

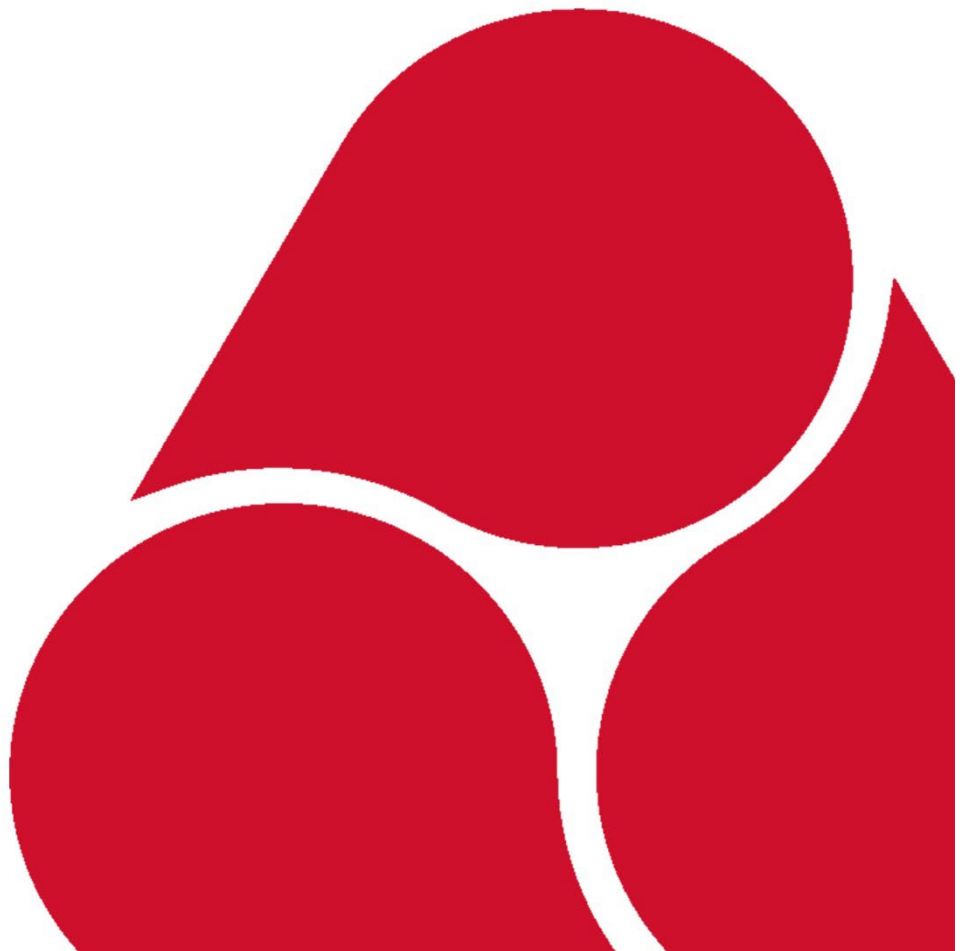


Office for Product
Safety & Standards

Emerging Technologies in the Field of Button Battery Safety

Literature Review

May 2025



Executive Summary

The ingestion of button batteries by children is a growing concern amongst both the public and Government. In response, the national consumer product regulator, the Office for Product Safety and Standards (OPSS), is undertaking wide-ranging work to review and improve their safety. This report will outline the development of emerging button battery safety technologies. It will describe their function, mechanism of operation, and what barriers hinder their adoption into products on the UK market.

To begin, the report will outline the current safety concerns associated with button batteries and summarise the current safety standards applicable to them. Next, emerging technologies in button battery safety will be reviewed. These have been grouped into three categories: bitterant-based and diagnostic methods, reactive safety technologies, and safe-by-design (SbD) methods.

For each innovation, the report will outline:

- the approach to minimising harm,
- the mechanism of physical or chemical action,
- the efficacy and effectiveness in reducing harm,
- the stage of research and development or commercialisation.

For each technology category, the report will discuss the current barriers to adoption into the market, and will close with a set of general considerations for the adoption of emerging button battery safety technologies.

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1 Introduction

1.1 Motivation for this report

The use of button and coin batteries in consumer products has become increasingly widespread. A recent campaign by the Child Accident Prevention Trust (CAPT), in partnership with the British and Irish Portable Battery Association (BIPBA), has highlighted their prevalence in a range of consumer products around the home. They can be found in children's toys (e.g. light-up fidget spinners), electronic goods (e.g. slim remote controls) and everyday household items (e.g. flameless tealights)¹. Of great concern is the potential for ingestion of these batteries by young children: they are small enough to fit into the mouth, but large enough to potentially become trapped in or near the oesophagus. Although most swallowed batteries are found in the stomach (43%) rather than the oesophagus (22%), common injuries—particularly mucosal damage and oesophageal strictures—are more likely to occur when they become lodged in the oesophagus². The main danger arises not from chemical leakage, but from choking or the battery reacting with bodily fluids such as mucus or saliva, which can lead to severe tissue damage³. While leakage carries a lower risk, it is not negligible — studies have shown that toxic metals may be released if a battery remains in the stomach for an extended period, adding to the potential harm^{4,5}.

1.1.1 A comparison of button and coin batteries

The 'button' and 'coin' labels for small, flattened-cylinder batteries are often used interchangeably, but there are important technical differences between them⁶. These are summarised in the table below.

	Button	Coin
Chemistry	Alkaline Silver oxide Zinc-air	Lithium-ion
Voltage	1.5 V	3 V
Diameter	6-12 mm	20-24 mm

¹ Child Accident Prevention Trust (CAPT) (n.d.). *Button Batteries: Where are they?* [online]. Available at: <https://capt.org.uk/button-batteries-where-are-they/> (Accessed: 05 August 2024).

² Tran, C. *et al.* (2025). Button battery exposure in children: a systematic review and meta-analysis, *Injury Prevention*, 31(4), pp. 265–271. doi: <https://doi.org/10.1136/ip-2024-045339>

³ Great Ormond Street Hospital for Children NHS Foundation Trust (GOSH) (2018). *Button batteries – using them safely* [online]. Available at: <https://www.gosh.nhs.uk/conditions-and-treatments/conditions-we-treat/button-batteries-using-them-safely/> (Accessed: 05 August 2024).

⁴ Sethia, R. *et al.* (2021). Current management of button battery injuries, *Laryngoscope Investigative Otolaryngology*, 6(3), pp. 549–563. doi: <https://doi.org/10.1002/liv.2.535>

⁵ Rebhandl, W., *et al.* (2002). Release of toxic metals from button batteries retained in the stomach: An in vitro study, *Journal of Pediatric Surgery*, 37(1), pp. 39–42. doi: <https://doi.org/10.1053/jpsu.2002.29435>

⁶ RS Components Ltd. (2023). *Button Batteries: The Comprehensive Guide* [online]. Available at: <https://uk.rs-online.com/web/content/discovery/ideas-and-advice/button-batteries-guide> (Accessed: 05 August 2024).

If ingested, coin batteries have a greater potential to cause harm than button batteries. Their larger diameter means they are more likely to become lodged in the oesophagus. Once they have become lodged, saliva or other bodily fluid may allow electrical conduction between the electrodes. The electricity provides the energy to drive the water splitting reaction, producing hydroxide ions at the negative electrode. Hydroxide ions cause alkaline caustic chemical burns, and tissue in contact with the negative electrode of the button battery is at the highest risk of damage⁷.

Electrolysis of water can theoretically occur at an applied voltage of 1.23 V, however in practice a higher voltage of 1.8–2.0 V is required. The extra 0.57–0.77 V required for the electrolysis reaction to occur is called the ‘overpotential’⁸. The higher voltage of a lithium-ion coin compared to a button battery means it has greater capability to cause tissue damage⁹. In the most serious cases, the button battery can perforate the oesophagus and cause fistula formation, which can be fatal¹⁰.

For convenience, we will use the term ‘button battery’ as a catch-all term to refer to both types of batteries in this report.

1.1.2 Emerging technologies in button battery safety

Tragically, there have been several high-profile incidents involving the ingestion of button batteries by children in recent years. Following the death of two-year-old Harper-Lee Fanthorpe in May 2021 in her Stoke-on-Trent Central constituency, former MP Jo Gideon has led a campaign to raise awareness of this issue and lobby for change¹¹.

As part of its wider work to improve consumer safety, OPSS is closely monitoring the emergence of technologies to improve the safety of button batteries. Several relevant innovations have been, or are currently, being developed by both academia and industry. Herein, we will describe the method of operation of those emerging technologies and identify any barriers to their adoption into the market.

This report will begin by summarising the current safety standards pertaining to button batteries in the UK. It will then review all the emerging technologies in button battery safety, inclusive of the scientific and grey literature, of which OPSS is aware. The innovations are grouped into three categories: bitterant-based and diagnostic methods, reactive safety methods, and safe-by-design methods. We consider the development stage of each innovation, including any reports on its efficacy and effectiveness, and what barriers exist to the adoption of those technologies into the market, if appropriate.

⁷ Chiew, A.L. and Chan, B.S.H. (2023). Management of button battery ingestion, *Clinical Toxicology*, 61(12), pp. 1017–1019. doi: <https://doi.org/10.1080/15563650.2023.2294622>

⁸ Raveendran, A., Chandran, M. and Dhanusuraman, R. (2023). A comprehensive review on the electrochemical parameters and recent material development of electrochemical water splitting electrocatalysts, *RSC Advances*, 13(6), pp. 3843–3876. doi: <https://doi.org/10.1039/d2ra07642j>

⁹ ProductIP (n.d.). *Coin and button batteries (cells)* [online]. Available at: [https://www.productip.com/kb/productipedia/compliance-resources/coin-and-button-batteries-\(cells\)](https://www.productip.com/kb/productipedia/compliance-resources/coin-and-button-batteries-(cells)) (Accessed: 05 August 2024).

¹⁰ Karimi, A. and Oduro-Dominah, L. (2024). Button battery ingestion in children. In: *Paediatric Anaesthesia Tutorial 519* [online]. World Federation of Societies of Anaesthesiologists (WFSA). Available at: <https://resources.wfsahq.org/atotw/button-battery-ingestion-in-children/> (Accessed: 06 August 2024).

