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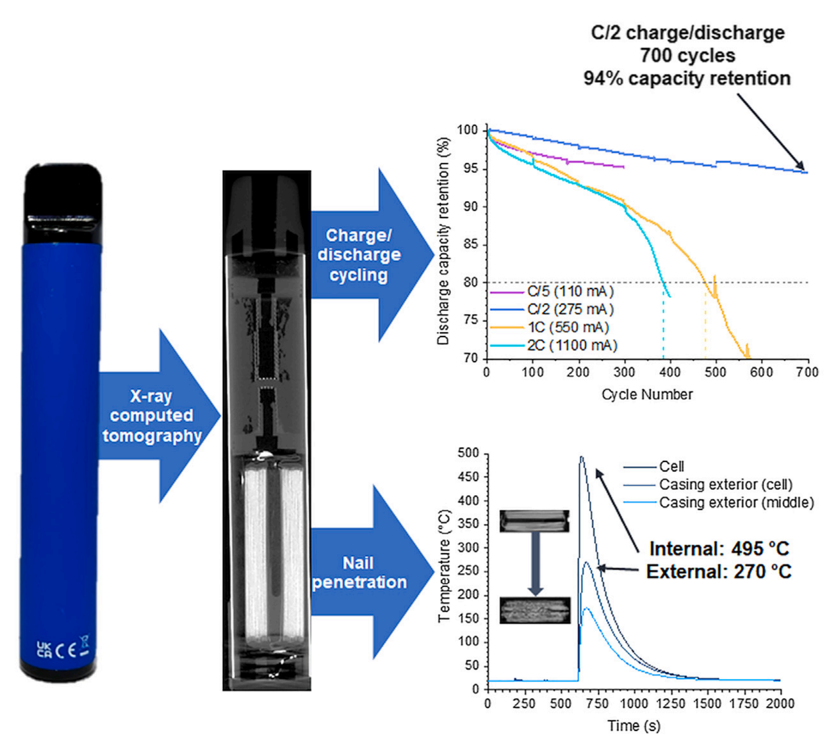
Up in smoke: Considerations for lithium-ion batteries in disposable e-cigarettes



Disposable e-cigarettes have increased in popularity in recent years. Many of the e-cigarettes that go to landfills after one use contain rechargeable lithium-ion cells. In this work, we quantify how many charge/discharge cycles the batteries in disposable e-cigarettes are capable of. We found that they could be cycled over 700 times. The disposal of these cells also presents a safety hazard as more batteries enter the waste stream. Using nail penetration testing, we saw a cell reach almost 500°C during thermal runaway.

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Highlights

Rechargeable Li-ion battery cells are widely used in single-use e-cigarettes

Disposable e-cigarette cells are potentially capable of over 700 cycles

A disposable e-cigarette cell reached almost 500°C during nail penetration testing

The disposal of so many rechargeable cells represents a huge waste of resources

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Up in smoke: Considerations for lithium-ion batteries in disposable e-cigarettes

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SUMMARY

In recent years, the use of disposable electric (e)-cigarettes containing lithium-ion batteries in the UK has led to remarkable wastage, the full environmental impact of which is yet to be realized. This study investigates the suitability for reuse and safety aspects of cells found in disposable e-cigarettes. Through electrochemical and safety characterization techniques, the cells' performance and hazards were evaluated. Rate capability and long-term cycling experiments showed that cells sold as disposable were capable of completing 474 cycles at 1C charge/discharge before reaching 80% capacity fade. A nail penetration test revealed significant gas expulsion and a maximum temperature of 495°C. However, the cell format prevented significant material ejection. This work outlines the potential health hazards and highlights the possibility for second-life use of disposable e-cigarette cells, shedding light on the environmental impact and safety considerations.

INTRODUCTION

Although the negative impact of smoking electric (e)-cigarettes is being researched, the possible environmental effects of their use and disposal have yet to be fully explored.[1–4] Since 2021, there has been a rapid rise in the popularity of disposable, single-use e-cigarettes. Uptake by young people in particular has been a major driver behind the booming sales of disposables. A survey by Tattan-Birch et al. found that, between January 2021 and April 2022, there was an 18-fold increase in participants who used disposable e-cigarettes.[5] The number of 18-year-olds using disposables increased from 0.4% to 54.8% over a 15-month period. The 2023 ASH (Action on Smoking and Health) report found that vaping among 11- to 17-year-olds grew from 11.2% in 2020 to 20.5% in 2023, with 69% of those most regularly using disposable e-cigarettes.[3] The Royal College of Paediatrics and Child Health recently called for a ban on disposable e-cigarettes, citing health concerns and environmental issues.[6] The rise in uptake in the UK has seen disposable e-cigarette brand Elf Bar rapidly outpace rechargeable rivals such as Juul and Blu (Table 1[7]).

