IEC TR 62660-4

Edition 1.0 2017-02

TECHNICAL REPORT

colour inside

**Secondary lithium-ion cells for the propulsion of electric road vehicles –
Part 4: Candidate alternative test methods for the internal short circuit test of IEC 62660-3**

IEC TR 62660-4:2017-02(en)

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Part 4: Candidate alternative test methods for the internal short circuit test of IEC 62660-3

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IEC TR 62660-4, which is a Technical Report, has been prepared by IEC technical committee 21: Secondary cells and batteries.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
21/891/DTR	21/899/RVC

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62660 series, published under the general title *Secondary lithium-ion cells for the propulsion of electric road vehicles*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

IEC 62660-3 provides the test procedures and acceptance criteria for safety performance of secondary lithium-ion cells and cell blocks used for propulsion of electric vehicles (EV) including battery electric vehicles (BEV) and hybrid electric vehicles (HEV). IEC 62660-3 specifies the internal short circuit test to simulate an internal short circuit of a cell caused by the contamination of conductive particle, based on IEC 62619. Because the test method based on IEC 62619 requires opening of the cell and care to be taken, the industry needs alternative test methods that could also be applied under certain conditions. This document provides candidates of alternative test procedures.

NOTE This test is to be conducted in a facility suitable to contain the potential for hazardous reactions up to and including an explosion and with staff trained to manage the risks.

SECONDARY LITHIUM-ION CELLS FOR THE PROPULSION OF ELECTRIC ROAD VEHICLES –

Part 4: Candidate alternative test methods for the internal short circuit test of IEC 62660-3

1 Scope

This Part of IEC 62660 provides the test data on the candidate alternative test methods for the internal short circuit test according to 6.4.4.2.2 of IEC 62660-3:2016. The internal short circuit test in this document is intended to simulate an internal short circuit of a cell caused by the contamination of conductive particle, and to verify the safety performance of the cell under such conditions.

This document is applicable to the secondary lithium-ion cells and cell blocks used for propulsion of electric vehicles (EV) including battery electric vehicles (BEV) and hybrid electric vehicles (HEV).

NOTE This document does not cover cylindrical cells.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62619:2017, *Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications*

IEC 62660-3:2016, *Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 3: Safety requirements*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62660-3 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp.

4 General provisions for alternative test

The internal short circuit test is specified in 6.4.4.2.1 of IEC 62660-3:2016. The other test methods to simulate the internal short circuit of cell caused by the contamination of conductive particle may be selected if the following criteria are satisfied, and agreed between the customer and the supplier:

a) The case deformation shall not affect the short circuit event of cell thermally or electrically. The energy shall not be dispersed by any short circuit other than the interelectrode short circuit.
b) One layer internal short circuit between positive and negative electrode shall be simulated (target).
c) Approximately the same short circuited area as that of 7.3.2 b) of IEC 62619:2017 shall be simulated.
d) The short circuited locations in the cell shall be the same as described in 6.4.4.2.1 of IEC 62660-3:2016.
e) The test shall be repeatable (see Table 1 of IEC 62619:2017).

The detailed test conditions and parameters of an alternative test shall be adjusted before the test according to the agreement between the customer and the cell manufacturer, so that the above criteria can be satisfied. The test result shall be evaluated by the disassembly of the cell, X-ray observation, etc.

If the test result shows more than one layer internal short circuit, or larger short circuited area, the test may be deemed as valid alternative test, provided that the acceptance criteria in 6.4.4.3 of IEC 62660-3:2016 are satisfied. The failure in an alternative test does not mean the failure in the test according to 6.4.4.2.1 of IEC 62660-3:2016, because the test condition of the alternative test may be more severe than the prescribed criteria.

NOTE In case the internal short circuit cannot be simulated, the test is invalid and the test data are reported.

5 Alternative test method

5.1 Alternative test method description

5.1.1 General

This subclause describes the test method of the indentation induced internal short circuit test as a candidate of alternative test methods in Clause 4. Table 1 provides the recommended test specifications of the test.

Table 1 – Recommended test specifications

Item	Recommendation
Test temperature (temperature of the test bench and cell)	25 °C ± 5 °C
State of charge (SOC) of the cell	Maximum SOC specified by the cell manufacturer
Press speed	0,1 mm/s or less
Press speed accuracy	± 0,01 mm/s
Position stability after pressurizing	± 0,02 mm
Maximum pressurizing capability	1 000 N or more
Pressure measuring method	Directly measured with a load cell
Pressure measuring period	5 ms or less
Temperature measuring period	1 s or less
Voltage measuring period	5 ms or less
Time to stop the indenter after voltage drop is detected	100 ms or less

5.1.2 Test preparation and test set-up

5.1.2.1 Cell preparation

For flat or pouch cell, no preparation is needed.

For prismatic cell with hard casing, casing could be thinned or removed by an appropriate method recommended by the cell manufacturer. Thinning or removal of casing should be conducted before the charging of cell and SOC adjustment. This operation should be conducted taking all the safety measures needed.

5.1.2.2 Test setup

The cell should be held in a manner not to move during the test. The cell should be electrically isolated from test bench.

A flat or pouch cell requires a fixation device. Figure 1 and Figure 2 show examples of the fixation device.

