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Article

Lithium-Ion Battery Thermal Runaway Suppression Using Water Spray Cooling

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Abstract: Despite the commercial success of lithium-ion batteries (LIBs), the risk of thermal runaway, which can lead to dangerous fires, has become more concerning as LIB usage increases. Research has focused on understanding the causes of thermal runaway and how to prevent or detect it. Additionally, novel thermal runaway-resistant materials are being researched, as are different methods of constructing LIBs that better isolate thermal runaway and prevent it from propagating. However, field firefighters are using hundreds of thousands of liters of water to control large runaway thermal emergencies, highlighting the need to merge research with practical observations. To study battery fire, this study utilized a temperature abuse method to increase LIB temperature and investigated whether thermal runaway can be suppressed by applying external cooling during heating. The batteries used were pouch-type ones and subjected to high states of charge (SOC), which primed the thermal runaway during battery temperature increase. A water spray method was then devised and tested to reduce battery temperature. Results showed that, without cooling, a thermal runaway fire occurred every time during the thermal abuse. However, external cooling successfully prevented thermal runaway. This observation shows that using water as a temperature reducer is more effective than using it as a fire suppressant, which can substantially improve battery performance and increase public safety.

Keywords: lithium-ion battery; thermal runaway; battery fire; fire protection; combustion; cooling

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1. Introduction

Even though li-ion technology has been in use since the 1970s, only in recent years have the fire hazards come to light. Scanning over the literature on lithium-ion batteries (LIB), there is a huge range of publications on li-ion technology, but the studies in battery fires are significantly fewer. Table 1 depicts a timeline of select LIB milestones showing a disparate development of technologies with greater focus on manufacturing and application developments and very little on risks and safety of LIBs. Table 1 also highlights the increase

in large-scale battery fires in recent years that parallels the technology implementation in large-scale battery utilization.

Table 1. Notable LIB safety milestones.

Year	Event
1817	Lithium metal discovered [1]
1901	Swedish engineer Waldmar Jungner invents a rechargeable nickel-cadmium battery [2]
1969	W.F. Myers and J.W. Simmons patent the Li-SO_2 battery [1]
1975	Sanyo CS-8176L solar-rechargeable calculator powered by a Li-MnO_2 battery [1]
1977	Exxon exhibits rechargeable Li-TiS_2 battery at Chicago Electric Vehicle Show [3]
2006	Dell and HP recall laptops due to fire risk caused by li-ion batteries [4,5]
2008	AT&T begins replacing 17,000 LMP batteries made by Avestor (who went bankrupt and ceased operations in 2006) after several fires [6–8]
2008	The Tesla Roadster is the first production electric vehicle to use lithium-ion battery technology [9]
2010	Lithium-ion batteries begin to be considered for grid-scale energy storage [10]
2011	NHTSA begins investigation into li-ion batteries in the Chevrolet Volt after numerous fires [11]
2012	First recorded Li-Ion BESS fire in Flagstaff, AZ [12,13]
2014	Tesla breaks ground on the first Gigafactory outside of Sparks, NV, USA [14]
2016	Global lithium-ion battery production tops 100 GWh [15]
2016	Samsung Note 7 cell phones recalled due to fires [16]
2016	NFPA publishes LIB hazard assessment [17]
2017	"Drone Nerds" brand recalls "hoverboards" because of fires [18]
2017	Rail car carrying Li-Ion batteries explodes outside of Houston, TX [19]
2017	Automotive journalist Richard Hammond crashes a Rimac Concept One electric hypercar. The vehicle caught fire on-scene and spontaneously reignited for several days afterward [20].
2017	The "first draft committee" for the future NFPA 855 standard (Standard for the Installation of Stationary Energy Storage Systems) meets for the first time [21].
2019	2 MWh BESS explodes in Surprise, AZ, USA, seriously injuring five firefighters [22]
2020	NFPA 855 is published [21]
2023	New York City, NY enacts legislation prohibiting the use of li-ion powered e-mobility devices without a UL registration [23]
2024	Tesla tractor trailer crashes along Interstate Highway 80 in AZ. The crash resulted in the truck's battery going into thermal runaway. Firefighters reportedly used 50,000 gallons of water to control the fire. The highway was closed for more than 12 h [24].
2025	A BESS facility in Moss Landing, CA, experienced a large fire due to a thermal runaway prompting the evacuation of nearly 1500 people. A month later, smaller fires were still being found due to continued thermal runaway propagation [25,26].

While it is unclear how often LIB-fueled fires occur, they pose a tremendous challenge for the global fire service [27]. Reckless use and handling of these materials have created serious risks to public safety [28]. Due to the unique thermal runaway characteristics of LIBs, conventional fire protection and fire suppression technologies are not sufficient to address battery fires [28]. The Arizona BESS fire [29], for example, and several EV fire cases demonstrated the challenges in fire protection technologies. The critical issue lies in the fact that it is hard to pinpoint electric faulting and fire initiation stages within a battery pack [30].

It has become apparent that LIB fires do not behave like typical fires as the fire services understand them [31]. In fact, what society generally calls a battery "fire" is not a fire at all due to the complicated electrochemical reaction that drives the rapid heating during LIB thermal runaway [32,33], which cannot be "extinguished" once it begins.

Conventional fire services' approaches to managing LIB fires have fallen into one of two categories: flow copious amounts of water for a prolonged period of time, or let it burn itself out [34]. However, there are use cases that preclude either one of those tactics: aircraft [35] and maritime vessels [36]. In both cases, fire suppression techniques and

environmental consequences are still critical risks to address. Therefore, in cases where LIB thermal runaway poses an unacceptable risk, more emphasis must be placed on the prevention of thermal runaway or limiting thermal runaway propagation.

Fundamentally, thermal runaway is a problem of energy balance: the battery is generating heat faster than heat can be dissipated, leading to material breakdown and a self-sustaining electrochemical reaction that further creates tremendous amounts of heat and pressure. This paper describes a series of experimental studies to investigate the possibility of enhancing the energy balance issue by enhancing LIB heat dissipation rather than directly addressing thermal runaway. The objective of this study is to provide a pathway to develop water-cooled battery technology that can prolong battery use during likely thermal abuses so that safety can be warranted to the battery pack. The experimental results show that cooling may be a better approach than fire suppression for a LIB with thermal runaway.

2. Literature Review

2.1. Mechanisms of Lithium-Ion Battery Fires

LIBs are made up of six primary components, as shown in Figure 1 [37–39].

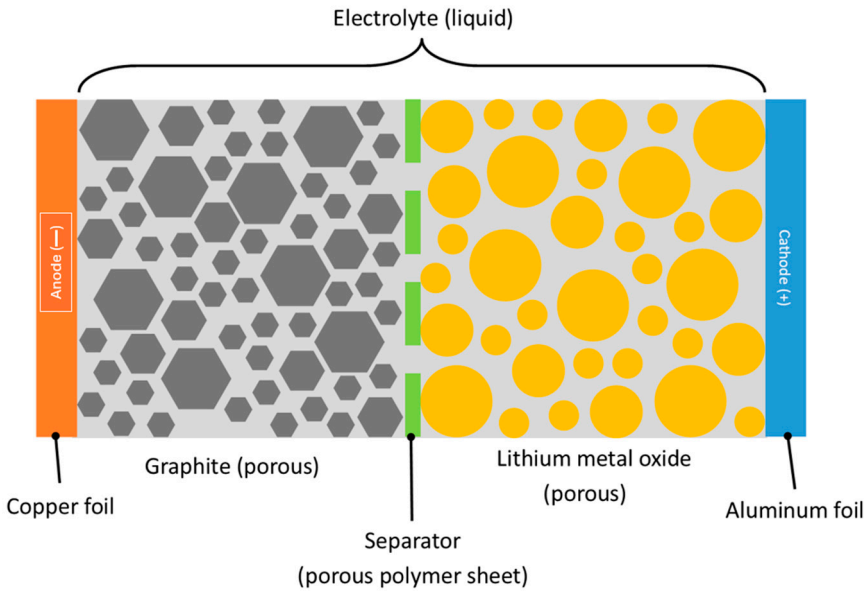


Figure 1. Simplified diagram of the materials of a LIB.