With the expanding market, the disposal of each e-cigarette comes with a significant environmental cost. Of particular concern is the presence of lithium-ion batteries (LIBs) within e-cigarettes, which pose hazards if not properly handled during disposal. Material Focus found that 1.3 million single-use e-cigarettes are thrown away in the UK every week.[8,9] This equates to approximately 10,000 kg of lithium taken to landfills each year, equivalent to 1,200 electric vehicles.[8] LIBs also contain hazardous nickel, cobalt, and toxic organic solvents, which can leach out into waterways.

CONTEXT & SCALE

Disposable e-cigarettes, powered by lithium-ion cells, have exploded in popularity in recent years. As the world moves toward electrification, lithium and other crucial materials used to make rechargeable batteries are in demand, yet the cells used in disposable e-cigarettes are sold as single-use. When disposed of incorrectly, they also pose a major fire risk. Anecdotal evidence indicates that e-cigarette disposal is widespread in UK cities, so although the streets of London are not paved with gold, they may be paved with lithium.

Here, we explore whether disposable e-cigarette cells are suitable for charge/discharge cycling, along with their response to damage. Cells harvested from disposable e-cigarettes showed impressive cycling performance, capable of over 700 cycles. When pierced with a nail, the exterior of the e-cigarette reached 270°C. This work highlights the waste of vital materials caused by the sale of disposable e-cigarettes and the urgent need for government intervention.

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Table 1. Market share of the e-cigarette market in 2022

Position						
2022	2021	Brand	Manufacturer	Sales volume/£million	Change/£million	Change/%
1	18	Elf Bar	Elf Bar, UK	322.1	318.4	8,526.9
2	8	Vuse	BAT	85.1	69.8	458.0
3	13	Geek Bar	Geek Bar	44.7	38.3	606.0
4	1	Juul	Juul Labs	42.0	−7.5	−15.2
5	3	Blue	Imperial Brands	42.0	−2.4	−5.3
6	5	10 Motives	BAT	36.8	−0.7	−1.8
7	new	Elux	Shenzhen Elux Technology	36.8	36.7	–
8	7	Edge	Afrapoco	21.1	1.0	5.0

The high energy density, power performance, and long cycle life of LIBs have been transformative for the electronics and automotive sectors, placing the technology at the forefront of efforts toward electrification and Net Zero. LIBs are often employed in applications where thousands of charge/discharge cycles are needed. Decades of intense research from scientists and engineers across the globe have been committed to developing battery technology. Manufacturing techniques have advanced to the point where batteries are accessible and affordable, reducing global dependence on fossil fuels. To put the advances into perspective, a 2.04 Wh cell used in a disposable e-cigarette would have cost over £150 in 1992, whereas the same cell can be bought for less than £1 today.[10]

Alongside supply chain concerns, there has been growing attention paid to the safety ramifications of LIBs being used in everyday devices.[11–14] Either due to poor manufacturing quality or damage, LIBs can ignite, causing fires and releasing hazardous gases.[14–16] Materials Focus found in 2021 over 700 fires in trucks and waste facilities were due to discarded batteries.[9] With recycling firms struggling to secure insurance due to the increased risks of fires, the Local Government Association has joined the call to ban disposable e-cigarettes.[17] An X-ray computed tomography (CT) study by Wu et al. found potentially dangerous manufacturing defects in e-cigarette batteries, including foreign matter and electrode misalignment.[18] Seitz and Kabir's review of e-cigarette injuries reports that they have been responsible for broken neck bones, missing teeth, and burns to the hands, thigh, and face.[19–22]

Here, we aim to address some of the questions surrounding the safety and reusability of the batteries found in disposable e-cigarettes. We have harvested cells from the market-leading disposable device and shown that they may be suitable for reuse, and demonstrated impressive performance at different discharging rates. We applied nail penetration testing to fully charged cells to assess the safety ramifications of these devices entering standard waste handling systems.

