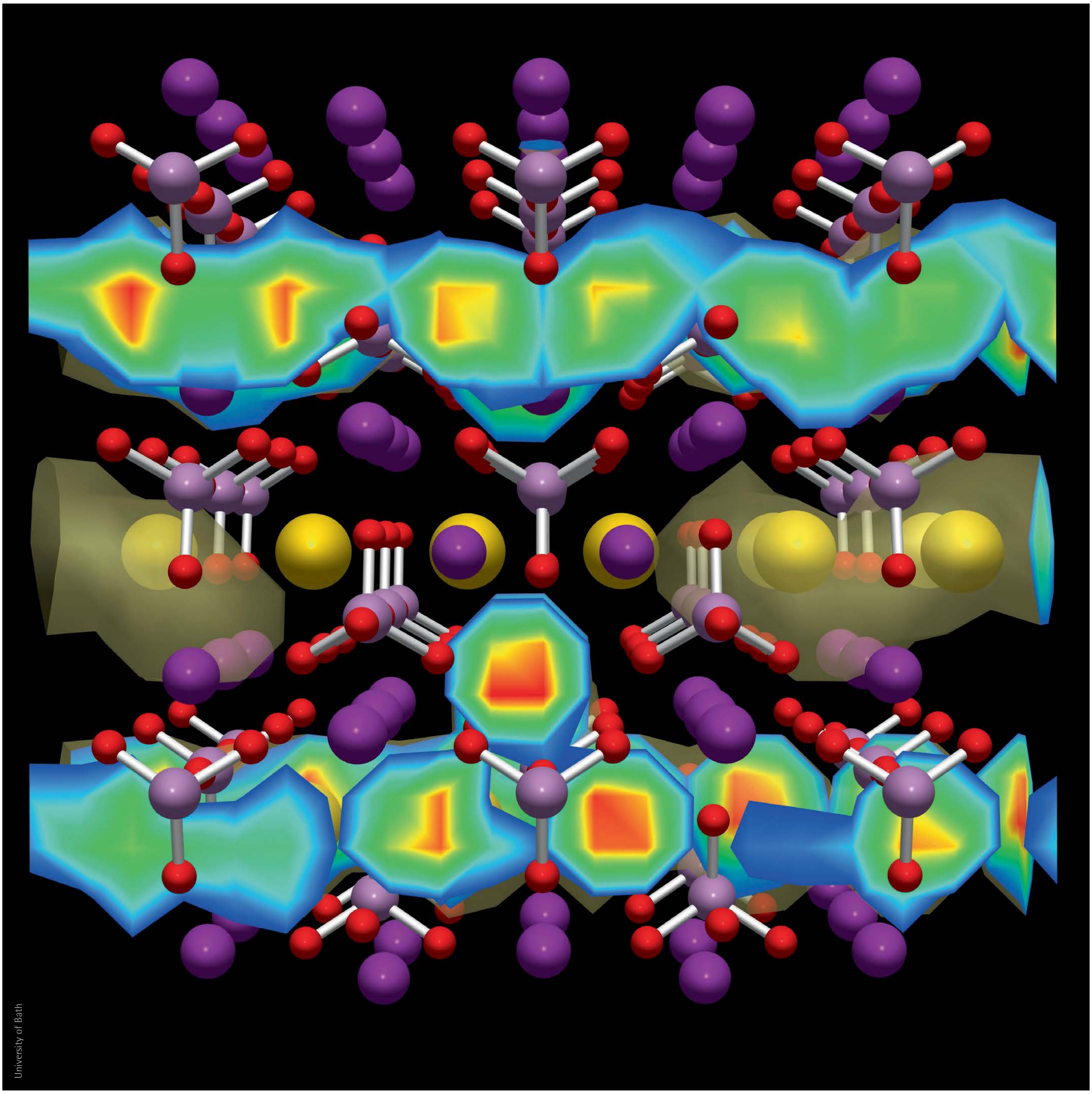
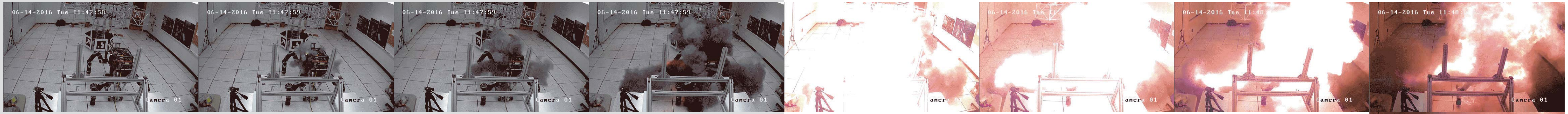
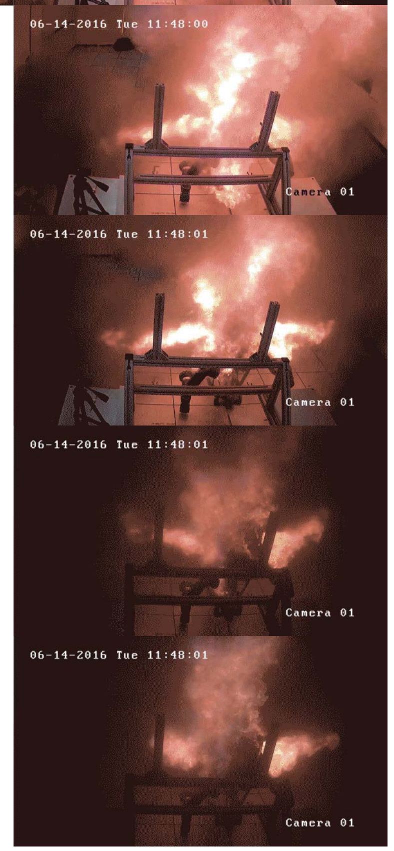