The positive and negative current-collecting materials are most commonly aluminum and copper foil, respectively. The aluminum foil positive-current collector (cathode) is typically coated in a lithium metal oxide (LMO) material. This LMO material is where the chemistry of the LIB comes from. Lithium-Nickel-Manganese-Cobalt (NMC), lithium-iron-phosphate (LFP), and lithium-nickel-cobalt-aluminum (NCA) are common LMO compounds. The copper foil negative-current collector (anode) is commonly coated in graphite. Separating the LMO from the graphite is a thin, porous polymer separator, which physically prevents the positive side from encountering the negative side and creating a short circuit. The graphite, LMO, and separator are flooded with an electrolyte solution which contains dissolved lithium salts. There are other materials that are generated as LIBs undergo their charge/discharge cycles [37,40], but the six components listed above make up the physical construction of a typical LIB.

LIBs have become the preeminent electrochemical energy storage technology because of their high energy density and long lifespan [32,41]. The combination of high energy density and the complex construction of the battery cell also means that when LIBs fail, the results can be quite complicated [42]. LIBs commonly fail due to phenomenology similar

to exploding or creating a fireball or intense heat. Most researchers agree that a thermal runaway is the root cause of the failure [43] and studies showed that thermal runaway can either originate from within the cell or external to the cell, where both external and internal origination can be broken down into four main root causes (Figure 2).

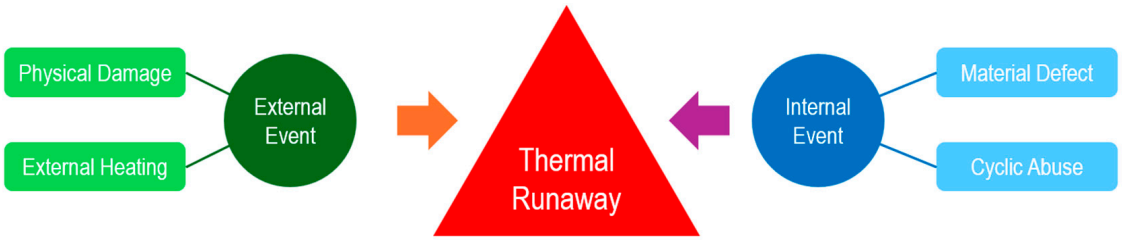


Figure 2. Causes of thermal runaway infographic.

Thermal runaway is a problem of heat management [43]. If a LIB begins to generate more heat than it can dissipate, then the battery materials begin to break down and react with each other. This situation can arise because of heat generation from either within the battery or from influences outside of the battery. Internal heat generation can broadly be categorized by some sort of material defect, or from cyclic abuse [44–46]. Externally, subjecting a LIB to enough heating can also eventually initiate a thermal runaway. Physically damaging LIBs can cause materials inside the battery to come into contact with each other, creating internal short circuits (ISC) [47,48].

Regardless of how the internal temperature of a LIB increases, thermal runaway can begin at relatively low temperatures and is usually initiated between the anode and electrolyte [33,49], This breakdown can begin at temperatures as low as 60 °C (140 °F). As the runaway is taking place, the temperature and pressure inside the battery cell continue to increase due to the breakdown of materials. The electrolyte will begin to break down and react with the intercalated lithium atoms at around 100 °C. Once the temperature reaches around 130 °C, the polymer separator begins to melt, leading to the cathode and anode shorting out and further increasing the temperature of the cell [33,49]. As the temperature continues to rise, eventually the breakdown and reactions of the various materials inside the cell will begin to release small amounts of oxygen. The generation of oxygen inside the cell, coupled with the very high temperatures and presence of flammable materials inside the cell, will cause burning to begin inside the cell [33]. Mikolajczak (2011) [49] suggests that the amount of oxygen created is so small that it is insufficient to initiate an internal fire, further pointing out that no significant amount of oxygen is found in LIB cell vent gases. It is worth noting, however, that in any fire there is very little oxygen in the fire gases [smoke] because the oxygen is consumed during combustion.

Finally, state of charge and LIB chemistry both influence LIB thermal stability [39,50]. Less energy-dense chemistries, such as LFP, remain stable at higher temperatures than chemistries with higher energy density, such as NMC [39]. SOC is also an important factor in determining thermal stability because there is a direct correlation between electrical potential (voltage) and overall stored energy potential for a thermal runaway [51]. Higher SOC will generally create a more energetic thermal runaway event.

Large-scale LIB packs are managed by battery management systems (BMS), which may keep track of the state of charge (SOC), state of health (SOH), state of energy (SOE), state of power (SOP), state of life (SOL), etc. [52] BMS is a software-driven, integrated system that may include thermal sensors. Current BMSs are not integral within battery cells [53] and can remain a challenge for rapid response to battery fires.

2.2. Advances Towards Safer LIB Technologies

LIB safety research can be placed into one of three categories: intrinsic safety, passive safety, and active safety [54]. Intrinsic safety looks at the LIB materials, how they contribute to thermal runaway, and what substitutions (such as sodium ion or solid-state batteries) could be made to improve thermal stability [55,56]. Passive safety looks outside the battery cell at methods of construction that improve resilience and limit the effects of thermal runaway [57–59]. Active safety looks at response and mitigation strategies when a thermal runaway has been detected. This can be in the form of early warning and response through BMS, forced air cooling, or cryogenic or liquid cooling [60]. Further research into active safety has looked at the effectiveness of various fire extinguishing mediums on a thermal runaway-induced fire [61–64].

2.3. Overview of Fire Classifications and Typical Fire Suppression

To correctly evaluate fire suppression methods against LIB thermal runaway, it is important to understand how thermal runaway is different from "fire". The Merriam-Webster dictionary defines "fire" as, "*the phenomenon of combustion manifested in light, flame, and heat*" [65]. Thermal runaways produce a lot of heat but do not necessarily involve combustion, which is defined as "*. . .an exothermic, or heat-producing, chemical reaction between some substance and oxygen*" [66]. This chemical reaction seeks to take a fuel material and oxidize it to more stable material, such as carbon dioxide and water.

A simplified equation of a combustion reaction of wood can be expressed as [67]

$$6C_{10}H_{15}O_7 + HEAT = C_{50}H_{10}O + 10CH_2O \rightarrow 6CH_2O + 3O_2 = 6H_2O + 2CO_2 + 2CO + 2C + HEAT \quad (1)$$

where a wood compound ($6C_{10}H_{15}O_7$) has heat applied to it. At approximately 150 °C, the wood begins to decompose and release gases in a process called pyrolysis. One of the principal gases that is released is formaldehyde ($C_{50}H_{10}O$). If heating is allowed to continue, at approximately 260 °C the formaldehyde will react with the oxygen in the air ($3O_2$) and begin a self-sustaining, exothermic reaction [67].

Likewise, if we consider a combustion reaction of a flammable liquid such as ethanol, we see a similar pattern [68]:

$$C_2H_5OH + 3O_2 + IGNITION = 2CO_2 + 3H_2O + HEAT \quad (2)$$

At elevated temperatures, or in the presence of an ignition source, the ethanol (C_2H_5OH) reacts with oxygen from the air ($3O_2$) and creates carbon dioxide ($2CO_2$) and water vapor ($3H_2O$) in an exothermic process.

Both of the above are classic examples of combustion via rapid oxidation with the air. Firefighting techniques are built around the understanding of combustion in this way, which can be described in a "fire tetrahedron", as illustrated in Figure 3.

Oxygen, heat, fuel, and chemical chain reactions are all required to start or sustain combustion. To extinguish a fire, this tetrahedron must be broken apart and the combustion process must be interrupted. The easiest way to prevent or stop a fire is to physically separate the fuel, oxygen, and heat or ignition source. The chemical chain reaction (combustion) will not begin if those three elements do not exist together. If physical separation is not possible, there are two primary mechanisms by which fires can be extinguished: cooling and interrupting the chemical reaction.

Cooling can affect fire in two ways: Cooling the fuel reduces the rate of pyrolysis of the fuel, and therefore reduces the rate of flammable vapor generation [69]. Alternatively, the flame may be cooled by modifying the air that is supplying oxygen to feed the combustion [66]. If the oxygen concentration of the air is lowered, either by smothering

or the use of a gaseous extinguishing agent, then the heat begins to be absorbed rather than generated.