¹¹ Gideon, J. (n.d.). *Time as the Member of Parliament for Stoke-on-Trent Central* [online]. Available at: <https://jogideon.com/stoke-central/> (Accessed: 05 August 2024).

1.2 Current button battery safety standards

Current standards pertaining to button battery safety in toys¹² and certain electronic products¹³ focus on ‘engineering controls’ (i.e., focusing on the design of the battery). This means restricting access to the button battery itself, by placing it within a compartment of the product that cannot be easily or accidentally opened by a child or other vulnerable person. Typically, this compartment must require a tool to open and be secured with captive screws. Alternatively, it must require two independent and simultaneous hand movements to open. In products where the battery might need to be replaced, ‘instructional safeguards’ are required. These provide information and warnings about the potential hazards of the product, through a physical marking and accompanying text.

A key Ministerial commitment was for OPSS to commission British Standards Institution (BSI) to work in collaboration with industry, charities and regulators to draft a new Publicly Available Specification (PAS) on button battery safety. This was published as PAS 7055:2021 on 30th April 2021¹⁴, and it must be reviewed at least every two years. It deals specifically with the safety of button batteries in consumer products that are outside the scope of previous standards. It provides clear requirements for manufacturers, retailers and others to follow. The PAS covers the whole lifecycle of the button battery in a consumer product, including but not limited to:

- **Packaging:** both reclosable and non-reclosable packaging should be child-resistant and conform to at least one of several applicable BS EN or ISO standards^{15, 16, 17, 18, 19};
- **Labelling:** the battery and its packaging should include appropriate pictorial and text warnings about the hazards of button battery ingestion;
- **Instructions:** to include the same warnings as above, as well as information on the symptoms that might arise from ingestion of a button battery;
- **Marketing:** retailers should offer clear safety information at the points of display of batteries in stores, and safety information should also accompany online sales;
- **Disposal:** retailers should dispose of or recycle batteries safely, including ensuring that children cannot access them, e.g. by regularly emptying recycling units;

¹² British Standards Institution (BSI) (2020a). *BS EN IEC 62115:2020+A11:2020 – TC Electric toys. Safety*. Available at: <https://knowledge.bsigroup.com/products/electric-toys-safety-1?version=standard> (Accessed: 26 October 2023).

¹³ British Standards Institution (BSI) (2020b). *BS EN IEC 62368-1:2020+A11:2020 Audio/video, information and communication technology equipment - Safety requirements*. Available at: <https://knowledge.bsigroup.com/products/audio-video-information-and-communication-technology-equipment-safety-requirements?version=standard> (Accessed: 26 October 2023).

¹⁴ British Standards Institution (BSI) (2021). *PAS 7055:2021 Button and coin batteries. Safety requirements. Specification*. Available at: <https://knowledge.bsigroup.com/products/button-and-coin-batteries-safety-requirements-specification?version=standard> (Accessed: 26 October 2023).

¹⁵ Standards Australia (2009). *AS 5808-2009 Child-resistant packaging - Requirements and testing procedures for non-reclosable packages for nonpharmaceutical products (EN 862:2005, MOD)*. Available at: <https://www.standards.org.au/standards-catalogue/standard-details?designation=as-5808-2009> (Accessed: 31 May 2024).

¹⁶ British Standards Institution (BSI) (2020c). *BS EN IEC 60086-4:2019 Primary batteries - Safety of lithium batteries*. Available at: <https://knowledge.bsigroup.com/products/primary-batteries-safety-of-lithium-batteries-2> (Accessed: 31 May 2024).

¹⁷ British Standards Institution (BSI) (2015). *BS EN ISO 8317:2015 – TC Child-resistant packaging. Requirements and testing procedures for reclosable packages*. Available at: <https://knowledge.bsigroup.com/products/child-resistant-packaging-requirements-and-testing-procedures-for-reclosable-packages> (Accessed: 31 May 2024).

¹⁸ British Standards Institution (BSI) (2016). *BS EN 862:2016 – TC Packaging. Child-resistant packaging. Requirements and testing procedures for non-reclosable packages for non-pharmaceutical products* [online]. Available at: <https://knowledge.bsigroup.com/products/packaging-child-resistant-packaging-requirements-and-testing-procedures-for-non-reclosable-packages-for-non-pharmaceutical-products-1> (Accessed: 31 May 2024).

¹⁹ Federal Trade Commission (1995). *§ 1700.15 Poison prevention packaging standards*. [online]. Available at: <https://www.ecfr.gov/current/title-16/chapter-II/subchapter-E/part-1700/section-1700.15> (Accessed: 31 May 2024).

- **Use within a consumer product:** consumer products that contain button batteries must also conform to the same standards and must ensure that the batteries are contained within a secure battery compartment.

Although following the requirements of PAS 7055:2021 is voluntary, there is an expectation from OPSS that manufacturers will meet either these requirements, or those of other applicable Standards, in order to effectively and clearly demonstrate the safety of their products.

2 Overview of Emerging Technologies

In addition to the engineering controls mentioned above, OPSS has identified several product-level button battery safety technologies. Some are already present on the UK market, but most remain in the proof-of-concept stage. The literature sources contributing to the review include academic literature, patents and patent applications, as well as other open sources.

The emerging technologies fall into three different categories, which have been labelled by OPSS according to their function and method of action. They are:

- Bitterant-based and diagnostic methods,
- Reactive safety technologies,
- Safe-by-design methods.

Innovations within these categories and their development stage are summarised in the Table below.

In the following sections, we will explore each of these categories. We will focus on their current market status and the opportunities that exist for further development in each area.

2.1 Tests of efficacy for emerging safety technologies

A common test used to demonstrate the efficacy of button battery safety technologies is the 'hydrated ham test'²⁰. In this test, the battery is placed between, and in contact with, two slices of ham that have been hydrated with synthetic saliva, mimicking human internal tissue and bodily fluids. The synthetic saliva is often a standard isotonic solution called Ringer's solution²¹.

The button battery is left for a set period, and the slices of ham are photographed to monitor the tissue damage over time. Electrical (voltage and current) measurements, and measurements of the pH of the ham slices, may also be performed over the course of the hydrated ham test. Due to the generation of hydroxide at the negative electrode, this is where the most tissue damage will be observed²².

²⁰ NBC Connecticut (2021). *CT Lab Hopes to Decrease Dangers of Ingested Button Batteries* [online]. Available at: <https://www.nbcconnecticut.com/investigations/nbc-ct-responds/ct-lab-hopes-to-decrease-dangers-of-ingested-button-batteries/2639914/> (Accessed: 13 August 2025).

²¹ The Editors of Encyclopaedia Britannica (1998). *Ringer's solution* [online]. Available at: <https://www.britannica.com/science/Ringers-solution> (Accessed: 12 July 2024).

²² US National Capital Poison Center (NCPC). *Mechanism of Battery-Induced Injury* [online]. Available at: <https://www.poison.org/battery/mechanism-of-injury> (Accessed: 05 August 2024).

Bitterant-based and diagnostic methods		Reactive safety technologies			Safe-by-design methods	
Bitterant-based methods	Diagnostic methods	Pressure-sensitive conduction methods	Chemical reaction with water	Fuse and short-circuit methods	Battery design modifications	Product design modifications
Bitterants	Saliva-staining dye	Quantum-tunnelling composite coating	Sacrificial metal casing	Polymer fuse	Smaller batteries and/or pin-point electrodes	Safer methods of storage
Bitterant labelling ink	Radiopaque marker	Mechanical pressure-sensitive conduction	Electrolysis-resistant electrode cladding	Metallic fuse	Non-toxic, low-capacity batteries	Wireless charging
	Urine-staining dye		Metal oxide electrode-deactivating layer	Quantum tunnelling expansion layer	Biocompatible power sources (triboelectric nanogenerator)	Solar-powered electronics
			Neutralisation coating	Water-sensitive short circuit layer		
			Water-reactive positive electrode bridge			

Legend

Present on UK or US market

Active pursuit to market

Proof of concept including demonstration of efficacy

Proof of concept

Not under development / theoretical

Status unknown

3 Bitterant-based and Diagnostic Methods

3.1 Bitterant-based methods

A bitterant is a chemical substance with a deliberately bitter, unpleasant taste. Adding a small amount of bitterant to a liquid product, or coating it on a solid product, affords the product the same bitter taste. It is thought that if a child or other vulnerable consumer puts the product into their mouth, they will be repulsed by the bitter taste and are therefore more likely to spit it out rather than ingest it, thus reducing the risk of harm from the product.

3.1.1 Bitterants

Button batteries coated with bitterants have been present on the UK market since September 2020^{23,24}. At this time, Duracell introduced a denatonium benzoate (Bitrex®) coating on their type 2016, 2025, and 2032 lithium-ion coin batteries. Bitrex® is used as a bitterant in many other potentially hazardous consumer products, such as antifreeze and detergents²⁵.

3.1.2 Bitterant labelling ink

Panasonic filed a patent application in 2022 for a button battery incorporating a bitterant²⁶. The novelty of their invention is incorporating the bitterant into an ink that can be used to mark the voltage, polarity, manufacturer and other markings (as prescribed in *BS EN IEC 60086-1:2021*²⁷) on the button battery. The ink can either be printed directly onto the (flat) surface of the battery, or if the markings have been stamped into the metal casing of the battery, it can be printed into the grooves of the stamp.

Furthermore, the ink can be made electrically conductive by incorporating a conductive constituent like carbon black²⁸. This will minimise the impact of the ink layer on the battery's electrical performance. The inclusion of a coloured or fluorescent pigment within the ink can further improve its safety function. A fluorescent pigment is particularly useful as the degree of fluorescence can be used to confirm that the bitterant ink has not degraded during storage of the battery.

3.1.3 Efficacy and effectiveness of bitterants

However, their efficacy in preventing children from ingesting harmful products is unclear. Several scientific studies in the 1980-90s showed that children might consume less of a

²³ PCMag UK (2020). *Duracell Is Making Coin Batteries Taste Horrible on Purpose* [online]. Available at: <https://uk.pcmag.com/news/128910/duracell-is-making-coin-batteries-taste-horrible-on-purpose> (Accessed: 05 August 2024).