The rise and rise of lithium-ion

Khai Trung Le speaks to Professor Saiful Islam and Dr Duncan Broughton on the litany of explosive incidents surrounding lithium-ion batteries, and why we may still be relying on the technology for decades to come.





In 2016, the high-profile failure of a lithium-ion battery made headline news in *Wired*, *the Mirror* and *the Daily Mail* among others. You're likely thinking of Samsung and the extensive problems, including a widely-reported federal flight ban across the USA, which led to the recall and discontinuation of 2.5 million Galaxy Note 7 smartphones. You could be reminded of e-cigarette explosions that hospitalised a 15-year old boy in California in January 2016 and Tennessee teenager Garrett Preston later in February. You may be thinking a little further back to December 2015's most popular Christmas gift, the hoverboard, which saw Amazon and USA retailer Target temporarily suspend sales in the wake of several battery failures.

None of these are, however, the incident I refer to. On 14 June 2016, the NASA Jet Propulsion Laboratory's entry in the DARPA Robotics Challenge, RoboSimian, a quadruped robot designed for search-and-rescue missions in high-risk environments, exploded and caught fire during a battery recharge. A damaged battery cell sent false information to the monitoring equipment, resulting in overcharging. Jay Whitacre, Professor of Materials Science at Carnegie Mellon University, USA, told *Wired* that 'a single lithium-ion cell is dangerous, but it can't cause a gigantic explosion.' The RoboSimian was equipped with 96, resulting in an explosion the equivalent of a stick of dynamite, according to NASA.

Lithium-ion battery failures are not a recent phenomenon, but there has been an influx of reported events over the last decade. Dell began recalling 4 million notebook laptops in December 2008 after six reports of exploding or flaming battery incidents. Sony issued a recall of 9.6 million laptop batteries in 2006, and of 1,700 in 2016. Crises surrounding lithium-ion batteries can also have costly ramifications, such as the 2013 worldwide grounding of all Boeing 787 Dreamliners – the first instance of an entire model being pulled out of service globally since 1979 – following battery fires at Boston Logan Airport and forcing an emergency landing in Japan, which saw the 787 sell for an average of US$116 million – a 48% discount from its listed price of US$225 million. The aforementioned Samsung Galaxy Note 7 recall is expected to cost the company US$5.3 billion.

Dr Duncan Broughton, Head of Professional Chemistry and Materials at the Atomic Weapons Establishment (AWE), UK, notes that lithium 'has never been a risk-free material to work with.' AWE's experience with lithium, which 'stretches back to the Manhattan Project, during the pre-battery days when one major use was in the nuclear industry,' has a committed focus on safe handling. However, Broughton lamented that this has not seeped into the public consciousness with wider use. 'The world has moved on, and batteries are one of the biggest uses for lithium. As we try and squeeze them into smaller and higher-density energy packets, we're taking safety margins down to minimal acceptable levels. This is where a lot of issues are coming from.'

