# BRITANNIA LOSS PREVENTION INSIGHT

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# ELECTRIC VEHICLE FIRES AN OVERVIEW FOR THE MARITIME SECTOR

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Dr Holling is a partner at Burgoynes specialising in the investigation of chemical incidents, and the origin and cause of fires and explosions. He has investigated over 700 cases throughout Europe, Africa, Asia, and Oceania.

Dr Holling's casework has involved the investigation of both land and marine incidents. His experience of marine incidents includes tankers, bulk carriers, general cargo, container, RORO ferries, and PCCs/PCTCs. He has also investigated fires starting in cars, trucks, heavy plant, and specialist mobile machinery, including battery powered vehicles. Investigations involving containerised dangerous cargoes have included consignments of bulk batteries and battery containing equipment.

## INTRODUCTION

**VEHICLES POWERED BY ELECTRICITY (EVs) WERE FIRST DEVELOPED IN THE 19TH CENTURY[1] AND WHILE THEY ENJOYED SOME POPULARITY, DURING THE EARLY 20TH CENTURY, VEHICLES POWERED BY INTERNAL COMBUSTION ENGINES (ICEs) BECAME WIDESPREAD SUCH THAT THEY DOMINATED THE VEHICLE MARKET UNTIL THE EARLY 21ST CENTURY. MAINSTREAM DEVELOPMENT OF EVs WAS HELD BACK BY THEIR LIMITATIONS IN TERMS OF SPEED AND RANGE, AND THEIR COMPARATIVELY LONG 'OVER-NIGHT' RECHARGE TIMES AND THEY EXISTED MAINLY AS SPECIALIST EQUIPMENT SUCH AS THE NASA APOLLO 15 LUNAR ROVER[2].**

Following important scientific progress, especially over the middle to late 20th century, the lithium-ion battery was developed, an advance which was recognised by a Nobel Chemistry prize[3] in 2019. This high-power battery technology has been widely adopted as the preferred energy storage technology of choice across a wide range of portable electrical products, including EVs. It is predicted that by 2022 there will be about 500 different EV models manufactured globally[4], a figure that is expected to increase in the coming years. Indeed, the impetus to move away from ICEs has motivated some governments to introduce, or at least to consider, legislation to ban the sale of new ICE vehicles from as early as the 2030s.

[1]USA Department of Energy 'The History of the Electric Car' September 2014.
[2]USA National Aeronautics and Space Administration – NASA History Apollo 15 Lunar Mission 31 July 1971.
[3]The Royal Swedish Academy of Sciences 'Lithium-ion Batteries' Nobel Chemistry Prize October 2019.
[4]BloombergNEF 'Electric Vehicle Outlook 2020'.

# THE ANTICIPATED GROWTH IN EV OWNERSHIP MEANS THAT MORE VEHICLES BEING TRANSPORTED BY SEA WILL BE POWERED BY ELECTRICITY

Closely parked car stowage on a PCC.

## TRANSPORTING EVs BY SEA

NEW VEHICLES ARE TRANSPORTED BY LAND AND/OR SEA, AND PURE CAR CARRIERS (PCCs) OR PURE CAR AND TRUCK CARRIERS (PCTCs) ARE AN INTEGRAL PART OF THAT GLOBAL VEHICULAR LOGISTICS NETWORK.

PCCs and PCTCs are widely employed to transport high volumes of new vehicles from their place of manufacture to various international markets. In addition, PCCs, PCTCs, and Roll On Roll Off ferries (ROROs) enable secondary market vehicles or fare paying passengers' vehicles to be transported between different ports. This high volume transport of vehicles requires that they are parked very close together on cargo decks to maximise stowage capacity, with the largest of such vessels being able to carry more than 8,000 standard vehicles across multiple decks. The anticipated growth in EV ownership means that more vehicles being transported by sea will be powered by electricity.

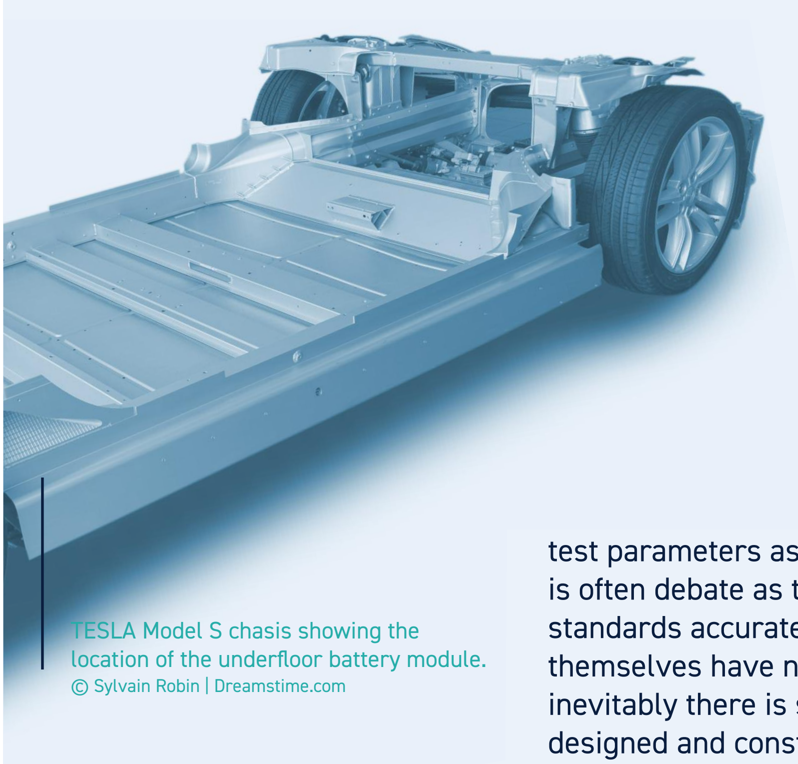
[5] USA Department of Transportation, National Highway Traffc Safety Administration 'Lithium-Ion Battery Safety Issues for Electric and Plug0In Hybrid Vehicles' October 2017 (Report no.: DOT HS 812418).
[6] Journal of The Electrochemical Society 'Review – Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions' 2020 (volume 67, 090559).
[7] www.batteryuniversity.com.

