

Spring 2018

# Spacecraft Fire Safety Research: Combustion of Lithium-ion Batteries to Predict Fire Scenarios

Elisabeth Meyer  
ekm25@ziips.uakron.edu

Please take a moment to share how this work helps you [through this survey](#). Your feedback will be important as we plan further development of our repository.

Follow this and additional works at: [http://ideaexchange.uakron.edu/honors\\_research\\_projects](http://ideaexchange.uakron.edu/honors_research_projects)

 Part of the [Aviation Safety and Security Commons](#), [Heat Transfer, Combustion Commons](#), and the [Space Vehicles Commons](#)

---

## Recommended Citation

Meyer, Elisabeth, "Spacecraft Fire Safety Research: Combustion of Lithium-ion Batteries to Predict Fire Scenarios" (2018). *Honors Research Projects*. 694.

[http://ideaexchange.uakron.edu/honors\\_research\\_projects/694](http://ideaexchange.uakron.edu/honors_research_projects/694)

This Honors Research Project is brought to you for free and open access by The Dr. Gary B. and Pamela S. Williams Honors College at IdeaExchange@UAkron, the institutional repository of The University of Akron in Akron, Ohio, USA. It has been accepted for inclusion in Honors Research Projects by an authorized administrator of IdeaExchange@UAkron. For more information, please contact [mjon@uakron.edu](mailto:mjon@uakron.edu), [uapress@uakron.edu](mailto:uapress@uakron.edu).

Spacecraft Fire Safety Research: Combustion of Lithium-  
ion Batteries to Predict Fire Scenarios

April 20, 2018

Course 4200 497-002

**Recipients:** Ed Evans, Lingyun Liu, George Chase, Marit Meyer

**Author:** Elisabeth Meyer

## **Executive Summary**

The National Aeronautics and Space Administration (NASA) is investing in the development of the next-generation of spacecraft designed to replace the current space shuttle and transport crew members to the International Space Station (ISS). This spacecraft is known as Orion, and it will not only be used to carry crew members to and from the ISS, but will also play an important role in NASA's journey to Mars.<sup>1</sup> In an effort to develop optimal subsystems for Orion, NASA is currently re-evaluating its standard onboard fire-protection methods and technologies.<sup>2</sup>

Fires pose many threats to crew safety and spacecraft integrity, especially with an abundance of stored energy in the form of fuel aboard any spacecraft. These threats underline the need for robust fire detection systems, like smoke detectors. Careful analysis and testing is required in order to develop these detectors and establish reasonable smoke concentration limits to trigger a fire alarm aboard a spacecraft.

This report documents the preliminary-phase testing that was completed in order to research and understand the impact a fire event will have on a spacecraft, specifically looking at the combustion of Lithium-ion batteries in a test chamber and the characteristics of a worst-case fire in order to eventually develop a smoke threshold to trigger the smoke detector alarm aboard Orion. The purpose of the experiments and data outlined in this report is to research characteristics of a battery fire, including pressure, temperature, and aerosol mass concentration to determine if there are trends that can help predict different fire scenarios which will aid in developing an alarm threshold for the Orion smoke detector.

Although an alarm threshold was not the direct product of this study, many meaningful conclusions about combustion in a confined volume were drawn by observing physical

characteristics of fires through video footage. It was concluded that whenever a flame underwent a large flare or a release of sparks, the event was closely followed by a spike in pressure inside the test chamber. The fact that physical characteristics of the fire correspond to chamber pressure is of interest to NASA's fire detection systems. If the pressure inside a spacecraft rises in the event of a fire, the crew will potentially have to open a pressure relief valve depending on the severity of the event, which can be extremely dangerous and is considered a last-resort measure. Other relationships between mass concentration and temperature were observed but will require additional testing to validate.

Through this study, I gained knowledge on fire safety and detection systems, Lithium-ion batteries and the dangers of thermal runaway, as well as the next-generation of space travel. I also realized that experimental design is an iterative process. What initially might appear to be a robust, meaningful test can easily result in data that is not useful, requiring another iteration of test method development with a more realistic approach.

Future work will be completed by members of NASA's Life Support Systems team to determine the smoke alarm threshold for the Orion capsule. Engineers are currently evaluating whether a fire detection system should be designed based on a worst-case battery fire or if a different combustion scenario should be considered. This has proven to be a major challenge: anticipating realistic emergency situations and developing methods to protect crewmembers. Meticulous analysis and prediction of the highest-probability events is crucial for the design of experiments and for the design of spacecraft fire safety systems.

## Introduction

Fire poses a serious threat to current spacecraft, especially since a spacecraft can carry many sources of stored energy in the form of fuel and combustibles. For successful future space exploration, robust fire detection systems must be developed in order to ensure crew safety, specifically for the Orion spacecraft. Orion is a new crew capsule that will carry humans farther into the solar system than ever before. The Orion spacecraft is designed to resist the extreme temperatures of a high-speed return to Earth and will play an important role in NASA's journey to Mars.<sup>1</sup> In an effort to provide new-and-improved subsystems to the crew capsule, NASA is reevaluating all elements of its current onboard fire-protection methods and technologies.<sup>2</sup>

One major element in any fire-protection system is the spacecraft smoke detector. A key challenge in developing smoke detector parameters for spacecraft is determining the smoke concentration threshold that triggers the smoke detector alarm. For the International Space Station (ISS), the limit is described as a smoke particle mass concentration of 2 mg/m<sup>3</sup>. This concentration is considered relatively low; the ISS is over 900 m<sup>3</sup> or approximately the size of a five-bedroom house.<sup>3</sup> Since the ISS has such a large habitable volume, a lower limit is required. Because a fire could easily go unnoticed by the crew, the alarm was designed to sound at a lower concentration of smoke to ensure even the smallest initiation of combustion is detected and extinguished immediately. However, the Orion capsule is only 9 m<sup>3</sup>, which poses the question of when the smoke detector alarm should be initiated for a much smaller habitable volume. An engineering analysis is required to establish a reasonable threshold for smoke particles to set off smoke detectors for a robust fire safety subsystem on the next generation of astronaut-occupied spacecraft. This report documents the test methods employed to understand worst-case fire scenarios that might occur on the Orion spacecraft. The tests performed are aimed at understanding combustion in a confined volume, the first step towards selecting a smoke concentration at which to trigger the detector alarm and designing a fire safety system. The purpose of this experiment is to determine if characteristics of the fires including pressure, temperature, and mass concentration can be correlated to one another in order to predict different fire scenarios.

## Background

In order to thoroughly evaluate and redesign spacecraft fire safety standards, several studies have been executed in the realm of fire safety, specifically on fire extinguishment, microgravity combustion, techniques of fire detection, spacecraft material flammability testing, and many more.<sup>4</sup> Fire safety testing is performed at the NASA White Sands Test Facility (WSTF) in Las Cruces, New Mexico. The WSTF has several testing capabilities to evaluate ignition susceptibility, burning propagation, and combustion characteristics.<sup>7</sup> In order to develop standard tests for fire safety, the "worst-case" fire scenario was identified as a laptop catching on fire in a spacecraft. A laptop was selected not only because of the hazardous source of stored energy in its battery, but also because of the toxic products that are released in the combustion reaction that

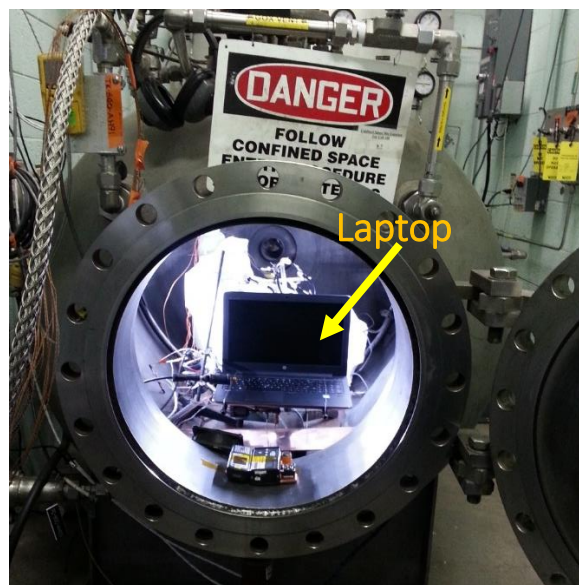
occurs when a laptop is burned. Lithium-ion batteries contained in laptops are at risk of thermal runaway in the case of a fire. Although very efficient, lithium-ion batteries can become extremely energetic fire sources due to their high density electrochemical energy content that can be converted to thermal energy. Exothermic reactions occur after flammable electrolytes in the battery heat up. The reactions are accelerated by a continuous increase in temperature, forming a potentially devastating fire threat to crew members.<sup>5</sup> To establish the amount of smoke particles that would set off the Orion smoke detector, two different tests were performed at the WSTF and are detailed in the Experimental Methods section.

## Experimental Methods

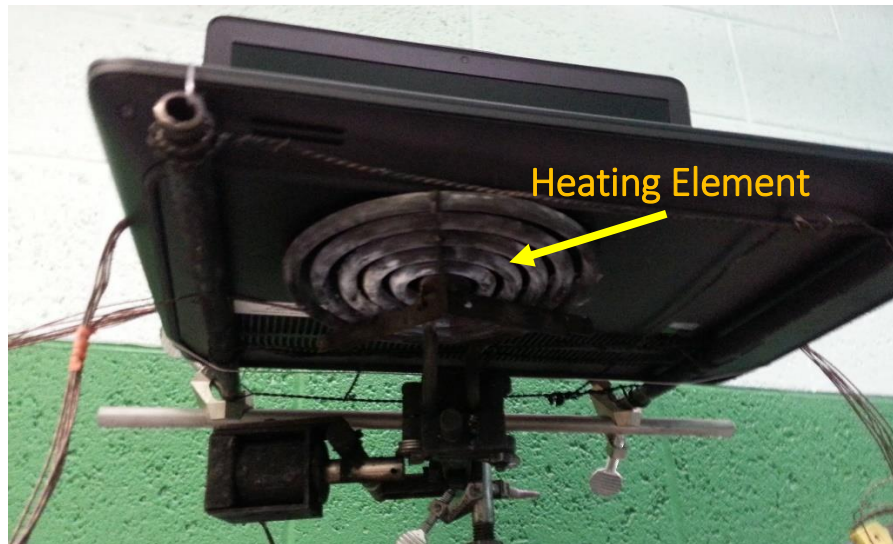
The following sections describe two tests that were performed at NASA's WSTF: testing involving laptop fires and testing involving battery fires. Both tests employed the same general setup and the methodology and limitations of each are described in detail.