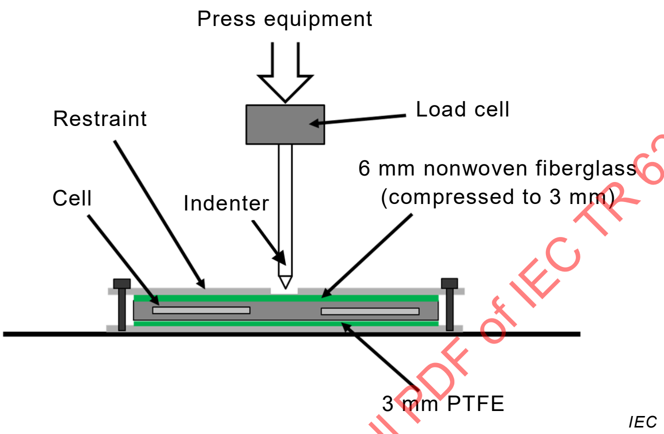

Figure 1 – Example of test setup 1

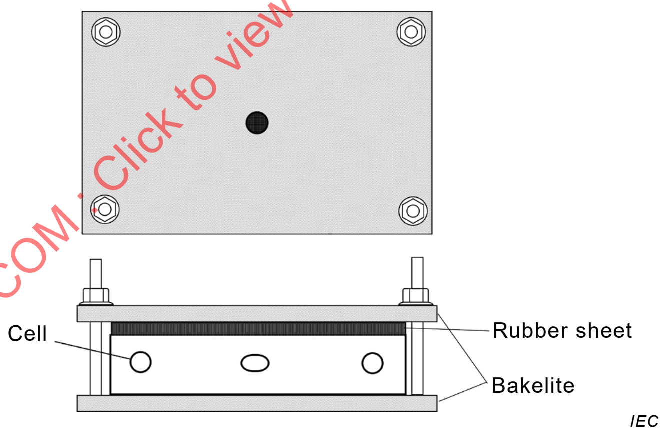

Figure 2 – Example of test setup 2

5.1.2.3 Indenter device

5.1.2.3.1 General

Two types of indenter device, as defined in 5.1.2.3.2 and 5.1.2.3.3 are proposed in this alternative test method.

5.1.2.3.2 Type 1: 3 mm ceramic nail

Type 1 indenter is a ceramic nail having a diameter of 3 mm ± 0,2 mm. The angle of the nail tip should be 45° ± 3°. Figure 1 shows an example of the ceramic nail's orientation to the cell electrode layers during the press.

5.1.2.3.3 Type 2: 1 mm ceramic nail with Ni tip

Type 2 indenter is a ceramic nail having a diameter of 1 mm ± 0,1 mm with a nickel (Ni) tip of 0,35 mm in height. The angle of the Ni nail tip should be between 28° and 45°. See Figure 3 and Figure 4.

A ceramic nail with a Ni tip is suitable for a prismatic cell with a hard casing and a flat or pouch cell.

The test using the Type 1 indenter is not applicable to the cells of which the casing is used as a part of the electrodes. If the casing is removed, this test may be applicable.

Dimensions in millimetres

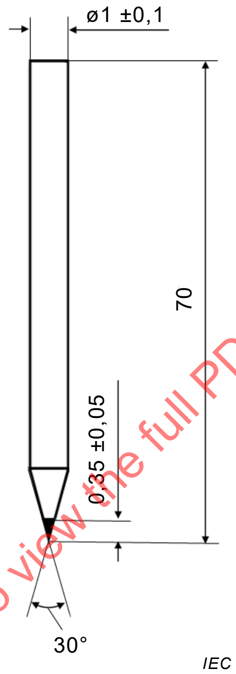

Figure 3 – Example of ceramic nail with Ni tip

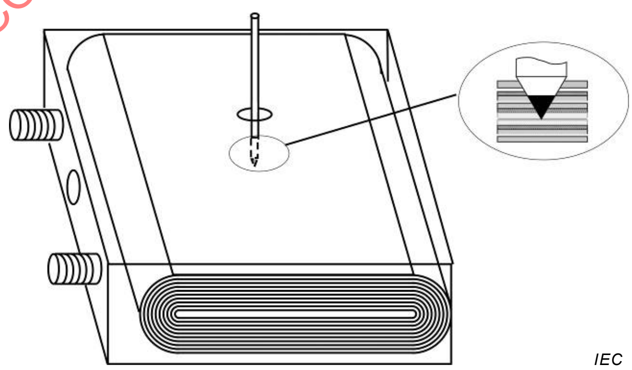

Figure 4 – Example of ceramic nail with Ni tip test

5.1.3 Test execution

The test should be conducted as follows:

a) Prepare the cell in accordance with 5.1.2.1.

b) Adjust the SOC of the cell in accordance with 5.3 of IEC 62660-3:2016, at the maximum SOC specified by the cell manufacturer.

c) Fix the cell to the test setup in accordance with 5.1.2.2. The indenter device should be selected according to 5.1.2.3, based on the agreement between the customer and the supplier. The indenter should be placed perpendicular to the electrode layers of the cell. The cell or the indenter should move along this perpendicular axis. The indentation location should be the same as IEC 62660-3:2016.

d) Press the indenter to the cell, or press the cell up to the indenter, with a constant velocity of less than 0,1 mm/s. Displacement of the indenter should be stopped when a voltage drop of at least 5 mV is detected. It is acceptable to use a voltage drop of less than 5 mV if a high accuracy voltage meter is used and the actual short location can be confirmed with an inspection of the internal short location after the test. The accuracy of the voltage meter should be reported. If the voltage drop of at least 5 mV is not detected until the indenter is depressed to half the thickness of a cell, the test should be stopped and considered as invalid, and the test should be conducted once again.

e) After the indentation stops, the indenter should remain in place until the end of the observation period. During the test, the cell voltage, the force of the press, the displacement of the press and the temperature of the cell should be recorded. The cell temperature should be measured on the surface of the cell, at a distance of less than 25 mm from the centre of the indentation. Sampling time for voltage and pressure recording should be 5 ms or less. Sampling time for other parameters recording should be 1 s or less.

5.1.4 Acceptance criteria

During the test and within 1 h of observation, the cell should exhibit no evidence of fire or explosion.

Annex A
(informative)

Test data

A.1 General

This annex provides information on the result of tests conducted according to Clause 5, and of relevant comparison tests.

The reproducibility of each test result is confirmed on several cell designs. Further test data need to be evaluated with cells that failed the test in 6.4.4.2.1 of IEC 62660-3:2016, etc.

