

# Basic Study on Thermal Runaway Propagation through Lithium Ion Cells

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## ABSTRACT

Lithium-ion cells are being used in an increasing number of electric and hybrid vehicles. Both of these vehicle types contain many cells. Despite various safety measures, however, there are still reports of accidents involving abnormal heat, smoke, and fire caused by thermal runaway in the cells. If thermal runaway in one cell triggers that of another and thus causes thermal runaway propagation, this can lead to rupture of the battery pack, car fire, or other serious accidents.

This study is aimed to ensure the safety of vehicles with lithium-ion cells by clarifying such accident risks, and so we investigated the process of *thermal runaway propagation*. In the experiment, we created a battery module made of seven laminate-type cells tightly stacked one on another. Then, we induced thermal runaway in one of the cells, measured the surface temperatures of the cells, and collected video data as the process developed. As a result, all of the seven cells underwent thermal runaway. We clarified the timing at which gas and flame eruptions occurred and the process of thermal runaway propagation. This experiment clarified one of the phenomena that occur during such propagation.

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## 1. INTRODUCTION

Lithium-ion cells are being used in an increasing number of electric and hybrid vehicles. However, if these cells are overcharged, internally short-circuited, or overheated, there is a risk of thermal runaway, which, depending on the type of cells, could cause abnormal phenomena such as high temperature and eruption of flammable gas. Generally, various safety measures (management of manufacturing quality of cells, proper design of cells, modules and packs, etc.) are taken to prevent the thermal runaway of lithium-ion cells. They include designing cells with a safe range of SOC, managing manufacturing quality to prevent internal short-circuiting due to the presence of foreign matter, managing charging to prevent overcharging, installing a current breaker to prevent external short-circuiting, or designing electric insulation at the level of modules and packs. However, cases of abnormal heat, smoke, and fire caused by such thermal runaway have recently been reported [1]. Suspected causes of these accidents include mistakes in designing the working-range SOC of the cells, the presence of foreign matter due to manufacturing errors, mistakes in designing the charging control device, and mistakes in designing the electrical insulation, but the causes have not been sufficiently clarified. Thus, it is difficult to claim that the thermal runaway of lithium-ion cells can be completely prevented. On the other hand, since both of these vehicle types contain many cells, thermal runaway in one cell may trigger that of another and thus cause *thermal runaway propagation* and, eventually, generate a large amount of flammable gas, which may raise the pressure inside the battery pack and rupture or explode it. We assume that an important factor in clarifying this rupture and explosion of the

battery pack is the interval between the start timings of gas and flame eruptions during the process of thermal runaway propagation (hereafter "gas and flame eruption timing").

As to the propagation of thermal runaway, an experiment assuming the transportation of commercial lithium-ion cell type 18650 has been reported [2]. The results of the report suggest that thermal runaway occurs every few minutes. On the other hand, for electric vehicles, it is essential to extend the cruising distance, which means increasing the volume energy density. Accordingly, we assume that lithium-ion cells used in electric vehicles will be placed with each cell tightly in contact with another. Due to this arrangement, once thermal runaway occurs in a cell, it is likely to spread to other cells.

The aim of this study was, considering the difficulty of eliminating accidents due to lithium-ion cells, to clarify the risk of accidents due to lithium-ion cells in vehicles and to collect basic data to help ensure safety in the event of a thermal runaway. For this purpose, we forcibly caused the thermal runaway of lithium-ion cells and tried to understand the process of its propagation. In this experiment, we created a module of seven laminate-type lithium-ion cells tightly stacked one on another and induced thermal runaway in one of the cells. Overcharging, which is one cause of thermal runaway, was selected to make it happen certainly and easily as a worst possible case. Through this experiment, we clarified the phenomena of thermal runaway propagation, the process leading to the propagation, and gas and flame eruption timing.

## 2. EXPERIMENT METHOD

In this experiment, two kinds of generic laminate-type lithium-ion cells were used. The experiment was conducted two times (Case A and Case B). In Case A, the cell used lithium manganese oxide as the positive electrode material and was 10 Ah in capacity, 115×207×6.1 mm in size, 270 g in mass, and 4.2 V in upper limit voltage. In Case B, the cell used ternary compound (nickel-manganese-cobalt) as the positive electrode material and was 25 Ah in capacity, 212×222×6.0 mm in size, 560 g in mass, and 4.2 V in upper limit voltage. Annex A shows the charging characteristics of each cell. Before the experiment, each cell was charged to 4.2 V as shown in Annex A.

Figure 1 shows the battery module structure and layout of thermocouples in this experiment. Seven laminate-type cells were piled in one stack, sandwiched between two Bakelite plates, and tightened with bolts at the four corners of the plates, as shown in Fig. 1(a). To measure the temperature, type K thermocouples with a cross-section of 0.9×1.3 mm were fixed to the surface of each cell (U1-U4, D1-D4, W1-W8). Here, U1-U4, D1-D4 measured the temperatures at the center of the cell surface, as shown in Fig. 1(a), while W1-W8 measured the temperature on the upper surface of Cell IV in Case A and Case B, as shown in Fig. 1(b) and (c). The interval between each of the thermocouples W1-W8 and U1 was 45 mm in the lateral direction and 25 mm in the longitudinal direction in Fig. 1(b).