### *Laptop Fire Testing*

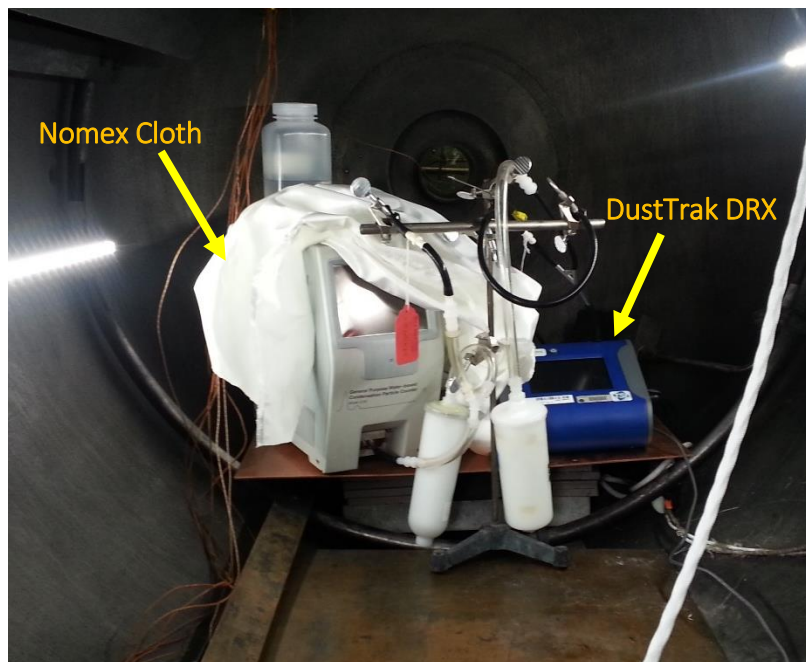
The first round of experiments utilized an HP Zbook 15 G4 laptop, which was selected for the test based on its mass, battery size, and its current flight certification and presence on the ISS. Different laptop configurations were tested (i.e. open vs. closed laptop), and a water delivery system similar to the current ISS portable-water mist fire extinguisher was employed to put out the fire. A pressurized testing chamber was used for the test. Since the WSTF is located at an altitude higher than sea level, atmospheric pressure is lower. To make test results relevant for all locations, the fire test should occur at atmospheric pressure, thus, a pressurized chamber was used. The chamber volume is 55 ft<sup>3</sup> or 1.56 m<sup>3</sup> and can be seen in **Figure 1**. The laptop was heated using a coiled heating element from underneath the laptop, as shown in **Figure 2**.



**Figure 1:** Test chamber at the WSTF containing laptop and particle measurement instruments and hardware.



**Figure 2:** Laptop was ignited using a coiled heating element similar to an electric stovetop.



**Figure 3:** Measurement instruments set up behind laptop to monitor smoke particle mass concentration in chamber.

The particle measuring device was placed behind the laptop in the chamber. The instrument is called DustTrak DRX, a commercial aerosol monitor developed by the company TSI. The instrument utilizes light-scattering laser photometers to give real-time aerosol mass readings and can measure aerosol concentrations between 0.001 and 150 mg/m<sup>3</sup>.<sup>6</sup> In order to protect the instrument during testing, Nomex cloth was used to cover the device and shield it from extreme heat.

A video recording of the fire was collected during the test using two different cameras with varying exposures in order to capture all stages of smoking, ignition, and burning. In addition, samples of

gases were collected in the chamber during combustion for analysis to determine the toxicity of the fumes produced.

### *Battery Fire Testing*

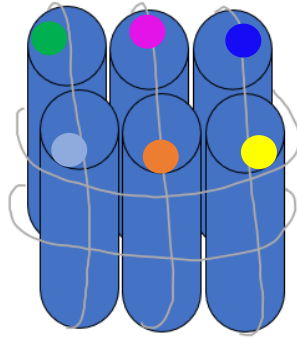
The need for a revised experiment became apparent when the data from the laptop experiment was obtained. In such a small chamber volume, the laptop fire experiment was not considered complete combustion since there was not enough oxygen present in the chamber to completely carry out the combustion reaction. Without a plentiful supply of air, the laptop's combustion is incomplete and results in much larger smoke particles and therefore a much higher mass concentration of smoke. The data from the laptop experiment provided such extreme "worst-case" scenarios that it proved to be neither realistic nor useful in completing the objective of the experiment.

In order to focus on a more realistic approach, it was decided that burning just a battery pack as opposed to an entire laptop would provide a similar worst-case fire scenario with significantly more reasonable mass concentration results as well as allow for complete combustion.

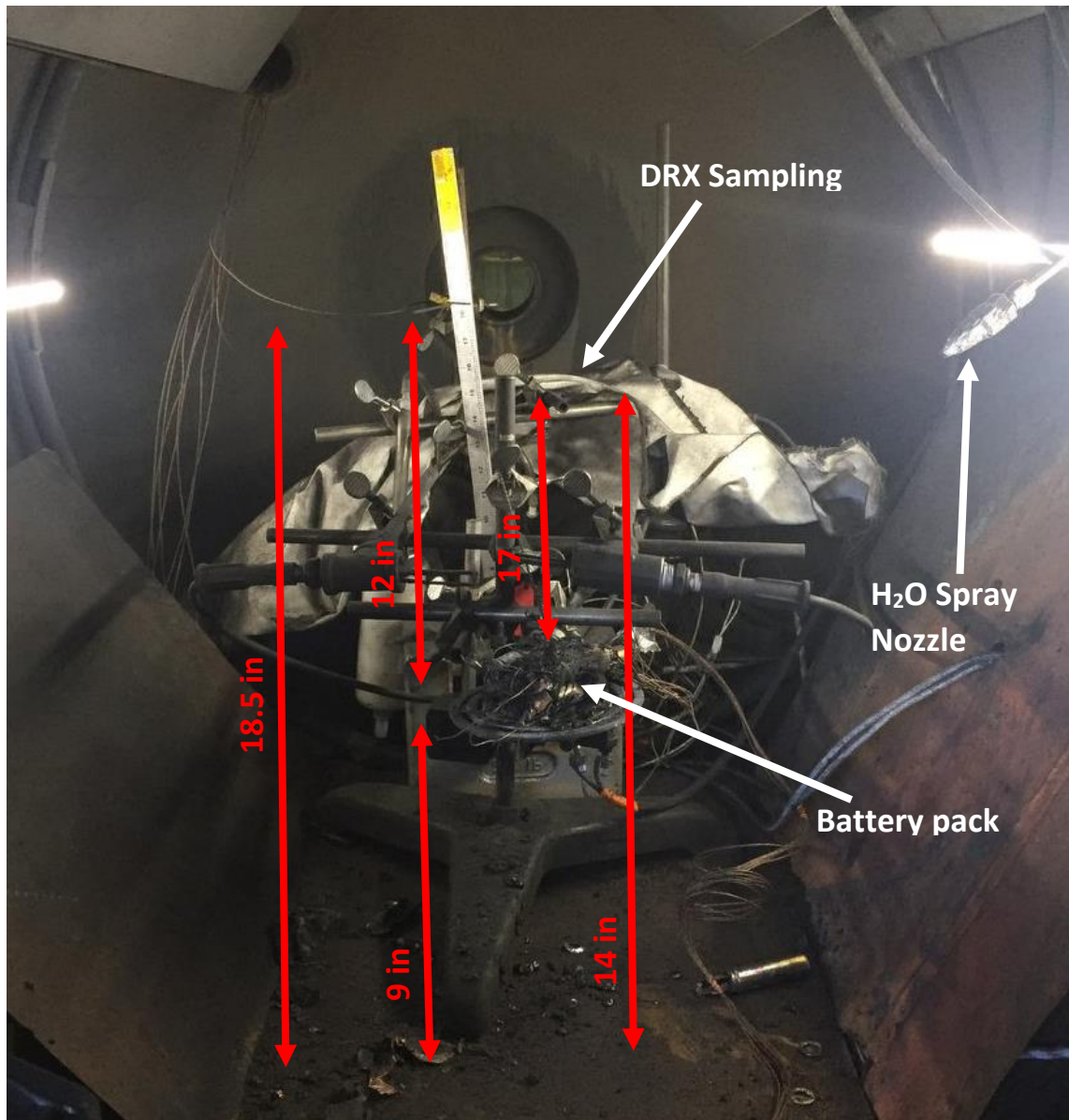
The test sample for the battery fire included six Lithium-ion battery cells, each with a thermocouple to provide temperature data upon ignition and propagation. Historical tests involving burning batteries unveiled the potential for rapid and violent ejection of battery cells. Ejected cells eliminate a heat source from the rest of the cells, resulting in a decrease of total energy input into the remaining cells.<sup>5</sup> In order to mitigate the risk of rapid projectile of a battery cell, all cells within the pack were secured to each other using a stainless steel wire, as shown in **Figure 4**. The arrangement of instruments within the chamber is depicted in **Figure 5**.