²⁴ Gartenberg, C. (2020). *Duracell's new coin batteries have a bitter coating that makes them taste terrible* [online]. The Verge. Available at: <https://www.theverge.com/2020/9/29/21493443/duracell-new-coin-batteries-bitter-coating-taste-terrible-child-protection> (Accessed: 05 August 2024).

²⁵ Macfarlan Smith Ltd (n.d.). *Who uses Bitrex®?* [online]. Available at: <https://www.bitrex.com/partners-using-bitrex/> (Accessed: 05 August 2024).

²⁶ Sano, Y. *et al.* (2022). Coin cell battery. World Intellectual Property Organization (WIPO) Patent Application WO2023047734A1. Available at: <https://patents.google.com/patent/WO2023047734A1/en> (Accessed: 05 August 2024).

²⁷ British Standards Institution (BSI) (2022). *BS EN IEC 60086-1:2021 Primary batteries - General*. Available at: <https://knowledge.bsigroup.com/products/primary-batteries-general-7?version=standard> (Accessed: 19 June 2024).

²⁸ Spahr, M.E., Gilardi, R. and Bonacchi, D. (2017). Carbon Black for Electrically Conductive Polymer Applications. *Polymers and polymeric composites*, pp.375–400. doi: https://doi.org/10.1007/978-3-319-28117-9_32

product when a bitterant has been added, such as those of Berning *et al.*²⁹, Sibert & Frude³⁰, and Hansen *et al.*³¹, with an accompanying proposal that bitterants could be useful in reducing exposure to harmful products.

On the other hand, the US Consumer Product Safety Commission (CPSC) concluded in a 1992 report that: 'There is no evidence that denatonium benzoate or any other possible aversive agent is actually effective at limiting ingestions of consumer products'³². Furthermore, two analyses of US poison control data for suicidal³³ or paediatric³⁴ ingestions of antifreeze by White *et al.* showed that legislation requiring the addition of bitterants to antifreeze had resulted in no change in frequency or severity of antifreeze poisoning incidents.

Therefore, from the limited evidence available, it is not clear that the addition of a bitterant coating to button batteries would improve their safety for consumers by reducing the likelihood of ingestion. As Klein-Schwartz noted in a review in 1991: 'aversive agents such as denatonium should augment but not replace proven methods of poison prevention including parental education and child-resistant closures'³⁵.

3.2 Diagnostic methods

Electrochemical tissue damage can occur in as little as two hours after button battery ingestion³⁶, making prompt diagnosis and treatment critical. However, there are few symptoms unique to button battery ingestion, such as heavy metal ingestion³⁷. The innovations in this section are designed to address these issues by facilitating more rapid and accurate diagnosis of a button battery ingestion case.

3.2.1 Saliva-staining dye

Button batteries incorporating a saliva-staining dye were placed on the US market in April 2024³⁸. Energizer's 3in1 Child Shield™ innovation³⁹ uses a combined food colouring-based dye and non-toxic bitterant coating, with the dye originally invented at the Victoria

²⁹ Berning, C.K., Griffith, J.F. and Wild, J.E. (1982). Research on the Effectiveness of Denatonium Benzoate as a Deterrent to Liquid Detergent Ingestion by Children. *Toxicological Sciences*, 2(1), pp.44–48. doi: <https://doi.org/10.1093/toxsci/2.1.44>

³⁰ Sibert, J. and Frude, N. (1991). Bittering agents in the prevention of accidental poisoning: children's reactions to denatonium benzoate (Bitrex). *Emergency Medicine Journal*, 8(1), pp.1–7. doi: <https://doi.org/10.1136/emj.8.1.1>

³¹ Hansen, S.R., Janssen, C. and Beasley, V.R. (1993). Denatonium benzoate as a deterrent to ingestion of toxic substances: toxicity and efficacy. *Veterinary and Human Toxicology*, 35(3), pp.234–236. Available at: <https://pubmed.ncbi.nlm.nih.gov/8351798/>.

³² US Consumer Product Safety Commission. *Final Report: Study of Aversive Agents*. Washington, D.C.: U.S. Consumer Product Safety Commission, 1992. Available at: <https://web.archive.org/web/20110616104140/http://www.cpsc.gov/LIBRARY/FOIA/foia99/os/aversive.pdf> (Assessed: 06 August 2024).

³³ White, N. C. *et al.* (2008). The impact of bittering agents on suicidal ingestions of antifreeze. *Clinical Toxicology*, 46(6), pp.507–514. doi: <https://doi.org/10.1080/15563650802119700>

³⁴ White, N. C. *et al.* (2009). The Impact of Bittering Agents on Pediatric Ingestions of Antifreeze. *Clinical Pediatrics*, 48(9), pp.913–921. doi: <https://doi.org/10.1177/0009922809339522>

³⁵ Klein-Schwartz, W. (1991). Denatonium benzoate: review of efficacy and safety. *Veterinary and human toxicology*, 33(6), pp.545–7. Available at: <https://pubmed.ncbi.nlm.nih.gov/1808826/>.

³⁶ Semple, T. *et al.* (2018). Button battery ingestion in children—a potentially catastrophic event of which all radiologists must be aware. *The British Journal of Radiology*, 91(1081). doi: <https://doi.org/10.1259/bjr.20160781>

³⁷ Royal Society for the Prevention of Accidents (RoSPA). *Button batteries* [online]. Available at: <https://www.rospace.com/policy/home-safety/advice/product/button-batteries> (Assessed: 06 August 2024).

³⁸ Paul, A. (2024). *A new button battery dyes kids' mouths blue if swallowed*, *Popular Science* [online]. Available at: <https://www.popsci.com/health/button-battery-dye/> (Assessed: 20 June 2024).

³⁹ Energizer. *World's First 3in1 Child Shield* [online]. Available at: <https://energizer.com/3in1childshield/> (Assessed: 20 June 2024).

University of Wellington, New Zealand⁴⁰. A patent was granted for this innovation in the USA in 2018⁴¹.

The dye and bitterant are combined with a salivating agent; in contact with saliva, it promotes further salivation and stains the saliva blue. This alerts the child's caregiver to the presence of the battery within the child's mouth, and to seek medical attention for them immediately. In the product's patent, it was proposed that the coating should also preferably include an emetic (to induce vomiting). However, later media reports about this technology do not mention the inclusion of the bitterant or the emetic in the coating, focussing instead on the function of the dye and salivating agent as an alert tool for caregivers.

The adoption of the innovation by Energizer suggests that a saliva-staining dye can be incorporated into existing manufacturing production lines relatively easily and cheaply. In addition, it is reported that the coating can be applied retroactively post-manufacture via a pen-applicator system⁴⁰.

The efficacy of the technology has been demonstrated under test conditions^{39,40}. However, a true assessment of its effectiveness will require a post-deployment analysis of incident data, such as that conducted by White *et al.* with US poison centre data on antifreeze ingestion³⁴.

3.2.2 Radiopaque marker

Landsdowne Labs⁴² was founded as a spin-out company from the academic research of Prof. Robert Langer and Dr Jeffrey Karp at Harvard-MIT. They filed a patent application in 2016⁴³ for an innovation to reduce the likelihood of misdiagnosis following the ingestion of a button battery. Their innovation is to mark the button battery with a distinctive symbol, using a material incorporating radiopaque elements in various substances (e.g., tungsten, silver iodide) or geometries (e.g., etching mark, sphere) with a different opacity to X-rays than the (stainless steel) button battery casing. When an X-ray image is taken following a possible button battery ingestion, the distinctive symbol will be observed on the button battery due to the contrast with the button battery casing. This will positively identify the ingested object as a button battery, rather than a coin (which would lack any distinctive symbol). This reduces the likelihood of a misdiagnosis of a button battery ingestion as a less-serious coin ingestion, and ensures prompt medical intervention.

The distinctive symbol on the button battery could be marked with either a radiopaque material (one more opaque to X-rays), or a radiolucent material (one more translucent to X-rays), relative to the button battery casing. Examples given of radiopaque materials that could be used include tungsten, gold or titanium. No examples of radiolucent materials are provided but might include plastics or carbon fibre, as these are already used as

⁴⁰ Stuff (2019). *Bright blue dye the solution to making button batteries safer for children* [online]. Available at: <https://www.stuff.co.nz/national/health/112067913/bright-blue-dye-the-solution-to-making-button-batteries-safer-for-children> (Assessed: 26 October 2023).

⁴¹ Ok, J. (2016). *Safety material and system*. United States Patent Application Publication US20160211501A1. Available at: <https://patents.google.com/patent/US20160211501A1/en> (Assessed: 06 August 2024).

⁴² Landsdowne Labs. [online]. Available at: <https://www.landsdownelabs.com/> (Assessed: 06 August 2024).

⁴³ Barenberg, S. A., Karp, J. M. and Laulicht, B. (2016a). *Biocompatible coated batteries, systems and methods related thereto*. World Intellectual Property Organization (WIPO) Patent Application WO2016179501A1. Available at: <https://patents.google.com/patent/WO2016179501A1/en> (Assessed: 06 August 2024).

radiolucent materials in medical devices⁴⁴. It goes without saying, human health effects would need to be carefully considered before use of such materials.

It is not known whether a prototype incorporating the radiopaque marker innovation has been manufactured, and no evidence of its efficacy is provided in the patent application⁴³. Furthermore, were the innovation to be adopted, its effectiveness in reducing the misdiagnosis of button battery ingestions would depend on its uptake across the button battery market. Until a significant proportion of the market had adopted the innovation, its effectiveness in discriminating between coin and button battery ingestions would be limited. A button battery incorporating the innovation would be expected to be positively identifiable in an X-ray image and aid diagnosis. However, if only a small proportion of the button batteries on the market were known to have adopted the innovation, a radiographer would still be unclear if a coin-like object without a distinctive symbol was indeed a coin, or just a button battery without a distinctive symbol. Hence, until there is widespread market adoption of the innovation, it would only provide limited diagnostic impact.