The interval between each of the thermocouples W1-W8 and U1 was 4.75 mm in the lateral direction and 5.25 mm in the longitudinal direction in Fig. 1(c).

In the experiment, to make the occurrence of thermal runaway most likely (to create the worst conditions), the broadest possible surfaces of the cells were put into contact with each other, so that the heat generated in thermal runaway was most easily transmitted to neighboring cells.

The first thermal runaway to trigger the subsequent process was caused by overcharging each Cell IV in Case A and Case B so that thermal runaway occurred without fail. The Cells were overcharged at constant current, of which the target value was set at 30 A for Case A and at 75 A for Case B.

In the experiment, the charging voltage and measured temperatures were recorded at the same time (in sync) by a data logger. Further, before the experiment, a flashing lamp was video-recorded at the same time as the input voltage to the lamp was recorded by the data logger, to ensure that the charging voltage, measured temperatures, and video data were synchronized. The sampling of the data logger was made at 100 ms intervals and the video recording at 30 fps.

## 3. RESULTS OF EXPERIMENT

### 3.1. Results of Video Data

Figure 2 shows the process of the experiment. In Case A, the first eruption (of smoke) started 9 min 57 sec after Cell IV was overcharged. The eruption once subsided but was shortly followed by a second eruption. This second eruption ignited the gas into flames. Thereafter, flame eruption and subsidence repeated, showing four eruptions in total. In Case B, the first eruption (of smoke) started 9 min 58 sec after Cell IV was overcharged. Thereafter, as in Case A,

four eruptions of gas and flame were observed. In acquiring the temperature and video data, we set the point of time at 10 s before the first eruption of gas or fire as the 0-s point.

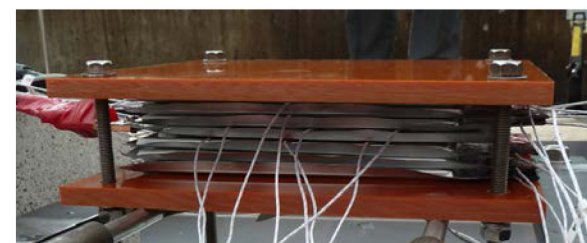
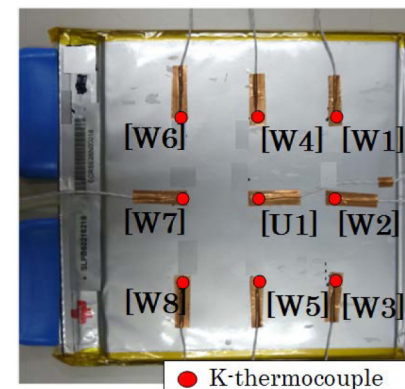
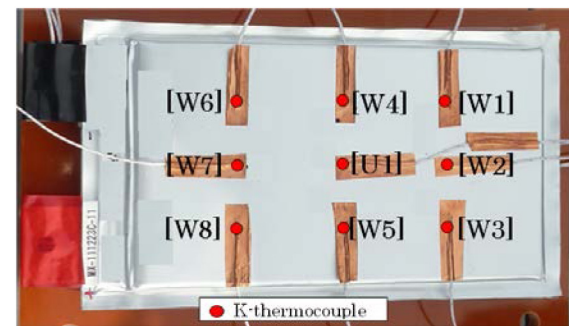
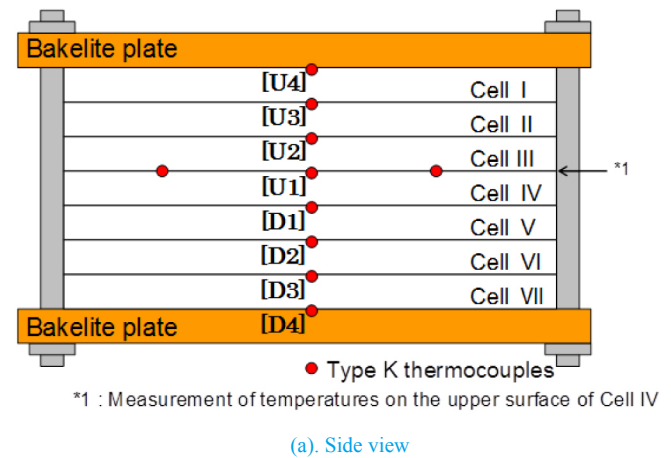


Fig. 1. Battery module configuration

Figure 2 shows the 10-s point in Case A (the first eruption of smoke) and the eruption of flame (during the third eruption of flame) and the 10-s point in Case B (the first eruption of smoke) and the eruption of flame (during the second eruption of flame).

