

Electronic Supplementary Information (ESI)

For

Early warning technology of common characteristic resistances for lithium-ion batteries with thermal runaway

1 Supplementary Figures and Tables

Table S1 Common characteristic temperatures (T_1, T_2, T_3) and their times (t_1, t_2, t_3) of the test batteries.

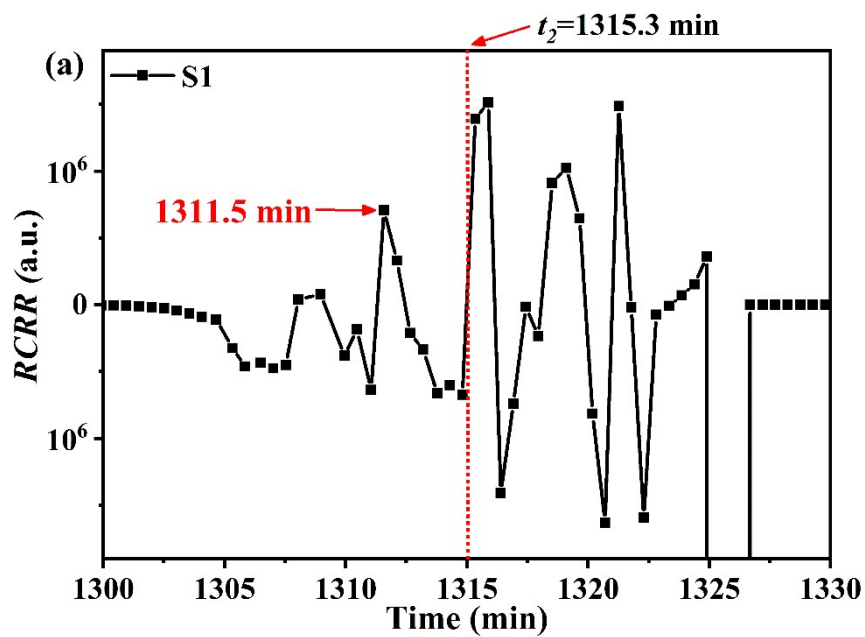
Test batteries	T_1 (°C)	t_1 (min)	T_2 (°C)	t_2 (min)	T_3 (°C)	t_3 (min)
S1	96.7	593.2	146.9	1315.3	789.7	1326.0
S2	97.3	591.3	148.6	1512.7	762.6	1523.9
S3	96.7	600.9	153.2	1140.5	759.5	1151.1

Table S2 Parameters of the resistance system before t_1 .

Test batteries	t_{R1} (min)	t_{R2} (min)	t_{R3} (min)	t_1 (min)	$\Delta t_1(t_1 - t_{R3})$ (min)
S1	496.5	500.6	548.7	593.2	44.5
S2	507.9	513.0	553.3	591.3	38.0
S3	488.8	507.4	575.0	600.9	25.9

Table S3 Key parameters of the resistance system near t_2 .

Test batteries	t_{R4} (min)	t_2 (min)	$\Delta t_2(t_2 - t_{R4})$ (min)
S1	1311.5	1315.3	3.8
S2	1505.0	1512.7	7.7
S3	1123.0	1140.5	17.5