A.2 Test data

A.2.1 Test results

Table A.1 shows the result of internal short circuit tests on several types of cells, using the indenters in 5.1.2.3, and other types of indenters for comparison. The forced internal short circuit (FISC) test in 6.4.4.2.1 of IEC 62660-3:2016 is also conducted as comparison test.

All cells in Table A.1 exhibited no evidence of fire or explosion, and met the acceptance criteria in 5.1.4.

In most of the tests except FISC test, the number of short circuited layers is larger than one layer, and also varies among the same cells.

Further data of each test are shown in A.2.2.

Table A.1 – Internal short circuit test results

Test No.	Indenter type or FISC	Cell	Chemistry or Capacity or Application (HEV/PHEV/BEV)	Type of cell and case thickness	Press speed mm/s	Target voltage drop for indenter stop mV	Test result: Voltage drop at indenter stop mV	Temp. rise °C	Number of short circuited layers	Pass-Fail	Optional info.	Fig. No.
1-1	FISC[d]	A	HC[a]/MNC[b], 5 Ah, HEV	prismatic	0,1	5	5	< 1	+[e]:2, −[f]:2	Pass		A.1
1-2					0,1	5	3	4	+:1, −:2	Pass		A.2
1-3					0,1	5	12	< 1	+:1, −:2	Pass		A.3
2-1	Type 2				0,1	5	7	23	+:4, −:4	Pass		A.4
2-2	Type 2	B	SC[c]/MNC, 5 Ah, HEV	prismatic	0,1	5	6	35	+:5, −:5	Pass		A.5
2-3					0,1	2	2	2	+:3, −:3	Pass		A.6
3-1	ø1 all ceramic nail	A	HC/MNC, 5 Ah, HEV	prismatic	1,0	25	20	20	+:7, −:6	Pass		A.7
3-2	Type 2				1,0	25	30	19	+:8, −:8	Pass		A.8
4	ø3 ceramic nail + Ni tip				0,1	2	2,4	0,9	+:2, −:3	Pass		A.10
5-1					0,1	5	13,4	7,5	+:3, −:4	Pass		A.11
5-2					0,1	20	21,4	21,4	+:8, −:8	Pass		A.12

Test No.	Indenter type or FISC	Cell	Chemistry or Capacity or Application (HEV/PHEV/BEV)	Type of cell and case thickness	Press speed	Target voltage drop for indenter stop	Test result					
							Voltage drop at indenter stop	Temp. rise	Number of short circuited layers	Pass-Fail	Optional info.	Fig. No.
					mm/s	mV	mV	°C				
6-1	Type 2	C	BEV	pouch	0,01	2	2	49	+:4, −:4	Pass		A.13
6-2							3	0,3	+:2, −:2	Pass		
6-3							12	0,1	+:1, −:2	Pass		
6-4							6	47	+:1, −:1	Pass		
6-5							3	52	+:3, −:3	Pass		
7-1	Type 2	D	HEV	pouch	0,01	2	10		+:3, −:3	Pass		A.14
7-2							4		+:3, −:4	Pass		
7-3							6	34	+:3, −:4	Pass		
7-4							10	43	+:3, −:4	Pass		
7-5							6	31	+:2, −:3	Pass		
8-1	ø3 all ceramic nail + 20° angle	C	BEV	pouch	0,01	2	1	47	+:5, −:5	Pass		A.15
8-2							1	53	+:5, −:6	Pass		
8-3							1	41	+:4, −:4	Pass		
8-4	Type 1						2	32	+:4, −:5	Pass		
8-5	Type 1						1	31	+:3, −:3	Pass		

Test No.	Indenter type or FISC	Cell	Chemistry or Capacity or Application (HEV/PHEV/BEV)	Type of cell and case thickness	Press speed mm/s	Target voltage drop for indenter stop mV	Test result: Voltage drop at indenter stop mV	Temp. rise °C	Number of short circuited layers	Pass-Fail	Optional info.	Fig. No.
9-1	ø3 all ceramic nail + 20° angle	D	HEV	pouch	0,01	2	5	26	+:2, −:2	Pass		A.16
9-2							7	36	+:2, −:3	Pass		
9-3							6	31	+:2, −:3	Pass		
9-4	Type 1						5	30	+:2, −:3	Pass		
9-5	Type 1						9	71	+:3, −:3	Pass		
10-1	FISC	C	BEV	pouch	0,01	2	2	< 1	+:1, −:1	Pass		A.17
10-2	FISC	D	HEV	pouch	0,01	2	2	< 1	+:1, −:1	Pass		A.18
11-1	FISC	E	graphite/MNC 21,5Ah, PHEV[g]	prismatic 0,7 mm	0,01	2	3,1	-	+:0, −:1	Pass	no smoke	A.19
11-2	FISC	F	graphite/NCA[h] 5 Ah, HEV	prismatic 0,5 mm	0,01	2	1,9	-	+:0, −:1	Pass	no smoke	A.20
12-1	ø1 ceramic nail + Ni tip (45°, 1 mm)	E	graphite/MNC 21,5Ah, PHEV	prismatic 0,7 mm	0,01	2	7,4	-	+:2, −:2	Pass	no smoke	A.21
12-2	ø3 ceramic nail + Ni tip (45°, 1 mm)				0,01	2	8,2	-	+:2, −:2	Pass	no smoke	A.22
12-3	Type 2 (30°)				0,01	2	9,6	-	+:2, −:2	Pass	no smoke	A.23