RESULTS AND DISCUSSION

Device components

Dismantling an e-cigarette revealed a sensor, battery cell, and atomizer embedded in a sponge soaked in liquid. Shown in Figure 1A, the cell is rated to 550 mAh with a nominal voltage of 3.7 V. The voltages of cells harvested from unused e-cigarettes were measured between 4.1 and 4.2 V.

The dismantled cell showed a typical cylindrical architecture, with the positive electrode cast on an aluminum current collector and negative electrode cast on copper. Both electrodes were cast double-sided and wound together with a separator and

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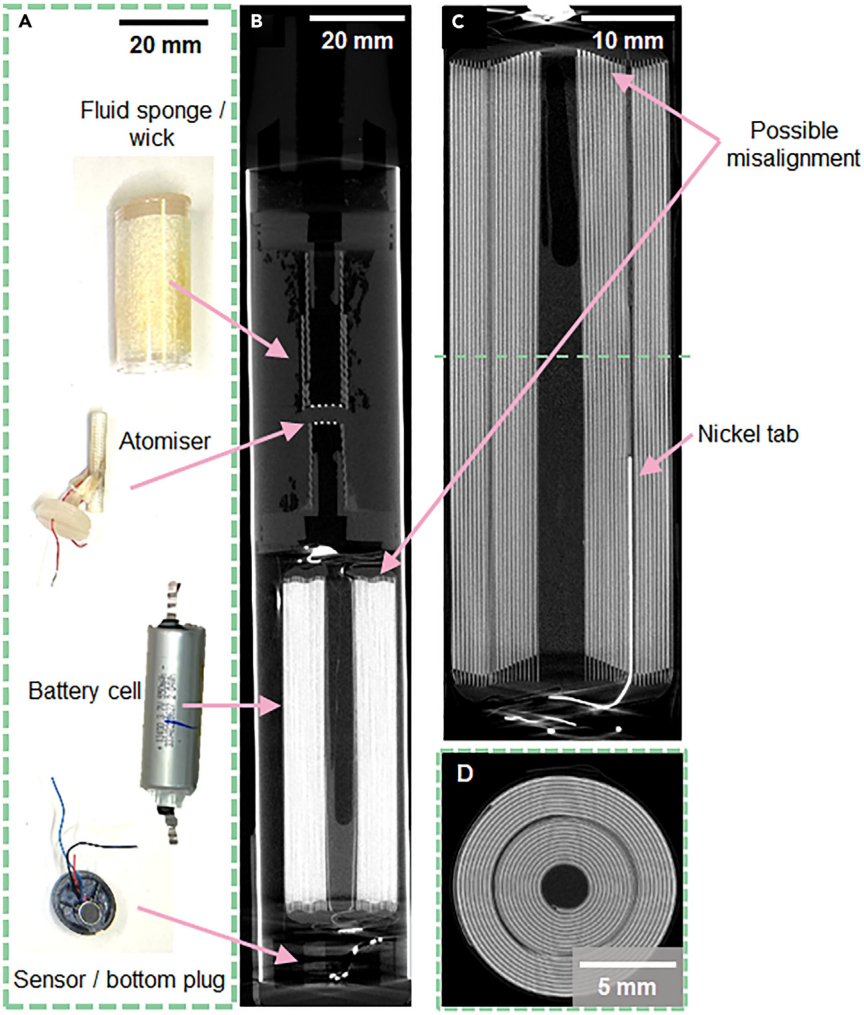

Figure 1. Images of the parts of a disposable e-cigarette and X-ray CT orthogonal slices on the whole device and the cell

(A) Parts harvested from a deconstructed e-cigarette investigated in this work: the sponge, atomizer, sensor, casing, and battery cell.

(B) Whole e-cigarette X-ray CT orthoslice showing the full cross-section of the e-cigarette. Annotations highlight the fluid sponge in the top half and the cell in the bottom half.

(C) A vertical orthoslice taken from the ROI tomography of the cell only. Annotations highlight the nickel tab and areas around the edges of the electrode that suggest possible misalignment.