LI-ION +

## LITHIUM-ION CELLS AND BATTERIES

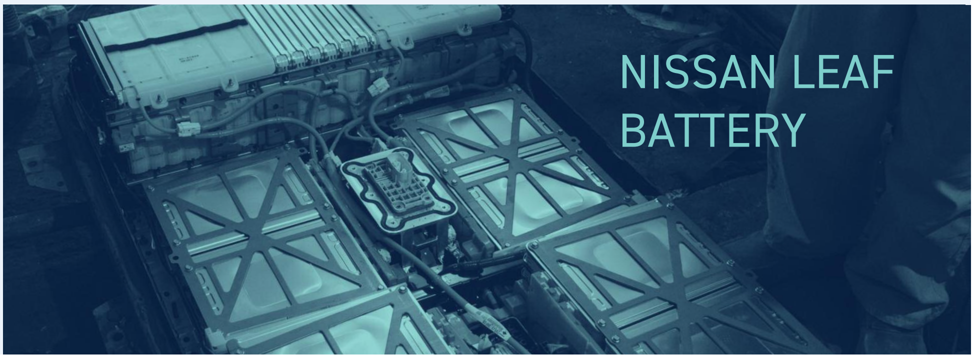
LITHIUM-ION CELLS AND BATTERIES CAN BE DESCRIBED SIMPLY AS HAVING A CARBON ANODE, A LITHIUM TRANSITION METAL OXIDE CATHODE, A POROUS PLASTIC MEMBRANE BETWEEN THE ANODE AND CATHODE (OTHERWISE KNOWN AS THE SEPARATOR) AND A LIQUID ELECTROLYTE THAT IS SOAKED INTO THE ANODE AND CATHODE MATERIALS ALONG WITH A SMALL QUANTITY OF A LITHIUM SALT[5]. The electrical energy released is the result of movement of lithium-ions between anode and cathode during discharging, with electricity passing through an external circuit, and the opposite directional migration of lithium-ions during charging.

Lithium-ion cells are manufactured as one of four different types, namely: button, cylindrical, prismatic or pouch. Button, cylindrical and prismatic cells typically have rigid outer metal cans, while pouch cells have a plastic film container. EVs commonly use either cylindrical or pouch cells which are formed into arrays of two or more cells to form battery modules. Multiple modules are linked together to form battery packs which are then arranged within a tough steel rigid enclosure to protect the lithium-ion cells from the expected rigours of road use.

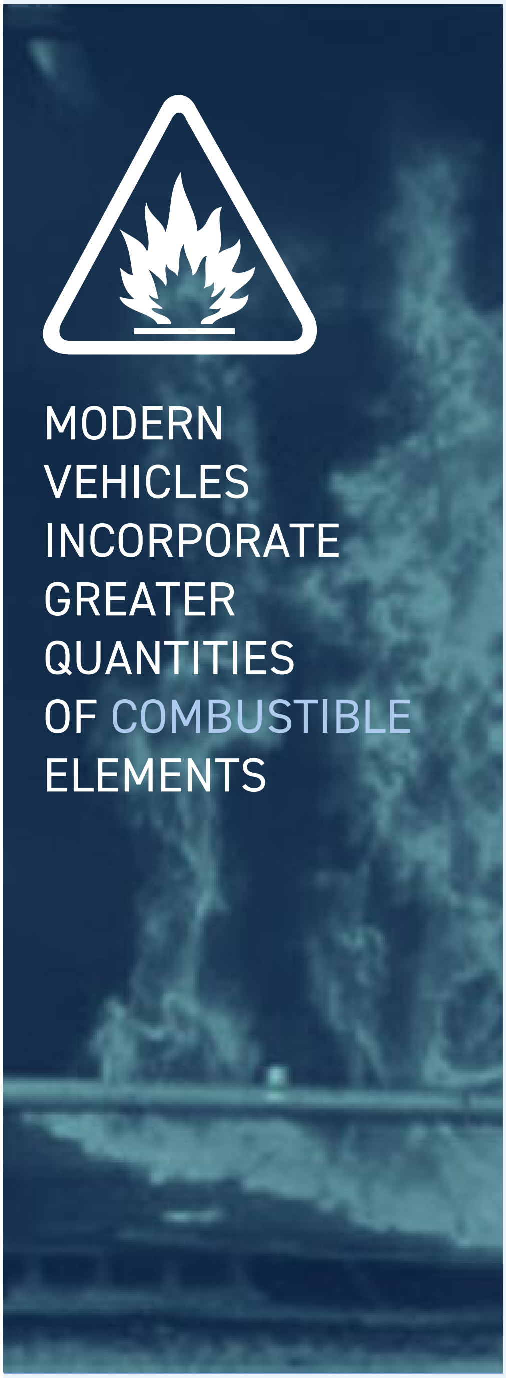


TESLA Model S chasis showing the location of the underfloor battery module.
© Sylvain Robin | Dreamstime.com

Lithium-ion batteries and EVs are subject to Governmental Regulations which often cross-reference national and/or international safety standards. However, these standards are not harmonised and each can have quite different test parameters as well as pass/fail criteria[6]. Furthermore, there is often debate as to whether the laboratory tests used in the standards accurately reflect real-life conditions. Manufacturers themselves have not adopted a universal battery system and inevitably there is some variety on how battery packs are designed and constructed. For example, a 30kWh Nissan Leaf battery pack is formed from 192 lithium-ion pouch type cells, which are grouped into 48 battery modules; on the other hand, a 100kWh Tesla S battery pack is formed from 8,256 cylindrical type cells, that are grouped into 16 battery modules[7].




A Nissan LEAF battery box open – showing the rechargeable cells.
© Svyatoslav Lypynskyy | Dreamstime.com




## VEHICLE FIRES

SOME OF THE MORE COMMON CAUSES OF ICE VEHICLE FIRES ARE ESCAPES OF FUEL OR OIL, MECHANICAL DAMAGE, CHAFING AND FRICTION AND ELECTRICAL FAULTS.

Manufacturers of ICE vehicles will issue repair or recall notices when defective elements in their products that can cause vehicle fires are identified. Manufacturers of EVs are no different and several global manufacturers have over the last few years made various recall announcements related to lithium-ion battery pack problems and their thermal failures. Examples include the ingress of water into battery packs along wiring looms and battery manufacturing issues stemming from the presence of extraneous metal particles[8].