3.2.3 Urine-staining dye

A further innovation disclosed by Landsdowne Labs is a urine-staining dye coating applied to the exterior of the button battery⁴³. If the button battery is ingested, the dye coating (e.g. methylene blue) is intended to be absorbed and stain the urine a non-yellow colour. This would indicate to an individual or caregiver that a button battery might have been ingested.

However, it is not known whether a prototype incorporating the urine-staining dye innovation has been manufactured, and no evidence of its efficacy is provided in the patent application⁴³. As the diagnostic method depends on the patient urinating at some time after the ingestion of the button battery, its efficacy may be limited if it cannot provide alert to a caregiver quickly enough (within 2 hrs of ingestion).

3.3 Barriers to adoption

There are few significant technical barriers to the adoption of the bitterant-based or diagnostic methods described here. Duracell and Energizer have already brought bitterant-coated button batteries to market, and Energizer's coating also includes a saliva-staining dye. The bitterants and dyes are typically applied to the button battery as an ink coating (for instance, in the case from Victoria University of Wellington⁴⁰, using a pen-applicator system during manufacture or on existing batteries), and so do not involve major changes to the design or internal components of the battery. Therefore, they are less costly and comparatively more straightforward to introduce into current manufacturing lines than other innovations, though further studies would be needed to assess their integration into production (e.g., whether process redesign or new equipment would be required). However, in contrast to the dye coating, the radiopaque marker innovation may be more challenging and costly to implement due to the technical and material requirements that must be met (such as additional risk assessments for worker exposure and hazards when handling carbon fibres).

However, it is not known whether a prototype of the radiopaque marker and the urine-staining dye have been manufactured and tested, and their efficacy and effectiveness also remain unknown. Although there is some evidence of bitterant and saliva-staining dye efficacy, their effectiveness in reducing button battery ingestions is not proven. Their

⁴⁴ Medical Device and Diagnostic Industry (MD&DI) (2001). *Radiolucent Structural Materials for Medical Applications* [online]. Available at: <https://www.mddionline.com/materials/radiolucent-structural-materials-for-medical-applications> (Assessed: 06 August 2024).

adoption is not mandated by legislation but has been undertaken voluntarily by manufacturers. Although they are likely to have some benefit as a 'last line of defence' that is relatively cheap to implement, they should not be considered as an ultimate solution to the problem of button battery ingestion.

4 Reactive Safety Technologies

A reactive safety technology is one which is triggered if the button battery comes into contact with water or a bodily fluid and renders the button battery safe. Three different approaches exist:

1. **Pressure-sensitive conduction methods,**
2. **Chemical reaction with water,**
3. **Fuse and short-circuit methods.**

None of the reactive safety technologies are currently present in button batteries on the UK or foreign markets.

4.1 Pressure-sensitive conduction methods

The first group of reactive safety technologies are pressure-sensitive conduction methods. When implemented, these technologies render a button battery non-conductive when insufficient pressure is applied to it. The button battery will conduct and discharge only when a pressure greater than a predetermined threshold (e.g., 4–24 N/cm² in the case of Landsdowne Labs⁴³, depending on design and application) is applied. In this way, the button battery will function as normal when placed into the housing of a typical device, where the electrodes are under a pressure greater than the threshold value. However, if the button battery came into contact with water or bodily fluids in the oesophagus, there will be insufficient pressure for the battery to conduct and discharge.

4.1.1 Quantum-tunnelling composite coating

The quantum-tunnelling composite coating (QTCC) technology is another innovation developed by Prof. Robert Langer and Dr Jeffrey Karp's teams at Harvard-MIT. It was first reported in 2014⁴⁵ and a patent was granted in the USA in 2017⁴⁶. It is designed to switch the battery off when it is removed from its intended operating environment inside of a product.

It uses an advanced material ('quantum-tunnelling composite') coating which is applied to either or both of the button battery electrodes. The QTCC consists of conductive metal microparticles (e.g., silver, gold, carbon particles) embedded in an insulating polymer matrix (e.g., silicone rubber). When insufficient pressure is applied (below the predetermined threshold pressure), the metal microparticles are too far apart to allow electrical conduction. The predetermined threshold pressure would be set such that it is much higher than the pressure likely to be experienced in the oesophagus upon ingestion. When sufficient pressure is applied, the metal microparticles are forced close enough together (< 1-5 nm) that electrons can undergo 'quantum tunnelling' through the insulating polymer between neighbouring metal microparticles. This allows electrical conduction from the negative electrode, and normal battery operation, only in a high-pressure environment (such as in the battery compartment of a product).

The insulating polymer matrix is continuous and provides waterproofing for the button battery. Hence, if the button battery is ingested and comes into contact with bodily fluids,

⁴⁵ Laulicht, B et al. (2014). *Simple battery armor to protect against gastrointestinal injury from accidental ingestion*. *Proceedings of the National Academy of Sciences*, 111(46), pp.16490–16495. doi: <https://doi.org/10.1073/pnas.1418423111>

⁴⁶ Laulicht, B. et al. (2017). *Safely ingestible batteries*. United States Patent Application US9741975B2. Available at: <https://patents.google.com/patent/US9741975B2/en> (Assessed: 06 August 2024).

the low pressure renders the button battery electrically insulating, and the waterproof polymer matrix ensures there is no ingress of water inside the button battery. This prevents any electrochemical damage to internal tissue.

The efficacy of the technology was proven by performing an *in vivo* study on pigs using a Rayovac 675 hearing aid battery inserted directly into the oesophagus under anaesthesia. When a QTCC button battery was inserted, there was no microscopic or macroscopic tissue damage monitored up to two hours after insertion of the batteries in 30-minute timeframes; in contrast, the conventional battery caused severe microscopic and macroscopic tissue damage⁴⁵. However, the use of the smaller Rayovac 675 battery (1.4V) in this study may not reflect the risks associated with larger, more powerful 3 V lithium coin cells (e.g., CR2032), which are more likely to lodge in the human oesophagus and experience higher applied pressures. Consequently, the results cannot be assumed to indicate the technology's performance for larger batteries.

The technology was first demonstrated in 2014⁴⁷, but there is no evidence of further development, and it is not currently commercially available⁴⁸.

4.1.2 Mechanical pressure-sensitive conduction

The mechanical pressure-sensitive conduction technology is a further innovation from Landsdowne Labs that was disclosed in a patent in 2016⁴⁹. It is again designed to only allow the button battery to discharge when sufficient pressure is applied to the electrodes. However, unlike the QTCC technology, a mechanical system is used to achieve this.

The negative electrode of the button battery includes a cap which can move between two positions when pressure is applied or removed. In the absence of sufficient applied pressure (below the predetermined threshold), the negative electrode cap is held in a position which is disconnected and electrically isolated from the main negative electrode. It is held in place by a compressible gasket and/or an elastomeric spacer. When sufficient pressure is applied, the compressible gasket and/or the elastomeric spacer compress and allow the negative electrode cap to move to a second position which is connected to the main negative electrode. This allows for electrical conduction from the negative electrode cap to the main negative electrode, and thus for the button battery to discharge.

Again, the threshold pressure is set such that it is much higher than would be expected in the oesophageal environment. Therefore, the negative electrode cap of an ingested button battery would be isolated from the main negative electrode and the battery would discharge, rendering it safe.

Since the disclosure of the innovation, it is not known whether a prototype has been manufactured, and no evidence of its efficacy is provided in the patent application⁴⁹.

⁴⁷ BBC News (2014). 'Quantum coat' makes batteries child-safe [online]. Available at: <https://www.bbc.co.uk/news/science-environment-29885832> (Assessed: 06 August 2024).

⁴⁸ British and Irish Portable Battery Association (BIPBA) (n.d.). *Button and coin batteries – Safety requirements*. [online]. Available at: <https://bipba.co.uk/button-and-coin-battery-ingestion-2/> (Assessed: 06 August 2024).

⁴⁹ Barenberg, S. A., Karp, J. M. and Laulicht, B. (2016b). *Pressure-sensitive batteries, systems and methods related thereto*. World Intellectual Property Organization (WIPO) Patent Application WO2016179504A1. Available at: <https://patents.google.com/patent/WO2016179504A1/en> (Assessed: 06 August 2024).

4.2 Chemical reaction with water

The second group of reactive safety technologies employs a direct chemical reaction with water to render the button battery safe upon ingestion. The intended chemical reaction with water delays or prevents the otherwise harmful electrolysis reaction from occurring.

4.2.1 Sacrificial metal casing

Panasonic filed a patent application in 2016 for an innovation which uses a sacrificial metal casing to reduce electrochemical tissue damage on ingestion⁵⁰. The internal electrochemical cell (negative electrode, positive electrode, separator and electrolyte) providing the power is hermetically sealed within an external casing, consisting of two layers. The internal layer of the two casing layers is stainless steel (typical of regular button battery casing) and provides the strength and corrosion resistance of the casing. The external layer is made of either aluminium, magnesium or one of their alloys.

Aluminium (or magnesium) are chosen because they are 'amphoteric' (a compound being able to react both as an acid and as a base) and will dissolve in both acidic and alkaline solutions. When a button battery employing this innovation comes into contact with water or bodily fluids, electrolysis of water will begin to occur at both electrodes. The solution surrounding the negative electrode terminal will become alkaline, whilst the solution surrounding the positive electrode terminal will become acidic. The external aluminium layer will begin to sacrificially dissolve at both electrode terminals, becoming positively charged ions.

At the negative electrode, electrical current from the battery is used to chemically 'reduce' the dissolved aluminium ions back to aluminium metal, which is then deposited back onto the negative electrode terminal. This chemical reaction happens in preference to the further electrolysis of water, thereby electrochemically limiting any associated caustic alkaline tissue damage.

At the positive electrode, the dissolved aluminium reacts with water and oxygen and is deposited on the positive electrode terminal as aluminium oxide (or aluminium hydroxide). Aluminium oxide (and aluminium hydroxide) is electrically insulating, and deposition will reduce and eventually stop current flow. This will limit any associated acidic tissue damage around that electrode terminal.

Furthermore, it is possible the aluminium metal could be deposited in the gap between the electrode terminals. If sufficient metal is deposited, the electrodes could become connected by aluminium and short circuit the battery. That would rapidly drain the battery and limit further tissue damage.