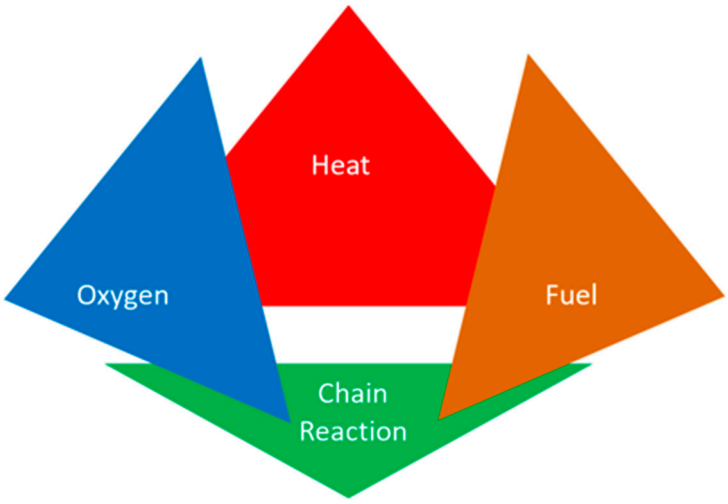


Figure 3. Visualization of the fire tetrahedron.

Interrupting the chemical chain reaction (combustion) involves introducing new chemicals to the combustion process. These new chemicals also break down in the high heat of a fire, but instead of adding to the reaction, these new chemicals bind to oxygen molecules as they are in the middle of the oxidation reaction [70]. Once the oxygen molecules have been captured, a new, inert, compound is formed. The combustion process will stop, and the fire will be extinguished when there are not enough free oxygen molecules left to sustain the exothermic oxidation reaction [70].

In contrast, the chemical reactions that occur during thermal runaway have less to do with taking oxygen from the air, and more to do with the reactions within the battery materials. The first stage of thermal runaway can begin at temperatures as low as 60 °C and involves the breakdown of the solid–electrolyte interface (SEI), as follows [33]:

$$(CH_2OCO_2Li)_2 + HEAT \rightarrow Li_2CO_3 + C_2H_4 + CO + 1/2O_2 + HEAT \quad (3)$$

In an example from [33], when the temperature inside the LIB reached 100 °C, the intercalated lithium begins to react with the organic solvent (ethylene carbonate in our example) used as the electrolyte. This reaction generates flammable hydrocarbon gases.

$$2Li + C_3H_4O_3 \rightarrow Li_2CO_3 + C_2H_4 + HEAT \quad (4)$$

As the exothermic process continues, the polymer separator melts at around 130 °C, which allows the electrodes to short circuit. The added heat from the short circuiting allows the metallic oxide coating on the cathode to decompose. This reaction will release oxygen from the oxide layer, which can react with the hydrocarbon gases that were generated during the reaction between the lithium and solvent [33,71].

$$Li_xCoO_2 + HEAT \rightarrow xLiCoO_2 + 1/3(1 - x)Co_3O_4 + 1/3(1 - x)O_2 \quad (5)$$

$$Co_3O_4 + HEAT \rightarrow 3CoO = 1/2O_2CoO \rightarrow Co + 1/2O_2 + HEAT \quad (6)$$

2.4. Oxidation and Its Role in Combustion and Electrochemistry

Since fires are a byproduct of combustion [65], and combustion is a rapid oxidation reaction [66], we must also acknowledge that oxidation itself is an electrochemical reaction that creates a change in the electrical potential of two materials [72]. As any battery undergoes a charge/discharge cycle, oxidation (and the inverse, reduction) occurs. This is

because as a base metal is oxidized, it gives up an electron to the oxygen molecule, therefore becoming electronegative.

From an electrochemistry standpoint, thermal runaway also involves oxidation and may involve combustion reactions. However, going back to the illustration of the fire tetrahedron, four elements (heat/ignition, oxygen, fuel, and a chemical chain reaction) must come together to create and sustain fire, and conversely those elements need to be separated to extinguish a fire, or prevent it from occurring in the first place. This is where a clear difference between LIB thermal runaway and fire can be identified. LIBs contain everything they need to sustain a runaway reaction. Unlike isolating one of the parts of the fire tetrahedron to interrupt combustion and extinguish a fire, the parts of a LIB that are interacting with each other to fuel thermal runaway cannot be separated. Figure 4 illustrates how, although fire and thermal runaway share certain elements, they act in different ways.

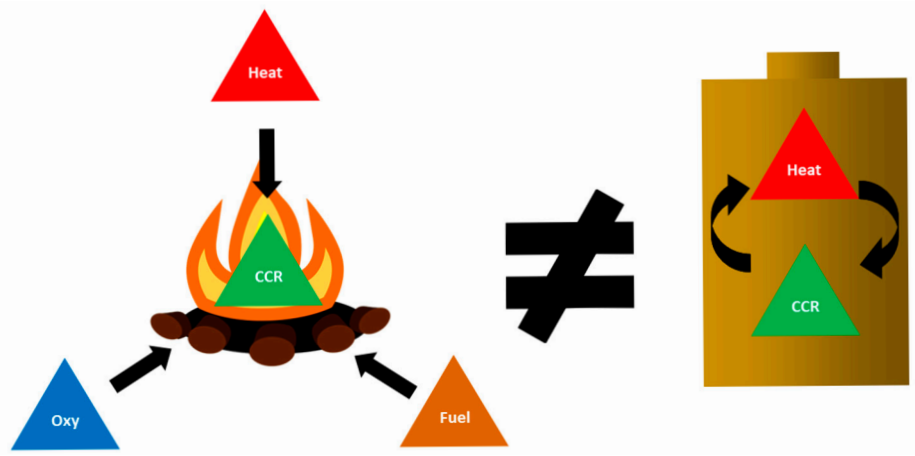


Figure 4. Elements of the fire tetrahedron compared to elements of thermal runaway.

2.5. Industry Perspectives

At the time of writing, industrial solutions for LIB fire mostly follow the fire protection solutions based on the understanding of fueled fires as Class A, Class B, and/or Class D as defined by NFPA 10 [73]. However, LIB thermal runaway-fueled fires do not fit into any of the existing NFPA 10 fire categories. Also, there is a common misunderstanding of lithium metal existing in a lithium-ion battery as terms such as "lithium battery" are used when referring to lithium-ion batteries. It is important to recognize that lithium batteries, or "lithium metal batteries", are a separate technology that utilize a different electrochemical reaction [74].

In the professional firefighting domain, most firefighting knowledge is derived from first-hand experience. In an opinion piece for *Fire Engineering* magazine, Boddy Halton commented: *"...as best I can tell after spending time with the best firefighters, ... At this point, we don't have "experts" on extinguishing these batteries when they go into what is called "thermal runaway..."* [75].

In 2022, the FDNY hosted a symposium on LIB fire information and tactics and made public several white papers, training bulletins, and research published by the NFPA and UL [76]. Manufacturers such as Tesla, General Motors, and Rivian have also published emergency response guides for firefighters responding to emergencies involving their products. These guides cover both high voltage shutdown and fire protection, and suggest the use of copious amounts of water, to the order of thousands of gallons per vehicle, to extinguish a fire and cool the battery pack [77,78]. Rivian further suggested that: *"...electric vehicle fires are best addressed with defensive firefighting and management of the environment to minimize risk. Only attempt to extinguish a fire if you have a specific need to do so"* [34].

2.6. Firefighting Effectiveness

Another aspect of LIB thermal runaway-fueled fire is how battery packs (or modules) are assembled. It is very difficult to affect the temperature of cells that may be undergoing thermal runaway because individual battery cells may be bundled together with plastic wrap or metal casings to form layered modules. These modules may be further grouped together inside larger plastic or metal housings. Those larger housings could be within a cabinet, in the case of fixed energy storage, or within the chassis of an electric vehicle. Figure 5 illustrates how batteries may be incorporated into larger assemblies.

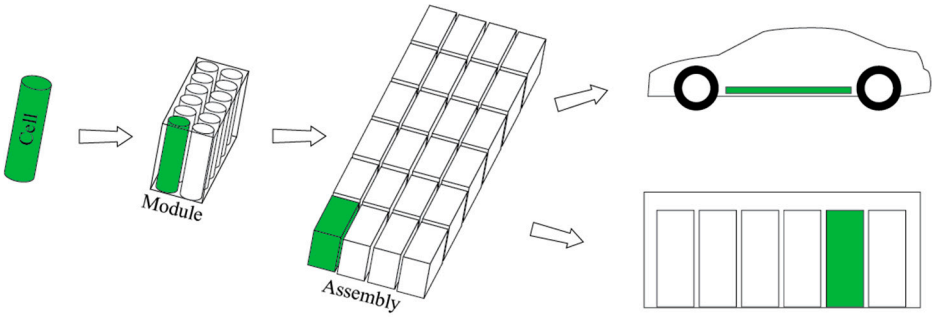


Figure 5. Example of how LIB cells can be incorporated into larger assemblies.