Test No.	Indenter type or FISC	Cell	Chemistry or Capacity or Application (HEV/PHEV/BEV)	Type of cell and case thickness	Press speed	Target voltage drop for indenter stop	Test result					
							Voltage drop at indenter stop	Temp. rise	Number of short circuited layers	Pass-Fail	Optional info.	Fig. No.
					mm/s	mV	mV	°C				
12-4	ø3 ceramic nail + Ni tip (30°, 1 mm)	E	graphite/MNC 21,5Ah, PHEV	prismatic 0,7 mm	0,01	2	2,1	-	+:1, −:2	Pass	no smoke	A.24
12-5	ø3 ceramic nail + Ni tip (45°, 1 mm)				0,1	2	2 362	-		Pass	smoke	A.25
12-6					0,001	2	8,5	-	+:1, −:2	Pass	no smoke	A.26
12-7	ø3 ceramic nail + Ni tip (60°, 1 mm)				0,01	2	2 391	-		Pass	smoke	A.27
13	ø3 ceramic nail + Ni tip (30°, 1 mm)	F	graphite/NCA 5 Ah, HEV	prismatic 0,5 mm	0,01	2	52	-	+:1, −:2	Pass	no smoke	A.28
14-1	ø3 ceramic nail + Ni tip (45°, 1 mm)	G	graphite/MNC and LMO[i] 60 Ah, PHEV	prismatic 0,85 mm	0,01	2	1 364	-	+:0, −:0	Fail	fire	A.29
14-2				prismatic 0,3 mm	0,01	2	1 455	-	+:0, −:0	Fail	fire	A.30
14-3	Type 2 (30°)			prismatic 0,05 mm	0,01	2	9,0	-	+:0, −:0	Pass	no smoke	A.31
14-4				prismatic 0 mm	0,01	2	2,0	-	+:7, −:8	Pass	no smoke	A.32
14-5				prismatic 0,05 mm	0,1	2	2,0	-	+:4, −:4	Pass	no smoke	A.33

Test No.	Indenter type or FISC	Cell	Chemistry or Capacity or Application (HEV/PHEV/BEV)	Type of cell and case thickness	Press speed	Target voltage drop for indenter stop	Test result					
							Voltage drop at indenter stop	Temp. rise	Number of short circuited layers	Pass-Fail	Optional info.	Fig. No.
					mm/s	mV	mV	°C				
15-1	Type 1	H	graphite/MNC 37 Ah, PHEV	pouch	0,01	5	2,0	26,4	+:12, −:12	Pass	no smoke	A.34a
15-2					0,01	5	5,0	13,4	+:8, −:8	Pass	no smoke	A.34b
15-3					0,01	5	3,0	36,5	+:4, −:4	Pass	no smoke	A.34c
15-4					0,01	5	5,0	52,8	+:9, −:9	Pass	no smoke	A.34d
15-5					0,01	5	5,0	25,0	+:6, −:6	Pass	no smoke	A.34e
16-1	Type 2				0,01	5	4,0	27,7	+:9, −:9	Pass	no smoke	A.35a
16-2					0,01	5	5,0	36,3	+:5, −:5	Pass	no smoke	A.35b
16-3					0,01	5	2,0	24,8	+:4, −:4	Pass	no smoke	A.35c
16-4					0,01	5	4,0	23,8	+:7, −:7	Pass	no smoke	A.35d
16-5					0,01	5	3,0	26,6	+:6, −:6	Pass	no smoke	A.35e

[a] Hard carbon

[b] Lithium manganese nickel cobalt oxide

[c] Soft carbon

[d] Forced internal short circuit test (IEC 62660-3:2016, 6.4.4.2.1)

[e] Positive electrode

[f] Negative electrode

[g] Plug-in hybrid electric vehicle

[h] Nickel-cobalt-aluminium

[l] Lithium manganese acid

A.2.2 Data of each test

A.2.2.1 Tests on cell A and cell B

A.2.2.1.1 FISC test result on cell A

The tests 1-1, 1-2 and 1-3 in Table A.1 are conducted according to 6.4.4.2.1 of IEC 62660-3:2016, with three samples of cell A (HC/MNC, 5 Ah, for HEV application). The test data are shown in Figure A.1, Figure A.2, Figure A.3, and Table A.1. Figure "a" of each figure shows the voltage and temperature change of cell within 1 h, and "b" is the magnified figure showing the voltage change when the short circuit occurs.

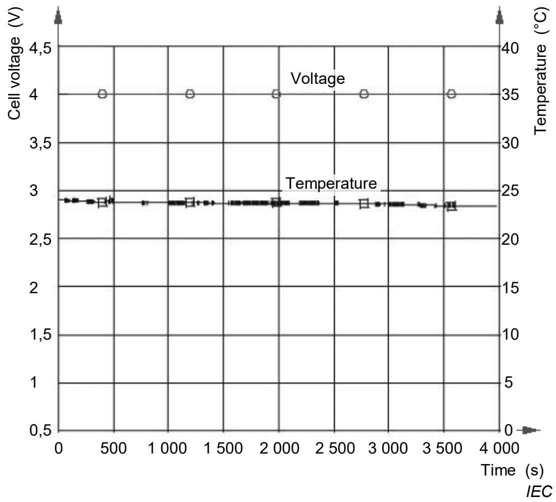

Figure A.1a

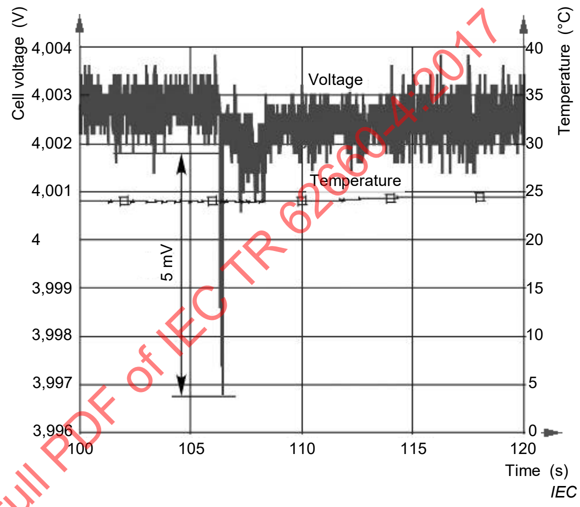

Figure A.1b

SOURCE: Japan Automobile Research Institute (JARI) acquired these data under the Project for the Promotion of New Energy Infrastructure Development in FY 2014, entrusted by Agency for Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure A.1 – Voltage and temperature of test 1-1