(D) A horizontal orthoslice taken from the ROI tomography of the cell showing the spirally wound electrode layers, with a small gap for the tab.

no central mandrel. Unlike most cylindrical cells, where the jellyroll is contained in a steel case, the electrode layers of the e-cigarette cell are encased in a packet of laminated aluminum, usually used in pouch cells. The metal interior of the e-cigarette casing and exposed wiring means that there is a significant risk of the cell shorting during cell harvesting. Dismantling this device would not be safe for a user to perform at home and would make recycling of the cell challenging at any scale.

An initial X-ray CT inspection was performed on a whole, unused e-cigarette (Figure 1B). A second region of interest (ROI) tomography focused on the battery cell (Figure 1C). Visible from both Figures 1B and 1C, there is misalignment between the electrode layers in the cell. The edges of the cathode coating and copper current collector do not perfectly line up. As shown in literature, misalignment could lead to safety hazards with mishandling or repeated cycling.[23] To investigate further, an ROI scan was performed on the cell *in situ* (Figures 1C and 1D). Here, we can see the misalignment in more detail, with the layers around the outside progressively dipping down toward the bottom of the cell. The interruption from the tab (shown in bright white in Figure 1C), marks the point where the layers climb up toward the middle of the roll. The lack of proper alignment in the cell suggests poor regulation of the pressure applied to the jellyroll during manufacture, with too much pressure leading to displacement of the layers. Comparing these findings with a similar study performed by Wu et al., there does not appear to be any foreign matter caught between the electrode layers.[18] However, there are some similarities in that both pieces of work have observed possible misalignment of the electrode layers, suggesting that there may be a lack of quality control around winding the cell jellyroll together.

Scanning electron microscope (SEM) images and energy-dispersive X-ray (EDX) spectroscopy analysis of the harvested electrodes can be found in Figure S1.

Electrochemical characterization

Two cells were harvested from used disposable e-cigarettes and used for electrochemical evaluation. A rate-testing protocol (Table S1) was employed to explore the cells operational limits. Figure 2 shows the discharge capacities and the voltage-capacity plots for the best-performing cell (cell 1). To further evaluate the performance of e-cigarette batteries, four cells were placed on long-term cycling tests at different rates (C/5, C/2, 1C, and 2C) until they reached 80% of their initial capacity or 150 days of cycling. Further electrochemical data can be found in Figure S2.

At C/20, the cells gave 590–600 mAh capacity. The difference between the measured and nominal capacity given by the manufacturer is possibly due to the choice of voltage range, where the cell may have been intended to be used with a shorter voltage window. The capacity decreased to 585–595 mAh at C/10 and 545–560 mAh at 1C. Because information was limited on the safe operation of the cells, 1C was the fastest rate used in this part of the experiment. As shown in Figure 2C, a rate of 2C was later used in long-term cycling. For cells that are treated as disposable, they showed impressive rate capability, with a <10% reduction in capacity between C/10 and 1C. The voltage profiles, shown in Figure 2B, maintain their shape across the different rates, with the initial voltage drop increasing with the rate.

Figure 2C displays the normalized discharge capacity retention profile. As C-rate increases, the rate of capacity loss also increases. The 1C and 2C cells maintain the same rate of capacity decrease for the first 300 cycles. The 2C cell exhibits a ''knee point'' at 300 cycles, where there is a distinct drop in capacity from 92% at 300 cycles to 80% by 384 cycles. The cell cycling at 1C does not exhibit a knee point until 396 cycles and took 474 cycles to reach 80% capacity.

The cycling performances of the cells at C/5 and C/2 are similar, and both displayed superior cycling performance than the cells cycled at higher rates. However, the cell at C/5 showed slightly higher capacity fade relative to the C/2 cell. This disparity is likely due to cell-to-cell variation rather than a C-rate effect. The C/2 and C/5 cells did not reach 80% capacity in the time frame of data collection. The cell at C/2 was taken off after 700 cycles at 94% capacity retention, and the C/5 cell at 300 cycles at 95% capacity retention. The capacity fade decreases slowly and linearly

