Hazard Assessment of Battery Energy Storage Systems

Technical Note 45

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1 INTRODUCTION

1.1 Scope

HSENI is aware of the hazards associated with large scale lithium-ion Battery Energy Storage System (BESS) sites. Consideration has been given to whether such sites should come under the COMAH and Hazardous Substances Consent Regulations, and following discussions with COMAH colleagues in HSE and HSA the view is that batteries alone would not bring a facility under COMAH (as batteries are regarded as articles and not dangerous substances under CLP).

Nevertheless, HSENI is still interested in the consequences of a fire in a battery container unit as there may be a need for HSENI to provide advice to Local Planning Authorities, comment on an environmental assessment, provide advice to fire fighters or review an operator's own risk assessment.

HSENI is aware that this is a relatively new area, with little available guidance, and has therefore requested that Atkins provide some initial advice based on the following scope:

- Review of incidents involving lithium-ion battery energy storage sites (and manufacturing sites)
- Review of technical papers/information, concentrating on any information relevant to major accident hazards
- Consideration of fire load (associated with the electrolyte)
- Consideration of potential for flammable vapour explosion
- Assessment of HF dispersion toxic hazard ranges to DTL/IDLH using ADMS
- Brief consideration of washout/deposition from fire plumes
- Brief consideration of firewater run-off issue (environmental hazard)
- Summary of key issues

It is emphasised that this Technical Note is only intended to provide brief advice in most of the above areas, and that in some areas there is very little available good information. HSENI has indicated that their main concern is the firefighter who could be facing a fire at one of these facilities, and therefore their principal interest is in the potential toxic fire plume, and potential explosion, associated with a single BESS container. This Technical Note therefore concentrates on those areas.

It is recognised that this has been a rapidly developing area over the last few years, and so the information presented in this Technical Note would benefit from regular review.

1.2 Background

A recent issue of Energy Storage News (11 January 2021) summarises the key hazards for firefighters:

> *Energy storage is a relatively new technology to fire departments across the US. While different fire departments have differing levels of exposure to battery energy storage systems (or BESS for short), the primary concern of each is the same: the safety and well-being of their first responders.*
>
> *Departments and local officials are, however, becoming increasingly aware of the hazards associated with battery storage and it is important that their concerns be properly addressed. Addressing these concerns in a complete and transparent manner has been seen not only to promote overall first responder safety but also to ensure project success. Perhaps the most defining characteristic of lithium-ion battery failures is a state known as 'thermal runaway', in which a battery cell experiences uncontrollable overheating, often accompanied by the release of large quantities of flammable off-gases.*
>
> *Thermal propagation from the failing cell may lead to incipient thermal runaway of adjacent cells, thus creating a cascading failure across the system, resulting in tremendous amounts of heat and gas. When these gases are allowed to accumulate in an enclosed space (such as a BESS container), an explosive atmosphere may develop, which, given an ignition source, may lead to a devastating deflagration (explosion) event. This blast wave can cause damage to nearby buildings and structures, as well as first responders who may be arriving on the scene, as was seen in the incident that unfolded in Arizona in 2019. Deep-seated fires are also common in lithium-ion failure events. These fires are not easily extinguished and may continue for hours, fuelled by heat and gas from cascading cell failures. Even if*

suppressed by water, stranded energy within the cells often causes reignitions, thus perpetuating the event.

Concerns based on environmental risks are also often cited by fire departments across the country. Large quantities of smoke and gas are often released during battery fires, with high levels of carbon monoxide and hydrogen cyanide measured on-site in Arizona at the time of the incident. Contaminated runoff water may also affect the surrounding area. Electrical hazards also exist during and after battery failure events and should not be overlooked.

2 REVIEW OF INCIDENTS

This section provides a brief review of incidents involving lithium-ion cells, and key lessons learned in terms of major hazard assessment. It is not intended to be comprehensive, but highlights important events such as the 2019 McMicken (Arizona) BESS explosion.

2.1 Incidents Involving Single Cells

Many billions of individual lithium-ion cells have been produced worldwide over the last 30 years, and there have been thousands of incidents which have been potentially hazardous. Many of these have been well reported in the press, and some have led to major product recalls. The majority of these incidents relate to Thermal Runaway (TR) events due to a short circuit within a cell between the anode and cathode. Such events are often apparently spontaneous and the precise cause of the short circuit is often not clear. Common causes can include:

- Impact/vibration/penetration
- Manufacturing defect
- Failure of the battery management system
- Overheating
- Overcharging
- Undercharging

It is also noted that as the widespread use of such cells has grown very rapidly, there is relatively little data on incidents that may be related to aging for current cell designs.

Incidents are generally most severe when a cell has a high State of Charge (SOC). Any major failure of a charged cell can lead to the rapid and energetic ejection of the electrolyte liquid, as a short (e.g. 1 to 2 m long) jet flame. It is noted that such failure events with charged cells are highly likely to ignite, but there are also situations where cascading thermal runaway can occur due to heat transfer between cells without any ignition, due to the highly exothermic nature of the thermal runaway.

The precise nature of an incident may depend on the cell size and whether the cell is cylindrical, pouch or prismatic. Large pouch cells are generally used in large scale BESS container units.

2.2 Incidents at BESS Facilities

Table 2-1 lists a number of incidents which have occurred at BESS facilities.

Table 2-1 Incidents at BESS Facilities

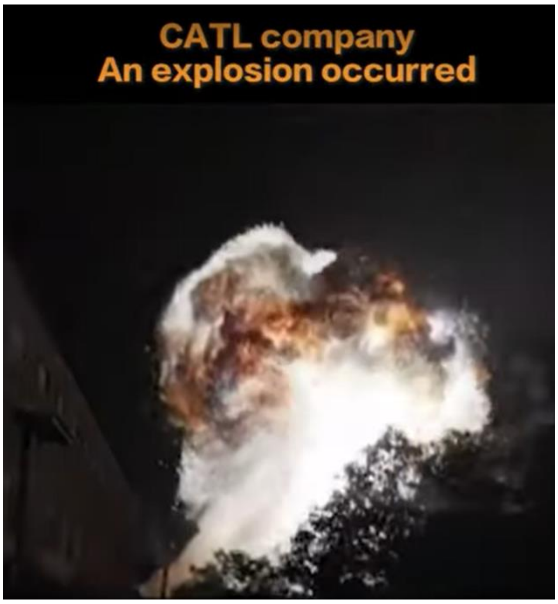
Location (Company)	Date of Incident	Description of Incident
Arizona, USA (Arizona Public Service Company)	Nov 2012	In November of 2012, a fire occurred at a state-of-the-art solar energy storage system that the Arizona Public Service Company (APS) was testing. The system, the relative size of a shipping container with a capacity of 1.5 MW, had been running since February of 2012. Similar to the First Wind fires, the fire department personnel allowed the fire to burn freely for some time. The cause of the fire was not reported. Ref. Blum and Long (2016)
Unknown	2014	A fire in a Li-ion battery storage unit caused an explosion that seriously injured fire fighters. Ref. Ronken (2017)
Yeongju, South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Cheonan, South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Geochang South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Munyeong, South Korea	Nov 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)

