2025: 124).

Therefore, from the perspective of ADR regulations (including Special Provision 376 for damaged batteries), the key is not only "what is inside" (lithium or sodium) but how the battery behaves as a whole. Although sodium offers hope for safer transport (e.g., the possibility of transport in a state of deep discharge to 0~V, which eliminates electrical energy as an ignition source), the lower thermal stability of its anode requires special attention in the design of packaging and emergency procedures (Boozula et al., 2025: 23).

To summarize the argument so far, sodium is not a "non-flammable alternative" to lithium. It is a technology with a different risk profile – less explosive than lithium NCM, but more sensitive to thermal initiation than lithium LFP.

Operational implications and recommendations for road transport in light of fire suppression research

Analysis of the subject literature and fire suppression test reports necessitates a redefinition of the safety approach in road battery transport. Current procedures, often based on standard extinguishing agents and general ADR regulations, may prove insufficient given the specifics of thermal runaway. The following presents an integrated operational model based on findings from research on extinguishing agent effectiveness and aviation-based prevention.

Although road regulations (ADR) are less restrictive regarding the state of charge than aviation ones, empirical data are unequivocal: the energy stored in a cell is the fuel for thermal runaway. In this regard, the International Air Transport Association (IATA) has introduced a strict State of Charge (SoC) limit of a maximum of 30% for the transport of lithium-ion and sodium-ion batteries. It has been proven that cells with a reduced charge are significantly less prone to uncontrolled temperature increases (*Battery Guidance Document Transport of Lithium Metal, Lithium Ion and Sodium Ion Batteries Revised for the 2025 Regulations*, 2025: 13). Furthermore, as previously mentioned, sodium-ion batteries possess a unique advantage – they can be transported in a state of total discharge (0 V) without the risk of chemical degradation, which eliminates electrical risk (*Battery Guidance Document…*, 2025: 4).

Recommendation 1: voluntary implementation of an SoC < 30% limit in the road transport of high-consequence dangerous goods is recommended, even if ADR regulations do not explicitly mandate it. For sodium technology, where technically feasible, transport in a passive state (0 V) is recommended.

The second area considered by the author is extinguishing agents. A key conclusion from the literature devoted to the analysis of fire tests is that traditional suppression methods, based on cutting off the oxygen supply (powders, inert gases), are ineffective against thermal runaway because this process is self-sustaining and does not require atmospheric oxygen for propagation. FAA (Federal Aviation Administration) studies and experiments on BESS systems have shown that the key to stopping propagation is a drastic reduction in the temperature of adjacent cells. Gaseous agents (such as Halon, Novec 1230, or CO_2) effectively extinguish visible flames but lack sufficient heat capacity to cool the cells, leading to their reignition (Maloney, 2014: 14; Mrozik et al., 2026: 22). The most readily available agent supporting heat exchange and cooling is water, and in particular, water mist and encapsulator agents, which have shown the highest effectiveness, extending thermal runaway propagation time by nearly 180% compared to no intervention (Mrozik et al., 2026: 1).

Recommendation 2: in the equipment of vehicles carrying significant quantities of batteries, standard powder extinguishers (ABC) should be treated exclusively as a means for extinguishing surrounding fires (tires, cabin). For direct combat with the load, the use of at least foam systems with high heat capacity, capable of penetrating the pack, is essential.

The third area the author decided to address is toxicity and vapor clouds. Extinguishing a battery fire is not only a struggle with temperature but also chemical emission management. The literature indicates a strong correlation between cooling effectiveness and vapor cloud production. Effectively extinguishing the flame while the internal cell reaction continues leads to the emission of vast quantities of flammable and toxic gases, which creates a real risk of a vapor cloud explosion in the enclosed cargo space of a semi-trailer (Mrozik et al., 2026: 21). Regarding toxins, although the electrolytes in lithium and sodium technologies are similar (carbonates), the combustion of sodium electrolytes (particularly those based on the $NaPF_6$ salt) generates significantly less hydrogen fluoride (HF) compared to their lithium counterparts ($LiPF_6$). However, the use of the NaFSI salt in sodium batteries is associated with the emission of irritating sulphur dioxide (SO_2) (Bhutia et al., 2024: 7).