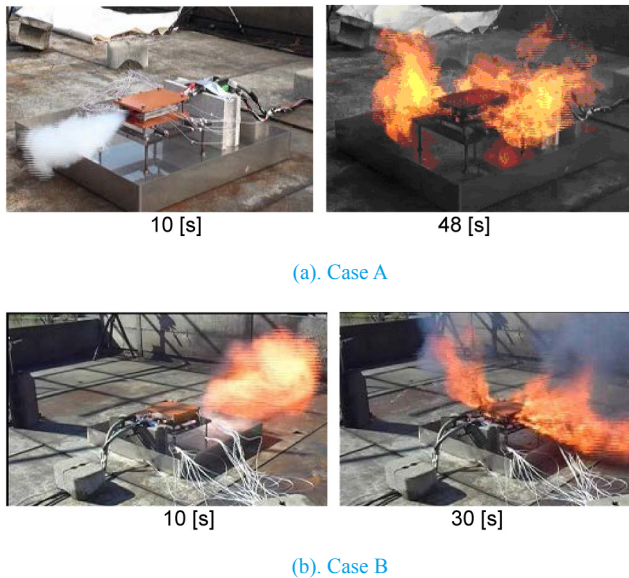


Fig. 2. Eruption of smoke and fire upon the start of thermal runaway and eruption of flames

From the video data with sound track, we extracted the time points at which the gas and flame eruptions started. The extraction was made in three ways: The first method, as shown in Fig. 2 (a) and (b) 10-s, consisted of extracting the time point at which we confirmed the eruption of gas and flames. This was applied to the 1<sup>st</sup> and 2<sup>nd</sup> eruptions in Case A and to the 1<sup>st</sup> eruption in Case B. The second method was used when a new eruption of gas and flames mixed with previous eruptions (2<sup>nd</sup> to 4<sup>th</sup> eruptions in Case B). Here, we defined as the starting point the time point at which we confirmed that the waveforms of the erupting sounds increased in amplitude. The third method was applied when we could not definitely confirm the increase in amplitude of the waveforms of erupting sounds (3<sup>rd</sup> and 4<sup>th</sup> eruptions in Case A). Here, we compared the video images before and during the erupting sound at one-second intervals, extracted two seconds where we did not see fire eruption and then we saw it, and defined the middle point of time between them as the time point when the fire eruption started.

Table 1 shows the time points at which the gas and flame eruptions started, extracted as explained above. The results of Table 1 may contain errors of up to  $\pm 1$  s. Table 2 shows the intervals between the time points at which gas and fire eruption started. Considering that the timing in question here concerned thermal runaway from heating, we calculated the time interval between the start of the 2<sup>nd</sup> and subsequent gas and flame eruption.

Table 2 shows that the time interval between the start of the 2<sup>nd</sup> gas and flame eruption and that of subsequent was on average 25 s in Case A and 17 s in Case B.

Table 1. Time points at which gas and flame eruptions started

| Time points at which gas and flame eruptions started | 1 <sup>st</sup> time (s) | 2 <sup>nd</sup> time (s) | 3 <sup>rd</sup> time (s) | 4 <sup>th</sup> time (s) |
|------------------------------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Case A                                               | 10                       | 19                       | 45                       | 69                       |
| Case B                                               | 10                       | 20                       | 37                       | 54                       |

Table 2. Intervals between the start of gas and flame eruptions

| Intervals between the start of gas and flame eruptions | 2 <sup>nd</sup> to 3 <sup>rd</sup> time | 3 <sup>rd</sup> to 4 <sup>th</sup> time |
|--------------------------------------------------------|-----------------------------------------|-----------------------------------------|
| Case A                                                 | 26                                      | 24                                      |
| Case B                                                 | 17                                      | 17                                      |

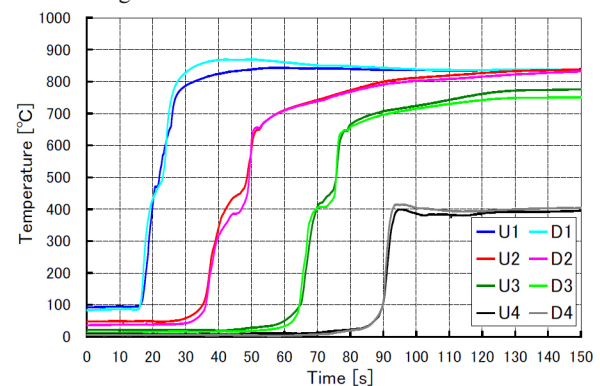
### 3.2. Results of Temperature Measurement

#### 3.2.1. Temperature Changes at the Center of the Cell

Figures 3 and 4 show the results of temperature measurement with U1-U4 and D1-D4 in Case A and Case B.

From Figs. 3 and 4, we obtained the following results:

- In Figs. 3 and 4, the surface temperature of all cells dramatically increased. After reaching the peak, the temperature tended to decline.
- Fig. 3(a) shows that in Case A, the temperatures of the thermocouple pairs placed symmetrically above and below Cell IV ([U1]-[D1], [U2]-[D2], [U3]-[D3], [U4]-[D4]) showed mostly similar changes.
- Fig. 3(a) shows that in Case A, the temperatures of the thermocouples placed between two cells ([U1]-[U3], [D1]-[D3]) rose to about 800°C. On the other hand, the temperatures of the uppermost and lowermost thermocouples ([U4]-[D4]) placed in contact with the Bakelite plates were about 400°C at the highest.



(a). Up to the 150-s point

Fig. 3.