This creates challenges for fire protection and suppression as the driving force for fires that result from thermal runaway is not easily accessible by external intervention. As previously discussed, cooling may be a viable method of limiting the spread of thermal runaway. However, that assumes that the cooling medium (water) can affect the materials that are generating the heat. Without access to the LIB cells, any cooling intervention will be ineffective as the cells in thermal runaway will need to expend their energy to the surrounding layers before being influenced by cooling. This is why the fire service frequently reports requiring tens of thousands of gallons (hundreds of thousands of liters) of water (Figure 6) to "extinguish" an electric vehicle fire [79].

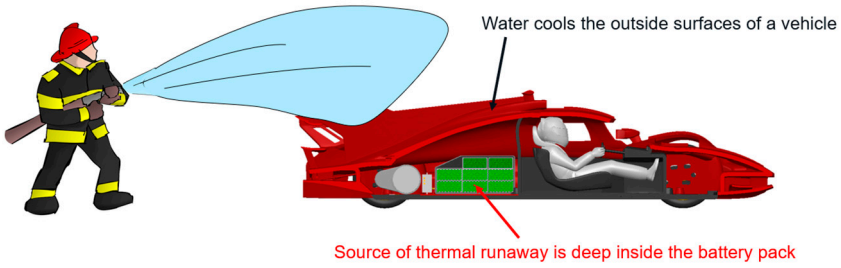


Figure 6. Illustration of typical fire suppression methods on thermal runaway that do not necessarily help with the fire safety of the driver.

3. Experimental Methodology

Thermal runaway is a problem of heat management. Hence, the experimental design involves adding a heat input of 900 W to the battery. From the first law of thermodynamics that energy is transferred into another medium, namely water, then the amount of water required to absorb that heat can be calculated as

$$0.9\text{kW}\ (from\ hot\ plate) = \dot{m} c_p \Delta T \tag{7}$$

where $\dot{m}$ is the mass flow rate of water, c_p is the specific heat of water, and ΔT is the temperature increase in water. If water is applied when the surface temperature of the LIB

is greater than 100 °C, the latent heat of vaporization of water can be leveraged to absorb more heat.

$$0.9\text{kW} = \dot{m}\left(c_p \Delta T + h_{fg}\right) \tag{8}$$

where h_{fg} is the latent heat of vaporization of water. For this calculation, we will assume that the water is applied to the LIB at a temperature of 30 °C and allowed to boil at 100 °C for a temperature rise of 70 °C (or 70 K). The specific heat and latent heat of vaporization are 4.19 kJ/kg-K and 2256 kJ/kg, respectively. Therefore, the mass flow rate of water needed to complete the energy balance is

$$\dot{m} = \frac{0.9\frac{\text{kJ}}{\text{s}}}{\left(4.19\ \frac{\text{kJ}}{\text{kgK}} \times 70\text{K}\right) + 2256\frac{\text{kJ}}{\text{kg}}} \tag{9}$$

$$\dot{m} = 3.5 \times 10^{-4}\frac{\text{kg}}{\text{s}} \tag{10}$$

Less than a gram of water per second is mathematically all that is required to absorb 900 W of heat in this scenario. This is in stark contrast to the hundreds of thousands of liters of water that have been required to "extinguish" certain thermal runaway-fueled fires. Therefore, a sequence of experiments is required to determine the proper intervention strategy for a successful thermal runaway interruption.

An experiment was designed to test the potential of additional cooling to suppress a lithium-ion battery during or before thermal runaway. The experiment used external heating to trigger thermal runaway ("control") and apply cooling, and hence involves a design sequence that requires iterations. Figure 7 shows the process flow diagram of the experimental design using iteration to detect the optimal trigger temperature.

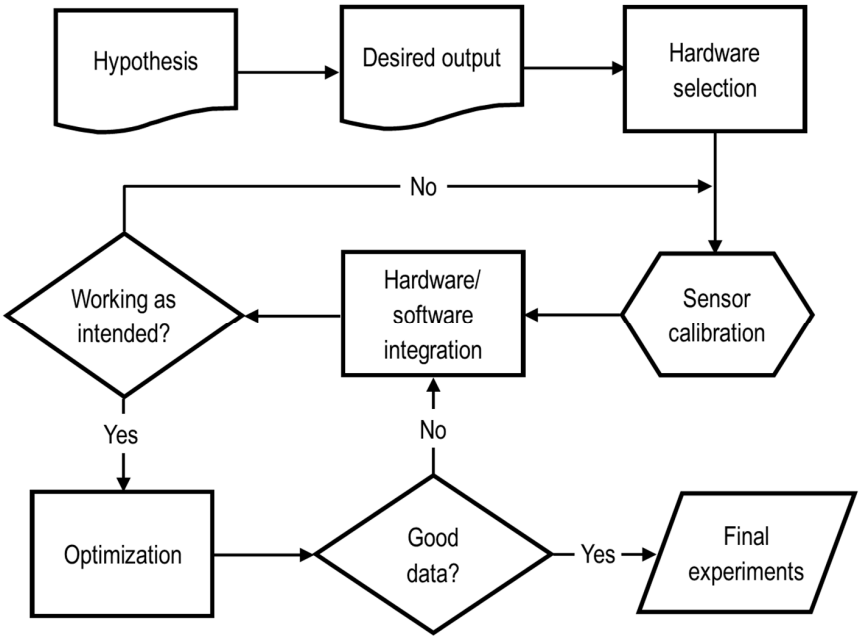


Figure 7. Experimental process flow diagram.

The experiment comprised two parts. The control tests resulted in battery failures to understand the failure mechanisms of the specific batteries used. Intervention tests were a repeat of the control tests, but with the additional external water cooling which would be initiated at a temperature as determined by the control. A schematic of the experimental apparatus is given in Figure 8.

The test apparatus comprises a hot plate, which is preset to 500 °C and placed inside a 5-sided steel box [80]. The hot plate is covered with aluminum foil to protect the hot plate

from battery shrapnel and water. A video camera and a thermal imaging camera are set up and the data acquisition system is placed on top of the box. Water tubing attached to the box is used during the intervention experiments. This tubing allows for a water hose to be connected, along with fittings for an in-line flow meter, pressure transducer, and thermocouple. The water spray flow rate is designed around 0.5 to 1 gallon per minute, which is slightly higher than a dripping effect but lower than a full open blast.

Signals from the thermocouples, flow meter, and pressure transducer were processed through a CompactDAQ (National Instrument, Austin, TX, USA) and recorded with Lab-VIEW. The specifications of the batteries used in the test are in Table 2. A detailed equipment list is provided in Table 3. The Lab-VIEW graphic program is included in Appendix A. Pictures of the completed apparatus are given in Figure 9a–d.

Table 2. Battery specifications.

Manufacturer	Samsung
Model	EB-B220AC
Capacity	2600 mAh/9.88 Wh
Voltage (Nominal/Maximum)	3.8 V/4.35 V
Date of Manufacture	Sept. 2020

Table 3. Experimental equipment list.

Description	Manufacturer	Model
Hot plate	Corning, Corning, NY, USA	PC-400D
Paddlewheel flow meter	Advanced Thermal Solutions, Norwood, MA, USA	ATS-FM-34
Pressure transducer (PT)	Honeywell, Charlotte, NC, USA	480-MIPAN2XX500PSAXX-ND
Thermocouples (TE)	Nanmac, Milford, MA, USA	A4A-T-2-2-PK
Video camera	Canon, Tokyo, Japan	Aixia HF S200
Thermal imaging camera	FLIR, Wilsonville, OR, USA	A600
Data acquisition system (DAQ)	National Instruments, Austin, TX, USA	cDAQ-9174 (with modules 9213, 9205, 9264, and 9219) running through LabVIEW 21.0
Live image feed management	Open Broadcaster Software	OBS Studio 30.0.0
Water flow control needle valve	McMaster-Carr, Elmhurst, IL, USA	455K13
Water spray nozzle	McMaster-Carr	32885K144

It has been shown that LIBs at higher SOC have more severe thermal runaway events [41,50]. Hence, the batteries were charged to approximately 90% SOC using a Neware battery testing system, model no. CT-4008Tn-5V6A-S1-U. In all, 15 identical batteries were prepared for testing.

During the control tests, batteries were heated until failure (packaging material disintegration). A battery was prepared by taping the thermocouple to the long edge of the battery and placing that battery on the hot plate with the long edge facing the cameras. In this setup, the battery will fail along the edge where the connection terminals are (short edge), so it is important to have one of the long edges facing the open side of the box, so that battery components are not ejected from the box during failure. With all data being recorded, power was supplied to the hot plate which then began to heat to a 500 °C setpoint.