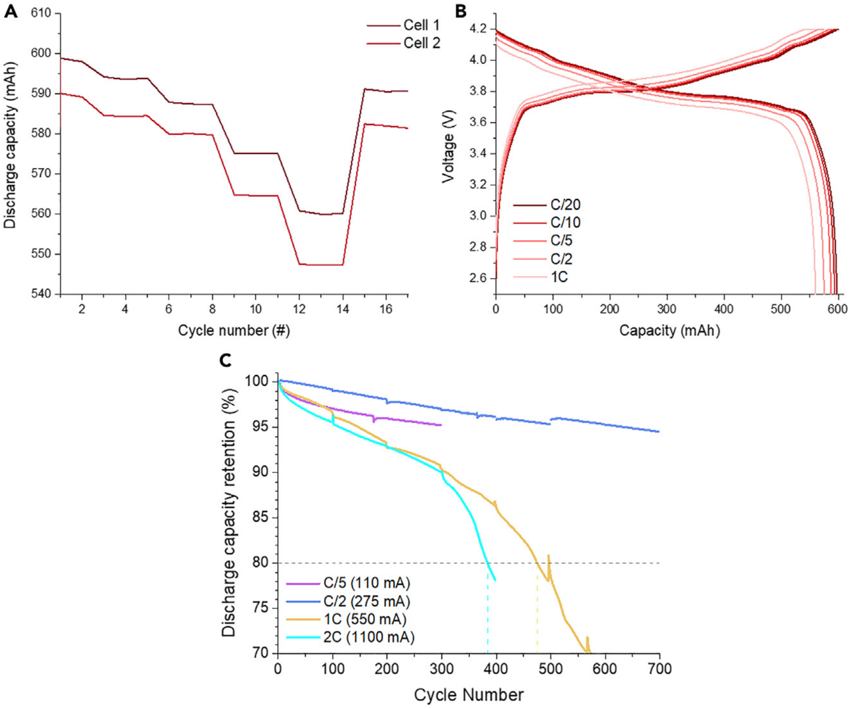

Figure 2. Electrochemical data from rate capability testing of harvested e-cigarette battery cells

(A) Discharge capacity vs. cycle number profiles for the two cells tested, cell 1 (dark red) and cell 2 (light red). The different C-rates used are indicated at the top of the figure.

(B) Voltage vs. capacity profiles for cell 1 only, taken at the last cycle of each C-rate (i.e., cycles 2, 5, 8, 11, and 15, respectively). The slowest rate, C/20, is indicated in dark red, with the chart getting progressively lighter in tone for faster rates.

(C) Capacity retention profiles for cells that have undergone long-term cycling, with capacity retention normalized to the capacity of the first cycle. The combined cycling data for each cell do not include the pause cycle performed every 99 cycles that takes the cell to 3.8 V, followed by a constant voltage hold until I < C/50. This is to ensure the combined long-term electrochemical cycling data are presented clearly.

throughout cycling. Higher C-rates are expected to induce accelerated degradation due to a number of mechanisms, including increased internal resistance, side reactions, and charge heterogeneities.[24–26]

Overall, the cycling performance of disposable e-cigarette batteries is excellent for cells sold as single-use, with even the cells cycled at a rate of 2C maintaining above 80% initial capacity for almost 400 cycles. This highlights the significant waste of materials that occurs when these devices, which contain potentially long-lasting batteries, are discarded. These batteries could last for a considerable period, emphasizing the need to address unnecessary waste. Speculatively, it could be that classifying these cells as single-use avoids the costs of thorough quality control and shipping preparation. Even if the manufacturing processes to produce these cells are not stringent enough for them to be sold as rechargeable, they still contain commodity materials that could be used in rechargeable cells.

To prevent the huge amount of waste caused by the disposal of these cells, stronger regulation is required. This could come in a number of forms, including forcing manufacturers to invest in recycling infrastructure, ''closing the loop'' so at least some of the raw materials are used again. Alternatively, manufacturers could be required to classify cells as suitable for repeated cycling, as well as make harvesting them from e-cigarettes a more straightforward task. This way, the cell could be removed and used in possible second-life applications. Both of these legislative solutions would involve considerable investment from suppliers, as well as government enforcement. They would also still involve fabricating rechargeable cells for a single, usable cycle. A nationwide ban would eliminate the problem while also solving the issue of uptake among children.