Fiery speculation

Samsung has not specified a cause of the failures around the Galaxy Note 7. But with lithium-ion incidents an increasingly prevalent topic, there is no shortage of speculation. In response to the 2006 battery recall, Sony posited several suggestions, including the lack of knowledge around how to properly integrate outsourced lithium cells into safe battery packs and applications, faulty manufacturing that contaminates cells with microscopic metal shards and the variance in battery configuration, thermal management and charging protocols across the industry as potential factors.

These issues are most keenly felt in the portable consumer electronics sector. Saiful Islam, Professor of Materials Chemistry at the University of Bath, UK, said, 'There are twin parallel challenges – while the current consumer lithium-ion battery would allow a decade-old Nokia phone to last a lot longer, smartphones are extremely power hungry. The electronics within current smartphone technologies have advanced, as has consumer desire. Companies are looking at new designs, making lighter and thinner phones, which has perhaps led to fabrication challenges, causing safety issues, self-thermal runaway, short circuiting and lithium dendrite formation.'

This has encouraged many to explore options beyond lithium-ion with technology that reprioritises safety, including Wolfgang Mack, Vice President of Business at supercapacitor manufacturer, Capacitor Sciences, USA. Citing information from Tesla revealing that while volumetric energy density had typically doubled every decade leading to 2005, the increase from 2005–15 was only 16.6%, Mack claims that lithium-ion batteries have reached 87% of commercially achievable cell limit for energy density, and the point of diminishing returns. 'To achieve the remaining 13% of the commercial achievable cell limits will be costly and slow, with limited returns on investment,' he said.

Institutions, including AWE, have gazed longingly at supercapacitors as a potential replacement for lithium-ion batteries. Broughton said, 'We have people looking at high-energy, high-density supercapacitors, as well as the nanotechnology going into producing those dielectric films that could mean significant advances in storage capacity. The advantage of recharge speeds, should the density reach acceptable levels, would be huge in the battery space. There are a few groups promising a supercapacitor breakthrough that could change the game, but whether they materialise is crystal ball gazing.' Efforts include a supercapacitor using 2D transition-metal dichalcogenides (TMD) integrated with 1D nanowires to increase structural integrity. Devised by a University of Central Florida, USA, research team led by Yeonwoong Jung, the proof-of-concept supercapacitor is capable of receiving 30,000 charge cycles without degradation and outperforms all current TMD-based supercapacitors, although the team has not specified what the capacity of the battery is.

However, Islam disagreed that improvements within lithium-ion batteries were halting, citing progress in other sectors. 'The current demand for ultra-thin portable electronics is greater than it ever has been, but lithium-ion batteries are being advanced through the work on electric vehicles. The requirements may be subtly different, but the research effort that informed battery technology for portable devices is now informing electric vehicles and large-scale storage.

'If you look at the current generation of cars – such as the BMW i8, the Nissan Leaf and the Tesla Model S – they all use lithium-ion batteries. Car manufacturers wouldn't have considered taking these steps without advances.' But he conceded that 'there's room for improvement. Considering how much effort and progress has been made in the last decade, what there won't be is a massive step change in lithium-ion just yet. That's why we need to look at new materials, and that's where materials science comes in.'

A collective effort

We may not have reached the precipice of what is capable with lithium-ion, but some of the most significant industry influences – namely, electric vehicles and renewable energy storage – require more than a straightforward scale-up of consumer batteries. The five-year EPSRC programme grant, Enabling Next-Generation Lithium Batteries, was established to explore future options, with Islam highlighting energy density, charge rates and safety and costs as priorities. The programme has revealed its target with unabashed precision – a next-generation lithium-ion battery with a cost of <£100/kWh, energy density of >300Wh/kg and power density of >2000W/kg, a calendar life of more than 10 years and lifetime of 3,000 charges.