Location (Company)	Date of Incident	Description of Incident
South Korea Jecheon	Dec 2018	Fire at lithium-ion peak load reduction plant. Ref. INERIS (2021)
Samcheok, South Korea	Dec 2018	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Yangsan, South Korea	Jan 2019	Fire at lithium-ion peak load reduction plant. Ref. INERIS (2021)
Wando, South Korea	Jan 2019	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Jangsu, South Korea	Jan 2019	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
Ulsan, South Korea	Jan 2019	Fire at lithium-ion peak load reduction plant. Ref. INERIS (2021)
Chligok, South Korea	May 2019	Fire at lithium-ion PV power plant. Ref. INERIS (2021)
McMicken Substation, Surprise, West Valley, Arizona, USA (Arizona Public Services)	19/4/2019	The incident occurred at two twinned grid-scale energy storage systems of 2 MW / 2 MWh at the McMicken substation. The explosion caused a “significant pressure wave” resulting in the injuries of four firefighters. Technical analysis by certification and standards group DNV GL indicated that the event had begun with internal cell failure in a single LG Chem 0.24 kWh pouch cell in the ESS. The fire suppression system onsite worked as designed, but it was inadequate to prevent or stop the cascading thermal runaway. Heat transfer between the cells in a module, and then between modules, in one of the battery racks caused the thermal runaway to propagate - facilitated by the absence of “adequate thermal barrier protections between battery cells,” which could have stopped or slowed the propagation. Whilst the incident was at first thought to be a fire, it was in fact a cascading thermal runaway from a single cell, through every other cell in the module, and then through all the modules in Rack 15 via heat transfer. It took around two hours from the first report of a suspected fire at the facility, at 17:48 local time on 19 April 2019, to around 20:04 before an explosion happened from inside the BESS. The BESS and its container were “essentially destroyed” and the incident left several firefighters injured. On the day of the incident, the BESS was performing solar smoothing applications - charging during the daytime from local solar generation and discharging electricity to the grid during the evening peak load. Data collected by APS found that just before 5pm on 19 April, there was a sudden drop in voltage during one of the system’s charge cycles. Thermal runaway began shortly after that. Smoke detection systems went into operation but off-gassing of battery cells as the thermal runaway cascaded through neighbouring modules caused a “flammable atmosphere within the BESS,” the DNV GL report said. Then, when firefighters opened the side container door around three hours after thermal runaway began, an explosion occurred within 2-3 minutes, causing the side and rear doors of the BESS as well as other debris to be ejected by the explosion. It is thought that opening the doors agitated flammable gases that remained and brought the gases into contact with a spark or heat source - causing the explosion. Ref. McKinnon, DeCrane and Kerber (2020) – Detailed incident report. DNV GL (2020) – Technical incident report. Energy Storage News (23 April 2019, 29 July 2020, 12 March 2021, 25 March 2021)

Location (Company)	Date of Incident	Description of Incident
Carnegie Road, Liverpool, England (Ørsted) See Figure 2.1	15/9/2020	Large grid battery system container fire at 20 MW BESS site which lasted several hours. Merseyside Fire & Rescue Service, local first-responders, said that crews were alerted shortly before 1am on 15 September and arrived to find a “large grid battery system container well alight”. A "massive bang" was heard as fire crews rushed to tackle the blaze. One resident said he "heard an explosion after midnight" while another said their house "shook”. Five fire engines were immediately on the scene after being alerted at 12.52am to reports of a blaze on Carnegie Road in Tuebrook. The fire service said that it had used main jets and ground monitors in tackling the fire, asking residents nearby to keep their windows and doors closed due to smoke from the incident. The blaze went on for several hours, with an update from the service at 7:30am noting that although operations at the site had been scaled down, firefighting was ongoing, with two ground monitor units and a main water jet still in use. A further update at 11:45am said one fire engine was still at the scene, with firefighting still continuing, although by that stage only one hand-held pump was in use. It was reported that the explosion caused a “significant pressure wave”, causing debris to be thrown between 6 and 20 metres away according to the fire department’s response report. The environmental impact from firewater runoff was also a major concern. Ref. Energy Storage News (16 September 2020 and 25 March 2021) • [redacted]
Ningxiang, Hunan Province, China (CATL Brunp Recycling Technology plant) See Figure 2.2	7/1/2021	Explosion and fire occurred at one of the old workshops of the battery recycling plant - 1 person was killed and 6 were seriously injured. CATL is a battery supplier to Tesla. • [redacted]

Figure 2.1 Incident at Carnegie Road, Liverpool (15/9/2020)

Figure 2.2 Incident at Ningxiang, Hunan Province, China (7/1/2021)



It is noted that there have been many incidents in Asia relating to BESS facilities, but details are generally scarce or unavailable.

2.3 Incidents at Battery Manufacturing Facilities

Table 2-2 lists a number of incidents which have occurred at battery manufacturing facilities.