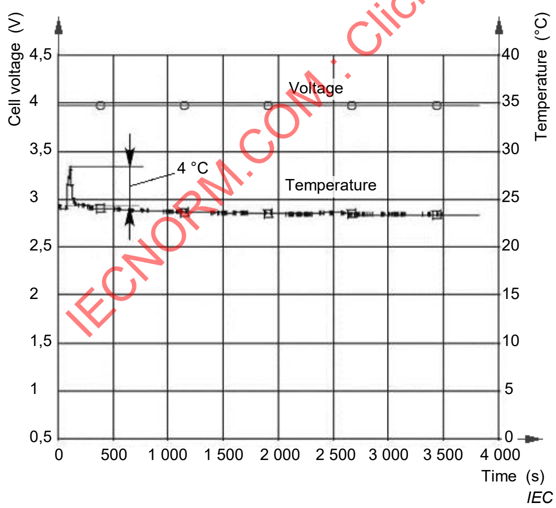

Figure A.2a

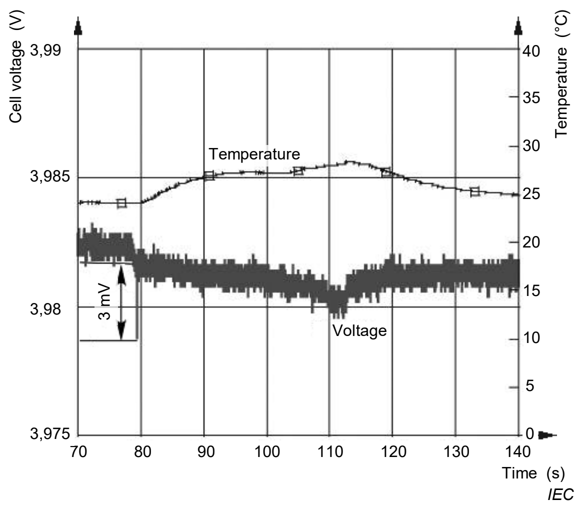

Figure A.2b

SOURCE: Japan Automobile Research Institute (JARI) acquired these data under the Project for the Promotion of New Energy Infrastructure Development in FY 2014, entrusted by Agency for Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure A.2 – Voltage and temperature of test 1-2

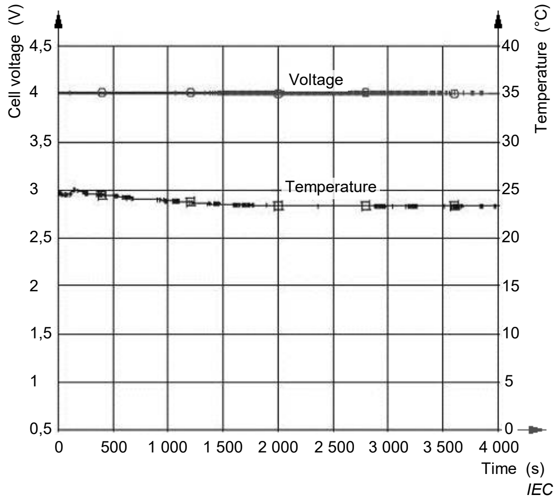

Figure A.3a

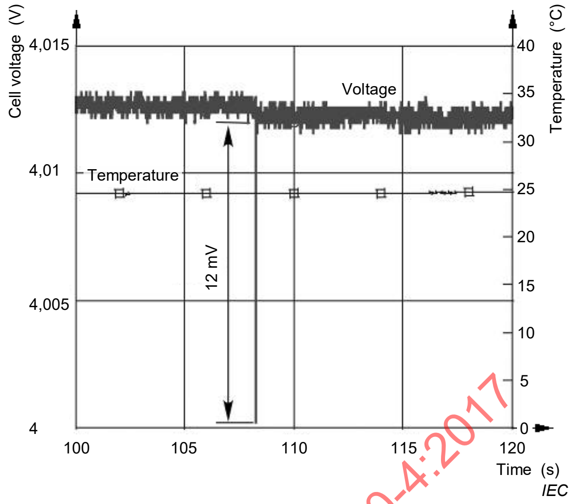

Figure A.3b

SOURCE: Japan Automobile Research Institute (JARI) acquired these data under the Project for the Promotion of New Energy Infrastructure Development in FY 2014, entrusted by Agency for Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure A.3 – Voltage and temperature of test 1-3

A.2.2.1.2 Tests with type 2 indenter

The tests 2-1, 2-2 and 2-3 in Table A.1 are conducted according to Clause 5 using type 2 indenter, on two types of cells: cell A and cell B (SC/MNC, 5 Ah, for HEV application). Test data are shown in Figure A.4, Figure A.5, Figure A.6 and Table A.1. The short circuit phenomena of test 2-1 and test 2-2 were more severe than FISC test in A.2.2.1.1. Test 2-3 was stopped at the voltage drop of 2 mV, and achieved almost the same result as the FISC test.