The efficacy of the innovation was proven using a hydrated ham test. The ham was assessed after 30 min at room temperature, and samples incorporating the sacrificial metal casing showed significantly less tissue damage than the control sample. Furthermore, the pH of the ham surface was measured after the test was complete. Whilst the ham in contact with the control sample had a very high alkaline pH (> 14), the test samples had a much less alkaline pH (6.8, 6.7 or 10.8).

It is not known whether further development has taken place since the disclosure of the invention, nor whether Panasonic intends to bring this innovation to market.

⁵⁰ Takahashi, T. and Yagishita, T. (2017). *Coin-shaped battery*. World Intellectual Property Organization (WIPO) Patent Application WO2017119033A1. Available at: <https://patents.google.com/patent/WO2017119033A1/en> (Assessed: 06 August 2024).

4.2.2 Electrolysis-resistant electrode cladding

Energizer filed a patent application for their electrolysis-resistant electrode cladding technology in 2013⁵¹. In their innovation, the electrodes are each clad with a conductive layer which prevents electrolysis of water from occurring. Specifically, the negative electrode cladding is 'resistant' to hydrogen formation and the positive electrode cladding is 'resistant' to oxygen formation (and dissolution under the acidic conditions generated around the positive electrode). If neither of these gases can be formed at their respective electrodes, then the overall electrolysis reaction which leads to tissue damage cannot occur.

The resistance to either hydrogen or oxygen formation at the respective electrodes is achieved by choosing electrode materials with a large overpotential for that specific reaction. Overpotential is the additional (electrical) energy that is required for an electrochemical reaction to proceed beyond its expected theoretical value, and this 'extra' energy is then often lost as heat. The patent suggests titanium, a titanium alloy or a copper-tin-zinc alloy, nickel or stainless steel as being suitable materials for the negative electrode. Similarly for the positive electrode, titanium, a titanium alloy, titanium nitride, tantalum, niobium, stainless steel, gold or boron-doped diamond are suggested as suitable materials.

The efficacy of the innovation was proven by measuring the pH, voltage and current of a prototype button battery and a control following immersion into synthetic saliva. One test showed that for the prototype, the pH of the synthetic saliva had only increased from around 6 to 7.5 after 1 hr, and the current had rapidly reduced to less than 1 mA. This indicates that the electrolysis reaction was suppressed for the cladded button battery and therefore hydroxide was not formed. In contrast, the pH of the control button battery had increased to 13 (alkaline) in approximately 40 mins, and the current was stable at 22-25 mA for 1 hr. This indicates that electrolysis of water was likely to be occurring.

It is not known whether further development has taken place since the disclosure of this invention, nor whether Energizer intends to bring it to market in the future.

4.2.3 Metal oxide electrode-deactivating layer

Landsdowne Labs first filed a patent application (assigned to Fenwood Labs) for their metal oxide deactivating layer innovation in 2021⁵², carrying the trademark ChildLok™⁴². A US patent was granted in 2022⁵³. A further, updated patent application was filed in 2023, where the authors provide detailed reasons as to why the overpotential concept proposed in their 2013 patent (discussed above in 4.2.2) is flawed, e.g., overpotential alone does not prevent harmful reactions; actual current and oxide formation are decisive⁵⁴.

The basis of their innovation is that one (or both) of the button battery electrode casings are modified to include two layers: an inner conductive layer and an (external)

⁵¹ Guo, J. and Huang, W. (2013). *Lithium coin cell construction to mitigate damage from ingestion*. World Intellectual Property Organization (WIPO) Patent Application WO2013106821A1. Available at: <https://patents.google.com/patent/WO2013106821A1/en> (Assessed: 06 August 2024).

⁵² Laulicht, B. et al. (2022a). *Safely ingestible batteries that rapidly deactivate in biological environments and methods of making same*. World Intellectual Property Organization (WIPO) Patent Application WO2022046791A1. Available at: <https://patents.google.com/patent/WO2022046791A1/en> (Assessed: 06 August 2024).

⁵³ Laulicht, B. et al. (2022b). *Safely ingestible batteries that rapidly deactivate in biological environments and methods of making same*. United States Patent US11469465B2. Available at: <https://patents.google.com/patent/US11469465B2/en> (Assessed: 06 August 2024).

⁵⁴ Laulicht, B. et al. (2024). *Safely Ingestible Batteries that Rapidly Deactivate in Biological Environments and Methods of Making Same*. United States Patent Application US20240088488A1. Available at: <https://patents.google.com/patent/US20240088488A1/en> (Assessed: 06 August 2024).

‘deactivating layer’, incorporating a ‘deactivating metal’. The deactivating metal is chosen such that it will form an electrically insulating oxide in contact with water, and thus deactivate the battery. Niobium, tantalum or an alloy or combination thereof are suggested as possible deactivating metals for either electrode. However, tungsten, rhenium or titanium are also suggested as possible deactivating metals. The inner conductive layer is in electrical contact with the deactivating layer in each case, so that the button battery is conductive and functions under normal (dry) conditions.

If a button battery incorporating this innovation was ingested and came into contact with bodily fluid, the deactivating metal is intended to oxidise and deactivate the button battery within 2 hrs. However, in some cases, the deactivating layer could oxidise within 15 mins. In this way, any electrolysis of water will only occur slowly (if at all), and there will be a significant reduction in chemical tissue damage.

The efficacy of this technology has been proven through extensive practical testing. A hydrated ham test was conducted with two prototype test batteries using a CR2032 positive electrode case made of tantalum or titanium, and a CR2032 negative electrode case made of stainless steel. These were both compared to a control using a stainless steel CR2032 positive electrode case. After 24 hr, the ham slice on the positive electrode side showed minimal damage for both the titanium and tantalum prototypes, but some discolouration on the ham slice on the negative electrode side was observed for the titanium prototype. For the stainless steel control, significant damage was observed to the ham slices on both the positive electrode and negative electrode sides. The pH of the ham slice on the negative electrode side of each button battery were also measured after 24 hrs. In the stainless steel control, the pH was 12.5, indicating alkaline conditions from the generation of hydroxide. For the titanium prototype, the pH had increased to 6.5 at 24 hr, whereas the tantalum prototype showed no change in pH over 24 hrs⁵⁴.

The delayed electrolysis technology is currently being commercialised⁵⁵. It is claimed that the technology ‘will not require major changes by manufacturers’⁵⁶, and so could be bought by them for use in their own button batteries in the future.

4.2.4 Neutralisation coating

Energizer have developed a coating for a button battery which will dissolve if the battery is exposed to saliva and release a food-grade acid, like citric acid⁵⁷. The innovation was first disclosed in 2018 and was granted a patent in the USA in 2020⁵⁷.

The acid released from the coating is intended to neutralise the hydroxide generated from electrolysis. It thereby reduces or prevents alkaline caustic chemical burns. A comparative hydrated ham test was performed over 4 hr on a pair of citric acid-coated CR2032 button batteries, and a pair of uncoated control CR2032 button batteries. The coated batteries showed a reduction in tissue damage after both 1 and 4 hr as compared to the control batteries, as assessed through qualitative visual inspection, with indicators including lighter burn marks, audible noise, and the scent of burning tissue.

⁵⁵ CT Insider (2022). *Fairfield startup working on child-safe battery technology* [online]. Available at: <https://www.ctinsider.com/fairfield/article/Fairfield-startup-working-on-child-safe-battery-17375478.php> (Assessed: 06 August 2024).

⁵⁶ Business Wire (2022). *Landsdowne Labs Awarded Patent for Button Battery Coating to Reduce Ingestion Injuries* [online]. Available at: <https://www.businesswire.com/news/home/20221011006244/en/Landsdowne-Labs-Awarded-Patent-for-Button-Battery-Coating-to-Reduce-Ingestion-Injuries/> (Assessed: 06 August 2024).

⁵⁷ Boolish, M. and Wemple, M. (2018). *Coatings for mitigation of coin cell ingestion*. United States Patent Application US20180076467A1. Available at: <https://patents.google.com/patent/US20180076467A1/en> (Assessed: 06 August 2024).

It is not known if or when the technology will be introduced to the market, or whether it has been developed since initial disclosure. As the acid is designed to be applied as a coating to the completed battery⁵⁷, it is possible that it could be integrated into existing manufacturing processes relatively easily.

4.2.5 Water-reactive positive electrode bridge

Fenwood Labs, another spinout company from the research of Langer and Karp, disclosed an innovation in 2020 which uses a water-reactive positive electrode 'bridge'⁵⁸. The positive electrode casing consists of two metallic layers, an inner and an outer layer, with an insulating layer between them. The inner and outer conducting layers of the positive electrode casing are connected by at least one positive electrode 'bridge'.

The positive electrode bridge is formed of an electrical conductor, typically a metal which will electrochemically oxidise and/or dissolve in an aqueous environment when a current flows through it. Examples for possible positive electrode bridge materials include stainless steel, magnesium or aluminium. If the button battery were ingested and came into contact with water or bodily fluids, the positive electrode bridge would electrochemically react: either dissolving, or forming an insulating metal oxide layer. In both cases, the two positive electrode casing layers would become electrically insulated from one another and no further current could flow. The button battery could no longer discharge and any (further) electrochemical tissue damage from electrolysis of water would be prevented.

The efficacy of the innovation was conclusively demonstrated in the patent application, through a variety of comparative tests of button batteries incorporating the water-reactive positive electrode bridge innovation and both commercial and lab-manufactured controls. These included measuring the pH over 3 hr after immersion in saline solution, measuring the voltage during immersion in Ringer's solution for 2 hr, a 4 hr exposure to porcine oesophageal tissue and a hydrated ham test.

In the porcine oesophageal test, the commercial and lab-manufactured controls showed tissue damage after 1 hr and severe tissue damage (necrosis) after 4 hr. In contrast, the exemplar incorporating the innovation showed minimal tissue damage. In the hydrated ham test, the pH of the control batteries was 10 after 1 hr, whereas it was only 8 after 1 hr for the exemplar. The ham in contact with the control batteries was discoloured and contained deposits from corrosion; in contrast, the exemplar showed only minimal discolouration and deposits⁵⁸.

It is not known whether further development has taken place for this innovation since disclosure, nor whether Fenwood Labs intend to bring it to market.