Safety evaluation

Nail penetration

To investigate the safety characteristics of disposable e-cigarettes, a nail penetration test was also performed on a fully charged cell (Figures 3 and S3). The thermocouple placed directly on the cell recorded the highest temperature (495°C). The exterior of the device gave lower temperatures: 270°C just outside the cell and 170°C near the cap. Although it appeared the casing of the device had insulated the cell, 270°C is still a significantly high temperature—possibly causing serious burns or igniting a fire. Although rare, fires such as these have occurred in the past.[27]

A video recording of the nail penetration test can be found in Video S1. Figure S4 shows a selection of still images from the test.

The video recording shows the nail impacted the outside of the casing, pierced through, and hit the cell. A large amount of smoke was released, greatly reducing visibility. Finally, the extraction system removed most of the smoke, and the e-cigarette became visible again, with the nail still inside the device. There were no flames or sparks observed during this test. The main observation is the sheer quantity of smoke the e-cigarette produced, which took almost 30 s to remove in a controlled environment with forced exhausting. Battery thermal runaway is known to give off a range of hazardous gases and carcinogenic particulates that could affect the health of an unprotected bystander of cell failure.[15,28]

X-ray CT was used to perform a post-mortem analysis of the e-cigarette in its entirety and an ROI scan on the cell (Figures 3C–3E). Both sets of images show the nail did not hit the cell cleanly but struck a glancing blow that drove a hole through off center. A deflected hit may have led to a less-catastrophic failure than had the nail landed directly. From the post-mortem CT, it was observed that the cell had largely held its integrity, with no major ejection of material. In typical cylindrical cells, the high pressures and temperatures that occur during thermal runaway can lead to an explosion, where large quantities of liquefied material are ejected.[28,29] Here, there has been no major ejection, likely due to a combination of two factors: the small energy of the cell (2.04 Wh) and the low melting point of the packaging. Even without ejection, the temperatures that are reached and the release of toxic gases still pose a health hazard. The whole e-cigarette scan shows that much of the sponge has disintegrated, likely due to the plastic melting. Consequently, much of the smoke and gas released may have been from the burning plastic, sponge, and nicotine fluid.

Conclusions

In this work, we have applied electrochemical and safety tests to cells harvested from disposable e-cigarettes. The purpose of this investigation was to determine two things: are the cells found in disposable e-cigarettes suitable for reuse, and how safe are they? We have used a rate capability test to investigate whether the cells are capable of rates up to 1C. The cell retained 90% of its capacity at 1C vs. C/20. All cells tested showed the ability to be cycled hundreds of times before exhibiting significant capacity fade. From a safety standpoint, we used a nail penetration test