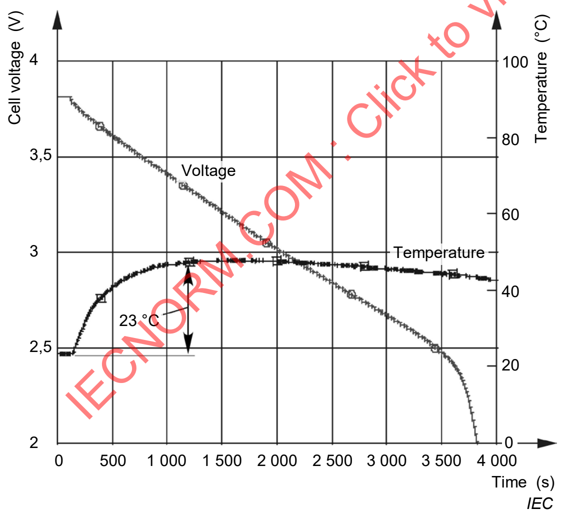

Figure A.4a

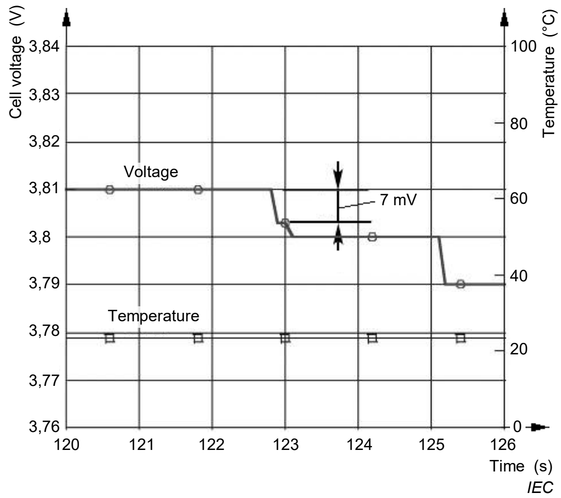

Figure A.4b

Figure A.4 – Voltage and temperature of test 2-1

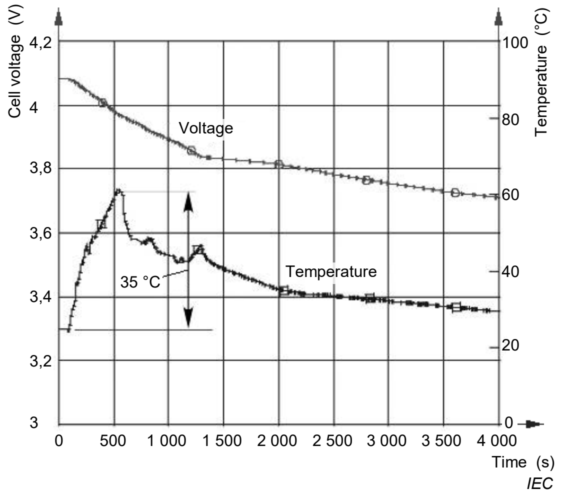

Figure A.5a

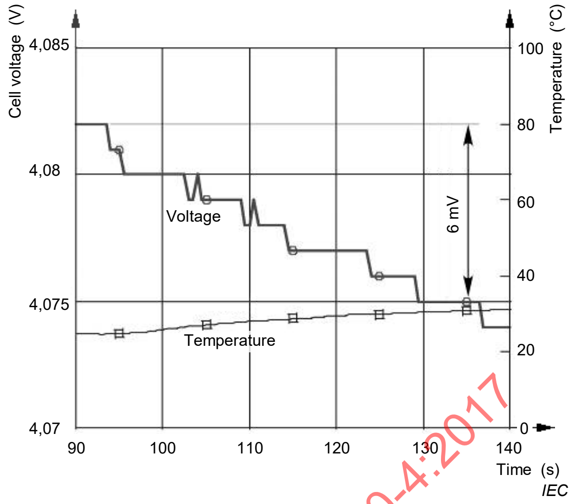

Figure A.5b

Figure A.5 – Voltage and temperature of test 2-2

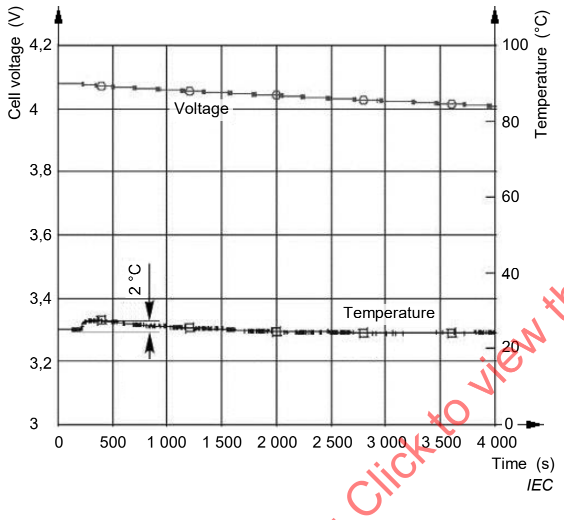

Figure A.6a

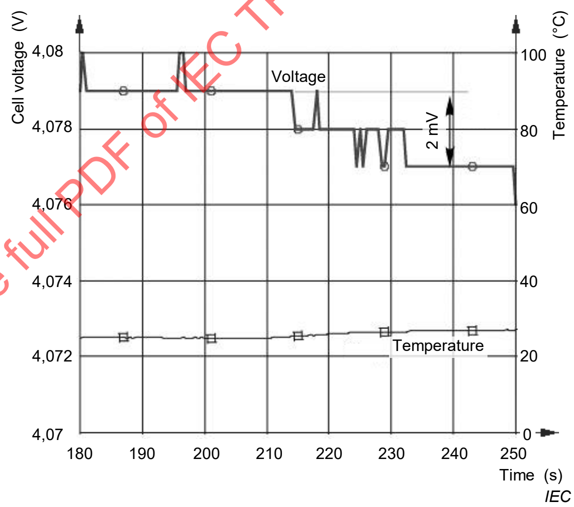

Figure A.6b

Figure A.6 – Voltage and temperature of test 2-3

A.2.2.1.3 Comparison tests of ceramic nails with or without Ni tip

The tests 3-1 and 3-2 in Table A.1 are conducted on cell A using type 2 indenter and the 1 mm-diameter ceramic nail without Ni tip. The test end condition was the voltage drop of 20 mV. The test data are shown in Figure A.7, Figure A.8 and Table A.1. The results of both tests are almost the same in the presence or absence of Ni tip.