Throughout the experiment, the orientation of the battery pack was varied in order to determine the optimal position for all 6 battery cells to become involved in the combustion. If a cell exceeded 850 degrees F (454 degrees C), then it was considered to have contributed significantly to the fire and thermal runaway took place. It was determined that laying the battery pack down horizontally was the optimum position for all battery cells to become involved. In addition, subsequent experiments included the objective of extinguishing the fire by simulating the portable-water mist fire extinguisher which is currently on the ISS. Because of the potential for water from the extinguisher to damage the instruments, mass concentration was not measured during these experiments. The water nozzle delivered 6 lbs of water to the flames, which is the capacity of the ISS fire extinguisher.





**Figure 4:** Six battery cells making up a battery pack held together by a stainless steel wire. The colored dots on each cell indicate the color-coding system used for the thermocouples when the temperature data was analyzed graphically.



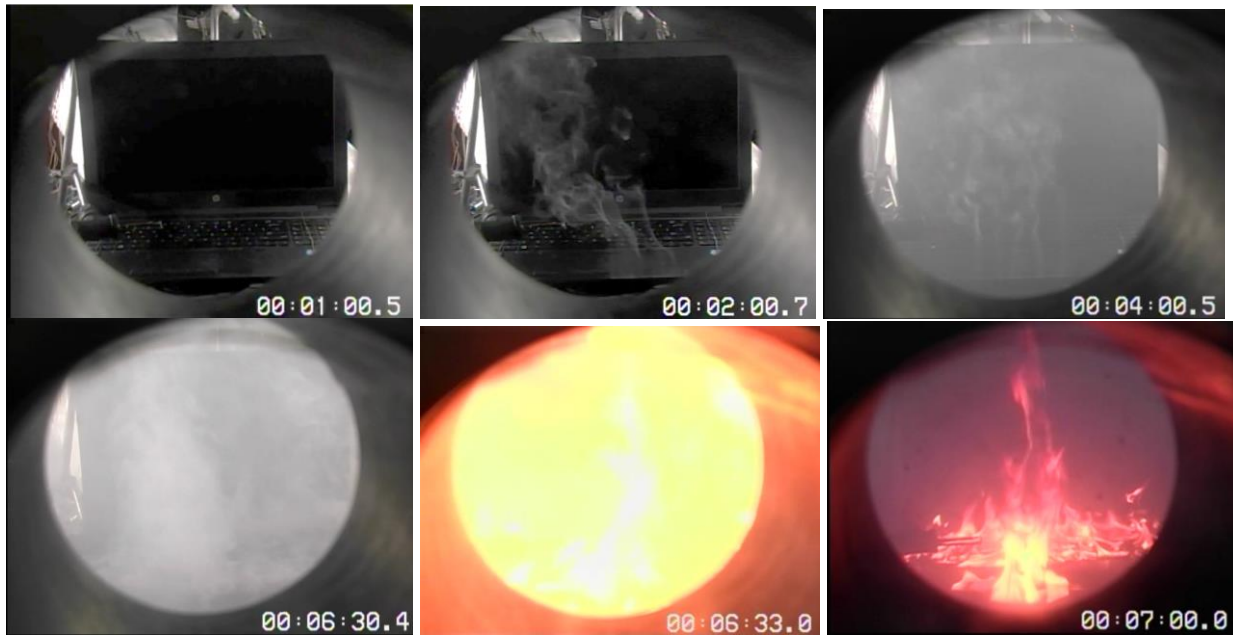
**Figure 5:** Photo of the testing chamber depicting the layout of each key test component, including the DRX DustTrak particle measurement instrument, the burned battery pack, and the nozzle to emulate the water mist fire extinguisher.

## Data and Results

### *Laptop Experiment*

There are several assumptions that had to be made in order to analyze the laptop fire data. First of all, the air in the chamber was assumed to be well-mixed. This is a poor assumption because in a microgravity environment, smoke from a fire concentrates at the source as opposed to rising to the ceiling, which would result in a non-uniform distribution of smoke within a confined space. In addition, the volume of the chamber is  $1.56 \text{ m}^3$  while the volume of Orion is  $9 \text{ m}^3$ . Thus, the smoke mass concentration measured in the chamber had to be extrapolated in order to accurately represent the Orion spacecraft. Mass concentration is the only measured data that was extrapolated, however. Pressure measured in the chamber was not extrapolated because Orion has a different volume.

During laptop testing, corrections had to be made to data due to complications with the DRX. The orifice restricting smoke flow into the DRX became caked due to large particles building up in the inlet. Thus, it was not straightforward to apply the dilution calculation because it is typical that the orifice supplies a fixed flow of smoke throughout the test. When the orifice is obscured progressively over time, several assumptions had to be made, such as estimating when and how much blockage occurred on the orifice. Data collected by the DRX after the orifice became partially clogged contains error. The data obtained from the laptop experiments is not analyzed in the scope of this report, however **Figure 6** and **Figure 7** show qualitatively the combustion experiment and its aftermath.



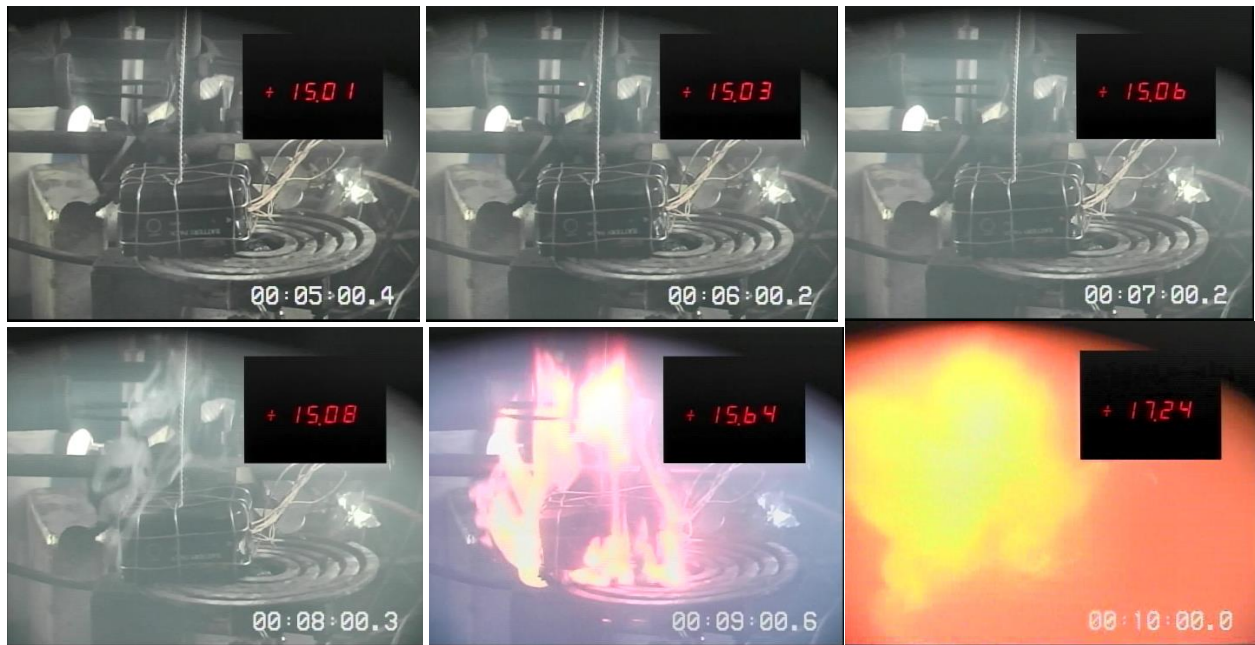
**Figure 6:** Screen captures at various time points of laptop fire video footage..As shown, there is visible smoke at the 2:00 minute mark, and at 4:00 minutes the laptop is hardly visible due to the high smoke particle concentration. Ignition occurs approximately 3 seconds after 6:30 minutes.