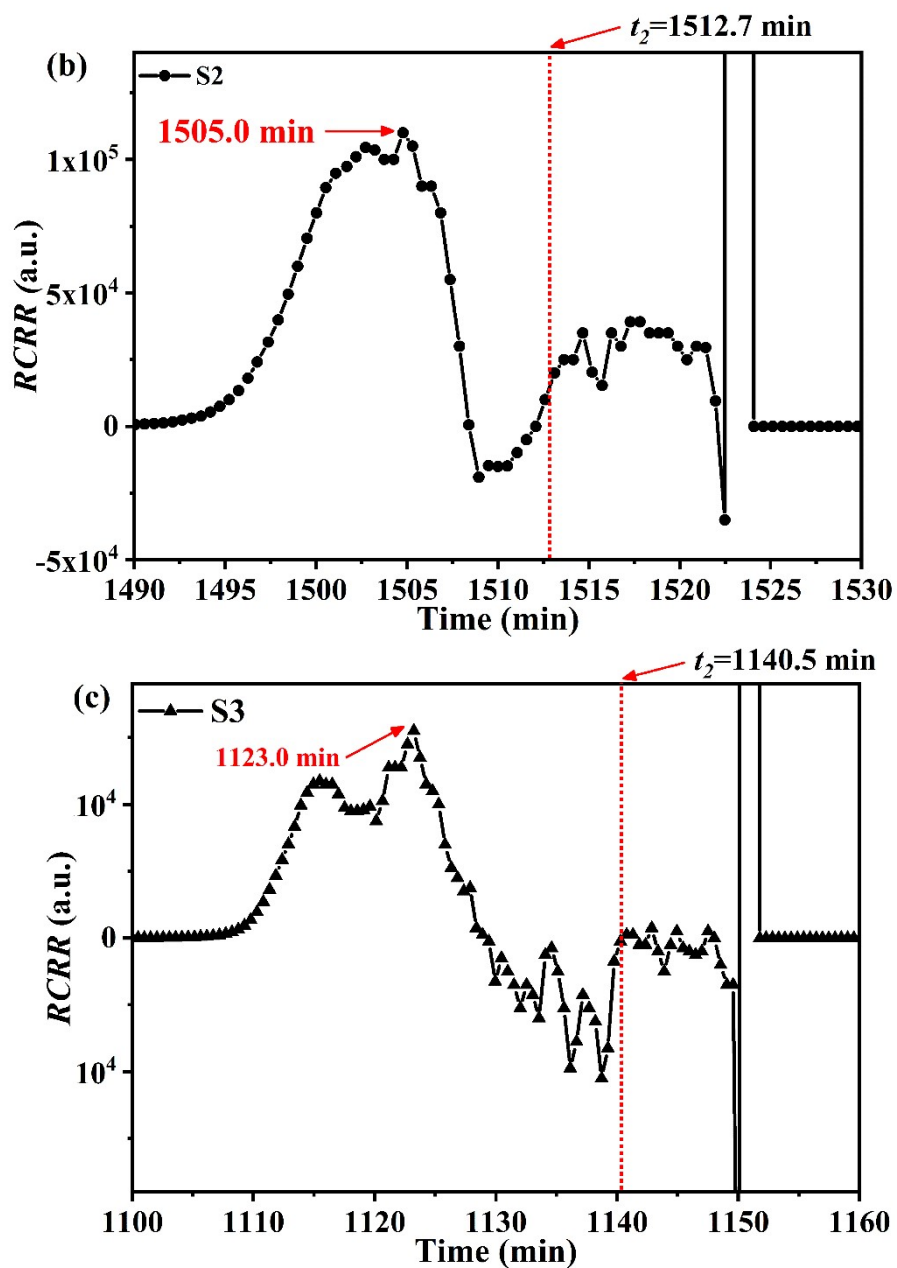


Figure S1 Special tendencies of *RCRR* before t_2 of (a) S1, (b) S2 and (c) S3.