Table 2-2 Incidents at Battery Manufacturing Facilities

Location (Company)	Date of Incident	Description of Incident
Koriyama City, Japan	4/11/1995	An explosion occurred at a Sony battery factory in Koriyama City, Japan, where cylindrical lithium-ion batteries for notebook PCs were manufactured. The fire occurred on the floor where batteries underwent final testing. Cells in this location were stored in racks 4-high under ambient temperature conditions. Ultimately, approximately 3 million cells burned, 7,000 m^2 of facility was damaged and two people were injured. Ref. Mikolajczak et al (2011)
Moriguchi, Osaka, Japan (Matsushita Battery Industry Factory)	Aug 1997	An explosion occurred at the Matsushita Battery Industry factory in Moriguchi, Osaka. The owner of the factory, T&T Dream, was a subcontractor for Matsushita. The factory carried out charge/discharge and check processes of cylindrical lithium-ion batteries. Cells in this location were stored on thirteen layers under ambient temperature conditions. Ultimately, approximately 1.22 million cells burned, 1,700 m^2 of facility was burned, buildings within a 175 m radius were damaged, and two people were injured. Ref. Mikolajczak et al (2011)
Karlstein, Germany (BMZ)	Aug 2008	A fire occurred at Batterie-Montage-Zentrum (BMZ) in Karlstein, Germany. The fire destroyed a production area and a warehouse. Ref. Mikolajczak et al (2011)
Pawcatuck, Connecticut, USA (Yardley Technical Products)	Sep 2008	A large format lithium-ion battery that was undergoing testing at Yardney Technical Products in Pawcatuck Connecticut caught fire. Ref. Mikolajczak et al (2011)
Dongguan City, China	2014	Fire in a lithium-ion battery factory in Dongguan City in China, which caused 5 deaths and 6 injuries. Ref. Niu and Li (2018)
China (Samsung SDI battery manufacturing facility)	8/2/2017	The fire occurred in the battery waste area of the factory, after faulty lithium-ion batteries went up in flames. • [redacted]
North Phoenix, Arizona, USA (Gruber Motor Company)	6/5/2017	Pallet of Li batteries caught fire and 5 minutes later the whole building was burning, producing toxic smoke which spread all over the north valley and forced evacuation of nearby buildings. • [redacted]
Peera Garhi, New Delhi India See Figure 2.3	2/1/2020	Battery factory collapses after explosion in fire during firefighting operations – killing 1 and injuring 19 other firefighters. • [redacted]

Figure 2.3 Incident at Peera Garhi, New Delhi, India (2/1/2020)

The incidents in Table 2-2 show that major incidents at battery manufacturing facilities are most likely to occur in the Formation, Aging and Testing stage, where large numbers of cells are being charged for the first time. Such events are less likely at BESS sites as the cells have been through all the necessary testing, but the nature of the potential incidents is similar due to the large number of cells present.

2.4 Other Incidents

Table 2-3 lists a number of incidents which have occurred at other facilities.

Table 2-3 Incidents at Other Facilities

Location (Company)	Date of Incident	Description of Incident
Germany	2017	A major fire broke out in a bicycle warehouse in Germany that also contained a large number of electric bicycles with Li-ion batteries. It proved an extraordinary challenge for the fire brigade and ultimately resulted in a total loss in the warehouse. Four employees suffered minor injuries. Ref. Ronken (2017) • [redacted]
Lyons Park industrial estate, Coventry, England	20/2/2020	Factory storing Li batteries goes up in flames. • [redacted]

Mikolajczak et al (2011) also lists a number of air transport incidents involving lithium-ion batteries.

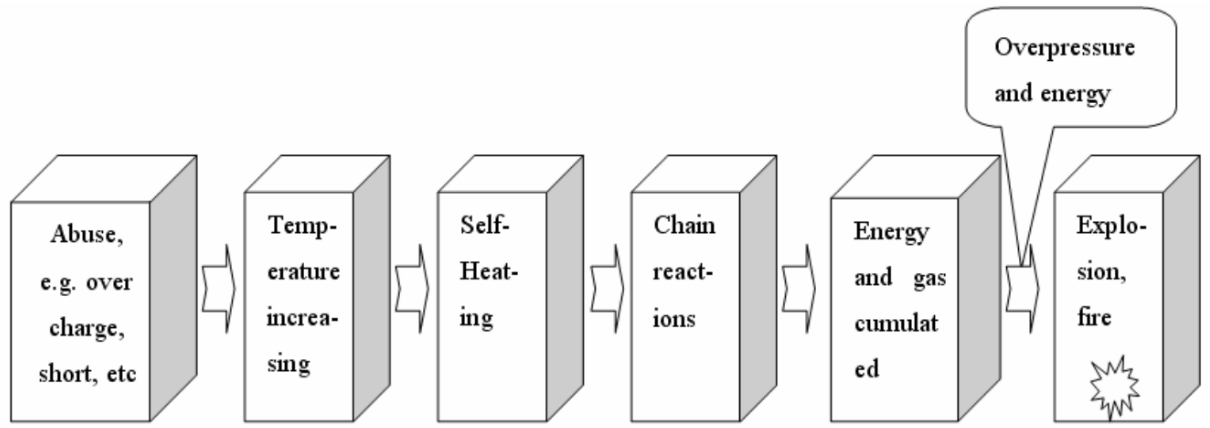
3 REVIEW OF LITERATURE

This section presents a brief literature review concentrating on information which is relevant in terms of major hazard safety issues.

3.1 Published Papers and Reports

Wang, Sun & Chu (2005) provide an overview of how lithium-ion cells can fail, leading to fire and explosion.

Figure 3.1 Development of Cell Failure (Wang, Sun & Chu, 2005)



Ditch and de Vries (2013) and **Ditch (2014)** describe a detailed study of the flammability characterisation of lithium-ion batteries in bulk storage, which tested the effectiveness of sprinklers and measured heat release rates etc. The overall goal was to develop sprinkler protection recommendations for bulk storage of Li-ion batteries. The test results show that fires can develop rapidly, reaching heat release rates of several MW for a single pallet of batteries.

Mikolajczak et al (2011) present a literature review of battery technology, failure modes and events, usage, codes and standards, and a hazard assessment during the life cycle of storage and distribution. The failure modes and root causes are discussed, together with information on flammable cell components and the fire behaviour of cells and battery packs. Key gaps in knowledge, such as the vent gas composition, are identified.

Blum and Long (2016) summarise a literature review and gap analysis related to Li-ion battery ESSs, as well as full-scale fire testing of a 100 kWh Li-ion battery ESS. The overall objective was to help enable the development of safe installation requirements and appropriate emergency response tactics.

Larsson, Andersson, Blomqvist and Mellander (2017) provide a useful study of toxic fluoride emissions from lithium-ion battery fires. It is shown that lithium-ion battery fires generate intense heat and considerable amounts of gas and smoke. It is noted that although the emission of toxic gases can be a larger threat than the heat, the knowledge of such emissions is limited. The paper presents quantitative measurements of heat release and fluoride gas emissions during battery fires for seven different types of commercial lithium-ion batteries. The results are validated using two independent measurement techniques and show that large amounts of hydrogen fluoride (HF) may be generated, ranging between 20 and 200 mg/Wh of nominal battery energy capacity. In addition, 15 to 22 mg/Wh of another potentially toxic gas, phosphoryl fluoride (POF_3), was measured in some of the fire tests. Gas emissions when using water mist as an extinguishing agent were also investigated. It is concluded that fluoride gas emission can pose a serious toxic threat and the results are crucial findings for risk assessment and management, especially for large Li-ion battery packs. The paper states that:

> *If extrapolated for large battery packs the amounts would be 2–20 kg for a 100 kWh battery system, e.g. an electric vehicle and 20–200 kg for a 1000 kWh battery system, e.g. a small stationary energy storage. The immediate dangerous to life or health (IDLH) level for HF is 0.025 g/m^3 (30 ppm) and the lethal 10 minutes HF toxicity value (AEGL-3) is 0.0139 g/m^3 (170 ppm). The release of hydrogen fluoride from a Li-ion battery fire can therefore be a severe risk and an even greater risk in confined or semi-confined spaces.*

Ronken (2017) also describes the risks and safety measures required for lithium-ion batteries, and emphasises the importance of a suitable risk assessment. Several incidents are also identified (see Section 2.2).