Islam noted that 'in the past, efforts to address these challenges have often been based on individual researchers or groups focused on science or engineering', and the EPSRC programme has recruited an interdisciplinary team across several leading UK universities. Islam and his University of Bath team will be exploring materials modelling, 'trying to understand and design materials from a fundamental level.' A team from the University of Oxford – Professors Peter Bruce and Peter Grant – will look at 'synthesis, structural categorisation and electro-chemical measurements, and manufacturing thin-film devices and large-scale fabrication.' Other investigators include 'Professor Clare Grey, from the University of Cambridge, a world leader in nuclear magnetic resonance and experimental structural techniques, and Professor Ian Ward, University of Leeds, who is looking at polymers.'

The EPSRC programme grant's focus on lithium-ion advancements includes exploring new classes of anode materials to overcome the disadvantages of poor safety and low power inherent to graphitic anodes currently used in almost all commercial lithium-ion batteries. Additionally, it will look at enhancing energy density through developing protective membranes for lithium metal electrodes using 3D polymer/ceramics interpenetration networks, and positing the shift away from flammable liquid electrolytes to solid-state alternatives using polymer electrolytes.

According to the EPSRC, 'more radical ideas and technologies beyond lithium-ion batteries, such as the lithium-air battery', as demonstrated by Islam during the 2016 Royal Institution Christmas Lectures, will also be looked at. 'There is a lot of good research going on,' Islam noted. 'But we're not going to see a lithium-air battery in a car for the next five years. There are chemistry and materials hurdles, particularly getting the right electrolyte – the electrode is expected to be lithium metal that has to react with oxygen to form a lithium oxide, but the electrolyte remains an issue.'

The University of Cambridge was celebrated for work exploring the potential of lithium-air batteries in November 2015. The technology has been seen by some as the

Previous page: Computer modelling of atomic-level lithium-ion diffusion in olivine-phosphate battery material.

Above: Footage of the NASA RoboSimian battery incident.

NASA JPL

'ultimate' battery due to a theoretical energy density 10 times that of lithium-ion and comparable to gasoline, but progress halted when research groups including IBM and the US Joint Center for Energy Storage Research were unable to overcome one of the principle conundrums of lithium-air – its inability to release the oxygen needed to react with the lithium beyond a few dozen charges. Professor Clare Grey's research team resolved this through the addition of compound mediators – lithium iodide and water – along with fluffy carbon. Grey's lithium-air battery is claimed to possess high energy density and a lifetime of more than 2,000 recharges. Although the team stated at the time that a practical lithium-air battery was more than a decade away, their findings resolved one of the principle obstacles.