Vehicle fires can occur while a vehicle is being actively driven, during periods of charging or idling, and also while parked and apparently turned off. Thankfully, vehicle fires are relatively rare events but there have been a number of serious fires involving tens, hundreds, or even thousands of parked vehicles on land[9, 10] and also while being transported on PCCs, PCTCs and ROROs[11, 12]. These fires have caused huge amounts of physical damage, financial losses, environmental pollution, and loss of life. These incidents and the vehicles involved have been studied[13,14,15], to try and gain a better understanding of the reasons for the fires in an attempt to reduce the likelihood of such incidents occurring in the future.

There are clear differences between how fires develop within multi-storey buildings and within multi-decked vessels but there are also some common aspects. These include vehicles being close to one another and low ceilings or decks above the vehicles: important factors when considering how a fire spreads. Another factor is that modern vehicles incorporate greater quantities of combustible elements, such as external plastic trim, that adds to the available fuel which can be ignited with relative ease.

PCC on fire in port © Jacksonville Fire and Rescue Department

## STUDY OF EV FIRES ON BOARD

THE JAPANESE SHIPOWNER NIPPON YUSEN KAISHA (NYK), TOGETHER WITH THE JAPANESE MARITIME DISASTER PREVENTION CENTRE (MDPC) AND THE BRITANNIA P&I CLUB, HAS RECENTLY CARRIED OUT A STUDY TO INVESTIGATE FIREFIGHTING OF EV FIRES ON BOARD PCCs, PCTCs AND ROROs[16]. As part of this project, full scale EV fire testing was conducted on a Nissan Leaf. The testing has shown that when an EV battery pack is subjected to a thermal runaway failure induced by an applied flame, the resulting fire can spread beneath the vehicle within ten minutes to the plastic trim at the wheel arches and other locations which subsequently burn readily, increasing the likelihood of fire propagation to an adjacent vehicle within 15 minutes of the onset of the thermal runaway. [Photographs 1 and 2].

Fire beneath vehicle emanating from lithium-ion battery pack spreads to rear wheel arch.
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Fire spreads from lithium-ion battery pack to wheel arches and front storage compartment.
Reproduced with kind permission of NYK

There are, of course, many variables that can influence the rate of fire spread in a particular incident. Vehicle burn testing has demonstrated that fire in a single vehicle can spread laterally to an adjacent closely parked facing vehicle within about five minutes[13]. Where vehicles were parked in parallel orientations separated by just over a car's width, it has been demonstrated that fires can initially take about 10 to 20 minutes to spread laterally to a second vehicle but, thereafter, the pace of fire spread to a third (or more) vehicle relatively rapidly[13]. For vertically stacked vehicles, such as in a vehicle stacker where the vehicles are separated by no-more than about 0.5 metres, fire can spread from a lower vehicle to the one above in a little over five minutes through ignition of the tyres and plastic trim beneath the wheel arches of the upper vehicle[13].

In tests where a water sprinkler system was utilised, the first of several sprinklers activated within four minutes of the fire starting[13]. However, that alone was not effective at extinguishing the fire within the vehicle where the fire started, which continued to burn for about one hour before it was extinguished by firefighter intervention.

[8]UK Government website portal: www.check-vehicle-recalls.service.gov.uk/recall-type/vehicle/make.
[9]UK Merseyside Fire & Rescue Service 'Kings Dock Car Park Fire' Protection Report April 2018.
[10]RISE Research Institutes of Sweden 'Evaluation of Fire in Stavanger Airport Car Park 7 January 2020' (Rise Report no: 2020:91).
[11]DNV GL 'Fires on RO-RO Decks' April 2005 (Paper no.: 2005-P018).
[12]DNV GL 'Fires on RO-RO Decks' April 2016 (Paper no.: 2016-P012).
[13]UK Department for Communities and Local Government 'Fire Spread in Car Parks' December 2010 (BRE Report no: BD2552).
[14]SP Swedish National Testing and Research Institute 'Model Scale Fire Tests on a Vehicle Deck on Board a Ship' 2002 (SP Report: 2002:05).
[15]Energies 'Experimental Study on the Fire-Spreading Characteristics and Heat Release Rates of Burning Vehicles Using Large-Scale Calorimeter' April 2019. (volume 12, 1465).
[16]Japan Maritime Disaster Prevention Centre 'Marine Firefighting Manual for PCC' March 2021.

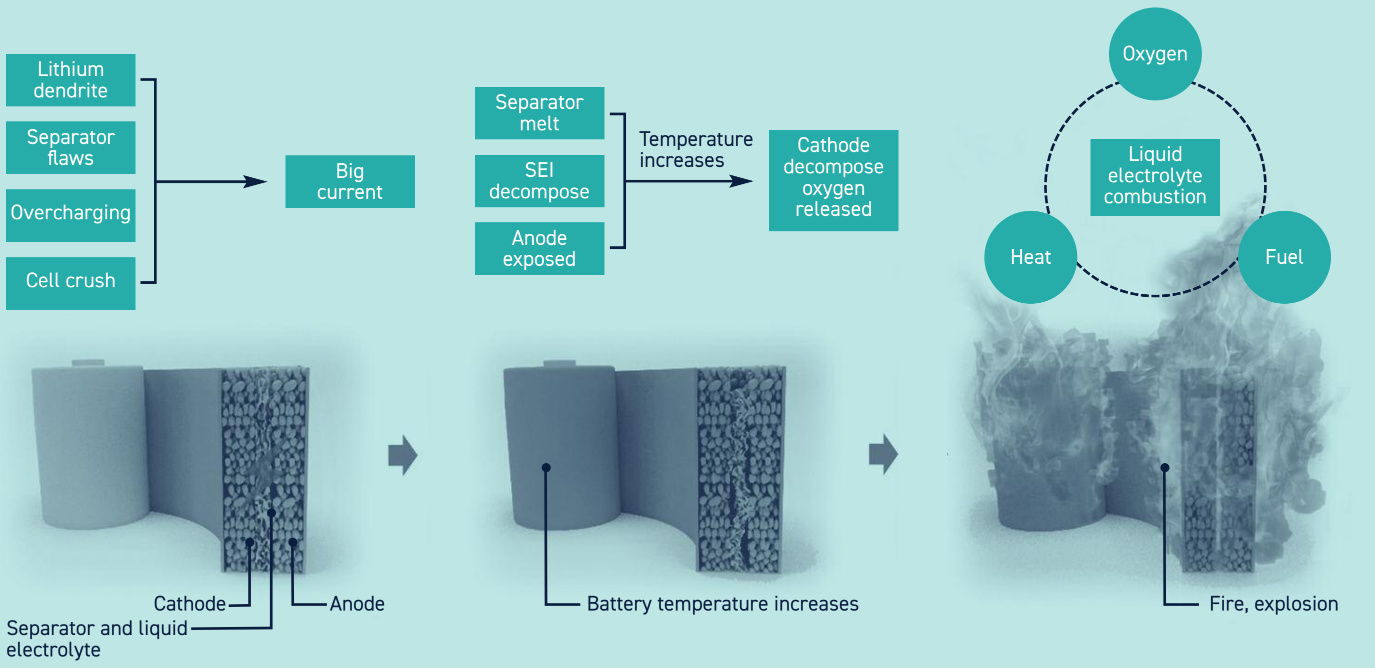
Despite the inability of the sprinkler system to extinguish fire within the protected areas of the vehicle, for example the passenger cabin, the activated sprinklers successfully prevented fire spreading to adjacent vehicles and provided time for firefighters to extinguish the fire while the incident remained reasonably manageable.