Niu and Li (2018) describe a fire risk assessment method for use in lithium-ion battery factories, and summarise the key areas where fire risks are significant, based on experience with such facilities in China. It is suggested that in the event of a short circuit, lithium can react with the various electrolyte components (ethylene carbonate, propylene carbonate, dimethyl carbonate) to form flammable gases such as propene (C_3H_6). A risk matrix is used to assess all stages of the battery manufacturing process. Several events are identified as likely to result in severe injury, but none are identified as likely to result in death. Serious events such as the spontaneous ignition of batteries in storage are identified as unlikely to happen in a lifetime.

Finegan et al (2019) describe detailed experiments where internal short circuits (ISCs) were caused in cylindrical 18650 cells. These ISCs cause the Li-ion battery to fail catastrophically due to thermal runaway. That is, at a critical temperature and in the presence of non-aqueous liquid electrolytes and oxygen, the active materials within a Li-ion battery can exothermically react. Exothermic reactions can become self-sustaining when local heat generation is greater than heat dissipation, resulting in violent combustion and total cell failure. During thermal runaway, it is estimated that about 2 litres of gas is generated per amp hour (Ah) of commercial $LiFePO_4$ and $LiNi_xCo_yAl_zO_2$ 18650 cells. It is noted that modern 18650 cells have capacities greater than 3 Ah, and can generate more than 6 litres of gas within about 2 seconds during thermal runaway, which is mostly flammable. In this short time (< 2 seconds), more than 70 kJ of heat can also be generated.

The Department for Business, Energy & Industrial Strategy (BEIS, 2020) reviewed the safety risks associated with domestic battery energy storage systems. The authors state that even though few incidents with domestic battery energy storage systems (BESSs) are known in the public domain, the use of large batteries in the domestic environment represents a safety hazard. Three hazard categories are identified:

- Excessive heat generated deep inside a battery pack as cells fail and thermal runaway propagates through the pack, highlights the need to design packs to minimize risk for propagation and limit spread of fire between cells/modules. Early detection and means for cooling individual cells as they begin to fail are important for avoiding thermal runaway of the full system.
- Cell and pack failures can generate large volumes of gases resulting from the rapid pressure build-up and vent release as the system heats up. Management of gases generated must be considered in pack and system design.
- The toxicity of gases generated from battery fires may require specific consideration in the design of ventilation systems.

Key considerations regarding risk mitigation are summarised as:

- The Battery Management System (BMS) has a central role in keeping cells within their operating window for voltage, current and temperature. BESS safety standards have specific requirements and tests which apply for the BMS.
- Internal cell faults, though rare, do occur. For well-constructed 18650 cells, the failure rate from an internal event is estimated as one in ten million (0.1 ppm). This translates to a single cell failure in every 10,000 BESS (assuming a 5 kWh BESS containing 500 18650 cells). This is not to say that 1 in 10,000 BESSs will fail, with significant risk of fire. Proper BESS design and construction should be capable of preventing propagation of cell failure across the battery pack. A single cell failure should be controllable.
- If the system is well designed, it should take into consideration propagation of a thermal event arising from a single cell. This is of great importance for the risk mitigation and will have a large impact on the overall risk assessment for the system. Control of single cell failures within a pack reduces the risk of complete system failure and residential fire. Assessment of cell failure propagation is captured in the standards applicable for domestic lithium-ion battery storage systems such as BS EN 62619 and IEC 62933-5-2.

The BEIS report also provides some statistics for the likelihood of failures, although it doesn't deal with large scale BESS installations. Hydrogen fluoride, CO and CO_2 are all identified as potential toxic combustion products following a thermal runaway. The potential for an explosion is also mentioned, either as a result of a cell failing violently due to an internal build-up of pressure, or as a result of ignition of flammable gases released from a cell. The total heat released during total combustion of lithium-ion batteries ranges from 30 to 50 kJ/Wh, or 4 to 10 MJ/kg, which is about 5-10 times less than for organic materials like plastic or paper. No projectiles were observed in any full scale testing of larger racks of batteries for energy storage systems. The violence of thermal runaway, and the gas volume generated, tends to increase with SOC.

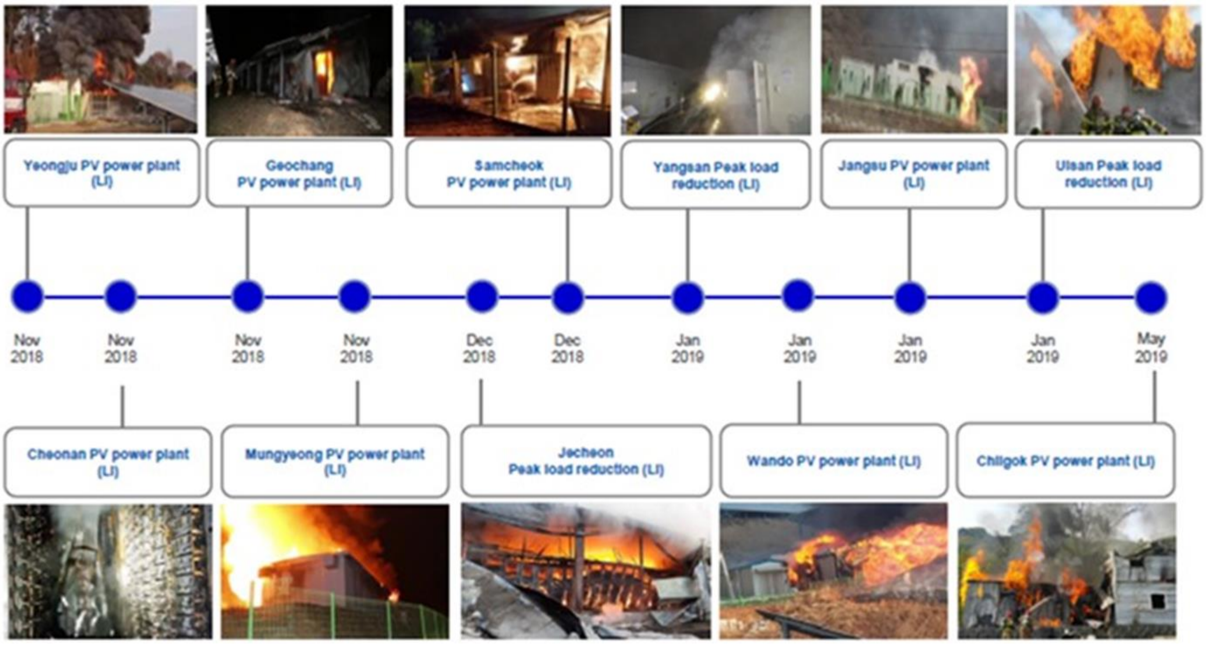
The BEIS report discusses the vent gases that can be generated, including volatile organic compounds (such as alkylcarbonates, methane, ethylene and ethane), hydrogen, carbon monoxide, carbon dioxide, soot and other particulates containing nickel, cobalt, lithium, aluminium, copper. The authors note that a major point of discussion is the amount of HF and other fluorinated compounds found in vent gases, because of their toxicity, and that this is still an open question. Some tests have indicated HF concentrations well in excess of 100 ppm.