**Figure 7:** Photo of a HP Zbook laptop post-fire.

## Battery Experiment

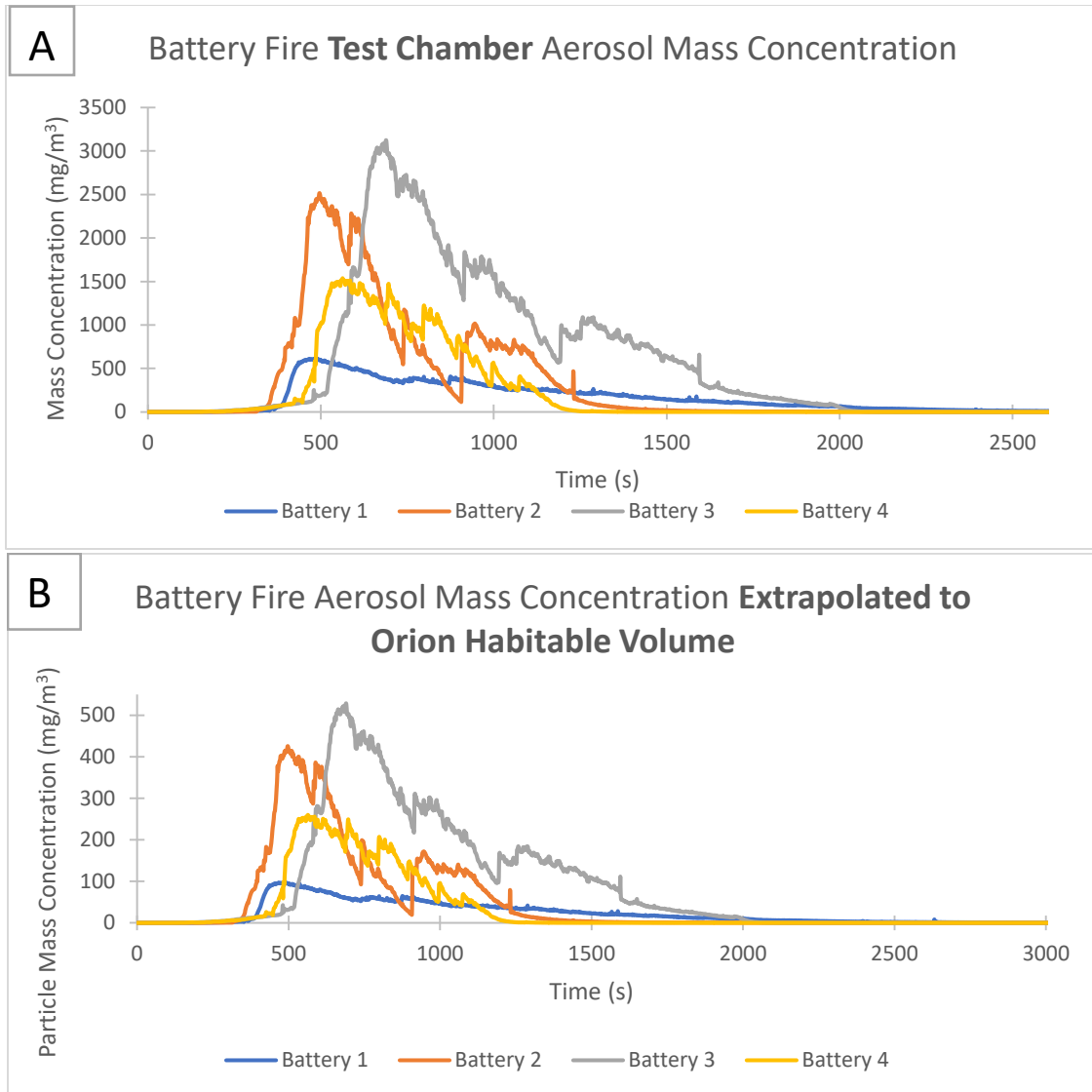
As mentioned previously, the combustion of a multi-cell battery pack provided much more realistic smoke concentration data than the laptop experiment. Although the experimental approach was improved with the battery, many of the same assumptions made in the laptop experiment had to be made for the battery experiment as well. The air was assumed to be well-mixed, and the volume of the chamber had to be extrapolated to the volume of Orion for smoke mass concentration graphs. The course of the combustion of is depicted in **Figure 8**, and **Figure 9** shows the battery after the experiment.



**Figure 8:** Screen captures at 1-minute intervals of battery fire video footage. The red numbers in the upper right corner of each capture is the pressure in PSI measured by a pressure transducer inside the chamber.



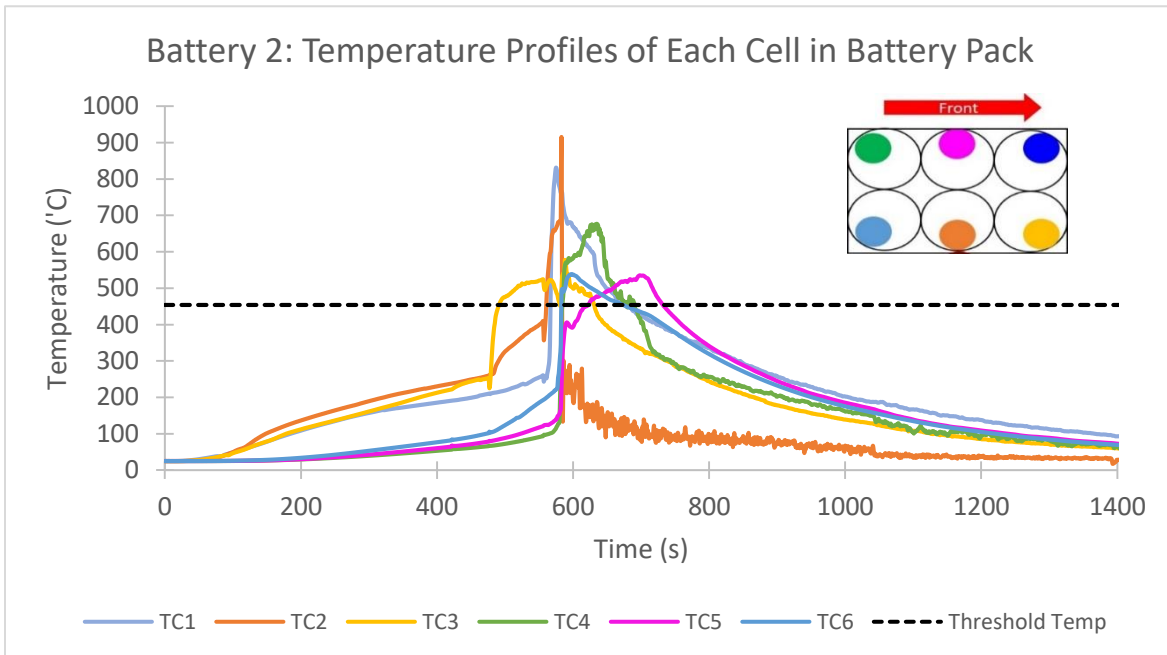
**Figure 9:** Photo of a battery pack after the completion of the experiment.



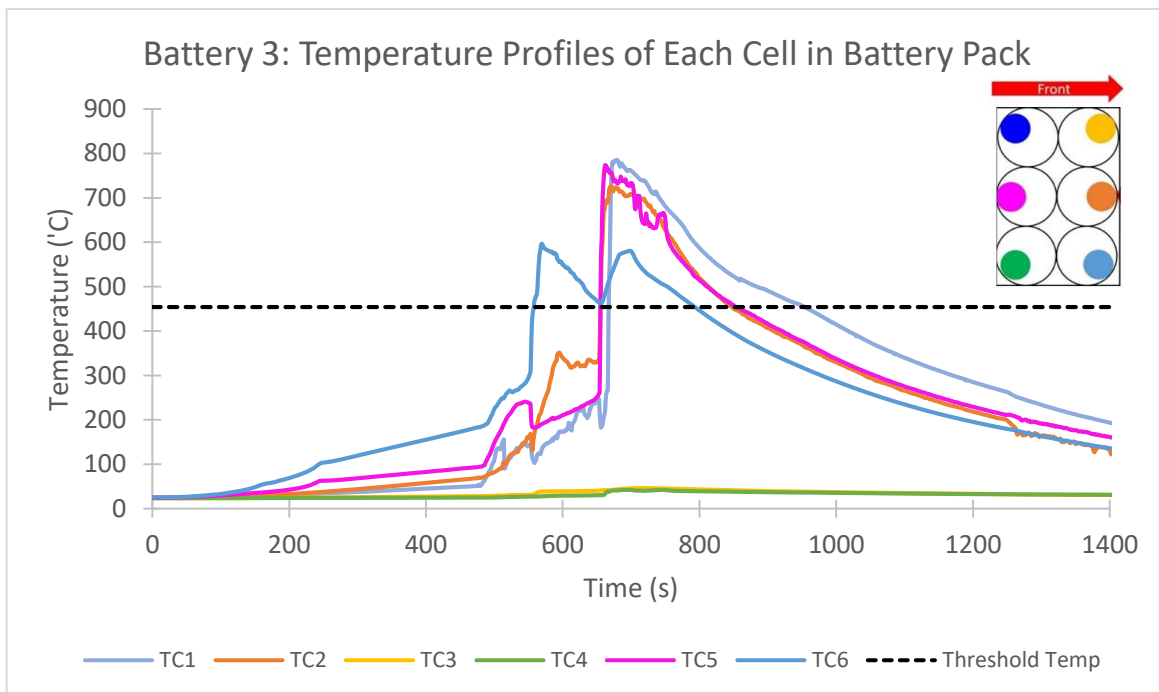
**Figure 10A and 10B:** The top graph depicts the particle mass concentration inside the test chamber over time for each battery. The bottom graph shows the same data extrapolated to the volume of Orion using the ratio of the chamber volume to the spacecraft volume. Almost 8,000 data points were recorded for each battery, which is why the experimental data is denoted as a curve as opposed to individual points.

**Table 1:** Table showing the Orion maximum particle mass concentration achieved during each run as well as the time at which the maximum concentration was reached.

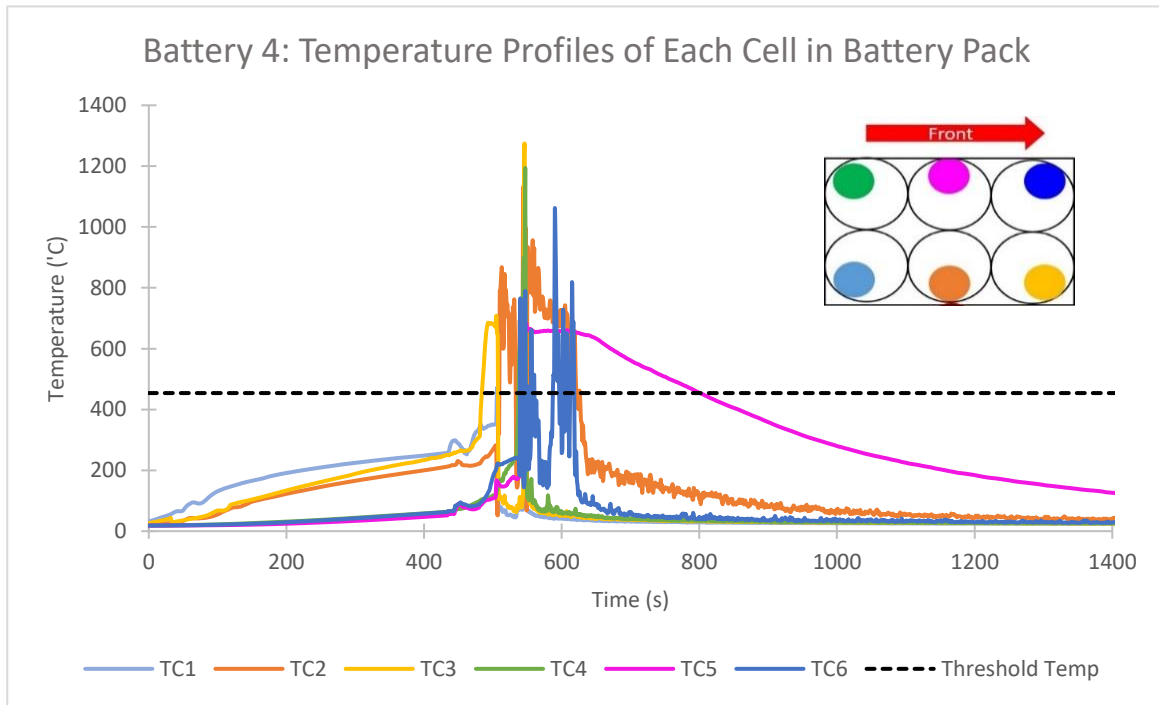
Battery	Max Concentration (mg/m <sup>3</sup> )	Time at Max Concentration (s)
1	96.9	484
2	218.1	497
3	248.1	690
4	188.1	564



**Figure 11:** Graph depicting the temperature profiles as read by the thermocouple on each battery cell for Battery 2. The figure on the top right of the graph indicates which cell corresponds to which curve by color. The black dotted line indicates the threshold of 454°C above which a cell is considered involved in the combustion.