Recommendation 3: emergency procedures for drivers and rescue services must account for the risk of a vapor cloud explosion after effectively "extinguishing" the visible fire. Opening the cargo space should be performed with the utmost caution.

Author's recommendations for road safety (safety framework)

Based on the preceding analysis of source materials, the implementation of an integrated safety model for the road transport of batteries is proposed, built upon three pillars:

Pillar I: Prevention (pre-transport):

SoC Verification: the introduction of a mandatory annotation in transport documentation regarding the battery's state of charge, which would allow emergency services to more rapidly assess the load's energy potential (a practice already established in air transport; see: *Battery Guidance Document Transport of Lithium Metal, Lithium Ion and Sodium Ion Batteries Revised for the 2025 Regulations…*, 2025: 13). It is essential that this annotation does not compromise the legibility of information required by the ADR Agreement concerning the sequence of information related to the description of the transported cargo;

Chemical Segregation: an absolute prohibition on packing batteries in a single outer packaging (as well as loading onto the same vehicle without physical separation) with explosives, flammable gases, or oxidizers. In the event of thermal runaway, the proximity of these materials leads to a catastrophe that is impossible to manage using conventional means. It should be critically noted that current ADR Agreement regulations (2025–2027 version, table 7.5.2.1) permit the co-loading of Class 9 goods (including batteries) with Class 1 explosives – specifically subclass 1.4S. This group includes, among others, small arms ammunition, cartridges for power devices, and signalling pyrotechnics. In light of the temperatures generated by thermal runaway, considering these loads as safe neighbours for batteries is an assumption that is, at the very least, debatable.

Pillar II: Monitoring (during transport):

- Early Detection: in the case of transporting large units (e.g., BESS containers), the installation of sensors in the cargo space capable of detecting not only smoke but also specific "off-gases" (e.g., CO, H_2, light hydrocarbons) that appear prior to the outbreak of fire (Bhutia et al., 2024: 6);
- Cargo Stabilization: the use of certified stowage and lashing methods that prevent mechanical damage to the cells (shocks, crushing), which are among the primary causes of internal short-circuit initiation.

Pillar III: Intervention (post-event):

- The “Flood & Cool” Tactic: if circumstances permit, the priority of the firefighting operation should be massive heat removal using water or firefighting foam, rather than attempting to “smother” the fire with gaseous or powder agents. In the absence of the possibility to use water or foam, the focus should shift to protecting the surroundings (evacuating the population or informing them of the necessity to seal windows and doors) and allowing the cells to undergo controlled burnout (Maloney, 2014: 14; Mrozik et. al., 2026: 25), while designating the impact zone described below;
- HF/SO_2 Impact Zone: in the event of controlled battery burnout, a safe zone must be designated, taking into account wind direction and the chemical specificity of the load. Information updates should be continuously relayed to the exposed nearby population. For Li-ion batteries, the primary toxic threat is hydrogen fluoride, whereas for Na-ion (containing FSI salt), it is sulphur oxides.

Summary

The conducted analysis proves that in the face of increasing energy density in modern cells, road transport safety cannot rely solely on passive compliance with the minimum legal requirements of the ADR Agreement. The evolution of hazards – from classic fuel fires to self-sustaining exothermic reactions inside cells – forces a paradigm shift: from “safe packaging” to “the safe energetic state of the cargo”.

A comparison of lithium-ion and sodium-ion technologies leads to non-obvious conclusions. Although sodium cells offer a unique logistical advantage in the form of the possibility of transport in a state of deep discharge (0 V), their lower thermal stability of the anode and the specificity of toxic emissions (SO_2) dictate caution and do not allow them to be treated as a completely safe technology. In both cases, the key risk factor remains the thermal runaway phenomenon, against which traditional extinguishing agents often prove ineffective.

The safety framework proposed in the article, based on the pillars of prevention (SoC control), monitoring (off-gas detection), and conscious intervention (the “Flood & Cool” tactic), represents an attempt to address gaps in current procedures (particularly in the areas of prevention and monitoring). The implementation of these recommendations, specifically the voluntary limitation of the state of charge in road transport and the tightening of rules for the segregation of explosives, can significantly reduce the likelihood of a land-based catastrophe on a scale comparable to the discussed maritime and aviation incidents.

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