Diaz et al (2020) provide a comprehensive review of fire safety information for lithium-ion batteries. The authors note that the majority of research has considered single cells, and there is much less safety information relating to larger scale fires involving pack, modules, or large numbers of cells. The review includes information on the various challenges faced by the industry, including detection and reliability issues and emergency response challenges. The use of water for fire fighting appears to be preferred, although there are still issues with reignition.

Rosewater et al (2020) presents a systematic hazard analysis of a hypothetical, grid scale lithium-ion battery powerplant to produce sociotechnical 'design objectives' for system safety. This includes key considerations for firefighter training objectives.

INERIS (March 2021) recently presented an overview of the lithium-ion cell assessments and modelling that they are currently undertaking in France. The presentation included brief details of fires at large scale energy storage sites in South Korea, as illustrated in Figure 3.2.

Figure 3.2 Examples of Fires at BESS Sites in South Korea (INERIS, 2021)



It was concluded that there was no single root cause for these events.

INERIS noted that there have been similar fires in Belgium, UK, France, US (Arizona) and Australia. A number of issues and uncertainties were identified in relation to fire protection and firefighting for such sites:

- Fixed fire fighting systems: water (sprinklers, water mist)?, Foam?, Inert gas?, Others?
- Fire fighter capacities for such a fire: drowning a battery container in water is not really an option
- Safety aspect of emergency response: gas toxicity and explosivity

One conclusion from their presentation was that the toxic combustion products from a small fire involving a lithium-ion battery are generally not significantly more hazardous than a comparable sized fire with packaging and plastics etc. However, for a large fire involving many lithium-ion cells, the view expressed was that the HF vapour was the most significant toxic concern.

3.2 Project Specific References

HSENI has provided several documents which relate to BESS sites. These are considered briefly below in terms of the key data which is relevant in terms of the assessment of major hazards.

Haigh (2020) provides an analysis of what might occur under a loss of control scenario at the Kells BESS and what chemical reactions might take place. The site is described as having a total energy capacity of 26.3 MWh with:

25 ISO containers
28 racks in each ISO container
6 modules in each rack
22 lithium-ion cells in each module

The total quantity of electrolyte on site is 28.6 tonnes, together with 9.5 tonnes of polyvinylidene difluoride, all of which may generate HF in a fire. A fire involving a single container is predicted to generate 20 to 210 kg of HF. This corresponds to 19 to 200 mg/Wh, consistent with the range suggested by Larsson et al (2017).

Marks (2020) provides technical details for the Newry Energy Storage Ltd BESS located approximately 85 m North of No. 68 Cloghanramer Road, Newry, BT34 1QG. The site is described as having a total energy capacity of 18.635 MWh with:

5 ISO containers (3,727,000 Wh for each ISO container)
10 racks in each ISO container (372,700 Wh for each rack)
26 modules in each rack (14,336 Wh for each module)
16 lithium iron phosphate (LFP) cells in each module (896 Wh for each cell)

Each of the 20,800 cells on site, each with a mass of 5.46 kg, includes:

540 g of polyvinylidenefluoride-hexafluoropropylene copolymer (PVDF-HFP)
486 g of ethylene carbonate
432 g of dimethyl carbonate
432 g of propylene carbonate
378 g of diethyl carbonate
378 g of ethyl methyl carbonate
162 g of lithium hexafluorophosphate ($LiPF_6$)

It is predicted that a full stoichiometric decomposition of $LiPF_6$ will generate 4 moles of HF (plus other fluorine compounds). This corresponds to 354.2 kg of HF per ISO container. Similarly, a full stoichiometric decomposition of the PVDF-HFP would generate 1,679 kg of HF. Marks states that these stoichiometric results are considered worst case, and a more foreseeable prediction is based on the work of Larsson et al (2017) (i.e. 200 mg/Wh) giving 738 kg of HF per ISO container.

3.3 Standards

Standards for energy storage systems include:

NFPA 855 - Standard for the Installation of Stationary Energy Storage Systems, 2020
This debut edition addresses the dangers of toxic and flammable gases, stranded energy, and increased fire intensity associated with BESS sites. It is designed to give first responders and those who design, build, maintain, and inspect facilities the information they need to prepare for ESS safety.

IEC 62619 - Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications, 2017
Specifies requirements and tests for the safe operation of secondary lithium cells and batteries used in industrial applications including stationary applications.

There are obviously many other standards which are important, but the above are some of the most directly relevant. NFPA 855 is one of the most useful in terms of major hazard and firefighting considerations.

4 CONSIDERATION OF FIRE LOAD

The main fire load within a BESS container is the electrolyte within each cell. The precise composition of the electrolyte generally involves several flammable liquids and lithium hexaflurophosphate, as detailed in Section 3.2 by Marks (2020).

The overall heat of combustion of the electrolyte is approximately 20,000 kJ/kg.

Electrolyte typically makes up about 40% of the mass of a cell in a BESS. For other cell designs, such as cylinder cells, it is typically closer to 15% of the mass.

Any fire is likely to start as a result of failure of a single cell, which then escalates by involving progressively more cells. In the very early stages, the fire may not be ventilation controlled, but the container would rapidly begin to fill with combustion products, and the fire would become ventilation controlled. If the container becomes breached then the fire will no longer be ventilation controlled.