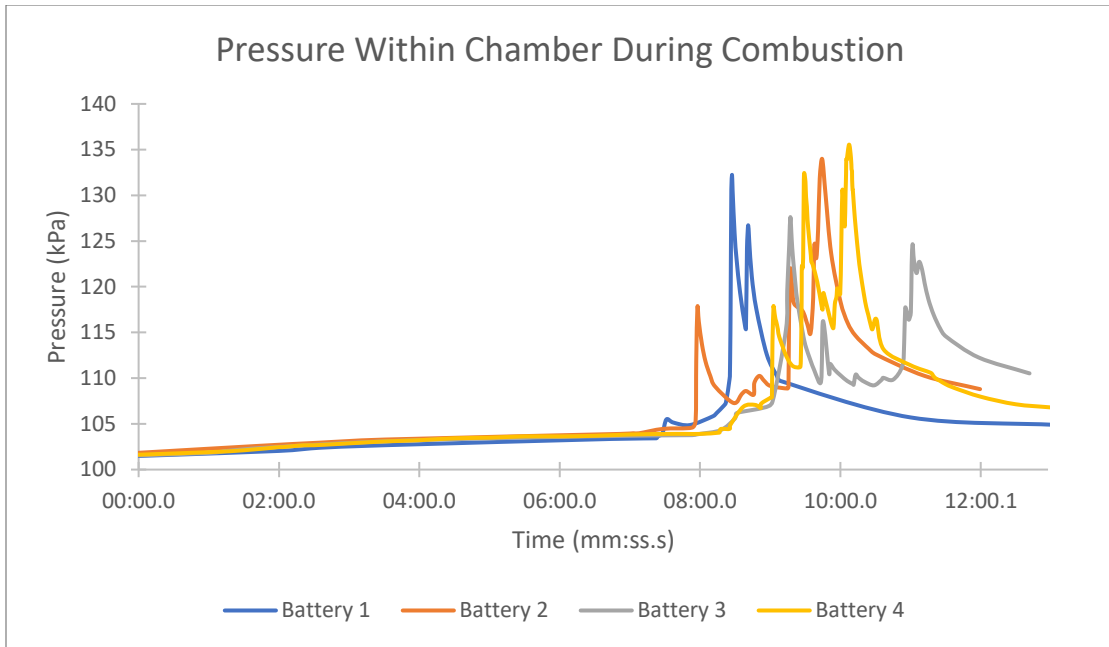
**Figure 12:** Graph depicting the temperature profiles as read by the thermocouple on each battery cell for Battery 3. The figure on the top right of the graph indicates which cell corresponds to which curve by color, as well as the vertical orientation of Battery 3 during testing. The black dotted line indicates the threshold of 454°C above which a cell is considered involved in the combustion.



**Figure 13:** Graph depicting the temperature profiles as read by the thermocouple on each battery cell for Battery 4. The figure on the top right of the graph indicates which cell corresponds to which curve by color. The black dotted line indicates the threshold of 454°C above which a cell is considered involved in the combustion.

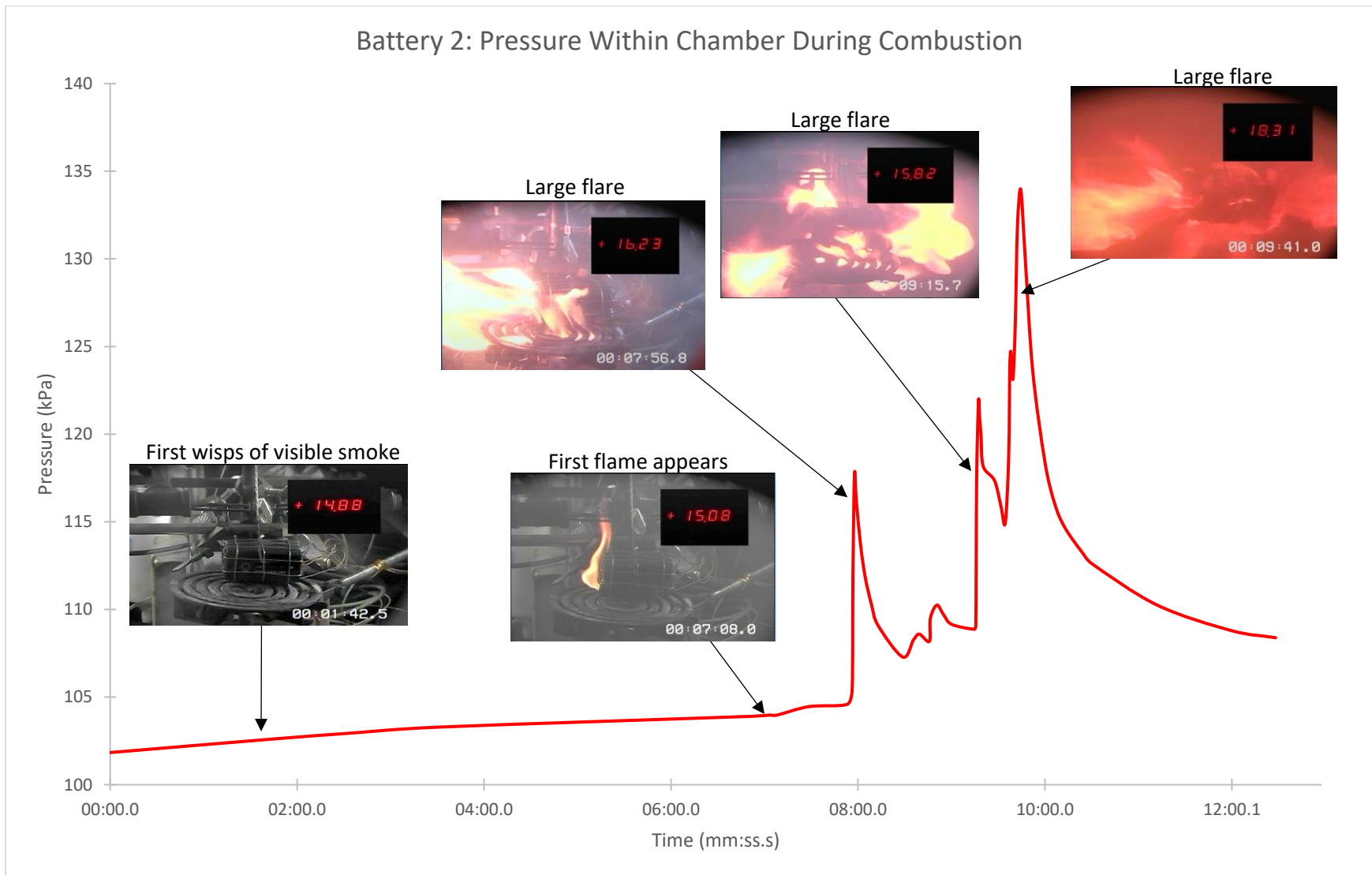
**Table 2:** Table showing the time, in seconds, in which each cell in the battery pack exceeded 454°C and thus became involved. Cells 3 and 4 never became involved in the combustion for Battery 3, denoted by “N/A.” The bottom row indicates the time range (in seconds) during which different cells exceeded the threshold for thermal runaway., calculated by taking the maximum and minimum seconds for each column. Temperature data is not available for Battery 1.

Cell	Color	Time at which cell became involved (s)		
		B2	B3	B4
1	Light Blue	567	668	506
2	Orange	561	656	508
3	Yellow	494	N/A	484
4	Green	585	N/A	538
5	Pink	623	658	545
6	Blue	583	560	540
<b>Window of involvement (s)</b>		<b>494 - 623</b>	<b>560 - 668</b>	<b>484 - 545</b>



**Figure 14:** Graph showing the pressure in kPa inside the chamber during the combustion of each battery.





**Figure 15:** A graph depicting the pressure profile inside the chamber during the testing of Battery 2. Notable events of the combustion are also pictured at the corresponding times on the curve.

## Discussion and Analysis

The purpose of this study was to compare different battery fire scenarios and determine if there are trends that can help predict other scenarios. The fire characteristics that were measured in these experiments were smoke aerosol mass concentration, pressure, and temperature of individual battery cells.