For vehicle fires occurring on PCCs, PCTCs and ROROs, where vehicles are parked very close together and on perforated decks within the same fire compartment, rapid lateral and vertical spread of fire from the vehicle of origin to those surrounding it could quickly turn a single vehicle incident into a more serious one. Early fire detection and fire-suppression are therefore of paramount importance.

## CAUSES OF AN EV FIRE

FIRES INVOLVING NUMEROUS EVs HAVE BEEN STUDIED[17] AND A COMMON CAUSE OF EV FIRE INCIDENTS IS DAMAGE TO THE EV BATTERY PACK WHICH ULTIMATELY RESULTS IN CATASTROPHIC FAILURE OF THE EV'S LITHIUM-ION BATTERY PACK VIA THERMAL RUNAWAY. Some mechanisms that can cause damage to the EV battery pack include: thermal stresses experienced during charging and discharging of the battery pack; extreme environmental temperature factors; ingress of water or high humidity; mechanical impact generated during severe collisions (perhaps in a marine setting during instances of significant cargo shifting during storms); electrical abuse; and design or manufacturing defects. Thermal runaway events occur when heat generated within a cell or battery exceeds the amount of heat that can be dissipated into the surrounding environment, causing its temperature to rise.

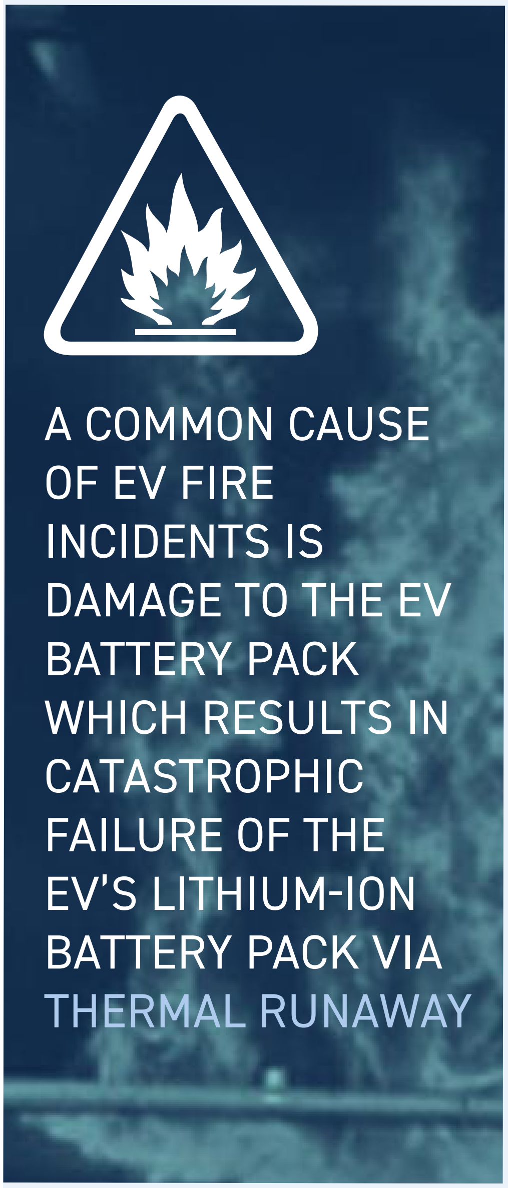
Stages of failure




**Stage 1:** The onset of overheating

**Stage 2:** Heat accumulation and gas release process

**Stage 3:** Combustion and explosion




Thermal runaway events induced in individual cells have been studied and it has been found that there are several stages of exothermic failure[18] involving different elements of the battery at different temperatures. The onset of the first decomposition stage occurs at the anode between about 80° and 90° Celsius. Further decomposition reactions involving the electrolyte occur at the cathode which commence at about 180° Celsius, causing rapid temperature increase of the failing cell. Once initiated, thermal runaway essentially causes the plastic film separator material to become compromised leading to the near instantaneous exothermic electrochemical reaction (short circuiting) between anode and cathode materials in direct contact that were previously intentionally kept apart by the separator[19, 20, 21, 22, 23].

Despite the benefits of lithium-ion battery technology, it has gained notoriety for being able to fail both spectacularly and catastrophically. One reason for this is that the electrolytes currently used in lithium-ion cells and batteries are typically formulated from one or more alkyl carbonates[24, 25], which are ignitable substances that are classified as flammable or highly flammable, or at least would become flammable at elevated temperatures. Based on estimated[26] electrolyte contents of about 10 to 16% of the entire mass of the batteries, a battery pack formed from 150 kilograms of lithium-ion pouch cells is estimated to incorporate about 15 to 24 kilograms of flammable electrolyte, a small proportion of which may be present in new cells as excess liquid electrolyte[27].

For new EVs, each vehicle battery pack is expected to be shipped at a state of charge of about 75% meaning the electrochemical energy stored in, for example, a 30kWh battery would be about 22kWh or 81 mega-Joules. In addition, current designs of EV battery packs contain flammable electrolytes which can contribute a further estimated 200 to 400 mega-Joules via combustion. In comparison, the volume of fuel within each tank of a new ICE vehicle is usually a small proportion of the tank capacity, probably around five litres, meaning the liquid fuel could contribute between about 170 to 200 mega-Joules via combustion.