The growth of the fire is therefore likely to be similar to fire growth in other situations, such as a warehouse fire, although the rate of fire growth is likely to be higher due to the exothermic nature of the thermal runaway event.

For the purposes of assessing the fire, a conservative assumption typically adopted by the HSE is that the entire contents are combusted over a relatively short period of 30 minutes (Atkinson and Briggs, 2019). This assumption can be useful for defining a heat release rate and maximum source term for toxic combustion products, but it is noted that in reality such fires could continue to burn for many hours. Lithium-ion fires are also well known for re-igniting after having been apparently extinguished.

5 POTENTIAL FOR EXPLOSION

The potential for explosion during the course of a major incident in a BESS ISO container is an important issue which has recently become better understood following several incidents.

It is well known that individual cells may fail explosively due to the build-up of pressure within the cell, but this will depend on the cell design. Pouch cells tend to fail easily on seams, and so, considered individually, may be less likely to explode than, for example, cylinder cells. However, when pouch cells are packed into a module it may be more difficult for gases to vent, and so an explosion may still be possible. The energy of such an explosion would depend on the module design. Such an event could produce a loud bang as the module fails, but the event is likely to be contained within the ISO container.

More significantly, it is also known that cell failures can generate quantities of flammable vapour. If a 10 Wh 18650 cell can generate 6 litres of gas (Finegan et al, 2019), an 896 Wh pouch cell could theoretically generate over 500 litres of flammable vapour. Several such failures could occur before the vapour ignites. Suppression systems can prevent flaming, though flammable vent gases can continue to be released due to cascading thermal runaway as a result of heat transfer between cells and modules. Ignition can then lead to a vapour cloud explosion (VCE) within the ISO container. The worst case is if such flammable vapour fills the entire ISO container (typical dimensions are 40 x 8 x 8.5 feet, or 77 m^3). It is noted that the 2019 McMicken incident only involved thermal runaway of the cells in a single rack, and this was still sufficient to generate enough flammable gas for a significant explosion.

Table 5-1 provides hazard ranges to various levels of overpressure for hydrocarbon vapour cloud volumes of 0.5, 5 and 50 m^3, based on a standard analysis using the TNO Multi-Energy Model with a typical ignition strength of 7 (based on the type of approach typically adopted by HSEGB for VCEs).

Table 5-1 Distances to Various Levels of Explosion Overpressure

Volume of vapour involved (m^3)	0.5 m^3	5 m^3	50 m^3
	Distance (m) to various levels of overpressure		
600 mbar	2	5	10
300 mbar	3	7	16
140 mbar	6	12	26
70 mbar	10	21	45

Any flammable vapours released from cells may be ignited almost immediately, without any generation of overpressure, but there have been several incidents where explosions have been reported in containers. This delayed ignition of vapour can occur if a fire suppression system prevents flaming. Continued release of vent gases from failed cells after the suppression system operates can then lead to a build-up of flammable gas, which can then ignite leading to an explosion. There have also been incidents with no suppression system where a build-up of flammable gas has occurred without a fire, until delayed ignition caused an explosion.

It is noted that HSEGB typically use 600, 140 and 70 mbar as the basis for defining the Inner, Middle and Outer land use planning zones for explosion hazards.

Table 5-2 provides some data from HSE (2005) on the effect on structures of various levels of blast overpressure.

Table 5-2 Effect of Various Levels of Explosion Overpressure

Damage Description	Incident Peak Side-On Overpressure (mbar)
General effects on buildings	
5% of exposed glass panes broken	1-3
50% of exposed glass panes broken	6-13
Near 100% of exposed glass panes broken	50-110
Limited minor structural damage	20-30
Doors and window frames may be blown in	50-90
Partial demolition of houses - rendered uninhabitable	70
Lower limit of serious structural damage	140
Partial collapse of walls and roofs of houses	140
Nearly complete destruction of houses	340-480
Probable total destruction of houses	690
Effects on UK brick built houses	
Category A damage (completely demolished)	690-1830
Category B damage (badly damaged and beyond repair)	240-590
Category Cb damage (uninhabitable without extensive repairs)	140-240
Category Ca damage (uninhabitable but repairable)	70-120
Category D damage (inhabitable but repairs required)	20-50
50% destruction of brickwork	280-480
Effects on plant	
Reinforced structures distort and unpressurised storage tanks fail	210-340
Wagons and plant items overturned	340-480
Extensive damage	>480
Failure of a pressurised storage sphere	>700

A recent Energy Storage News (25 March 2021a) focussed on the potential explosion issue at BESS sites, stating:

> *The challenges of explosion prevention – with flammable gases needing to be vented "very rapidly" – in the event of a battery fire have been highlighted at this week's Energy Storage Summit USA.*
>
> *Speaking at the event, hosted by our publisher Solar Media, Matthew Paiss, technical advisor, battery materials & systems at Pacific Northwest National Laboratory (PNNL), referenced the two most recent high-profile battery fires, with one at utility Arizona Public Services's (APS) energy storage facility in 2019 and one at Ørsted's 20 MW project in Liverpool, England in 2020.*
>
> *Both explosions caused a "significant pressure wave", with the APS incident resulting in the injuries of four firefighters and the Liverpool incident causing debris to be thrown between six and 20 meters away according to the fire department's response report.*
>
> *Paiss explained that there are "many similar battery enclosures operating today that could experience the exact same kind of failure".*
>
> *He said that most systems being deployed today do include a deflagration vent – which is used to vent gases after deflagration occurs – but "what is not very common in systems is deflagration prevention" which he described as typically being a mechanical exhaust system.*

It was also stated (Energy Storage News, 25 March 2021b) that:

Per Onnerud … said that statistically, some failures will always happen.

While some experts have said that failure may only occur in one of every 10 million battery cells, energy storage projects are getting larger and contain more cells. Meanwhile the cells themselves are individually getting larger and therefore produce more gas if active materials like electrolyte catch fire.

Explosions caused by that gas and fires caused by propagation should not be acceptable, Onnerud said. Battery design should be such that failures should be prepared for, and so that those failures can be dealt with "elegantly".

The incident report for the 2019 McMicken Arizona incident (McKinnon, DeCrane and Kerber, 2020) provides photos which show that, when the fire service arrived, there was a low level cloud of vapour around the container (possibly associated with the suppression system), as shown in Figure 5.1.