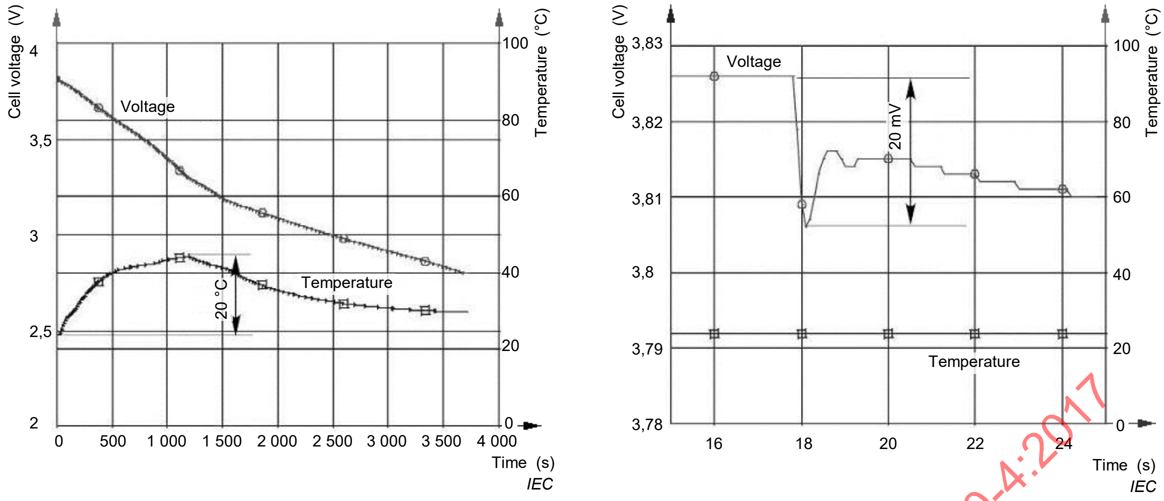

Figure A.7a

Figure A.7b

Figure A.7 – Voltage and temperature of test 3-1

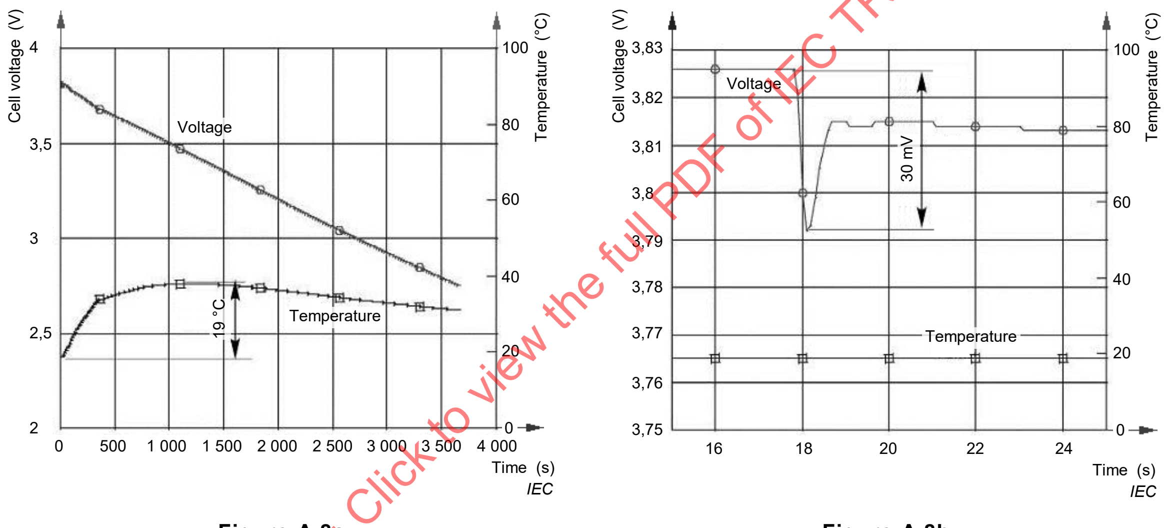

Figure A.8a

Figure A.8b

Figure A.8 – Voltage and temperature of test 3-2

A.2.2.1.4 Comparison of indenters with different size

The test 4 in Table A.1 is conducted on cell A using a 3 mm-diameter ceramic nail with Ni tip as shown in Figure A.9. The indenter was automatically stopped when the voltage drop of 2 mV or more was detected. The test data are shown in Figure A.10 and Table A.1.