The experimental procedure for the intervention test is identical to the control test up until a predetermined temperature before battery failure. At the temperature, a water spray was introduced to the top of the battery. There was no target flow rate of water, rather the volumetric flow rate, temperature, and pressure of water were recorded in order to determine the mass flow of water through the system. The hot plate remained on, while the water spray was on, until the total test duration reached ten minutes. After an additional

five minutes, the water spray was turned off. The battery continued to be observed, and data continued to be collected for an additional fifteen minutes with the intention of looking for any signs of battery heating (thermal runaway) after the discontinuation of the cooling water. Each test was repeated three times.

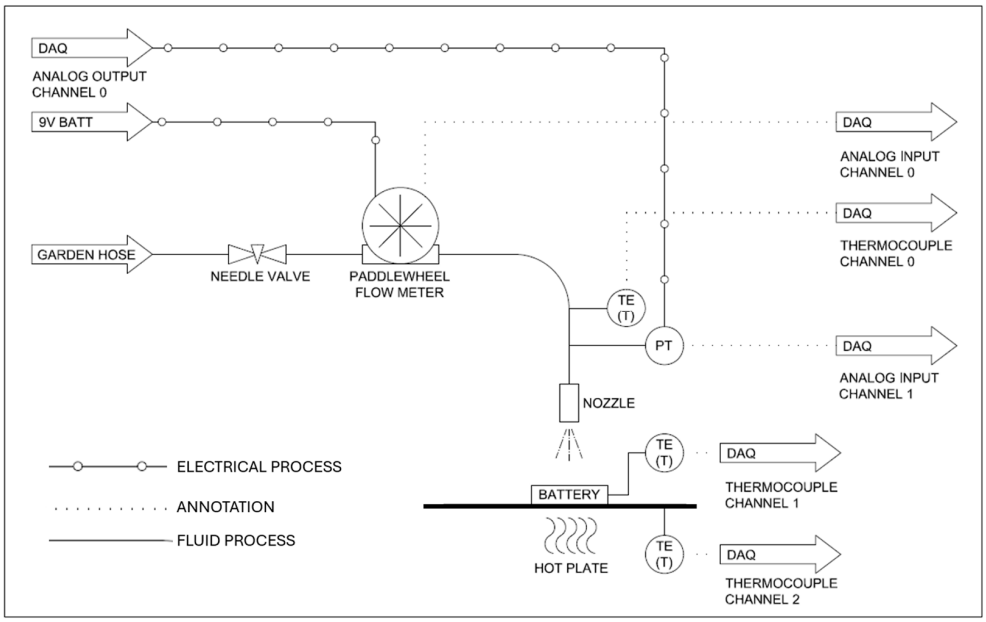


Figure 8. Experimental apparatus schematic. Equipment abbreviations are listed in Table 3.



Figure 9. Photographs of the experimental setup showing (**a**) the enclosure with video and thermal cameras, (**b**) hot plate placement within the enclosure, (**c**) National Instruments CompactDAQ configuration, and (**d**) experiment recording platform utilizing Open Broadcaster Software (OBS Studio 30.0.0) to record all data streams simultaneously.

4. Results and Discussion

4.1. Control Tests

Figure 10 is a plot of battery temperature during the control test. Some notable observations from these tests are that the batteries remain stable until failure, and obvious physical deformities can occur prior to failure. The other notable finding was that upon review of the video footage of the tests, the batteries swelled over the span of roughly 15 s, beginning at 94 °C, as indicated by the battery thermocouple, or 85 °C, as indicated by thermal imagery. Figure 11a–d are still frames captured by the thermal imaging camera with the outline of the battery highlighted.

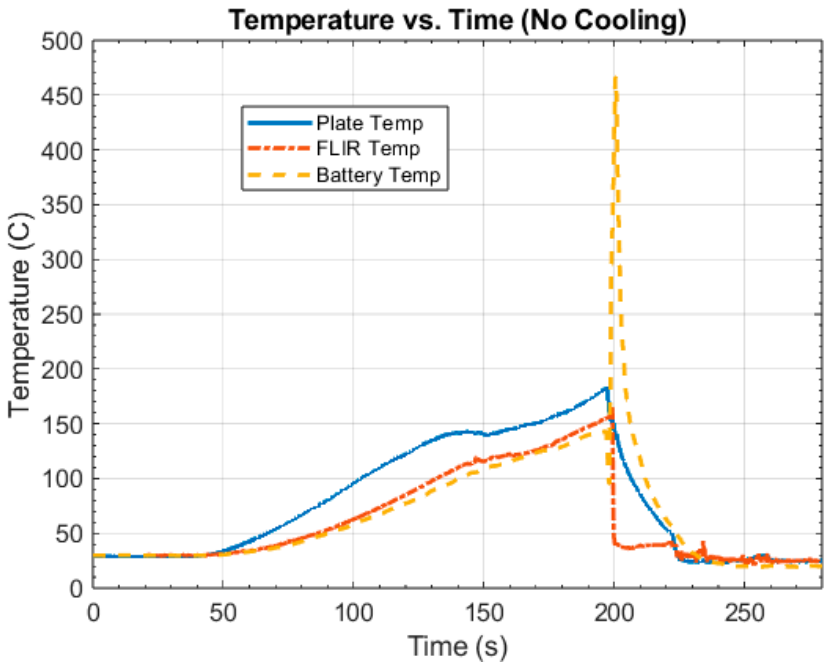


Figure 10. Temperature curves from control test.

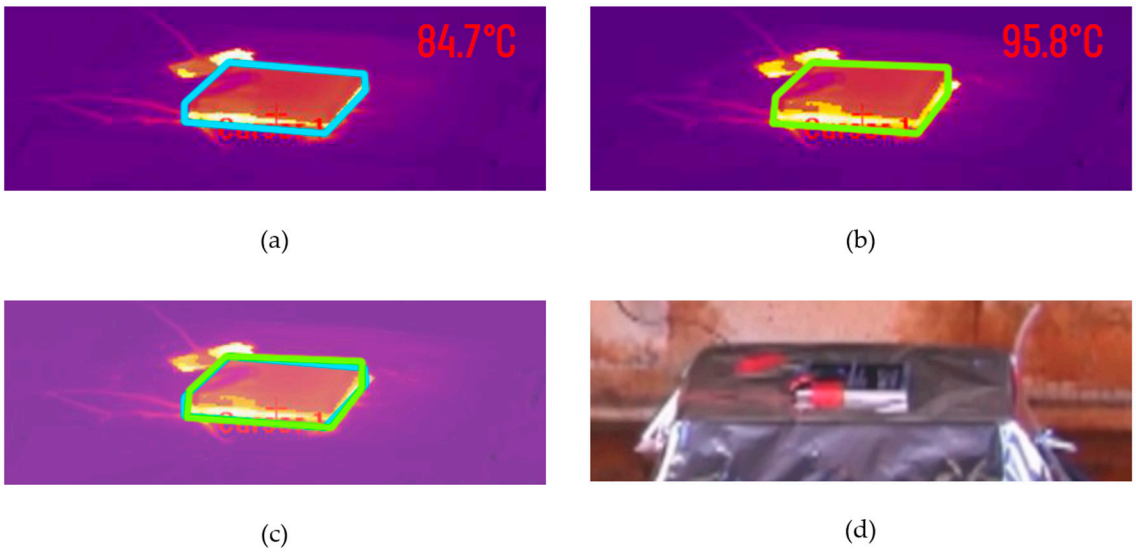
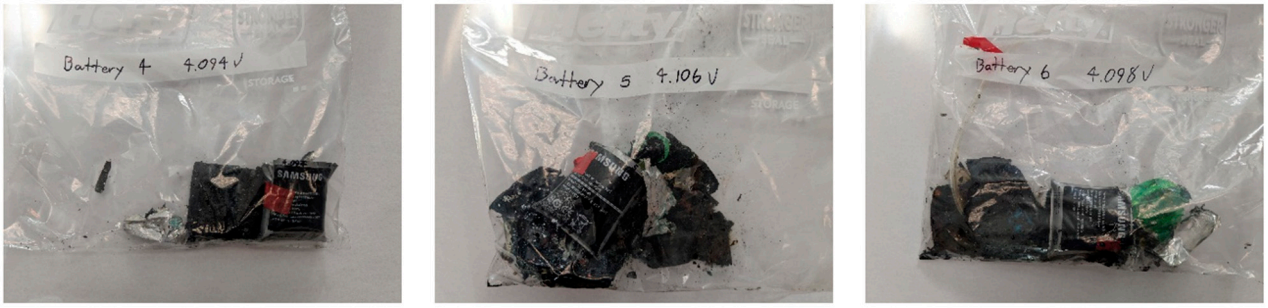


Figure 11. Battery images from control test. The thermal image in panel (**a**) shows the battery (outline added during analysis) before swelling, panel (**b**) shows the battery after swelling, and panel (**c**) is an overlay created during analysis comparing the two outlines, which clearly show a deformity. The image in panel (**d**) is a reference showing the battery's location on the hot plate. (In panels (**a**–**c**) bright white color indicates highest temperature and red color indicates heated areas, purple or magenta color indicates ambient temperature).