4.3 Fuse and short-circuit methods

The final group of reactive safety technologies are fuse and short-circuit methods. The fuse innovations employ a component which is electrically conductive in normal conditions but becomes insulating if ingestion and contact with water or other bodily fluids was to occur. As an aside, it is true that the 'water-reactive positive electrode bridge' of 4.2.5 also satisfies this criterion. The short-circuit innovation works in the opposite fashion, using a component which is insulating under normal conditions but becoming electrically conductive in an ingestion scenario. Due to the location of the component, its conduction

⁵⁸ Laulicht, B. *et al.* (2020). *Batteries that deactivate in a conductive aqueous medium and methods of making the same*. World Intellectual Property Organization (WIPO) Patent Application WO2020251998A1. Available at: <https://patents.google.com/patent/WO2020251998A1/en> (Assessed: 06 August 2024).

causes a short circuit between the electrodes, which rapidly reduces the button battery voltage to safe levels.

4.3.1 Polymer fuse

IBM first disclosed an innovation for a button battery incorporating a polymer-based fuse in 2012⁵⁹. This was followed by a further patent, granted in the USA 2017⁶⁰. The innovation consists of a conductive polymer 'fuse' layer which sits on top of the negative electrode. A metal wire mesh protective grid can be placed over the polymer fuse layer to increase its robustness.

The polymer fuse layer is electrically conductive under normal conditions, allowing the button battery to function normally. In acidic or alkaline aqueous conditions, such as those encountered in the oesophagus or stomach, the polymer fuse will decompose. The fuse will 'blow' and becomes insulating. This isolates the negative electrode and stops further current flow which prevents (further) tissue damage.

The polymer within the fuse layer is a 'block copolymer', consisting of two different 'blocks' of monomer subunits: a hydrophilic block and a hydrophobic block. The hydrophobic block provides structural integrity to the polymer, especially after decomposition. The hydrophilic block provides a 'scaffold' for the conductive element of the fuse layer.

The patent provides several examples of how the hydrophilic block can facilitate the overall conductivity of the fuse layer. The hydrophilic block can be designed to provide a matrix within which conductive metal nanoparticles can be embedded. Alternatively, the hydrophobic block can co-ordinate metal salts which provide the required conductivity.

In acidic or alkaline aqueous conditions, the hydrophilic block of the copolymer disintegrates, and the fuse becomes electrically insulating. This could be through an acidic or alkaline chemical degradation of the polymer, or through the release of the co-ordinated metal salts or embedded nanoparticles providing the conduction. In either case, the polymer fuse disintegrates and becomes insulating, preventing current flow.

The patent suggests that conventional button batteries could be retrofitted with a polymer fuse. It is not known whether a prototype incorporating the polymer fuse innovation has been manufactured, and no evidence of its efficacy is provided in the patent application⁶⁰.

4.3.2 Metallic fuse

The metallic fuse technology was developed by a team from the University of Groningen and Delft University of Technology in the Netherlands. A Dutch patent was granted in 2022⁶¹.

In this innovation, at least one metallic fuse links the negative electrode and the negative electrode casing, and/or the positive electrode and the positive electrode casing. The fuse itself consists of a conductive metal wire (such as aluminium, nickel, stainless steel or gold) embedded in a dielectric layer. The dielectric layer could be a solid material (e.g. paper, plastic or glass) or simply air.

If the battery comes into contact with water or bodily fluids, a relatively high current will be able to flow through the water, between the electrodes. This is estimated to be 0.5 A or

⁵⁹ DiPietro, R. A. *et al.* (2015). *Polymer fused batteries*. United States Patent US9130200B2. Available at: <https://patents.google.com/patent/US9130200B2/en> (Assessed: 06 August 2024).

⁶⁰ DiPietro, R. A. *et al.* (2017). *Polymer fused batteries*. United States Patent US9793519B2. Available at: <https://patents.google.com/patent/US9793519B2/en> (Assessed: 06 August 2024).

⁶¹ Fransiscus, G. *et al.* (2022). *Fused button battery*. Netherlands Patent NL2027247B1. Available at: <https://patents.google.com/patent/NL2027247B1/en> (Assessed: 06 August 2024).

above, whereas the maximum current of button batteries is typically 0.1 A. This high current will rapidly melt the fuse and break the circuit. No further current can flow, and so tissue damage is limited⁶². The fuse is reported to melt in less than 5 s.

The efficacy of the metallic fuse technology has been demonstrated upon immersion tests in synthetic saliva (Ringer's solution). A CR2032 prototype incorporating the innovation was immersed in Ringer's solution, and by measuring the current delivered by the button battery, it was shown that the fuse can melt in 0.2 s.

This technology, given its relatively recent invention and proof of concept demonstration, is in an early stage of development. However, as the technology is reported to be compatible with button battery manufacturing processes⁶³, it is possible that this will allow an accelerated commercialisation.

4.3.3 Quantum tunnelling expansion layer

The quantum tunnelling expansion layer is another innovation from Landsdowne Labs disclosed in a patent application in 2016⁴³. In this innovation, a layer (the "expansion layer") surrounds the negative electrode and the positive electrode. Under normal (dry) conditions, this layer is sufficiently thin that electrons can quantum tunnel through it. The button battery will therefore function as normal, as the electrons can tunnel from the negative electrode through the expansion layer, round the circuit, back through the expansion layer and into the positive electrode.

In contact with water, the expansion layer is designed to swell. This will prevent electrons from quantum tunnelling through the layer, as it is now too thick. The expansion layer thus insulates the battery in a wet environment, such as in the oesophagus, and prevents current flow and associated electrochemical damage.

Like the other technologies disclosed in the same patent application (the radiopaque marker and urine-staining dye innovations)⁴³, it is unknown whether a prototype has been manufactured, and whether the efficacy of the innovation has been demonstrated.

4.3.4 Water-sensitive short circuit layer

Duracell have developed a technology that works in an opposite fashion to the fuse technology. It was first disclosed in 2019 and was granted a patent in the USA in 2020⁶⁴. The technology comprises a water and/or alkaline-sensitive layer placed between the two electrodes. It is electrically insulating under normal conditions but becomes conducting when in contact with water, especially in alkaline conditions. Therefore, a direct conductive pathway is introduced between the electrodes, which 'shorts' the battery and rapidly decreases the voltage to a safe level.

Several chemical mechanisms are proposed for the functioning of the water-sensitive short circuit layer. In one example, the water-sensitive layer consists of a soluble ammonium salt (e.g. ammonium chloride) and an insoluble copper salt (e.g. copper carbonate), embedded within a water-soluble polymer (e.g. polyvinyl acetate) matrix. Upon ingestion, electrolysis of water will generate hydroxide ions. These react with the ammonium chloride to produce ammonia (it is worth noting that this is potentially hazardous in itself, as generation of

⁶² University of Groningen (2023). *UG/ UMCG and TU Delft join forces for child-friendly button cell battery* [online]. Available at: <https://www.rug.nl/about-ug/latest-news/news/archief2023/nieuwsberichten/ug-umcg-and-tu-delft-join-forces-for-child-friendly-button-cell-battery?lang=en> (Assessed: 06 August 2024).

⁶³ Innovation Origins (2023). *TU Delft and RUG/UMCG develop child-friendly button cell battery* [online]. Available at: <https://innovationorigins.com/en/tu-delft-and-rug-umcg-develop-child-friendly-button-cell-battery/> (Assessed: 06 August 2024).

⁶⁴ Pozin, M. and Paxton, W. F. (2020). *Battery cell with safety layer*. United States Patent US10637011B2. Available at: <https://patents.google.com/patent/US10637011B2/en> (Assessed: 06 August 2024).

ammonia could cause the battery to swell and could cause bodily burns). The ammonia can then react with the insoluble copper carbonate to produce a water-soluble copper-ammonia complex. This copper-ammonia complex can diffuse to the negative electrode, where the copper ion will be reduced to copper metal and deposited. The deposited copper will grow as a dendrite from the negative electrode towards the positive electrode. Once the positive electrode and negative electrode are fully conducted by a metal dendrite pathway, the button battery will short circuit.

In a second example, a water-soluble copper salt (e.g. copper sulphate) and a metal powder (e.g. zinc) are embedded within a water-soluble polymer. Under normal, dry conditions, the copper sulphate and the zinc powder are interspersed within the polymer matrix and cannot react with one another. However, in contact with water, the copper sulphate will dissolve, and can react with the zinc powder. Copper metal will form and again be deposited as a growing dendrite. Any remaining, unreacted zinc powder can act as 'bridges' for copper dendrite growth, accelerating the process of forming a short circuit between the two electrodes.

In both examples, a conducting pathway is provided between the electrodes, which rapidly 'shorts' the button battery. This reduces the voltage below the threshold for electrolysis to occur. The threshold voltage is determined by the overpotential required, but is usually at least 1.5 V. In principle, short circuiting the button battery could reduce the voltage to 0 V.

The performance of the button battery in normal operation, specifically its voltage and battery capacity, are reported to remain unaffected by the incorporation of this innovation. Moreover, it is claimed that some examples of the coating could be durable enough to be stored for at least 90 days in conditions of up to 65% relative humidity without unintentionally shorting. Various printing methods are proposed for depositing the water-sensitive short circuit layer onto the button battery, including inkjet printing and spraying methods. If the layer can be applied to a complete button battery, it may reduce manufacturability and cost barriers to its incorporation.

The efficacy has been proven by measuring the voltage of the battery after immersion in Ringer's solution. In one test, the voltage of a prototype incorporating the innovation dropped below 1 V in 5 mins. In another example, nine samples of a different prototype were placed in contact with an aqueous solution. After 2 hr, the measured voltage of all samples was below 0.7 V, and the measured pH was 7 or below. In a third example, a different prototype was placed in contact with an aqueous solution, and the voltage was reported to drop below 1.2 V in less than 6 min 40 s⁶⁴. In all cases, the tests demonstrated that the innovation could prevent electrolytic chemical damage if a button battery were to be ingested. However, there is no known evidence of a hydrated ham test or equivalent to assess tissue damage in this instance.

It is not publicly known how far commercialisation has progressed with this technology, nor when or if Duracell will introduce it into the market.