[17] Fire Technology 'A Review of Battery Fires in Electric Vehicles' 2020 (volume 56,1361 to 1410) and its errata Fire Technology 'Correction To: A Review of Battery Fires in Electric Vehicles' 2020 (volume 43, 1411).
[18] Journal of Power Sources 'Diagnostic Examination of Thermally Abused High-Power Lithium-Ion Cells' 2006 (volume 161,648 to 657).
[19] Nature Communications 'In-Operando High Speed Tomography of Lithium-Ion Batteries During Thermal Runaway' 2015 (volume 6, 6924).
[20] Royal Society of Chemistry 'Investigating Lithium-Ion Battery Materials During Overcharge-Induced Thermal Runaway: An Operando and Multi-Scale X-ray CT Study' 2016 (volume 18, 30912 to 30919).
[21] Journal of the Electrochemical Society 'Tracking Internal Temperature and Structural Dynamics During Nail Penetration of Lithium-Ion Cells' 2017 (volume 164, A3285 to A3291).
[22] Journal of Power Sources 'Direct Observation of Internal state of Thermal Runaway in Lithium Ion Battery During Nail-Penetration Test' 2018 (volume 393, 67-74).
[23] Journal of The Electrochemical Society 'Review – Thermal Safety Management in Li-Ion Batteries: Current Issues and Perspectives' 2020 (volume 167, 140516).
[24] The Electrochemical Society Interface 'How Electrolytes Influence Battery Safety' Summer 2012.
[25] Journal of The Electrochemical Society 'Flammability of Li-Ion Battery Electrolytes: Flash Point and Self-Extinguishing Time Measurements' 2015 (volume 162, A3084).
[26] Royal Society of Chemistry Advances 'Thermal-Runaway Experiments on Consumer Li-ion Batteries with Metal-Oxide and Olivine-Type Cathodes' 2014 (volume 4, 3633).
[27] Journal of The Electrochemical Society 'Amount of Free Electrolyte in Commercial Large Format Prismatic Li-Ion Battery Cells' 2019 (volume 166, A779).

Therefore, the total energy contained within a new EV battery pack is significantly more than usually contained within a new ICE vehicle's fuel tank, an increase that would be multiplied many hundreds or thousands of times during maximum cargo capacity stowage on PCCs, PCTCs and ROROs.

The involvement of an ICE vehicle's fuel tank in a fire would usually result in fuel spillage that would, at least momentarily, increase the intensity of a fire, and quite possibly cause further fire spread laterally or vertically downwards away from the vehicle due to flowing burning liquid. The involvement of a charged EV's battery pack in a fire would cause at least one of the battery's lithium-ion cells to fail, thereafter causing a cascading failure of the battery modules throughout the battery pack[28, 29], resulting in a rapid intensification of the fire. The failing battery cells would release their stored electrochemical energy internally and that would cause heating of the battery materials to several hundred degrees Celsius. That heat would most likely evaporate, boil, or decompose the electrolyte, and ultimately cause the rupture of the cells involved via thermal runaway. The escaping vapours, gases, or volatile decomposition products such as hydrogen, methane, ethane, ethylene, carbon monoxide, and carbon dioxide[30] would be released into the local environment surrounding the EV. If the vapours and gases are within an ignitable range, and if an ignition source is present, an intense fire can result, as is often seen in the many video clips shared on social media[31, 32, 33].

Electrical discharges at the failing battery pack provide viable ignition sources for the escaping gases and vapours, although the heating of the substances within the failing battery to temperatures above their auto-ignition temperature would cause them to spontaneously enflame upon contact with air. The released gases and vapours would more likely than not generate an intense flare of flame. However, if there was an initial local accumulation of the released gases and vapours within a flammable range before ignition, a deflagration (explosion) could occur[34]. Either of those events could potentially spread the fire to a neighbouring vehicle. The potential for oxygen gas to be generated during the catastrophic failure, albeit in limited volumes, could further intensify the fire that is initially produced.

[28] Journal of The Electrochemical Society 'Experimental Analysis of Thermal Runaway and Propagation in Lithium-Ion Battery Modules' 2015 (volume 162, A1905 – A1915).
[29] Journal of Power Sources 'Experimental Investigation of Cascading Failure in 18650 Lithium Ion Cell Array: Impact of Cathode Chemistry' 2020 (volume 446, 227347).
[30] DNV GL 'Technical Reference for Li-Ion Battery Explosion Risk and Fire Suppression' November 2019 (Report no.: 2019-1025, Rev. 4).
[31] https://www.youtube.com/watch?v=sAQlLu5ttOk
[32] https://www.youtube.com/watch?v=Le6KNI9YsH0
[33] https://www.scmp.com/video/china/3136069/electric-bus-bursts-flames-sets-nearby-vehicles-fire-china; https://www.youtube.com/watch?v=T71cVhxG_v4&t.
[34] USA Sandia National Laboratories 'Explosion Hazards from Lithium-Ion Battery Vent Gas' 2019 (Report no.: SAD2019-6428J).

## ARE EV FIRES DIFFERENT TO ICE VEHICLE FIRES?

UNSURPRISINGLY, AN EARLY CONCERN IN RELATION TO EVs WAS WHETHER OR NOT THEY WOULD BEHAVE DIFFERENTLY TO ICE VEHICLES WHEN INVOLVED IN A FIRE. Full scale vehicle burn testing of EVs and ICE Vehicles has shown that fires that start within the passenger space of either type of vehicle behave comparatively similarly[35, 36]. However, the fuel in the tank in ICE vehicles and the battery pack in EVs do give rise to differences in fire behavior and, therefore, there are specific firefighting actions that need to be adopted to manage EV fires safely and successfully.

## FIREFIGHTING FOR EV FIRES

THE INCREASING POPULARITY OF EVs, AND THE EXPECTED FUTURE DOMINANCE OF SUCH VEHICLES, HAS ALREADY LED TO THE DEVELOPMENT OF FIRST AND SECOND RESPONDER SAFETY PROTOCOLS TO ADDRESS GAPS IN RESPONDERS' EDUCATION, AWARENESS AND EXPERIENCE IN HANDLING EV FIRES[37, 38, 39].