Swelling of a LIB is an indication that pressure inside the battery is increasing from material decomposition [81]. Data collected during the control tests indicated that about 1 min after the battery temperature reached 100 °C, failure occurred. The coefficient of variance (COV) of failure temperatures of the three specimens was 4.3%, indicating that 100 °C can be defined as the failure temperature for this test. It was decided that the temperature threshold for initiating cooling measures in the intervention tests would be 100 °C. Figure 12a–c are images of the three LIB specimens that were tested during the control tests.



(a) (b) (c)

Figure 12. LIB specimens at the conclusion of the control tests. (**a**) Battery 4, (**b**) Battery 5, (**c**) Battery 6.

4.2. Intervention Tests

The initial conditions for the intervention tests were the same as for the control tests. As noted in the control test, a battery deformity was noticed at 100 °C, so this temperature was used as the signal to initiate the water spray. Figure 13 is a plot of the battery temperature and water mass flow during the intervention test. Also shown in Figure 13 is the actual flow rate during the intervention.

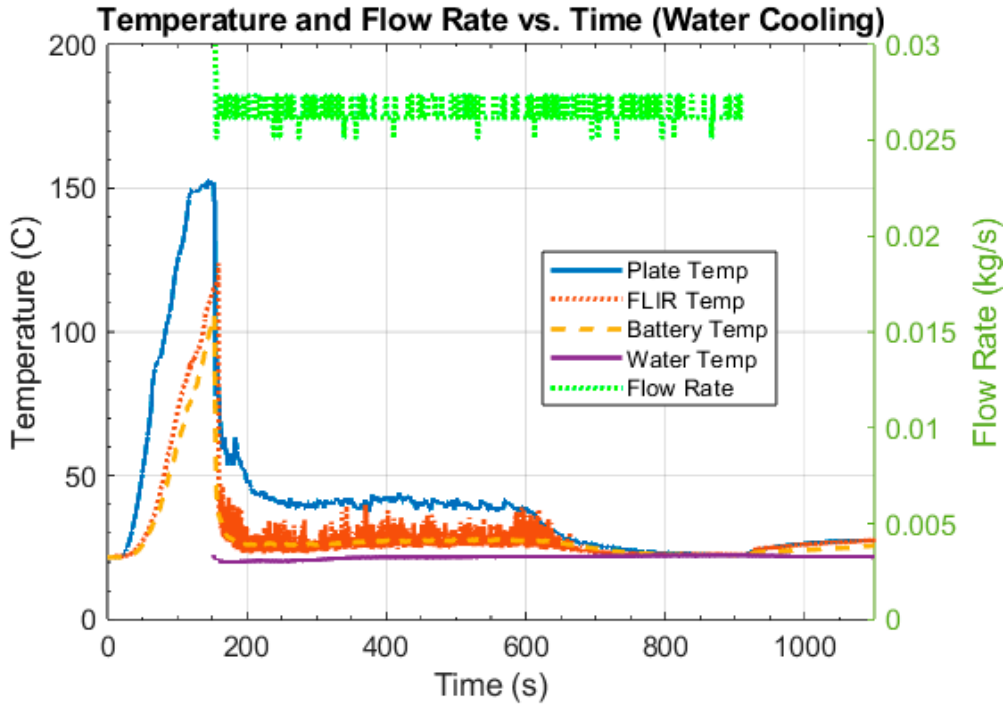
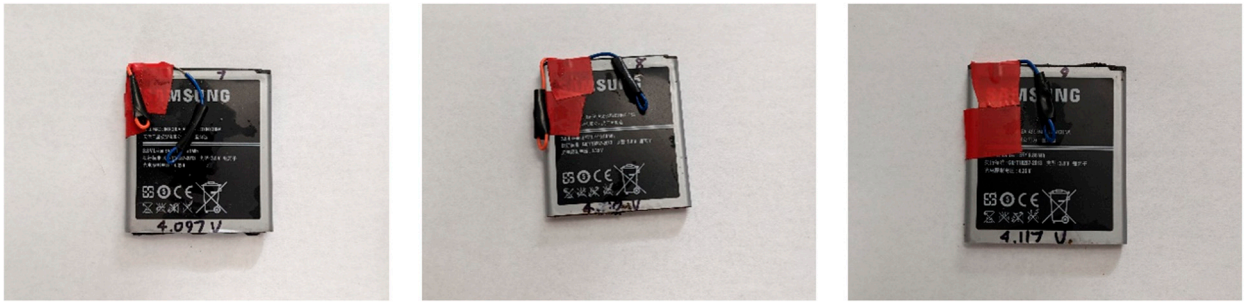


Figure 13. Temperature curves from intervention tests along with water mass flow.

The LIB temperature briefly exceeded 100 °C prior to the introduction of water spray. Then, the temperature quickly dropped. During the next 7 min, the temperature fluctuated

but trended neither up nor down. This may be attributed to the hot plate remaining on and trying to put heat into the battery, while the water spray tries to cool the battery. Once the water spray was discontinued, the temperature fluctuations smoothed out and reached an equilibrium temperature a few degrees above the beginning-of-test temperature. Figure 14a–c show the conditions of the intervention test specimens after testing.



(a) (b) (c)

Figure 14. Condition of test specimens after the intervention tests. (**a**) Battery 7, (**b**) Battery 8, (**c**) Battery 9 (Numbers labeled on the batteries are specimen number).

After the intervention tests, the battery voltages were measured and found to have very little changes, despite the external deformation. Additional test results are presented in Appendix B.

4.3. Discussion

The plots of both tests are overlaid together in Figure 15. Along with physical evidence that the battery did not fail during the second test, the data suggest that early cooling may be a viable option for thermal runaway prevention if it can be applied directly to the battery surface. The test apparatus provided highly repeatable qualitative data. The results of all three tests of both Parts 1 and 2 were similar to each other.

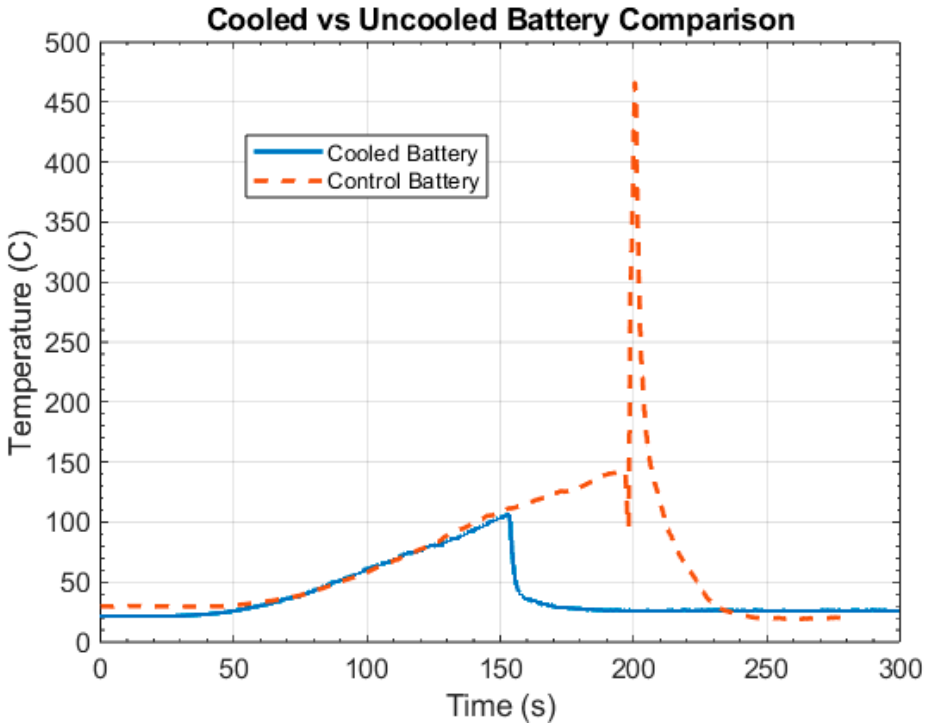


Figure 15. Overlay of control and intervention curves.