4.4 Barriers to adoption

There are several general barriers to the adoption of reactive safety technologies by button battery manufacturers. These are outlined below.

The first barrier to adoption is **manufacturability**. These innovations typically require a significant modification to the (internal) components of a standard button battery to incorporate the desired safety functionality. They may rely on advanced materials science or engineering concepts, and these could be technically demanding to implement at scale.

A key contribution to manufacturability is **cost**. Current manufacturing production lines are unlikely to be able to accommodate these design changes without costly modification. In addition, a more complicated battery product will also be comparatively more expensive to manufacture per unit, increasing the unit cost. However, it is possible that with further development, along with economies of scale, these costs might decrease to a reasonable level.

A further barrier to adoption is **maintaining battery performance**. If a safety innovation requires an additional layer, or a physical mechanism to be introduced inside the battery, less internal volume is then available for the 'active' battery components providing the power. This will result in a decrease in the button battery performance, particularly the energy density battery capacity (how much electrical energy the button battery can provide)⁶⁵. A reduction in performance, or an increase in cost, will reduce the market competitiveness of the button battery and result in a reduced uptake by consumers.

⁶⁵ Wind & Sun Ltd (2023). *Battery Capacity* [online]. Available at: <https://www.windandsun.co.uk/blogs/articles/battery-capacity> (Assessed: 16 August 2024).

5 Safe-by-Design Methods

The final class of technologies are safe-by-design (SbD) approaches, which we have chosen to consider from a 'hazards to human health' perspective. The rationale behind their development is to make the button battery an inherently safe product by 'designing out' the associated hazards.

5.1 Button battery design modifications

5.1.1 Smaller batteries and/or pin-point electrodes

Two safe-by-design approaches were suggested in a scientific paper by Paull in 2021⁶⁶:

1. **Reducing the diameter of 20 mm lithium coin batteries:** this reduces the risk that these higher voltage batteries will get lodged in the oesophagus.
2. **Use of recessed, pin-point electrodes:** this significantly reduces the surface area available for contact with tissue, thereby reducing the risk of chemical burns.

However, to the best of our knowledge, neither of these approaches are being actively pursued by manufacturers.

5.1.2 Non-toxic, low-capacity batteries

A collaboration between BlueThink SpA⁶⁷ and Italian academic researchers reported a new design of battery in 2017 which will not cause caustic damage to tissues if ingested⁶⁸. Their 10 x 15 x 1 mm 'green cell' (GC) battery uses an aluminium-air chemistry. It delivers 2 V, a higher voltage than typical aluminium-air batteries (which usually deliver less than 1.7 V⁶⁹).

The safety of the battery is threefold. Its small size means it is far less likely to become lodged in the oesophagus in the first place, when compared to a larger, 20-24 mm Li coin battery. The aluminium and porous carbon mesh electrodes are (chemically) of reduced toxicity. Finally, it has a very low 'battery capacity' (a measure of electrical charge delivered) of 2.5 mA h. This is compared to the 220 mA h of the commercial lithium coin, or 20 mA h of the silver oxide button batteries that the researchers used as comparisons in their study. The much lower energy density means that electrolysis of water does not occur, and so no caustic tissue damage is possible.

The efficacy of the design was proven by performing a variation of the hydrated ham test, where a battery was placed inside a short segment of extracted pig oesophageal tissue. No tissue damage was observed after 12 hours at both macroscopic and microscopic levels when the GC was used. In comparison, the oesophageal tissue segments with silver oxide button or lithium coin batteries inserted into them exhibited significant damage at both macroscopic and microscopic levels after only six hours.

⁶⁶ Paull, J. (2021). Button Batteries and Child Deaths: Market Failure of Unsafe Products. *International Journal of Clinical and Experimental Medicine Research*, 5(3), pp.297–303. doi: <https://doi.org/10.26855/ijcemr.2021.07.011>

⁶⁷ BlueThink S.p.A. [online]. Available at: <https://www.bluthink.it/> (Assessed: 06 August 2024).

⁶⁸ Rossi, A. *et al.* (2017). Safe Energy Source in Battery-operated Toys for Children. *Journal of Pediatric Gastroenterology and Nutrition*, 65(5), pp.496–499. doi: <https://doi.org/10.1097/mpg.0000000000001555>

⁶⁹ Arai, H. & Hayashi, M. (2009). SECONDARY BATTERIES – METAL-AIR SYSTEMS | Overview (Secondary and Primary). *Encyclopedia of Electrochemical Power Sources*, pp.347–355. doi: <https://doi.org/10.1016/b978-044452745-5.00099-x>

It is not known how far commercialisation has progressed with this technology, nor when or if BlueThink will introduce it into the market. The researchers state that 'from a commercial point of view, the GC performance, both in terms of power and duration, is compatible for the application in small toys for which it was conceived'⁶⁸. In low-power devices, it is therefore plausible that the lower battery capacity will not be a barrier to commercialising this technology.

5.1.3 Biocompatible power sources (triboelectric nanogenerator)

One safe-by-design approach to button battery safety is to use an alternative, biocompatible power source. By definition, a biocompatible power source will not produce an adverse effect when in contact with a living system⁷⁰, and so hazards would be reduced if ingested. Many advances have been made in this area as part of research and development for implantable medical devices^{71,72}. It is important to note that biodegradability⁷⁰ alone, although important for reducing the environmental impact of button battery use, would not be sufficient for satisfying safe-by-design criteria, as human health considerations are also required^{73,74}.

A Chinese academic team have reported a safe-by-design biocompatible power source using a triboelectric nanogenerator (TENG)⁷⁵. A TENG is an energy-harvesting device which converts (waste) mechanical energy into electrical energy using the triboelectric effect. The triboelectric effect is the build-up of dissimilar electric charge on two materials when they are placed in contact and then moved apart or rub against one another; it is commonly encountered as the phenomenon of static electricity⁷⁶. When two different materials rub together, electrons are transferred to the material with the higher affinity for electrons, and this material builds up a negative charge. A complementary positive charge is left behind on the other material. A TENG generates an electric current by harnessing the triboelectric effect, through the pressing together or moving apart of these two different materials. In this way, mechanical energy can be directly converted into electrical energy.

The TENG prototype uses two biocompatible materials as the 'friction layers' to harness the triboelectric effect: carboxymethyl chitosan (CMCS) and carboxymethyl cellulose sodium (CMC-Na) nanofiber membranes. Both nanofiber membrane materials are water soluble. Gold foil is used for both electrodes, one adhered to each of the nanofiber materials.

At rest and in contact, the CMCS has the higher electron affinity and so electrons are transferred from the CMC-Na to the CMCS. The CMC-Na therefore carries a positive charge, and the CMCS carries a negative charge. The fabricated prototype was shown to

⁷⁰ Vert, M. *et al.* (2012). Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). *Pure and Applied Chemistry*, [online] 84(2), pp.377–410. doi: <https://doi.org/10.1351/pac-rec-10-12-04>

⁷¹ Kim, Y. J. *et al.* (2013). Self-deployable current sources fabricated from edible materials. *Journal of Materials Chemistry B*, 1(31), p.3781. doi: <https://doi.org/10.1039/c3tb20183j>

⁷² Kim, Y. J. *et al.* (2013). Biologically derived melanin electrodes in aqueous sodium-ion energy storage devices. *Proceedings of the National Academy of Sciences of the United States of America*, 110(52), pp.20912–20917. doi: <https://doi.org/10.1073/pnas.1314345110>

⁷³ Yin, L. *et al.* (2014). Materials, Designs, and Operational Characteristics for Fully Biodegradable Primary Batteries. *Advanced Materials*, 26(23), pp.3879–3884. doi: <https://doi.org/10.1002/adma.201306304>

⁷⁴ Esquivel, J. P. *et al.* (2017). A Metal-Free and Biotically Degradable Battery for Portable Single-Use Applications. *Advanced Energy Materials*, 7(18), pp.1700275–1700275. doi: <https://doi.org/10.1002/aenm.201700275>

⁷⁵ Yan, K. *et al.* (2020). A non-toxic triboelectric nanogenerator for baby care applications. *Journal of Materials Chemistry A*, 8(43), pp.22745–22753. doi: <https://doi.org/10.1039/d0ta08909e>

⁷⁶ Alam, S. N. *et al.* (2023). An introduction to triboelectric nanogenerators. *An Introduction to Triboelectric Nanogenerators*, 34, pp.100980–100980. doi: <https://doi.org/10.1016/j.nanoso.2023.100980>

be capable of achieving a short-circuit current of 20 nA and an open-circuit voltage of 3 V. This was shown to be sufficient to power a variety of low-power consumer devices⁷⁵.

To demonstrate the safety of the TENG, an acute systemic toxicity test was conducted with ICR mice. Yan *et al.* showed that there was no significant weight change, or observable symptoms, after the mice consumed either the CMCS or the CMC-Na nanofibers, compared to a control group. This represents good initial evidence of the safety of the TENG device. However, further tests, such as a hydrated ham test or an *in vivo* insertion test might need to be conducted to fully demonstrate safety upon ingestion.

5.1.4 Barriers to adoption

Safe-by-design methods that invoke modifications to the design of the button battery have similar barriers to adoption as reactive safety technologies. These are **manufacturability**, **cost**, and **maintaining battery performance**. The innovations in this category have a fundamentally different design, operating characteristics and set of target products to button batteries currently on the market. They are unlikely to be compatible with current manufacturing production lines, presenting significant capital costs, and may present challenges for manufacture at scale.

In addition, they are unlikely to be able to match the high performance of current button batteries. However, the inventors of both the non-toxic, low-capacity batteries and the TENG demonstrated that their inventions could perform well in low-power products. In this subset of the market, these innovations may be sufficiently competitive.

A further barrier to adoption of button battery modification safe-by-design methods is the **restrictive ‘form factor’** (prescribed physical size, shape and dimensions) of the button battery itself. A button battery is manufactured to be a specific size and shape to fit within other consumer products, such as toys and electronics. Any change to the design of the battery in the future would make it incompatible with these products. Therefore, any new technology that requires a change to the size or shape of the battery will be immediately commercially disadvantaged, because it will not be able to function in current consumer products.