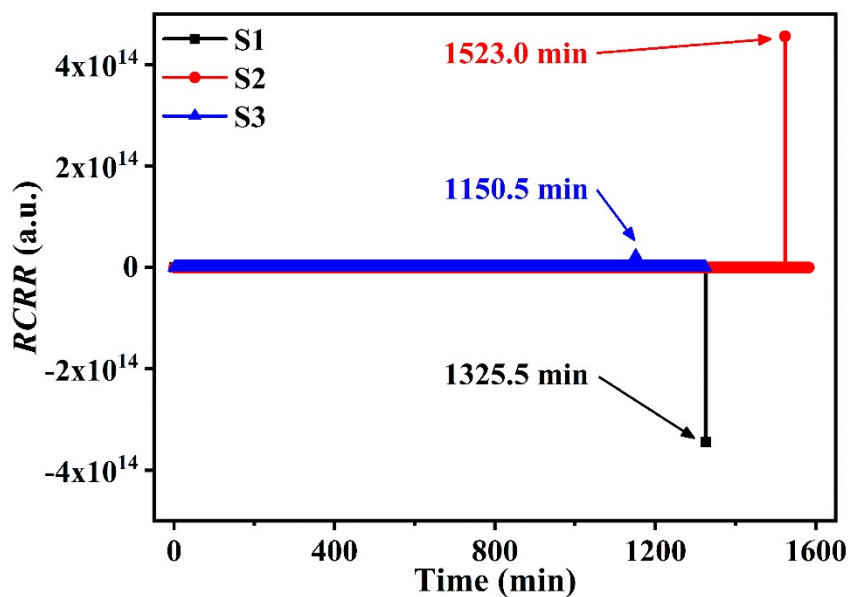


Figure S2 Peaks of $RCRR$ for the test batteries.

Table S4 Parameters for the verification of the resistance system.

Test batteries	$t_{R_{max}}$ (min)	t_3 (min)	$\Delta t_3 (t_3 - t_{R_{max}})$ (min)
S1	1325.5	1326.0	0.5
S2	1523.0	1523.9	0.9
S3	1150.5	1151.1	0.6

Table S5 Comparison of key time points between experimental measured values and thermodynamics calculated values.

Test batteries	t_{R_3} (min)			t_{R_4} (min)			$t_{R_{max}}$ (min)		
	Calculated value	Measured value	Deviation (%)	Calculated value	Measured value	Deviation (%)	Calculated value	Measured value	Deviation (%)
S1	540.5	548.7	1.52	1310.8	1311.5	0.05	1325.0	1325.5	0.04
S2	542.0	553.3	2.08	1502.4	1505.0	0.17	1523.0	1523.0	0.00
S3	550.8	575.0	4.39	1125.4	1123.0	-0.21	1150.6	1150.5	-0.01

2 Thermodynamics calculation

The thermodynamics calculation for Figure 4 is carried out based on Arrhenius formula (Equation S1) and Nernst equation (Equation S2) in order to further verify the technology proposed through the experiments mentioned above. In the following equations, R_0 is the gas constant, F is Faraday's constant, A , A_1 , A_2 are constants. E_a is activation energy, T is temperature, ΔG is Gibbs free energy, n is mole number of electrons involved in the reaction, E is potential, which equals to the open circle voltage (OCV), R is the resistance measured. And k is rate coefficient that positively correlated with the rate of chemical reactions. As the resistance is negatively correlated with the rate of reactions, the relationship between k and R is described as Equation S3. Based on Equation S3, Equation S1 is transformed into Equation S4. After differentiation, the variation of R with T (dR/dT) is calculated with Equation S5 and displayed in Figure 4.

As for relationships between the calculated E with t , and T with t , are given with the data measured in the ARC experiments.

$$k = Ae^{-E_a/(R_0T)} \quad (S1)$$

$$E_a = \Delta G = -nFE \quad (S2)$$

$$k \propto \frac{1}{R} \quad (S3)$$

$$R = A_1 \frac{1}{\frac{nFE}{R_0T}} \quad (S4)$$

$$\frac{dR}{dT} = \frac{A_2 \cdot E}{T^2} \cdot e^{\frac{-nF}{R_0} \cdot \frac{E}{T}} \quad (S5)$$

3 Defined symbols and abbreviations

Table S6 List of defined symbols and abbreviations

Defined symbols or abbreviations	Explanation
LIBs	lithium-ion batteries
TR	thermal runaway
T_1	the beginning temperature of self-exothermic process
T_2	the onset temperature of TR
T_3	the top temperature throughout the TR procedure
ARC	accelerating rate calorimeter
HWS	Heat-Wait-Search mode of the ARC experiment
AC	alternating current
CRR	change rate
R_1	abnormal resistance
R_2	reminding resistance
R_3	warning resistance
R_4	decision resistance
R_{max}	the maximum resistance
SOC	state of charge
ESI	electronic supplementary information
SER	self-exothermic rate
RMS	the alternating root mean square
U	voltage
I	current
R_n	the internal AC resistance
CRR	the change rate of resistance
$RCRR$	relative change rate of resistance