While pouch cell format LIBs were used in current study, other studies have performed experiments using water sprays over cylindrical cell format LIBs with similar effects of temperature suppression [82,83]. This suggests that the suggested technique can be applied to cylindrical LIBs.

Furthermore, there is the potential for multiple stages of cooling to suppress potential fire scenarios, all while prolonging the use of LIBs. This second observation is particularly critical for aviation and aerospace applications, where the extension of LIB useful life without extensive amounts of water can help the vehicle to reach safety and protect passenger lives. However, no studies to this effort can be found in the literature to date.

Comparing the water spray technique to other fire suppression techniques such as cryogenic cooling, foam cooling and compressed air cooling, it is still more cost-effective and easier to install. But the most important thing to consider is the effectiveness in rapid temperature cooling, as shown in current study. Because water (except pure water) is conducive to electricity, an effective design of battery cooling using water spray is to design the water spray away from exposed electrical connections. This is an important consideration to ensure the prolonged use of the batteries. There have been suggestions for battery immersive cooling systems during power charging [57], which may be a game-changer for future large-scale battery power applications.

Currently, this study is still inadequate to demonstrate accurately the amount of water saved when compared to complete fire suppression using water. Future studies are needed to establish both quantitative and qualitative effectiveness of cooling of LIBs during thermal runaway, including repeated cooling and the optimal time and location of cooling intrusion. The last point is related to the battery pack and cell design and is critically associated with the intended energy use scenario. Hence, LIB manufacturers need to be engaged in future studies.

5. Conclusions

The findings from this study offer a compelling argument for rethinking how thermal runaway in lithium-ion batteries is addressed; not merely as a firefighting problem, but as a thermal management challenge that can be mitigated through proactive cooling strategies. By introducing water spray cooling at the critical pre-runaway phase, the experiment demonstrated significant potential to prevent catastrophic battery failure using a fraction of the water typically employed in current emergency response protocols. This suggests that thermal runaway is not an inevitable outcome of battery abuse or failure, but a manageable risk if early-stage intervention is enabled through precise monitoring and access to the cells.

This work provides an important foundation for the development of integrated thermal mitigation systems in large-scale battery energy storage systems (BESS), electric vehicles, and other high-density LIB applications. With the right telemetry, system design, and cooling infrastructure, manufacturers and fire safety engineers could shift from a reactive model to a preventative one, minimizing both fire risk and resource consumption. Future research should focus on upscaling these experiments, testing system-level integration of active cooling, and evaluating real-world implementation scenarios. As the demand for LIBs continues to rise, so too must the innovation in safeguarding their deployment across energy systems.

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Data Availability Statement: Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

LIB	Lithium Ion Battery
SOC	State of Charge
SOH	State of Health
SOP	State of Power
SOE	State of Energy
SOL	State of Life
HP	Hewlett Packard
AT&T	American Telephone and Telegraph Company
LMP	Lithium Metal Polymer
NHTSA	National Highway Traffic Safety Administration
BESS	Battery Energy Storage System
AZ	Arizona
NV	Nevada
GWh	Gigawatt Hour
NFPA	National Fire Protection Association
TX	Texas
MWh	Megawatt Hour
NY	New York
UL	Underwriters Laboratory
EV	Electric Vehicle
LMO	Lithium Metal Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
LFP	Lithium Iron Phosphate
NCA	Lithium Nickel Cobalt Aluminum Oxide
ISC	Internal Short Circuit
V	Volt
CCR	Chemical Chair Reaction
US	United States
FDNY	Fire Department of New York
FSRI	Fire Safety Research Institute

Appendix A. LabVIEW Data Acquisition Block Diagram

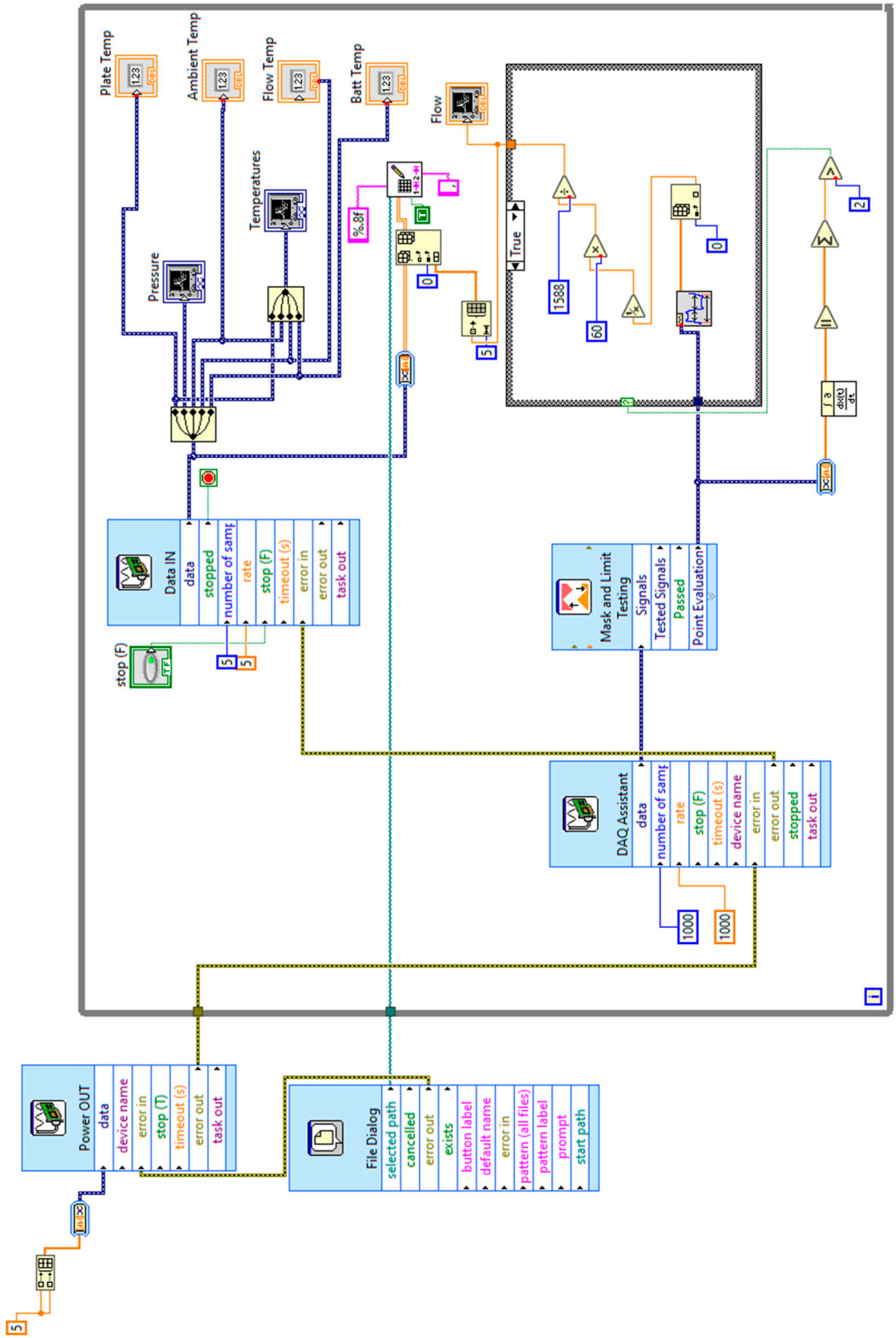


Figure A1. LabVIEW block diagram.