Figure 5.1 Photos of ESS Prior to Explosion (McKinnon, DeCrane and Kerber, 2020)

When firefighters were satisfied that HCN and CO concentration had dissipated sufficiently, they proceeded to open the container door. The report describes what then happened to the four firefighters, stating:

At the moment of the deflagration event, the firefighters outside the hot zone described hearing a loud noise and seeing a jet of flame that extended at least 75 ft outward and an estimated 20 ft vertically from the southeast-facing door. In the event, E193 Capt and E193 FE were ballistically propelled against and under the chain-link fence that surrounded the ESS. E193 Capt came to rest approximately 73 ft from the opened door beneath a bush that had ignited in the event. E193 FE came to rest approximately 30 ft from the opened door. HM193 FF1 was projected toward the transformer and distribution box to the east of the ESS and remained within the fenced area. The entire HAZMAT team lost consciousness in the deflagration event. The event also dislodged or removed the SCBA face pieces and helmets from all of the HAZMAT team members.

6 ASSESSMENT OF TOXIC FIRE PLUME

The literature is clear that a wide range of toxic combustion products could be generated in a fire. However, there seems to be reasonable agreement that for a major fire the most significant in terms of toxicity is hydrogen fluoride.

The quantity of HF generated can be estimated based on stoichiometric decomposition, or on experimental data. The approach of Larsson et al (2017), who suggest 20 to 200 mg/Wh based on experimental data, seems to be the most widely adopted approach, and use of the upper bound is likely to provide a cautious best estimate. For a fire involving an entire 5 MWh ISO container (i.e. slightly more than the 3.7 MWh ISO containers at Newry) this would correspond to 1,000 kg of HF.

The duration of the release is conservatively taken to be 30 minutes, which is consistent with the approach recommended by Atkinson and Briggs (2019) for warehouse fires. This implies a release rate of 0.56 kg/s. It is emphasised that in reality there would not be a constant release rate for 30 minutes, but it would grow exponentially to a maximum before gradually decaying over much longer than 30 minutes. However, it is noted that the HSE SLOT and SLOD are based on integrated dose, and so the precise time variation is not important for such criteria.

The other key factor in any toxic fire plume dispersion assessment is the buoyancy of the fire plume, as defined by the convective heat content of the fire plume. The major source of any heat release is likely to be the electrolyte, of which there could be up to about 10 tonnes in a single ISO container. Based on a typical heat of combustion of 20 MJ/kg for the electrolyte, and a release duration of 30 minutes, this would correspond to about 100 MW. In practice, combustion would not be complete and only a fraction would become convective heat in the fire plume (see below). It is noted that BEIS (2020) indicated a heat release of 30 to 50 kJ/Wh, which would correspond to 83 to 138 MW over 1800 seconds for a 5 MWh facility, which is reasonably consistent with the value of 100 MW.

Any generation of HF which is released from the ISO container will be advected downwind, though the plume will tend to rise due to the buoyancy of the hot fire plume. The container may also entrain some or all of the fire plume into its downwind wake, which may spread the plume out and bring it down to ground level, depending primarily on the wind speed.

The dispersion of a fire plume depends principally on the wind speed. At low wind speeds, a fire plume tends to rise buoyantly (see Figure 2.1) and ground level concentrations tend not to be significant. At higher wind speeds, there is generally more dilution of the plume, but it may not lift off the ground, and so moderate to high wind speeds generally represent the worst case for such fire plumes. A range of weather conditions has therefore been considered, namely D2, D5, D10 and F2. It is noted that atmospheric stability may also have some effect, and so stable F2 conditions have also been considered, although (unlike many toxic gas assessments) it is not expected that F2 will be the worst case in terms of hazard ranges.

As noted above, the heat content of the fire plume is a key parameter in determining the degree of buoyant plume rise - a higher heat flux leads to greater plume rise and lower ground level concentrations. Based on CERC (2018), the heat flux is typically calculated as:

$$F_b = (1 - \alpha_r)\, \varepsilon\, H_c\, m$$

Where F_b = Heat flux (W)
α_r = Fraction of heat radiated (typically 0.3)
ε = Efficiency of combustion (taken as 0.5)
H_c = Heat of combustion (J/kg) - taken as $2\text{x}10^7$ J/kg (based on electrolyte)
m = Mass rate of combustion (kg/s) (taken as 1,000 kg of electrolyte over 1800 seconds)

This suggests a relatively high heat flux of 4 MW.

However, in view of the considerable uncertainty associated with making such an estimate of the effective heat flux, and the extent of possible heat losses (e.g. to sprinkler water) the approach adopted was to assume an effective source diameter of 5 m, with a flux of hot air with a vertical velocity of 1 m/s and an excess temperature of 100°C. This corresponds to a lower heat flux of $\pi \times 2.5^2 \times 1 \times 100 \times 1012 \times 0.9 / 10^6 = 1.8$ MW (NB heat capacity of air is 1012 J/°C/kg, density of air at 115°C is 0.9 kg/m^3). The source was conservatively assumed to be located on the lee side of the ISO container at a height of 1 m, leading to significant entrainment in the wake of the container.

Dispersion modelling of the HF releases has been conducted using ADMS 5.2.4 which is well suited to modelling the dispersion of such fire plume releases. In addition to the source term and weather categories referred to above, the following input data has also been used in ADMS.

ISO container dimensions	2.6 m high, 2.4m wide, 12.2 m long
Atmospheric temperature	15°C
Surface roughness length	0.1 m
Surface energy flux	0 kW/m^2 for D2, D5 and D10 conditions; -6 kW/m^2 for F2 conditions
Boundary layer height	800 m for D2, D5 and D10 conditions; 100 m for F2 conditions
Relative humidity	65%
Averaging time	30 minutes

Most of these parameters have relatively little effect on the dispersion results; the most significant inputs being the wind speed and heat flux. The entrainment of the release in the container wake has been included in the ADMS modelling. This entrainment increases as the wind speed increases, and in D10 conditions the release is almost fully entrained in the container wake and the plume centreline is effectively at ground level.