Fire suppression by first responder using water fog lance.
Reproduced with kind permission of NYK

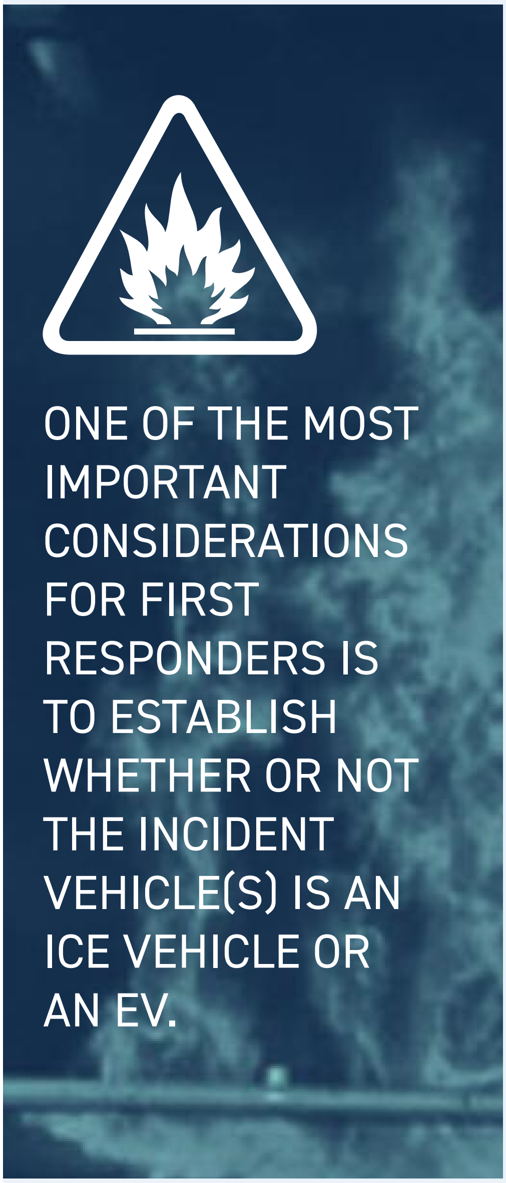
Fire suppression by firefighting team using water fog lances from multiple positions.
Reproduced with kind permission of NYK

These protocols are intended to raise awareness of new hazards, such as high voltage electrical circuits, and highlight the risks faced by those attending EV collision and fire casualties, as well as post incident management.

Following the NYK project, a guide has recently been published by MDPC[16] that sets out tactics and considerations for first and second responders to vehicle fires on car decks, including EV fires. The guide presents firefighting tactics for situations when the fire can be directly accessed from the same deck or when access to the fire is not directly possible except from the decks above or below. The guide also describes how manual firefighting using fog applicators and piercing nozzles could be used to good effect in vehicle firefighting.

The recent tests conducted by MDPC showed that using water fog lances could be used successfully to rapidly extinguish the vehicle fire [Photographs 3 and 4].

[35] Second International Conference on Fires in Vehicles 'Comparison of Fire Behaviors of an Electric-Battery-Powered Vehicle and Gasoline-Powered Vehicle in a Real Scale Fire Test' September 2012.
[36] Second International Conference on Fires in Vehicles 'Comparison of Fire Consequences of an Electric Vehicle and an Internal Combustion Engine' September 2012.
[37] USA National Fire Protection Association 'Alternative Fuel Vehicle Safety Training – Hybrid and Electric Vehicles Module – Student Manual'; USA National Fire Protection Association 'Emergency Field Guide – Hybrid, Electric, Fuel Cell, and Gaseous Fuel Vehicles' 2018.
[38] USA National Transportation Safety Board 'Safety Risks to Emergency Responders from Lithium-Ion Battery Fires in Electric Vehicles' November 2020 (Report no: NTSB/SR-20/01)
[39] Society of Automotive Engineers International 'Surface Vehicle Recommended Practice – Hybrid and EV First and Second Responder Recommended Practice' July 2019 (Report no: J2990).




## FIND OUT WHAT TYPE OF VEHICLE IS INVOLVED

ONE OF THE MOST IMPORTANT CONSIDERATIONS FOR FIRST RESPONDERS IS TO ESTABLISH WHETHER OR NOT THE INCIDENT VEHICLE(S) IS AN ICE VEHICLE OR AN EV. Current advice for first responders is to assume that they are facing an alternative vehicle type (EV) unless demonstrated otherwise. For a vessel carrying new vehicles this might be easier to establish because the vehicle types will be known or the information will be readily available based on the cargo information supplied prior to or at the time of loading. The question may be more difficult to answer for first responders on RORO vessels carrying passenger vehicles or PCCs and PCTCs carrying used vehicles, as there will probably be a mix of ICE vehicles and EVs. While the presence or absence of an exhaust pipe would enable differentiation between ICE vehicles and EVs, it would still not eliminate the possibility of the vehicle being a hybrid vehicle.

## IMMOBILISE/DISABLE THE VEHICLE

ONCE IT HAS BEEN ESTABLISHED THAT THE VEHICLE IS PARTIALLY OR WHOLLY AN EV, THE NEXT STEP FOR FIRST RESPONDERS IS TO TRY AND IMMOBILISE AND, IF POSSIBLE, DISABLE THE VEHICLE. EVs carried on PCCs or PCTCs will be lashed to the decks unless the synthetic fiber straps used have already been compromised by the fire. Firefighting actions will depend heavily on the locus of the fire at the vehicle and whether it has spread to neighbouring vehicles when first responders arrive at the scene. It is important to note that current standard vehicle firefighting equipment and tactics involving water or other common fire extinguishants can still be used[40].

## ELECTRICAL RISKS

THE NEW HAZARD THAT FIRST RESPONDERS TO EV INCIDENTS NEED TO BE ALERT TO IS HIGH-VOLTAGE ELECTRICAL CIRCUITRY. First responders **must** avoid using tools that could inadvertently come into contact with the EV's high-voltage parts, such as its primary wiring harnesses, and must not use tools to forcibly penetrate the outer casing of the battery pack, otherwise personal injuries could result. Before cutting any cables, first responders should refer to the emergency guides for the specific EV for relevant instructions and guidance. In the case of new EVs carried as cargo on PCCs and PCTCs, it would be expected that the manufacturer of the new vehicles supplies such quick reference guides to vessels in advance of loading operations, or for those documents to be otherwise readily available onboard. There may be difficulty in obtaining the manufacturer guides where passenger vehicles or secondary market vehicles are transported. However, in anticipation of this issue, there would be some merit in vessel operators either proactively maintaining a library database on board or asking those having their vehicles transported to provide such documentation in advance.