From the mass concentration and temperature data presented, several qualitative correlations can be inferred from general trends. In terms of battery cells igniting within a pack, it was hypothesized that a spike in mass concentration would correspond to another cell being ignited and that a distinguishable step up in concentration would be observed in concentration as different cells became involved. However, from **Figures 11, 12, and 13** it is clear that most cells in each battery pack became involved at around the same time since each curve in each figure reaches a maximum in a similar time span. **Table 2** shows the time frame in which individual cell ignited, or the “window of involvement.” Individual battery cells in tests 2-4 all became involved in approximately the same time span (60-120 s) and at approximately the same point in the combustion, at around 500 s. Unfortunately, temperature data is not available for Battery 1, so no conclusions can be drawn about the temperature behavior of cells in Battery 1. It was noted, however, in the test documentation that there were no explosive ejections, only more steady flames, and thus it was concluded that thermal runaway did not occur in any of the cells in the battery pack.

A similar trend was observed for the aerosol mass concentration data, shown in **Figures 10A and 10B**. The only difference between the two graphs is the y-axis scale since **Figure 10B** was extrapolated to the smoke concentration that would have occurred, had the battery fire been in the volume of Orion. The time point at which a maximum concentration was achieved for each battery is shown in **Table 1**, and all are within approximately 200 s of one another. In addition, Battery 1 achieved about half the concentration as the other three batteries tested because none of the cells went into thermal runaway.

When compared to the concentration data, a cell’s initial spike in temperature usually occurs around the same time that the mass concentration reaches a maximum. A series of graphs showing comparisons of mass concentration to temperature can be seen in the appendix on **Figures 1A-6A**. For the cells that became involved, the temperature peaks measured by each thermocouple line up closely with the concentration peak in several figures, such as for Battery 3 in **Figure 3A and 4A**. However, for Battery 4, temperature data varies significantly as shown on **Figure 5A and Figure 6A**. Combustion and smoke testing is notoriously unrepeatable, so there are a number of factors that may have caused this variation.

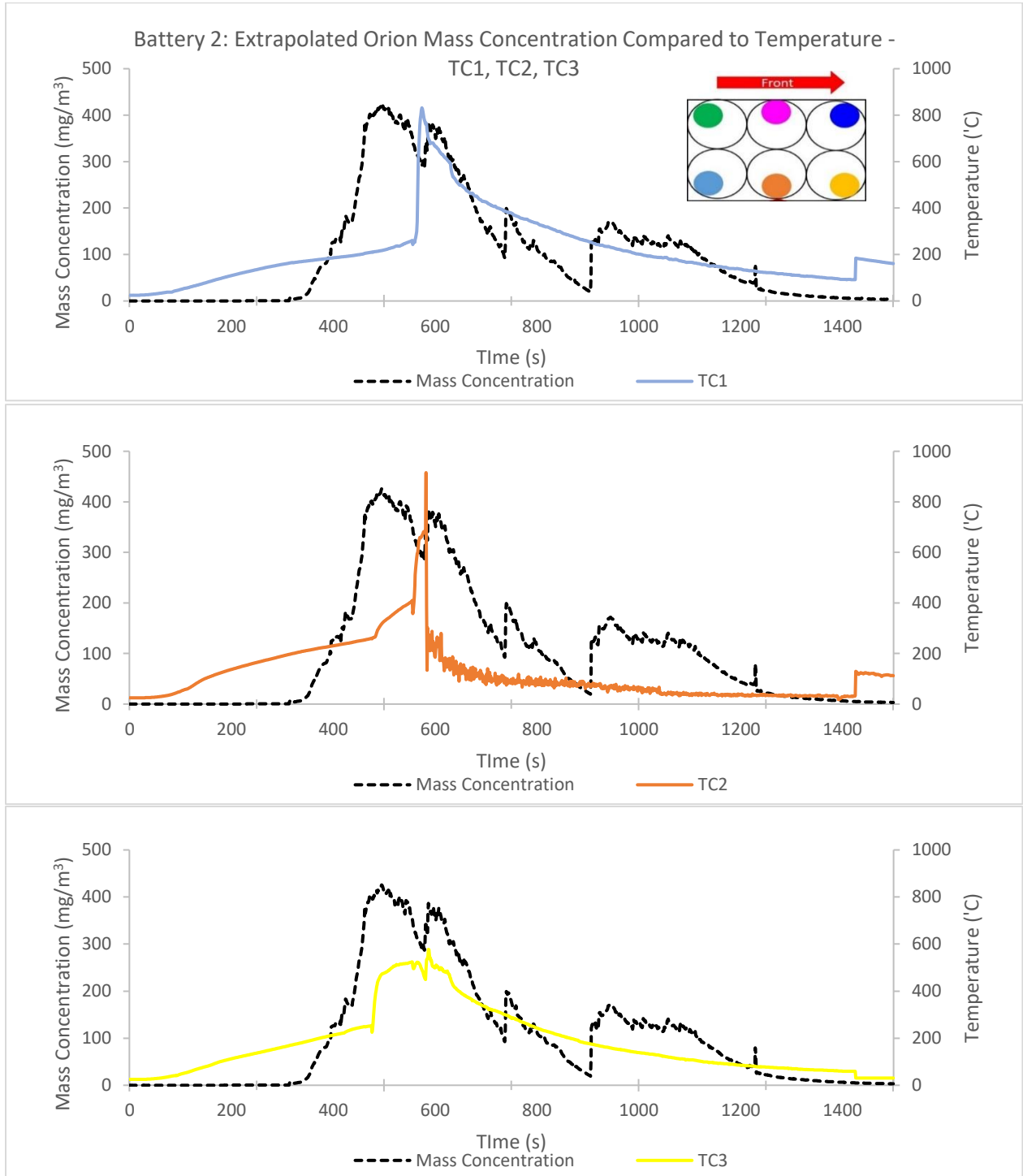
Another parameter measured in the scope of this experiment is chamber pressure, which was recorded in the video footage of the combustion. The pressure inside the chamber undergoes several peaks throughout the test for each battery, as depicted in **Figure 14**. The video footage for each battery was closely analyzed to determine if trends in the combustion correlated to trends in pressure. A sample of this analysis is shown in **Figure 15**. It was observed that whenever the flame underwent a large flare or a release of sparks, the event was closely followed by a spike in

pressure. When cells inside the battery pack ignite, more fuel is provided to the combustion reaction causing a flare in the flame, a corresponding heat release, and thus an increase in chamber pressure. The fact that physical characteristics of the fire correspond to the pressure is of interest to NASA's fire detection systems. If the pressure inside a spacecraft rises significantly in the event of a fire, the crew would have to open a pressure relief valve, which can be extremely dangerous and is considered a last-resort measure that should only be employed if the crew's safety is seriously threatened.

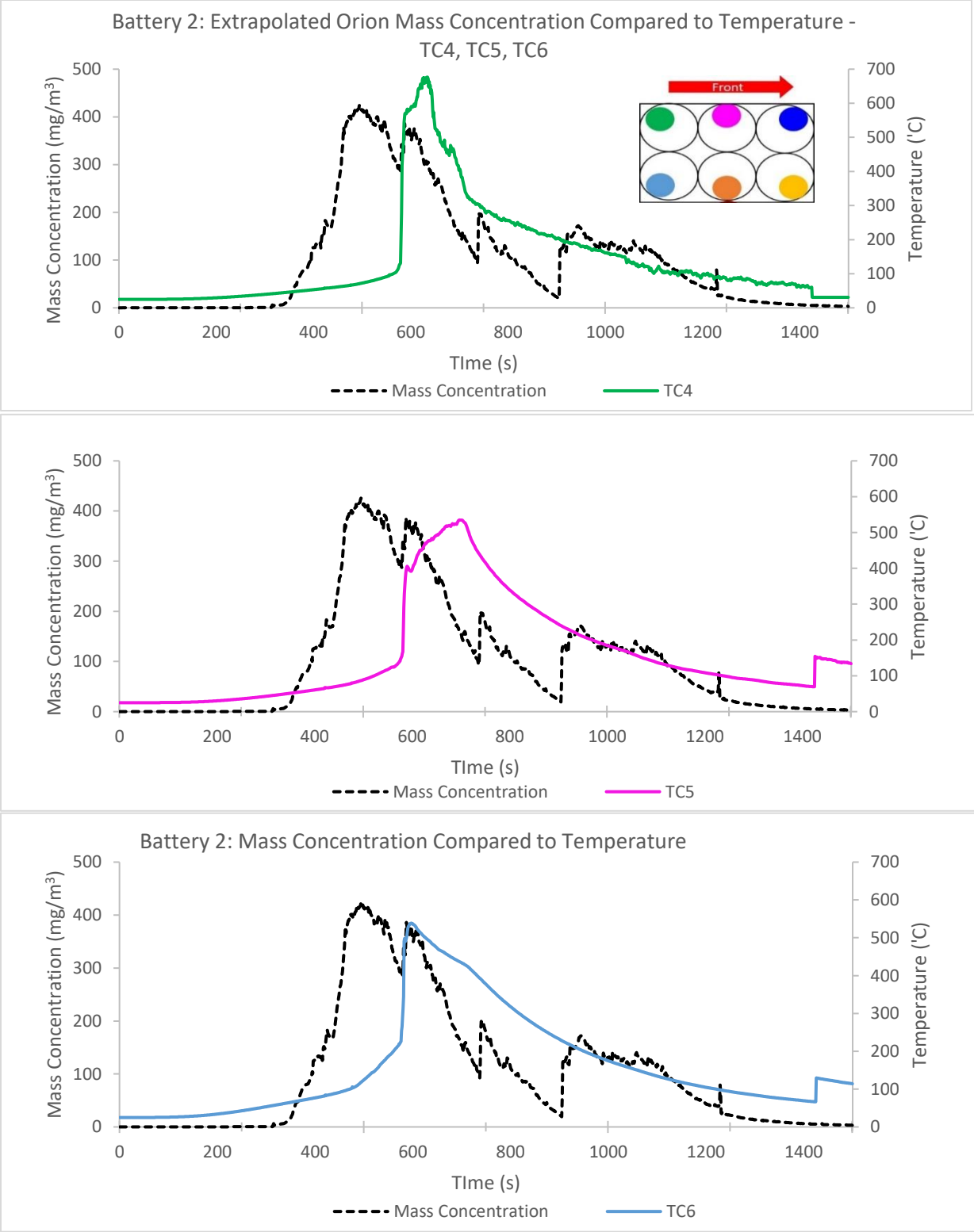
Sources of error in this experiment could stem from the assumptions that were made about the air in the test chamber. The DRX measured aerosols in its immediate proximity. The assumption that the air was well mixed was made, meaning that the air in the chamber has the same smoke mass concentration throughout its entire volume, when in reality, this could vary significantly since smoke rises in the presence of gravity. In low gravity, smoke does not rise because there is no buoyant air flow; however, the ventilation system will distribute the smoke throughout the spacecraft cabin volume. With more time and resources, in subsequent experiments multiple mass concentrations can be taken in different areas of the chamber to understand if this assumption is valid.