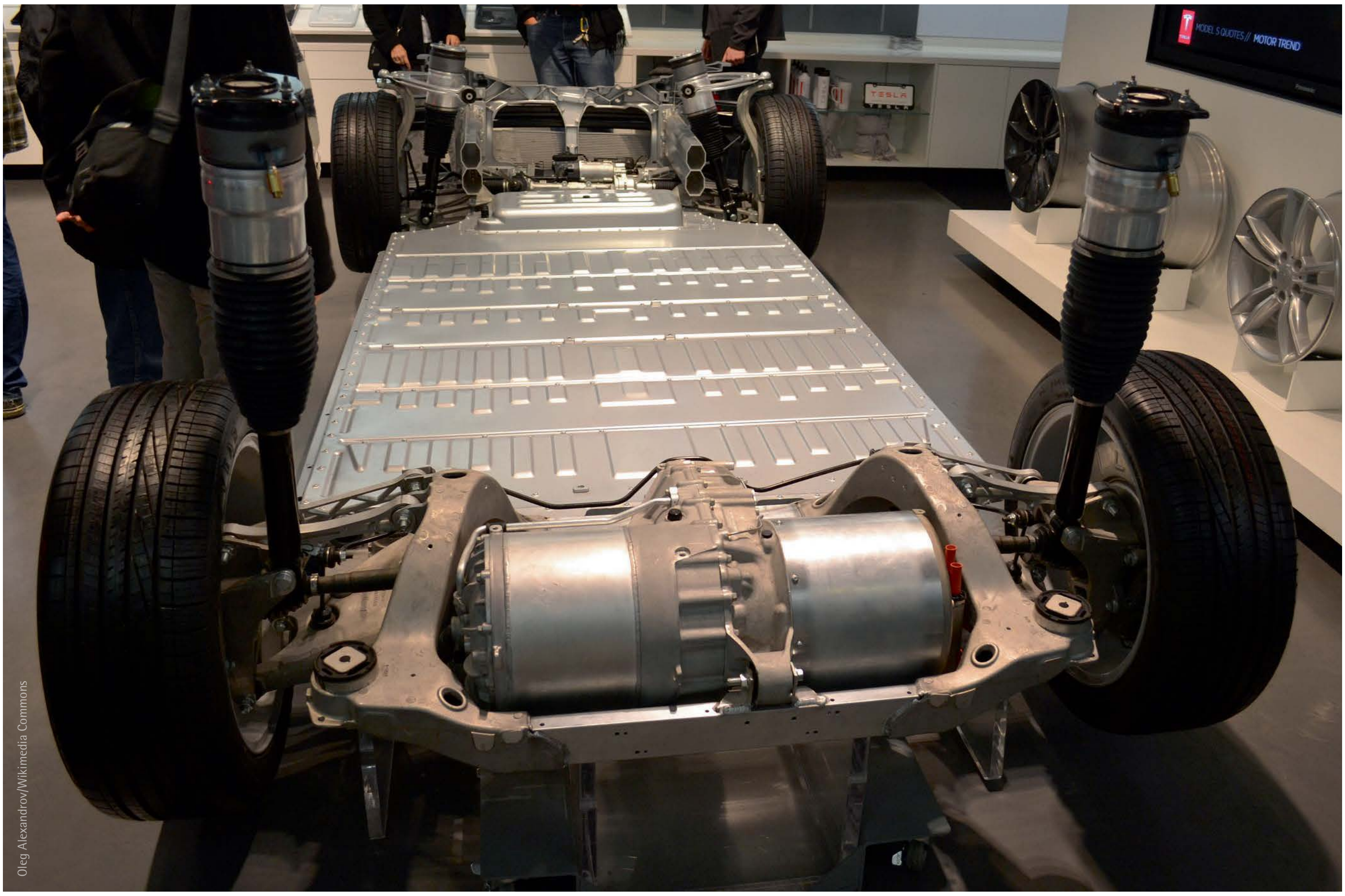
However, the Cambridge team's findings were later separately challenged in May 2016 by Venkat Viswanathan, Associate Professor of Mechnical Engineering at Carnegie Mellon, and Yue Shen, Associate Professor of the Power and Energy Storage Battery Laboratory, Huazhong University, China. Each separate dissent, published in *Science*, protests that the addition of lithium iodide does not produce sufficient energy to instigate the release of air from the lithium hydroxide to resolve the issue of recharge. 'The breakthrough is not a breakthrough,' said Viswanathan. 'And we are in a sense no further along in lithium-air than we were.'

Power behind the throne

In June 2016, Islam spoke at the International Meeting on Lithium Batteries in Chicago, USA, one of the largest gatherings of scientists and industry figures within the battery space. In one slide, he attempted to summarise the different avenues of research being explored. 'Within lithium ion, people are looking at electrolytes, polymer, ionic liquids and solid-state batteries including garnet. Beyond lithium-ion, sodium and magnesium batteries are being considered, and beyond that into intercalation such as lithium-air and lithium-sulphur.'

However, the iron grip lithium-ion has on the battery market looks unlikely to be reduced any time soon, with marketing intelligence company, Transparency Market Research, USA, forecasting lithium-ion battery market increases from US$29.68bln in 2015 to US$77.43bln in 2024. Put simply, no other technology packs more energy per unit weight than lithium-ion, nor has the tremendous industry commitment. It is no surprise that it continues to reside at the head of the table.

Regardless which way the wind blows, Islam was positive that the role of materials science will be essential. 'Materials performance lies at the heart of energy technologies, and new materials and designs are critical in breakthroughs in clean energy. It is gratifying that our fundamental energy materials research could have such a direct impact on applied areas.'



Oleg Alexandrov/Wikimedia Commons

Below: A Tesla Model S battery, which sits in the car underside. Electric vehicles are becoming increasingly prevalent, with the Nissan Leaf, BMW i8 and Tesla Model S each using lithium-ion batteries.