[40] Energies 'A Review of Lithium-Ion Battery Fire Suppression' 2020 (volume 13, 5117).

## BATTERY CASINGS

IF THE FIRE INVOLVES THE EV's MAIN BATTERY PACK, FIRE EXTINGUISHMENT CAN BE SIGNIFICANTLY HINDERED BY THE TOUGH STEEL CASING SURROUNDING THE BATTERIES WHICH PREVENTS WATER FROM BEING EASILY APPLIED INTO THE BATTERY PACK, MAKING IT HARD TO COOL THE FAILING LITHIUM-ION CELLS. If it is only possible to externally cool the battery pack, then the fire suppression or battery cooling time will be prolonged and could take hours rather than minutes, and copious amounts of water will be needed to do this. If cooling is stopped too soon and the internal content of the battery pack remains hot, then fumes and smoke may continue to be emitted from the battery pack and reignition of those volatile substances can occur.

Flames emitting from the battery pack were persistent.
Reproduced with kind permission of NYK



Fumes are emitting from the lithium-ion battery pack after the passenger space fire has been extinguished.
Reproduced with kind permission of NYK

## POST-FIRE ISSUES

ONCE THE FLAMES HAVE BEEN EXTINGUISHED IT IS STILL IMPORTANT TO DEAL WITH THE BATTERY PACKS AND MANAGE THE INCIDENT AS THERE REMAINS A POSSIBILITY THAT A DECOMPOSING LITHIUM-ION BATTERY PACK CAN GENERATE AN EXPLOSIVE AND/OR TOXIC ATMOSPHERE. EV battery packs also pose a further risk in that damaged battery cells which still retain charge can catastrophically fail hours, days or even weeks after the primary incident was seemingly extinguished. The issue is especially problematic for PCCs, PCTCs and ROROs which may have limited supplies of fixed firefighting foam or carbon dioxide on board, and which could have been used up during the primary incident and so any subsequent fires or explosions may not be properly managed.

The recent tests conducted by MDPC also found that the battery pack was difficult to extinguish and it remained hot after the cabin fire was extinguished [Photographs 5 and 6], which aligns with other published findings[38]. The cessation of water fog spray at a battery module resulted in eventual reignition of the vapours, gases and decomposition products emitting from it.


A firefighter spraying water into a battery pack during overhaul of a burnt EV.
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It was only when water could be added into the EV's battery pack, via its safety vent plug which is accessible from within the passenger space, that the battery pack was able to be successfully cooled from over 300º Celsius to below 50º Celsius [Photograph 7]. It is apparent from temperature data [Figure 1] logged by MDPC during the fire test that after the spraying of water into the battery pack was stopped, the internal temperature of the battery rose rapidly again to about 100º Celsius at which point it plateaued. The data indicates that the internal temperature of the battery pack was probably being moderated by the boiling/evaporation of water, and that additional water would be required to be sprayed into the battery pack at regular intervals until the battery had fully dissipated its stored electrochemical energy as heat. It is evident that the ability of a lithium-ion battery pack to remain internally hot due to difficulties in physical cooling of the internal components presents a particularly problematic firefighting consideration, especially if multiple EV battery packs become involved in a major fire incident.

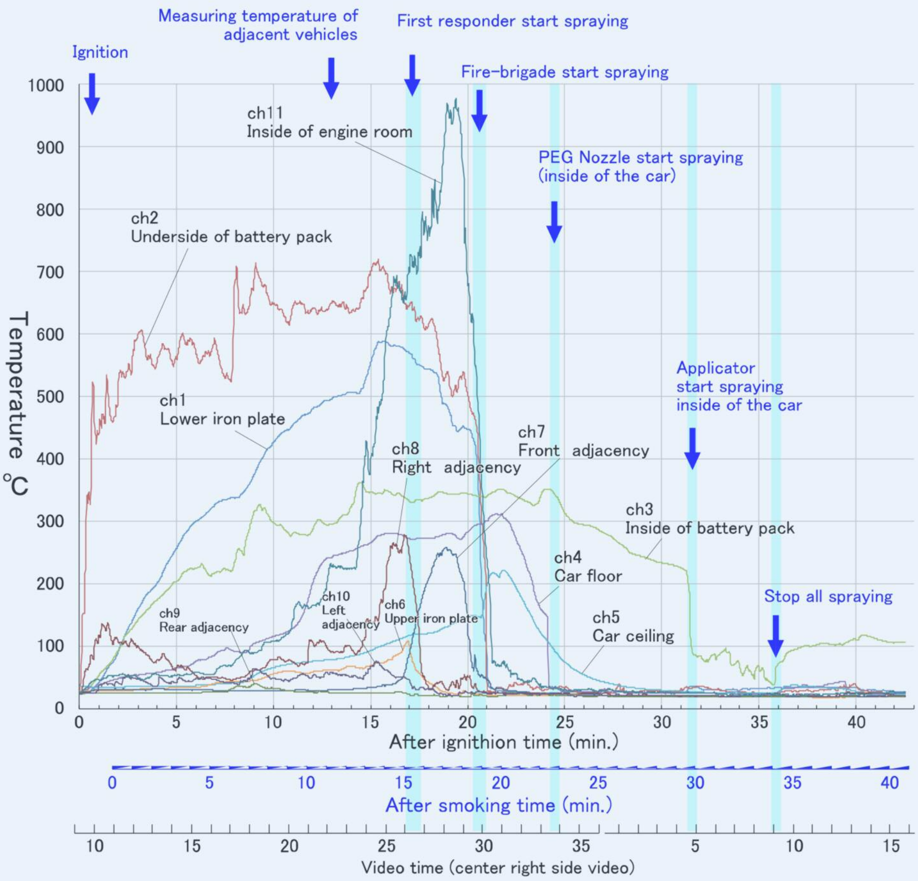


Figure 1: Temperature data recorded during full scale burn and fire extinguishment test.
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THE RISE OF THE 'BATTERY-AGE' AND THE INCREASING POPULARITY OF EVS PRESENTS A NUMBER OF NEW HAZARDS AND RISKS.