5.2 Product design modifications

The continuing development of alternative power sources for small electronic products, particularly solar-powered electronics, could eliminate the need for button batteries altogether in the future.

5.2.1 Safer methods of storage

Several stakeholders, including Jo Gideon (former MP for Stoke-on-Trent Central)⁷⁷ and the Australian Competition and Consumer Commission (ACCC)⁷⁸, have highlighted a novel Australian product called BattGuard™. This product provides a safe storage solution for used button batteries until they can be recycled.

The BattGuard plastic unit comes preloaded with working button batteries; when one needs to be replaced in a consumer product, the used battery is inserted into one end of the BattGuard and is thereafter stored irretrievably and safely. Simultaneously, a new battery becomes accessible from the other end, to be immediately inserted into the

⁷⁷ Comment Central (2023). *Government must act to ban button batteries* [online]. Available at: <https://commentcentral.co.uk/government-must-act-to-ban-button-batteries> (Assessed: 06 August 2024).

⁷⁸ Australian Competition and Consumer Commission (ACCC) (2019). *Button Battery Safety Issues Paper*. Available at: <https://www.productsafety.gov.au/product-safety-laws/safety-standards-bans/safety-investigations/button-battery-safety-investigation> (Assessed: 06 August 2024).

consumer product. Once the BattGuard is full of used batteries (and depleted of new ones), it can be recycled wholesale, without the need to handle loose batteries.

Information on the development of the BattGuard is not readily available from their website⁷⁹. Marketing on social media states that the technology is patent pending, although no reference to the patent application could be found. It is not known when or if the product will enter the market, or the company's current status.

5.2.2 Wireless charging

Wireless charging is an increasingly common innovation in public places and the domestic environment, relying on electromagnetic induction. It conveniently eliminates the need for charging cables and any (potentially conflicting) plug or port requirements⁸⁰. It can also allow electronic products to be hermetically sealed, as an internal battery can be recharged *in situ* without the need to be removed and recharged externally (or charged via a port)⁸¹. As the battery can be rendered completely inaccessible, any safety concerns arising from exposure to the battery are alleviated. As the button battery can be recharged, there will also be a reduction in battery waste.

A team from the Nano and Advanced Materials Institute, Hong Kong, has invented a system which enables wireless charging of a rechargeable button battery. It was first disclosed in 2020 and granted a patent in the USA in 2022⁸². It includes a voltage regulation circuit, which ensures a constant voltage output of between 1.8 V and 3.3 V in loading currents between 10 μ A and 300 mA. This covers a wide range of rechargeable button battery voltages. Their innovation is reported to be 'bendable up to an angle of 90 degrees in order to permit its incorporation into various housing shapes or incorporation into flexible, wearable electronic devices'. The efficacy of the innovation was demonstrated by measuring the charging voltage and current, and discharging voltage and current, of a LIR (lithium-ion rechargeable) 1654 coin battery charged using the wireless charger.

The patent reports that there is no reduction in charging function with a bend of 30, 60 or 90°. This suggests that the innovation will be compatible with the wide variety of form factors of consumer products containing button batteries⁸².

5.2.3 Solar-powered electronics

Solar-powered electronics are already present on the UK market⁸³; some high-end, wearable, 'smart' electronics include a photovoltaic cell which will charge the batteries in sunlight, or even indoor light in some products. The photovoltaic cell is designed to act as a secondary, passive charging mechanism, with mains charging remaining the primary method. The extended lifetime afforded to the battery by the solar charging means that it will have to be replaced less regularly, and this will contribute to improved safety. In addition, the prolonged life of the battery will reduce waste. However, the price premium on solar-powered wearable electronics means that they are not accessible to all consumers and are only present in a small subset of products.

⁷⁹ BattGuard. Available at: <https://battguard.com.au/> (Assessed at: 26 October 2023).

⁸⁰ Powermat Technologies Ltd. *Why Do Consumer Electronics Need Wireless Power?* [online]. Available at: <https://powermat.com/wireless-charging-consumer-electronics/> (Assessed: 06 August 2024).

⁸¹ Electronics Europe News (eeNews) (2018). *Wireless charging eliminates the cable mazes in your homes* [online]. Available at: <https://www.eenewseurope.com/en/domain/eenews-wireless/> (Assessed: 06 August 2024)

⁸² LEE, C.Y., LU, S. and Liu, C. (2020). *Wireless charging for rechargeable button cell battery*. Available at: <https://patents.google.com/patent/US20200144860A1/en> (Assessed: 06 August 2024).

⁸³ Digital Trends (2022). *The benefits of solar-powered smart wearables* [online]. Available at: <https://www.digitaltrends.com/home/benefits-of-solar-powered-smart-wearables/> (Assessed: 06 August 2024).

This is a promising avenue of product development. Products including a photovoltaic cell as an additional charging source are likely to grow in number and prevalence as their efficiency grows and their price falls, increasing their accessibility to consumers. However, in the short to medium term they are unlikely to eliminate the need for the emerging button battery safety technologies outlined in this report.

5.2.4 Barriers to adoption

The safe-by-design methods requiring modifications to product design have a particular set of barriers for their adoption. The Battguard™ innovation, for which information is limited, is excluded from the discussion.

Wireless charging and solar photovoltaics are both well-established as sources for electronic consumer products. However, to the best of our knowledge, wireless charging products designed to be used with button batteries are not yet commercially available. Barriers to adoption include **cost** and **efficiency**.

The major barrier to adoption is likely to be **cost**. Consumer product manufacturers would be required to modify their products to accommodate the (extra) circuitry required for wireless charging. This would require potentially costly design and manufacturing line modifications, leading to increased unit cost for their products. Furthermore, a wireless charger will likely have a relatively high unit cost compared to a replacement pack of (non-rechargeable) button batteries. Together, the wireless charging-enabled product may therefore struggle to compete on price against its regular, non-rechargeable alternative.

Wireless charging is **typically 70-80% efficient**, which is lower than for wired charging, which is typically 90-95% efficient⁸⁴. The efficiency of the button battery wireless charger is unknown but might reasonably fall within the 70-80% range. This may manifest in longer charging times, and slightly higher costs per recharge, as compared to wired charging.

⁸⁴ Anker Innovations (2024). *How Efficient Is Inductive Charging: Efficiency Insights* [online]. Available at: <https://www.anker.com/blogs/chargers/how-efficient-is-inductive-charging> (Assessed: 17 August 2024).

6 Further Barriers to the Adoption of Emerging Technologies

6.1 Competitiveness and market considerations

Button battery manufacturers consider a range of factors alongside safety, including **profitability and product competitiveness**. A safety technology that is associated with increased costs or a reduction in battery performance is unlikely to be adopted unilaterally, as it would make the button battery uncompetitive with those from other manufacturers.

However, two manufacturers (Duracell and Energizer) already have button batteries with a bitterant coating on the market. This might indicate that, providing the cost is not commercially prohibitive, manufacturers are willing to adopt safety technologies in the absence of regulatory requirements to do so. Furthermore, several of the biggest manufacturers, (Duracell, Energizer and Panasonic)⁸⁵, each hold at least one recent patent for an explicitly safety-focussed technology. This implies that there is a genuine willingness amongst manufacturers to invest in research and development of safety technologies, and to bring these to market where feasible.

It is unclear how significant consumer preference would be in driving the adoption of new safety technologies. Arguably, consumer preference for safer batteries could render less-safe products uncompetitive, and thereby provide an incentive for widespread adoption of a particular safety technology. However, previous research by OPSS has shown that **‘consumers rarely consider product safety when making purchase decisions’**⁸⁶, so it is unclear whether this strategy would be successful. Moreover, market fragmentation into ‘safer’ and ‘less-safe’ batteries could introduce additional challenges in the supply chain and in quality assurance processes for toy manufacturers.

A related barrier to adoption of reactive safety and safe-by-design technologies is that of **intellectual property (IP)**. Many of the technologies discussed in this report, including all the reactive safety technologies, are under patent protection. This means that other manufacturers cannot make use of the innovation without the consent of the patent owner⁸⁷. The direct adoption of a particular technology by all manufacturers (for instance to comply with new legislation) would only be possible with the appropriate license agreements in place. The full legal ramifications of this scenario are beyond the scope of this report but could present significant challenges both for manufacturers and regulators.

6.2 Limited innovation pool

A final barrier to adoption is the relatively limited innovation pool for button battery safety. There are only a small number of players, particularly in academia and research. Although there is a significant UK research effort in battery technology⁸⁸, where there is a focus on

⁸⁵ Valuates Reports (n.d.). *Global Button Cell Batteries Market Size, Manufacturers, Supply Chain, Sales Channel and Clients, 2024-2030*. [online]. Available at: <https://reports.valuates.com/market-reports/QYRE-Auto-3V9243/global-button-cell-batteries> (Assessed: 06 August 2024).

⁸⁶ UK Department for Business, Energy & Industrial Strategy (Office for Product Safety and Standards) (2020). *Consumer Attitudes to Product Safety: Research Report* (BEIS Research Paper Number 2020/032). Available at: <https://www.gov.uk/government/publications/consumer-attitudes-to-product-safety> (Assessed: 06 August 2024).

⁸⁷ World Intellectual Property Organization (WIPO) (n.d.). *Patents – What is a patent?* [online]. Available at: <https://www.wipo.int/patents/en/> (Assessed: 06 August 2024).

⁸⁸ UK Research and Innovation (UKRI) (2023). *Delivering the future of battery technology* [online]. Available at: <https://www.ukri.org/news/delivering-the-future-of-battery-technology/> (Assessed: 06 August 2024).

safety it is typically on improving general Li-ion battery safety (preventing thermal runaway and battery fires)⁸⁹, and not on the specific issue of button battery ingestion.

The scarcity of players is likely due to the difficulty in securing funding in this niche market. As these technologies are unlikely to improve performance or reduce cost, it is relatively difficult to secure return on investment, and the emergence of new entrants to the market is potentially unlikely.

⁸⁹ Christensen, P. *et al.* (2023). *Improving the Safety of Lithium-ion Battery Cells*, *Faraday Insights* 17. Available at: <https://www.faraday.ac.uk/policy/#reports> (Assessed: 06 August 2024).

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