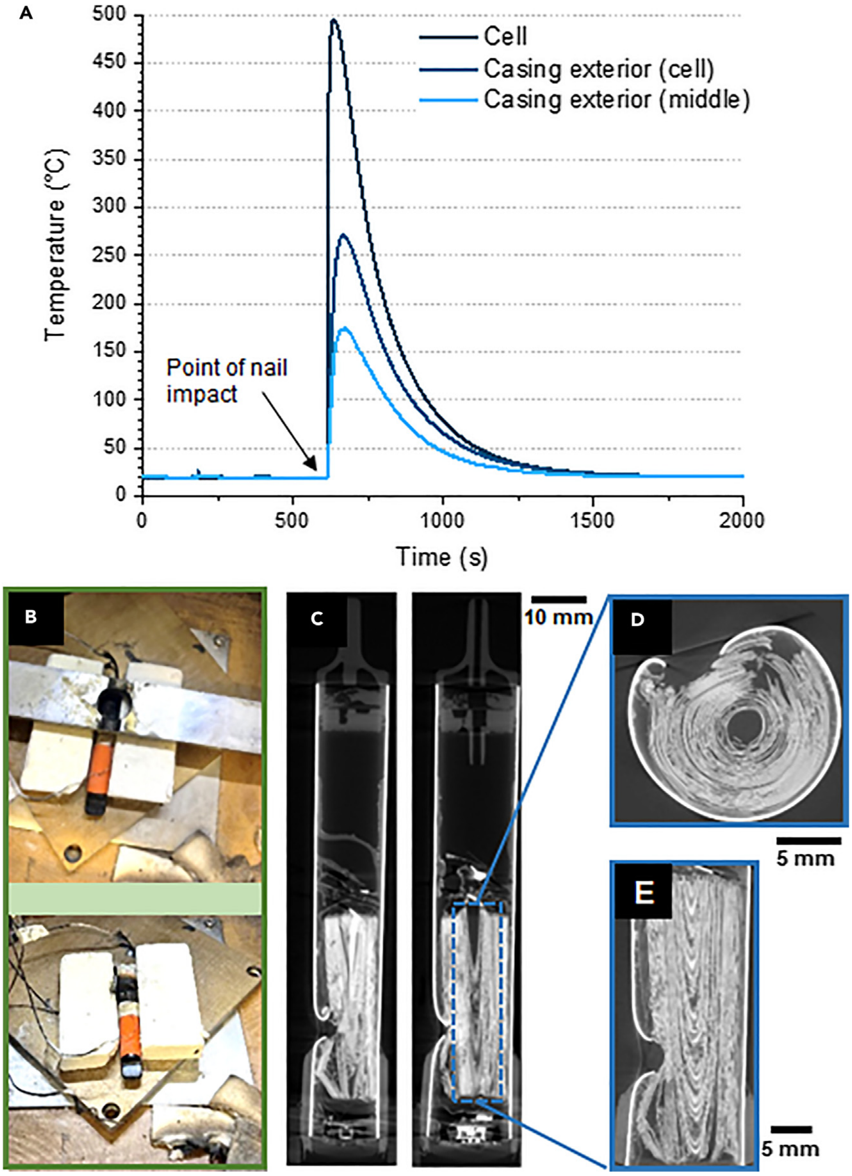

Figure 3. Temperature data and images from a nail penetration test of a disposable e-cigarette

(A) Temperature profile from three thermocouples placed on various points of a disposable e-cigarette during a nail penetration test. Camera and X-ray CT orthoslice images showing the disposable e-cigarette after a nail penetration test.

(B) Photographs taken of the e-cigarette after the nail penetration test with the clamp on (top) and the clamp bar removed (bottom).

(C) CT vertical orthoslices taken from two different orientations of the whole pen.

(D) Horizontal orthoslice taken from the battery cell ROI CT.

(E) Vertical orthoslice taken from the battery cell ROI CT.

See also Figures S3 and S4 and Video S1.

with the cell inside the casing to replicate a scenario where an unused disposable e-cigarette is damaged. The cell expelled a large amount of smoke and a maximum temperature of 495°C. Post-mortem CT revealed that some components of the e-cigarette had melted and likely contributed to the ejected gas. However, imaging also showed that the cell had not undergone a significant material ejection or explosion. This is likely due to the cell format, where the electrode layers are wound together similar to a typical cylindrical cell, but the cell assembly is encased in laminated aluminum packaging. Overall, this work has demonstrated that fully charged disposable e-cigarette cells pose a significant health hazard if not handled with care. Furthermore, cells sold as single-use are capable of repeated cycling, possibly as part of a second-life application. We speculate that the cells are sold this way to evade safety standards required for recharging, despite containing all the necessary materials. Stronger regulation, either through investment in recycling, reclassification of cells, or a nationwide ban, is required to prevent waste of precious materials.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be direct to, and will be fulfilled by the lead contact, Paul R. Shearing (paul.shearing@eng.ox.ac.uk).

Materials and availability

This study did not generate new unique materials.

Data and code availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Full details of experimental procedures can be found in the supplemental information.

Device dismantling

Disposable e-cigarettes were dismantled by loosening the bottom cap with a screwdriver and pliers in a fume hood before sliding out the sensor, the battery cell, fluid sponge, and filament within. The battery cell was removed from the other components by cutting the individual wires with wire cutters and removing any surplus electrical insulation, including around the cell tabs.

The cell was first discharged slowly to a safe lower voltage limit of 2.5 V to ensure most of the energy was removed from the battery. First, discharged at a C/2 rate, left to rest for 4 h, discharged again to 2.5 V at C/10 rate, rest for 4 h, and then a C/100 rate to 2.5 V. One cell was transferred to an argon-filled glovebox (MBraun, LABstar, Garching, Germany), where both O_2 and H_2O levels were maintained below 0.5 ppm, to harvest the anode and cathode layers. The battery was carefully opened by cutting the pouch cell from both electrode tabs. The volatile electrolyte components were left to evaporate for 24 h before peeling away the pouch. The cell jellyroll was unwound, and the electrode layers and separator were carefully detached from each other. The electrodes were rinsed with dimethyl carbonate (DMC) to remove residual electrolyte salt and allowed to dry in the glovebox for a further 24 h.