## FUTURE DEVELOPMENTS TO MITIGATE RISKS

THE RISE OF THE 'BATTERY-AGE' AND THE INCREASING POPULARITY OF EVs PRESENTS A NUMBER OF NEW HAZARDS AND RISKS. However, these developments also present opportunities which have the potential to lower the risk of fires on PCCs, PCTCs and ROROs. Some of these opportunities are set out below:

### BATTERY TECHNOLOGY

Improved battery technology will, over time, be anticipated to decrease the risk of battery fires. Improvements to the design, construction and materials used in batteries[41, 42, 43], the installation of sensors within a battery to monitor internal thermal condition[44], even adjustments[45, 46] or drastic changes to the battery chemistries[47], may all reduce the likelihood of catastrophic faults occurring. Replacement of the flammable alkyl carbonate electrolytes by non-flammable alternatives[48, 49] could also reduce the likelihood of catastrophic battery failure culminating in an intense fire.

### TESTING AND REGULATION

Together with technological advances, the development of more rigorous global regulatory standards, and also improved battery testing protocols before commercialisation, will be expected to help reduce the risks of EV battery fires.

### FIRE DETECTION

Adoption of existing or new fire sensing technologies on board PCCs, PCTCs and ROROs should improve the success of early stage fire detection, a crucial advantage that will allow the fire to be extinguished before it gets out of control[50]. For example, using thermal imaging cameras and/or carbon monoxide gas detectors should allow fires to be detected and then assessed at an earlier stage. At present it is not possible to use such technologies on ships carrying ICE vehicles as well as EVs, because exhaust systems and emissions from ICE vehicles could cause the camera systems and sensors to activate even when there was no actual fire. Of course, if the ship carried purely EVs then these new technologies could be put in place.

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[41] iScience 'Current and Future Lithium-Ion Battery Manufacturing' 2021 (volume 24, 102332).
[42] Cell Reports Physical Science 2 'Prevention of Lithium-Ion Battery Thermal Runaway Using Polymer-Substrate Current Collectors' March 2021 (100360).
[43] Science Advances 'Materials for Lithium-Ion Battery Safety' 2018 (volume 4, eaas9820).
[44] Nature Scientific Reports 'Lithium-Ion Battery Thermal Safety by Early Internal Detection, Prediction and Prevention' September 2019.
[45] American Chemical Society Energy Letters 'How Comparable Are Sodium-Ion Batteries to Lithium-Ion Counterparts?' 2020 (volume 5, 3544-3547).
[46] American Chemical Society Chemical Reviews 'Promises and Challenges of Next-Generation "Beyond Li-Ion" Batteries for Electric Vehicles and Grid Decarbonisation' 2021 (volume 121, 1623-1669).
[47] Journal of Power Sources 'A Perspective on Organic Electrode Materials and Technologies for Next Generation Batteries' 2021 (volume 482, 228814).
[48] Journal of The Electrochemical Society 'Non-Flammable Inorganic Liquid Electrolyte Lithium-Ion Batteries' 2020 (volume 167, 070521).
[49] Batteries 'Recent Advances in Non-Flammable Electrolytes for Safer Lithium-Ion Batteries' 2019 (volume 5, 19).
[50] Bureau Veritas RISE Stena 'Firesafe II' WP1 – WP4 series of reports December 2018.

## FIREFIGHTING TECHNOLOGY

At present, fires are usually suppressed and extinguished using fixed carbon dioxide or water-foam systems, supplemented by traditional seawater firefighting hoses and lances. This firefighting approach is reactionary in that it is only used when the emergency arises, and at this stage it may already be too late. Active fire-suppression, such as the protection of spaces using hypoxic (oxygen-reduced) atmospheres[51] through use of nitrogen gas generators, is increasingly being used to protect historic, sensitive, computer server and high-value facilities, as well as inerting chemical tanks, and could be adopted on all vessel types to supplement the existing standard reactive carbon dioxide, water-foam and water firefighting options. An advantage of an active hypoxic, nitrogen-enriched atmosphere is that the fire suppressing media can be continually generated from air.

Alternative fire suppression technologies that might also be considered could involve covering a burning vehicle in a large fire blanket to contain any flames and suffocate the fire or at least suppress the fire until water resources can be put in place. This technology has already been successfully demonstrated in conventional scenarios[52], and even on a burning EV[53]. The evaluation of the suitability of their use in a maritime environment, perhaps with tweaks to take account of PCC, PCTC and RORO settings, might also prove a useful addition to available, rapidly deployable, firefighting resources and could benefit from further research and development.

## POST-INCIDENT DANGERS

After a fire, damaged EVs need to be suitably managed as it is known that fires from damaged lithium-ion batteries can re-start hours, days or even weeks after the initial fire thus putting the vessel in further danger until the damaged EVs are discharged. In those situations where a vessel has already depleted its carbon dioxide or water-foam resources, such secondary fires could prove catastrophic for the vessel. Yet again, the adoption of hypoxic atmospheres and the ability of the vessel to generate them from air at will, and/or the use of vehicular sized fire blankets, might prove their worth during post incident management of EV fires.

[51] USA National Fire Protection Association Research Foundation 'Review of Oxygen Reduction Systems for Warehouse Storage Applications' November 2018.
[52] The Korean Institute of Fire Science & Engineering 'Application of Car Fire Blankets to Car Fires' 2021 (volume 35, 143-149); www.youtube.com/watch?v=L4wwBo1irFo&t; www.youtube.com/watch?v=SJnLTvvYUWE.
[53] Centro Zaragoza Instituto De Investigation Sobre Vehiculos S.A. Magazine 'A Prueba la Innovación en la Lucha y Prevencion de Incendios en Vehículos' [To Test the Innovation in the Fighting and Prevention of Fire in Vehicles] (volume 83, 26-29) March2020; www.youtube.com/watch?v=yO8cVWOqZcg&t.

# EVS ARE LIKELY TO DOMINATE THE FUTURE OF CARGO TRANSPORTED ON PCCs, PCTCs AND ROROs.

**CONCLUSION**

ULTIMATELY, EVs ARE LIKELY TO DOMINATE THE FUTURE OF CARGO TRANSPORTED ON PCCs, PCTCs AND ROROs, BUT THE RAPID ADOPTION OF THESE VEHICLES WILL RESULT IN DIFFERENT HAZARDS AND RISKS AFFECTING THE SAFETY OF SHIPS AND THEIR CREWS. Anticipated improvements to battery technology will not completely eliminate the risk of a fire. Accordingly, fire detection, fire suppression and firefighting strategies and tactics on board PCCs, PCTCs and ROROs will all need to evolve in tandem with the new technologies developed.


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