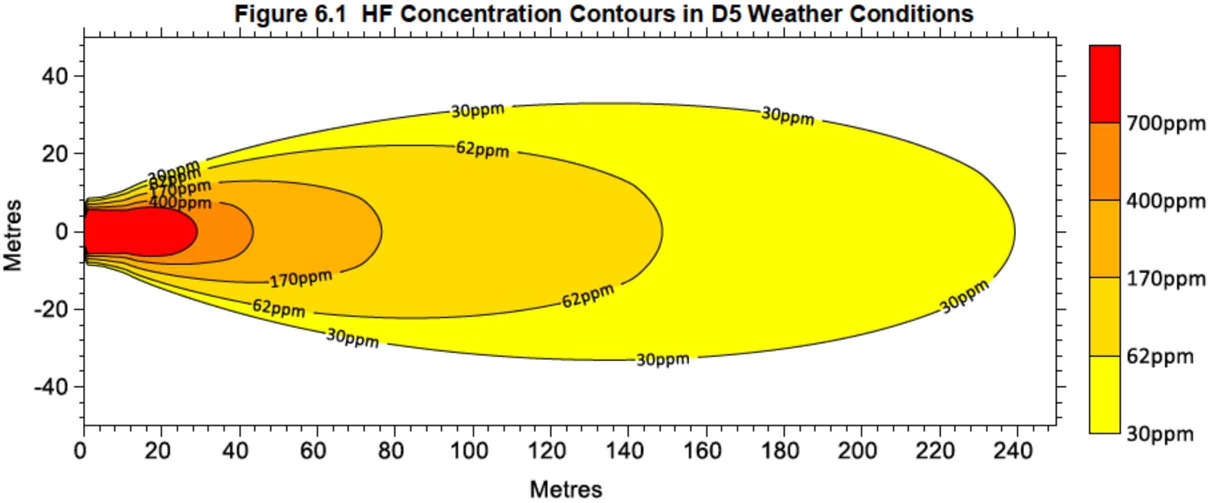
Table 6.1 presents results for the downwind hazard ranges to the HF IDLH, AEGL (10 and 30 minute), HSE SLOT and HSE SLOD for each of the representative weather categories.

Table 6.1 Outdoor Hazard Ranges to SLOT for HF Releases

Criterion	Concentration (ppm)	Outdoor hazard range (m)			
		D2	D5	D10	F2
IDLH	30	85	240	200	85
AELG-3 (30 min)	62	50	150	130	50
AELG-3 (10 min)	170	25	80	70	25
SLOT	400	20	45	40	20
SLOD	700	15	30	30	15

Table 6.1 shows that the worst case hazard ranges tend to occur at moderate wind speeds of 5 m/s. At this wind speed the plume rise is not very significant. As the wind speed increases, the plume rise still decreases, but this is more than compensated by the additional dilution. Figure 6.1 illustrates the ground level concentration results for the worst case D5 weather conditions.

Figure 6.1 HF Concentration Contours in D5 Weather Conditions



It is worth noting that the worst case conditions for toxic hazard ranges may occur in very typical (i.e. D5) weather conditions.

The analysis presented above is considered to be conservative in that the actual heat release rate is likely to be higher, so the worst case conditions would probably occur in higher wind speeds (e.g. D10), but with shorter hazard ranges. There are also some conservatisms in the magnitude of the HF source term, and in the assumption that all the HF is released over 30 minutes, and that people remain exposed in the plume rather than escaping.

It is also noted that, even without a significant fire (due to the fire suppression system), the 2019 McMicken Arizona incident showed that significant concentrations of toxic gases from cell venting, such as HCN and CO, could escape from a container.

7 ASSESSMENT OF WASHOUT AND DEPOSITION

Any fire plume which contains particulates will tend to deposit these particles to the ground, which can lead to issues relating to foodstuffs and clean-up.

Whilst a fire involving a BESS ISO container may generate some such particulate matter, including metal oxides, this has not been regarded as a significant issue in the literature.

Similarly, if there is rain, or water sprays are used on the fire, then there will be some washout (wet deposition) of both particulate and soluble gases. It is noted that gases such as HF are reasonably soluble in water, so water curtains are sometimes used to reduce the airborne concentration of HF following an HF release.

This washout can lead to contamination of ground and water, but again it is not considered to be a significant issue in the literature.

8 FIREWATER RUN-OFF

The HSEGB generally assesses major fires using methods developed by Carter (1989 and 1991) and Atkinson and Briggs (2019). Atkinson and Briggs (2019) state that:

> *There are many examples of chemical warehouses fires that have caused major environmental damage through contaminated firewater run-off. One use of fire plume toxicity assessment is to support "let burn" decisions in planning for and dealing with large fires.*

It is noted that a major concern at the Carnegie Road fire (see Table 2-1) was fire water run-off and potential environmental harm.

There is currently no good data on the significance of firewater from such fires in terms of their impact on the environment, but it is likely to be similar to that from comparable sized fires involving plastics and packaging. There may be specific concerns if the firewater is not contained and can reach sensitive environmental receptors.

9 SUMMARY

This Technical Note provides a high level review of the major hazard issues associated with large scale Battery Energy Storage System (BESS) sites using lithium-ion batteries in an ISO container. It is emphasised that the intention was not to provide a comprehensive review or assessment, but to provide an overall understanding of the key issues, with the principle aim of assisting HSENI to provide more informed advice.

The review has considered published literature and project documents provided by HSENI to establish current best practice for the analysis of such hazards, in terms of source terms and heat loads. A number of incidents involving lithium-ion batteries have been reviewed to provide context and understanding, and some quantitative assessment of fire and explosion hazards has been presented, concentrating on the hazards associated with explosions and dispersion of the toxic fire plume.

Key points which have been identified in the course of producing this Technical Note are:

- Any ISO container BESS has the potential to catch fire due to an unpredictable and spontaneous thermal runaway in a cell. The event may escalate to a fire involving the entire container. There is also a potential for an explosion. The design and mitigation measures in place should ensure that thermal runaway events do not escalate to involve an entire ISO container, but this remains a credible event which should be considered for emergency planning purposes.

- The generation of toxic combustion products from such fires can pose a hazard to those in the vicinity. The main concern appears to be hydrogen fluoride, although there are many other toxic combustion products. Toxic gases such as CO and HCN can also be generated in vent off-gas. This Technical Note provides a reasonably cautious assessment of the HF dispersion and hazard ranges for a worst case fire event, and shows that the HSE SLOT could be exceeded at up to about 45 m, with much higher concentrations in the immediate vicinity.

- The most significant risk to those in the immediate vicinity, or to firefighters, is from potential explosions of flammable vent gases from cells failing due to thermal runaway (either with or without fire). This Technical Note provides some predictions of the potential consequences of such explosion events in terms of the possible levels of blast overpressure. It is noted that there have been several incidents involving significant explosions at BESS sites. It is recognised that cells and modules can undergo cascading thermal runaway without any flaming or ignition, and still generate significant quantities of toxic and flammable gas, with the potential for a delayed explosion.

It is stressed that the assessment of BESS containers in terms of major accident hazard analysis is a new and rapidly developing area, and whilst the assessments here are considered to be reasonably robust, and consistent with current thinking, it is likely that there will be significant developments in the coming months and years.

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