From the collected data, qualitative correlations were able to be drawn. However, although combustion experiments provide insightful data which can be pipelined into efficient fire safety system design, in most combustion experiments, results typically have poor repeatability. In addition, the NASA Life Support Systems team is currently evaluating whether or not a fire detection system should be modeled around tests involving a battery. On the Orion capsule, it is unlikely that a battery will start burning on its own. There are always materials surrounding a battery that ignite and burn before the battery itself reaches critical temperatures. One major challenge in fire safety design is anticipating emergency situations; a fire can ignite on Orion in an infinite number of ways. This is why meticulous analysis and prediction of the highest-probability events is crucial for the design of spacecraft fire safety systems.

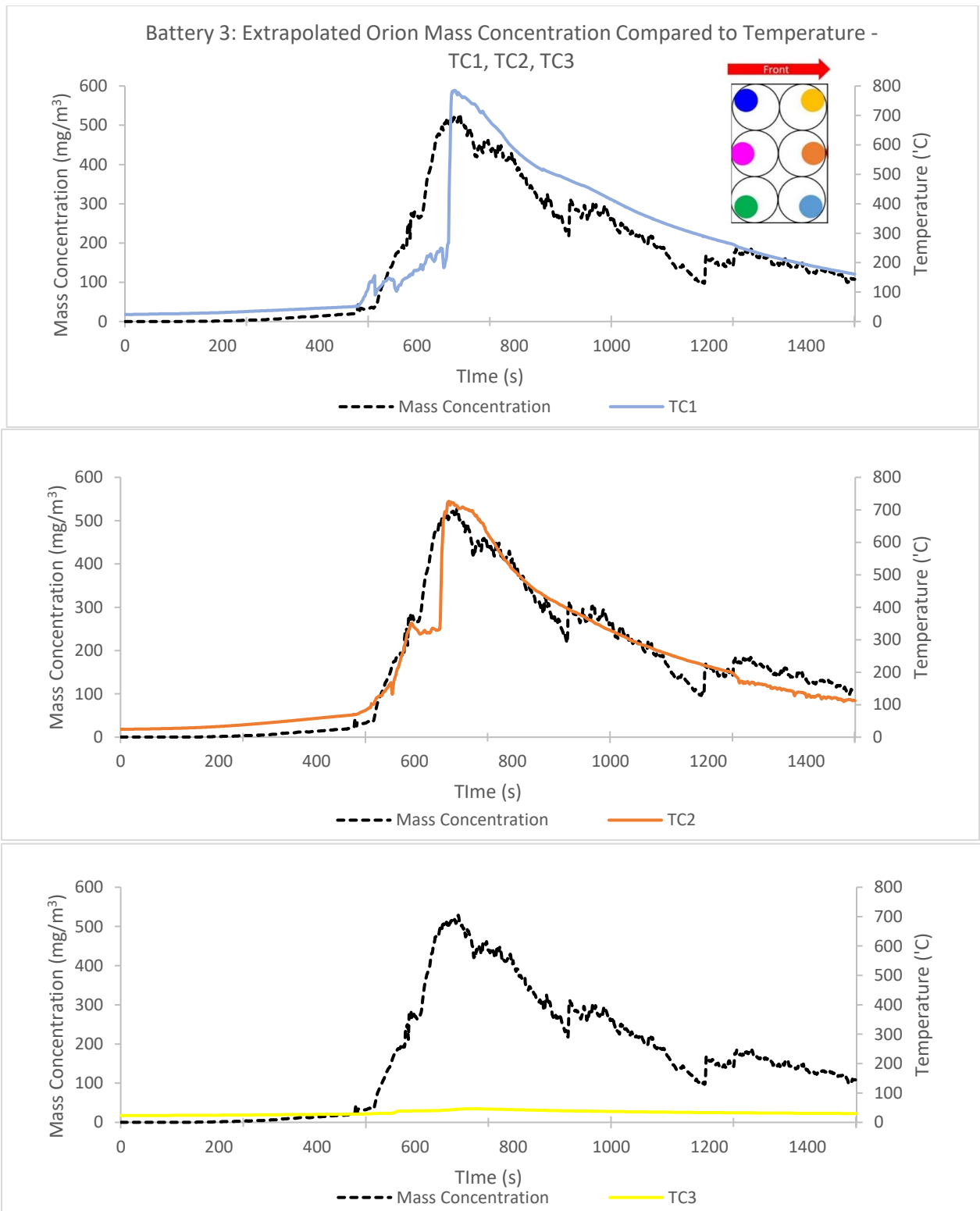
# Appendix



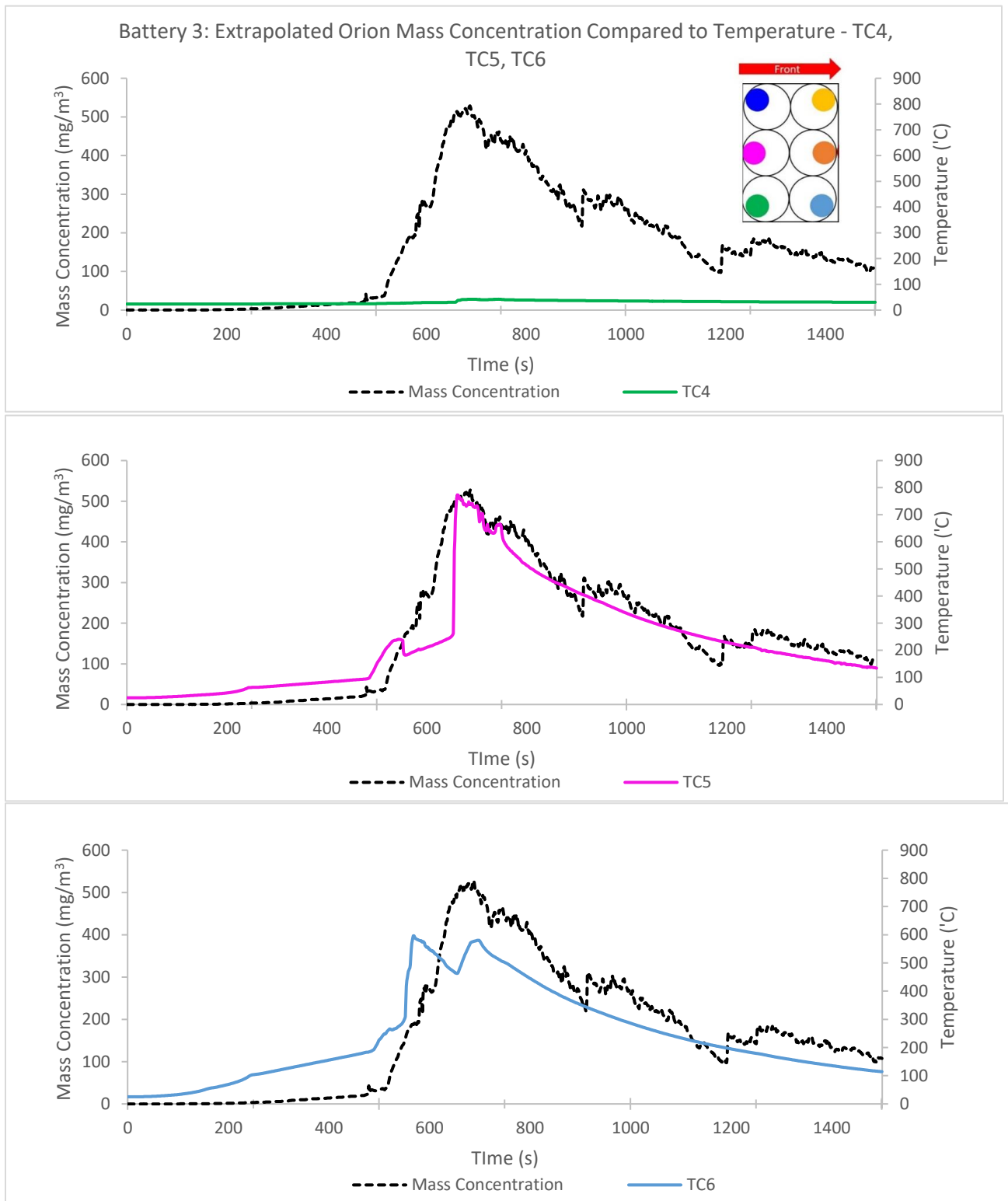
**Figure 1A:** Graphs depicting the concentration curves overlaid by the temperature curves from Thermocouple 1, 2, and 3 from top to bottom for Battery 2.