Appendix B. Data from Other Tests

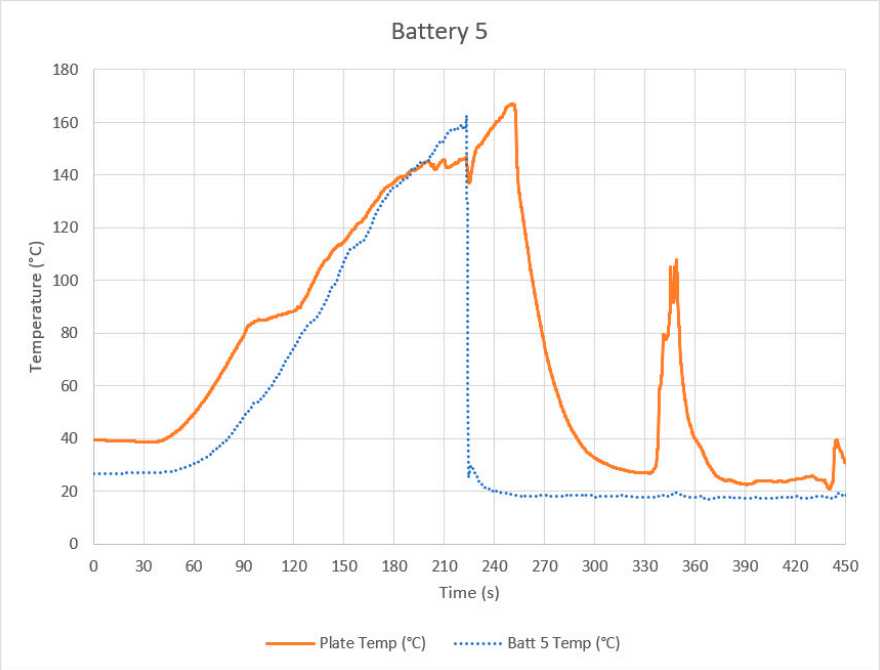


Figure A2. Temperature curve from control test—Battery 5. This data set was not included in the results due to the battery thermocouple becoming detached during the catastrophic failure of the battery.

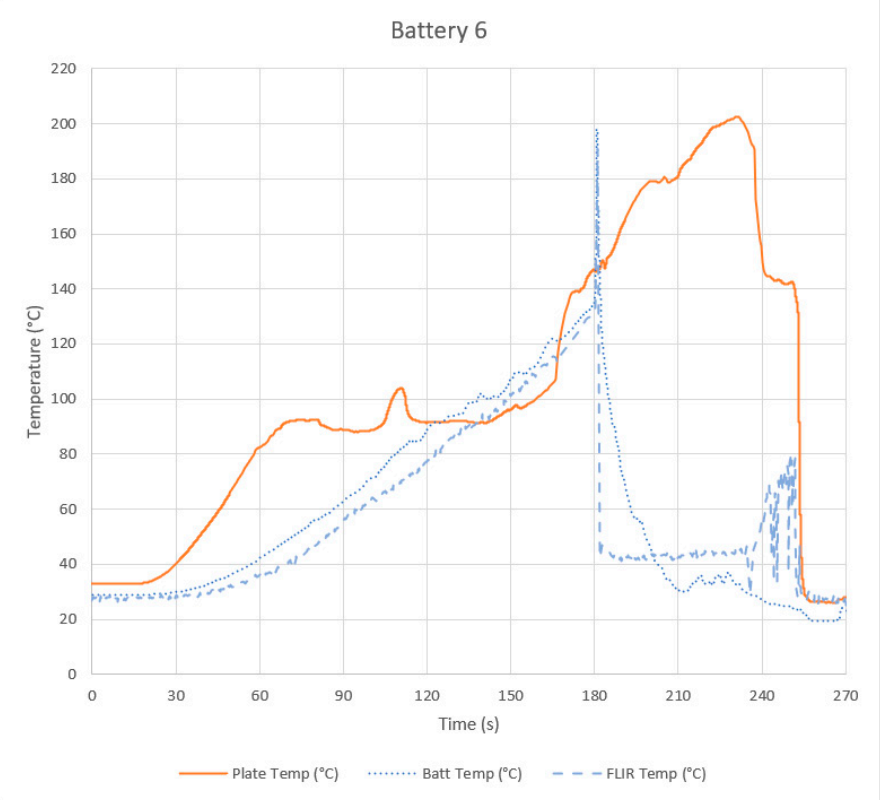


Figure A3. Temperature curve from control test—Battery 6. This data set was not included in the results due to water from a previous test getting between the hot plate heating element and aluminum foil covering the hot plate. This caused erratic hot plate temperature readings during the heat-up phase of this test as the water boiled off.

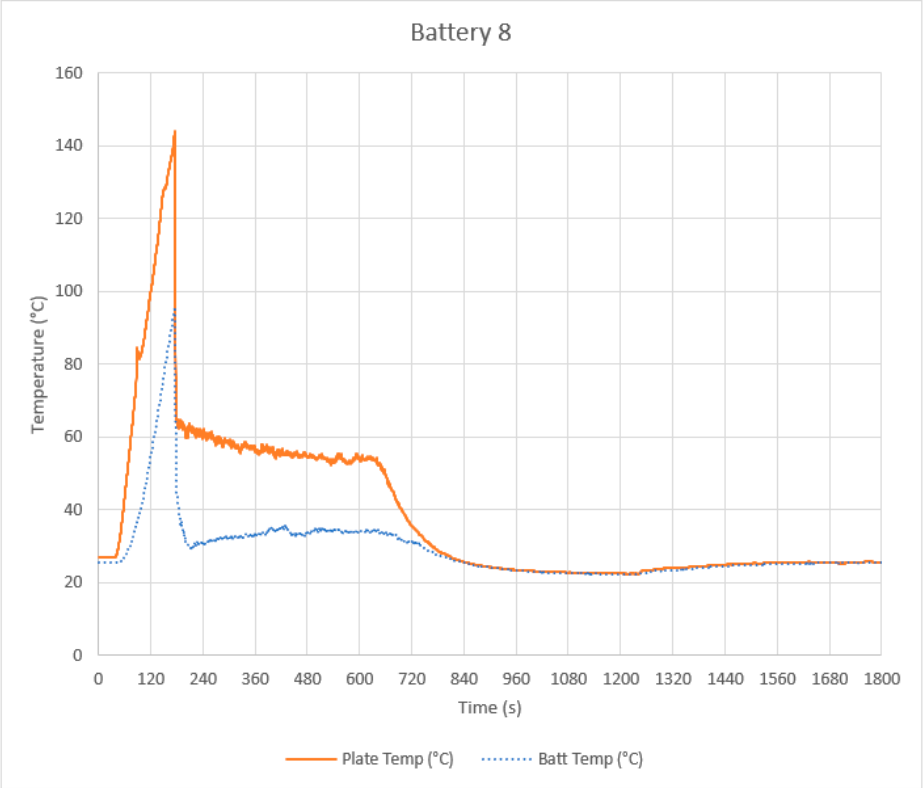


Figure A4. Temperature curve from intervention test—Battery 8. This data set was not included in the results due to the flow meter failing to transmit data.

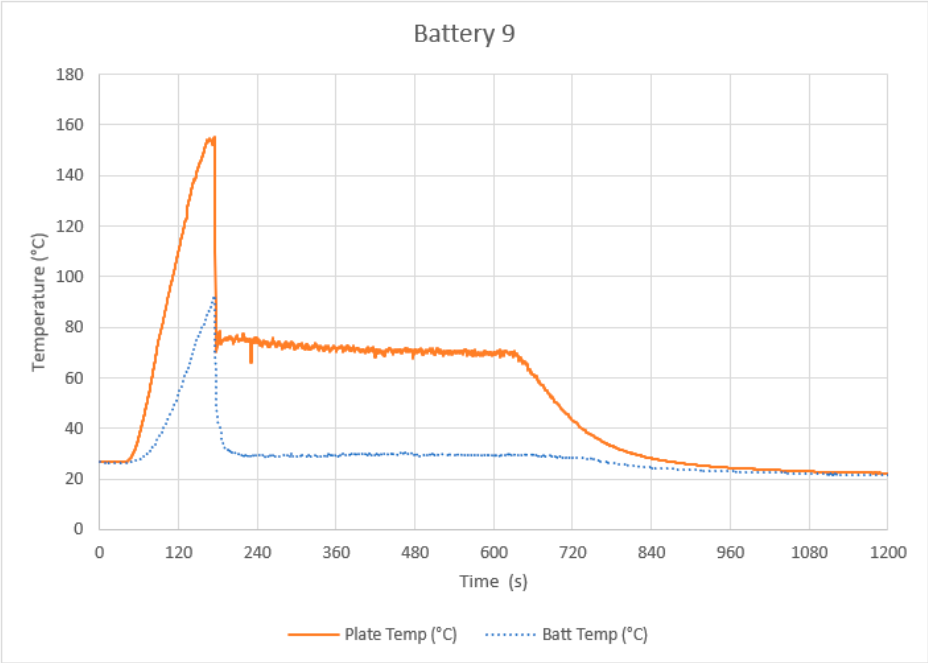


Figure A5. Temperature curve from intervention test—Battery 9. Despite attempted repairs, the flow meter again failed to transmit data. Thus, this data set was not included in the results.

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