X-ray CT imaging

Whole e-cigarette and ROI scans were performed using a Nikon XT 225 (Nikon Metrology, Tring, UK) X-ray CT system. A tungsten source with an accelerating voltage of 200 kV and current of 90 μA was used to take 3,176 projections. A 0.1 mm copper filter was used to optimize the image. Scans of the full e-cigarette achieved a spatial resolution of 53 μm, whereas the ROI scans of the battery cell gave a spatial resolution of 18 μm. Datasets were reconstructed using CT Pro 3D software with a filtered back projection algorithm. Visualization and image renderings were performed using Avizo 3D (Avizo, Thermo Fisher Scientific, Waltham, Massachusetts, USA).

SEM imaging and EDX analysis

SEM/EDX images were acquired using a Zeiss EVO 10 SEM (Carl Zeiss AG, Germany). The SE1 signal was used with an accelerating voltage of 15.00 kV to capture images at 1,000× and 5,000× to produce images with pixel sizes of 293 and 58.59 nm, respectively. Samples were prepared in a glovebox and affixed to carbon tape, before transfer to the SEM in a sealed container.

Electrochemical testing

Electrochemical testing was performed on the cells only after dismantling of the e-cigarette assembly. The harvested cells were tested using a Biologic BC-815 cycler (BioLogic, Seyssinet-Pariset, France), attached using crocodile clips. A rate capability testing protocol was used according to the parameters in Table S1. Parameters used in the rate capability test for extracted e-cigarette cells. A nominal capacity of 550 mAh was used to calculate the current used.

Testing was performed at ambient temperature (≈22°C), with the cells placed in an ammunition canister for safety purposes. A K-type thermocouple was attached to the exterior, near the center, of each cell to record any temperature changes and ensure the cell did not exceed a safe upper-temperature limit.

Further long-term electrochemical testing was then performed on a different set of four cells following removal from the e-cigarettes. These tests measured the long-term electrochemical performance of four cells that were extracted from disposed e-cigarettes. Cycling was performed using a Maccor 4300 cycler, in a Maccor MTC-20 temperature chamber maintained at 25°C. Cells were cycled according to the parameters outlined in "long-term cycling" in Table S1, until they reached either 80% capacity fade relative to the first cycle, or after 150 days, whichever condition occurred soonest. Every 99 cycles, cells were charged to 3.8 V to review the data before continuing cycling. A K-type thermocouple was placed on each cell during cycling to monitor temperature fluctuations.

Nail penetration testing

The nail penetration test was performed using an MTI Nail Penetration Tester (MTI, Richmond, CA, USA). The nail penetration system was stationed inside a walk-in fume hood, and a BOFA (BOFA International, Dorset, UK) extraction system was attached to the nail penetration chamber to remove particulates and scrub both organic vapors and trace acid gases. The BOFA exhaust was discharged into the fume hood for extraction via the building ventilation (only species such as CO_2, CO, H_2, and light hydrocarbons should remain). The battery cell was removed from the e-cigarette prior to testing and charged to 100% state-of-charge (4.2 V) before being placed back into the casing. A small hole was drilled in the side of the casing to allow attachment of an N-type thermocouple to the side of the cell itself. Two additional N-type thermocouples were also placed on the exterior of the casing, one near the cell and the other approximately halfway up the casing. The entire e-cigarette was placed between two heatproof blocks to hold it in place before being clamped down with a bar from the top. A stainless steel nail of 4 mm diameter was driven into the cell with an approximate velocity of 10 mm/s using a 9 bar compressed air supply.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.11.008.

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AUTHOR CONTRIBUTIONS

H.T.R: conceptualization, methodology, investigation, writing – original draft, and writing – review & editing. A.F.: conceptualization, methodology, investigation, writing – original draft, and writing – review & editing. L.R.: conceptualization, methodology, investigation, and writing – review & editing. M.B.: investigation and writing – review & editing. D.J.L.B.: supervision, project administration, and funding acquisition. R.J.: writing – review & editing, supervision, and funding acquisition. P.R.S: conceptualization, writing – review & editing, supervision, project administration, and funding acquisition.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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