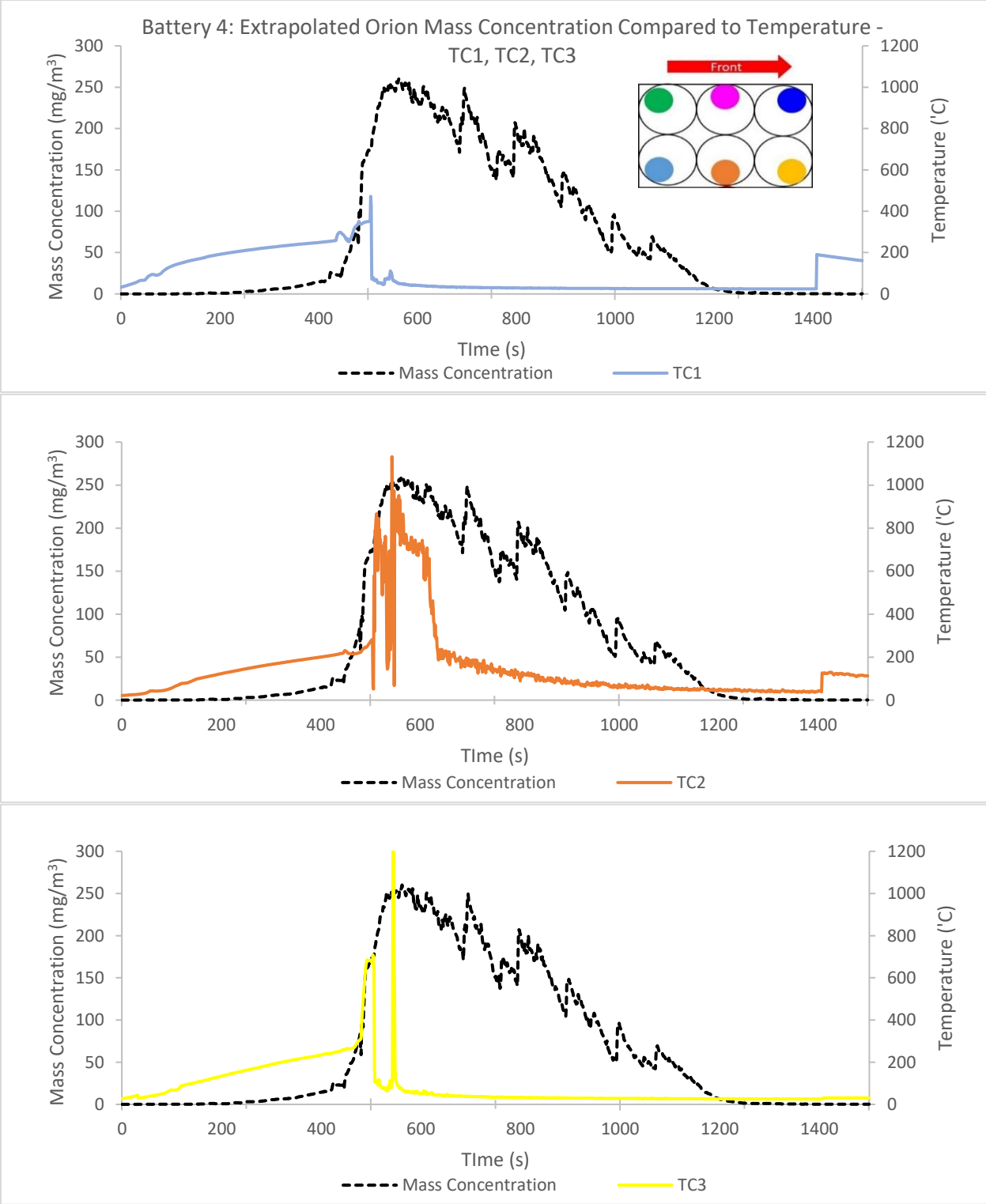
**Figure 2A:** Graphs depicting the concentration curves overlaid by the temperature curves from Thermocouple 4, 5, and 6 from top to bottom for Battery 2. Note the different temperature scales compared to Figure 1A



**Figure 3A:** Graphs depicting the concentration curves overlaid by the temperature curves from Thermocouple 1, 2, and 3 from top to bottom for Battery 3. As shown, cell 3 did not become involved in the combustion since it never reached 454°C.

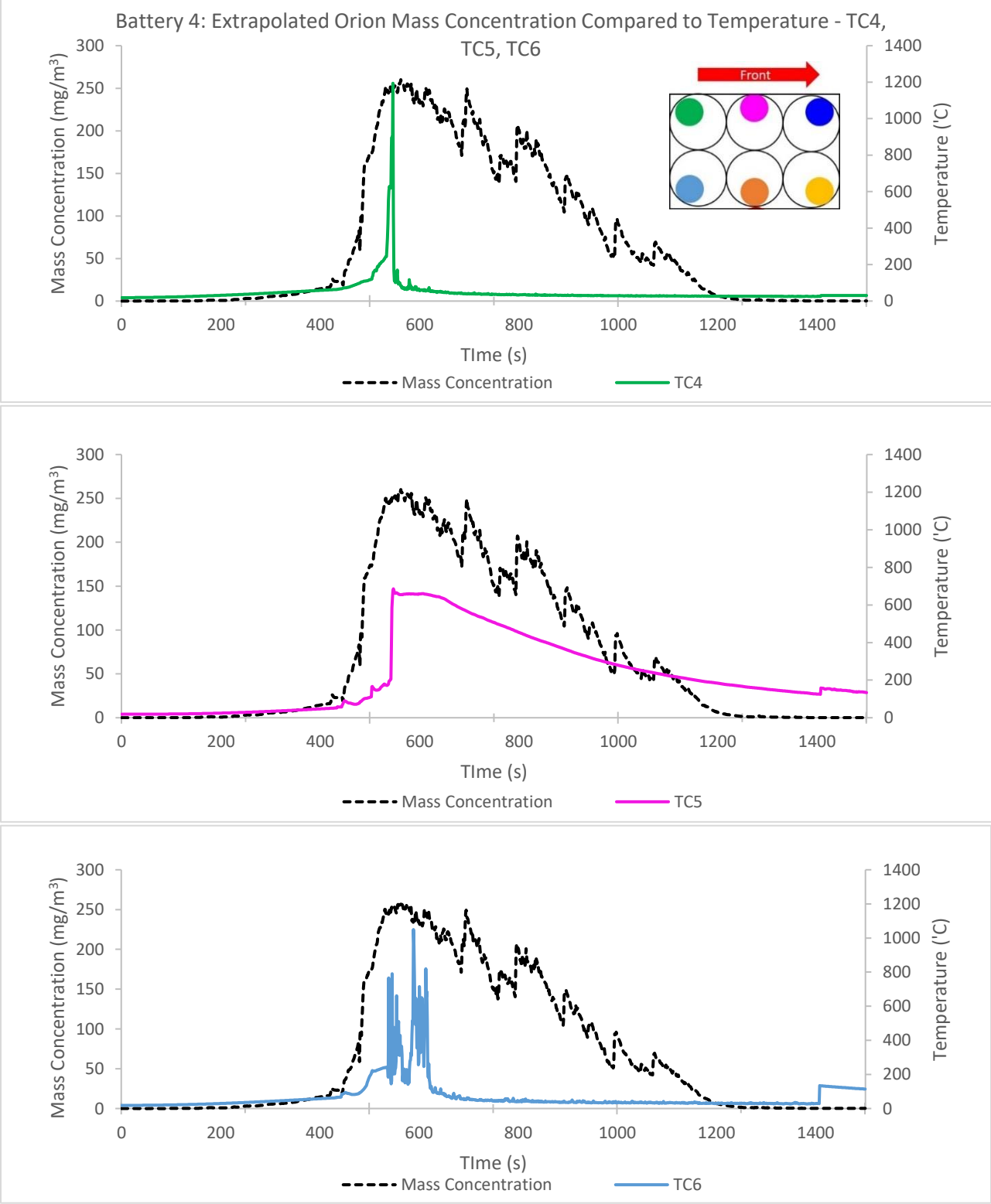


**Figure 4A:** Graphs depicting the concentration curves overlaid by the temperature curves from Thermocouple 4, 5, and 6 from top to bottom for Battery 3. As shown, cell 4 did not become involved in the combustion since it never reached 454°C.



**Figure 5A:** Graphs depicting the concentration curves overlaid by the temperature curves from Thermocouple 1, 2, and 3 from top to bottom for Battery 4.





**Figure 6A:** Graphs depicting the concentration curves overlaid by the temperature curves from Thermocouple 4, 5, and 6 from top to bottom for Battery 4.

## References:

1. Garcia, M. Orion Spacecraft <https://www.nasa.gov/exploration/systems/orion/index.html> (accessed Apr 11, 2018).
2. Carriere, T.; Butz, J.; Naha, S.; Brewer, A.; Abbud-Madrid, A. Fire Suppression Tests Using a Handheld Water Mist Extinguisher Designed for Spacecraft Application. *42nd International Conference on Environmental Systems* **2012**.
3. Garcia, M. Facts and Figures <https://www.nasa.gov/feature/facts-and-figures> (accessed Apr 11, 2018).
4. Ruff, Gary. Research Needs in Fire Safety for the Human Exploration and Utilization of Space. *NASA Center for Aerospace Information* **2001**.
5. Juarez, A.; Harper, S. A.; Hirsch, D. B.; Rodriguez, B. R.; Young, G. M.; Tarver, S. B. Development of a Standard Test Scenario to Evaluate the Effectiveness of Portable Fire Extinguishers on Lithium-ion Battery Fires. *43rd International Conference on Environmental Systems* **2013**.
6. DUSTTRAK DRX Aerosol Monitor 8533 <http://www.tsi.com/dusttrak-drx-aerosol-monitor-8533/> (accessed Apr 11, 2018).
7. Corbett, J. Materials Flight Acceptance [https://www.nasa.gov/centers/wstf/testing\\_and\\_analysis/materials\\_flight\\_acceptance/index.html](https://www.nasa.gov/centers/wstf/testing_and_analysis/materials_flight_acceptance/index.html) (accessed Apr 12, 2018).