Dimensions in millimetres

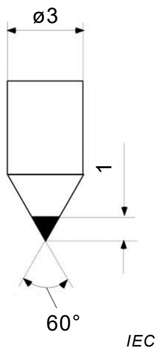

Figure A.9 – ø3 mm ceramic nail with Ni tip

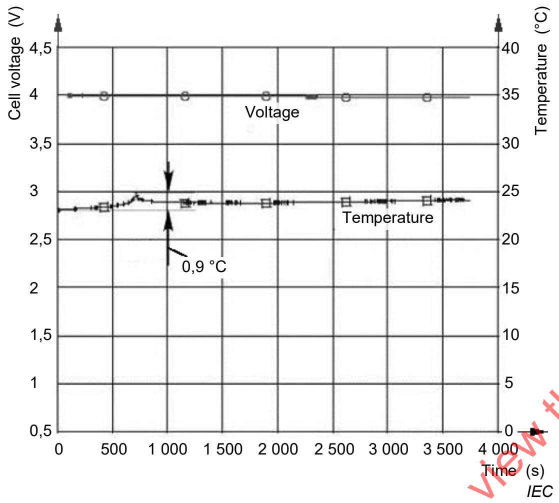

Figure A.10a

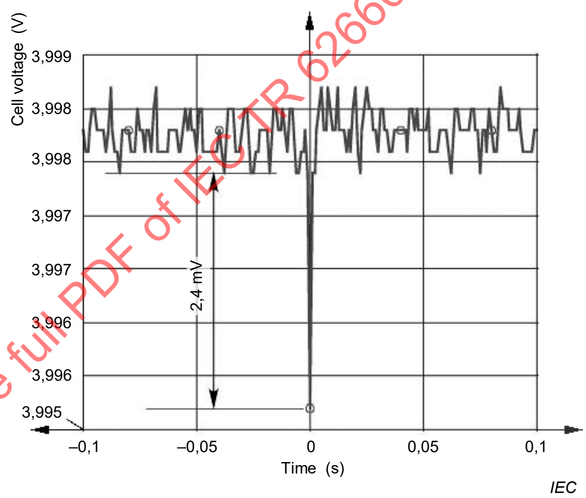

Figure A.10b

SOURCE: Japan Automobile Research Institute (JARI) acquired these data under the Project for the Promotion of New Energy Infrastructure Development in FY 2014, entrusted by Agency for Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure A.10 – Voltage and temperature of test 4

A.2.2.1.5 Comparison of test stop condition

The tests 5-1 and 5-2 in Table A.1 are conducted on cell A, using a 3 mm-diameter ceramic nail with Ni tip, and with different test stop conditions of voltage drop. According to 5.1.3, the indenter should be stopped when at least 5 mV voltage drop is detected. The test 5-1 in Figure A.11 was stopped when 5 mV voltage drop was detected, and the test 5-2 in Figure A.12 was stopped when 20 mV voltage drop was detected. The data of both tests show that the internal short circuit of fewer layers can be simulated when the test is stopped at smaller voltage drop.

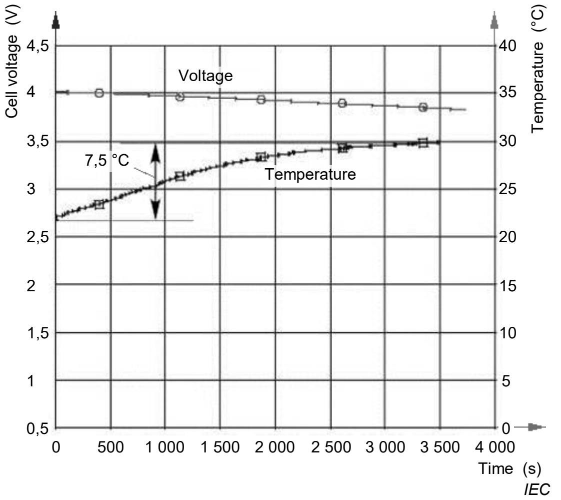

Figure A.11a

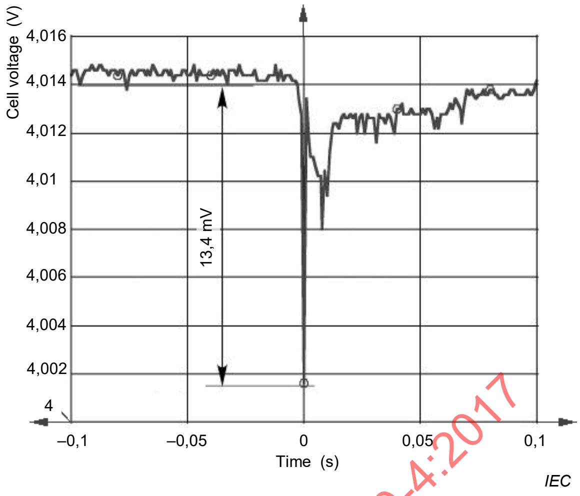

Figure A.11b

SOURCE: Japan Automobile Research Institute (JARI) acquired these data under the Project for the Promotion of New Energy Infrastructure Development in FY 2014, entrusted by Agency for Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure A.11 – Voltage and temperature of test 5-1

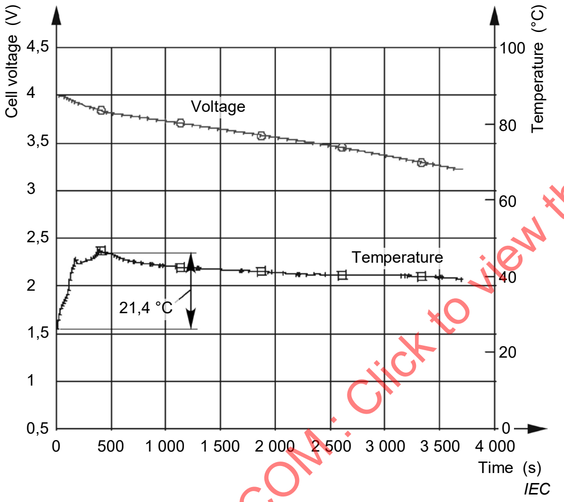

Figure A.12a

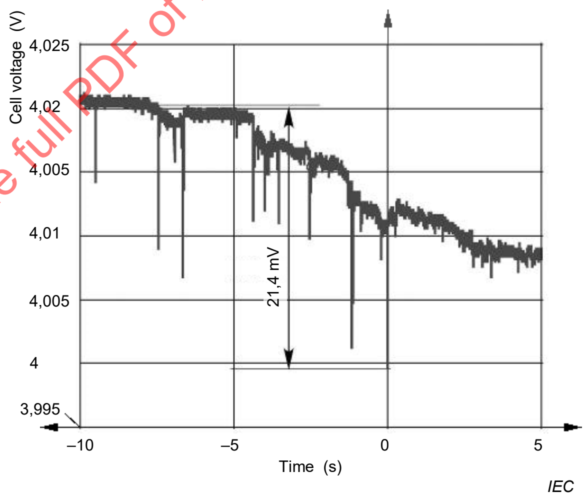

Figure A.12b

SOURCE: Japan Automobile Research Institute (JARI) acquired these data under the Project for the Promotion of New Energy Infrastructure Development in FY 2014, entrusted by Agency for Natural Resources and Energy / Mitsubishi Research Institute, Inc.

Figure A.12 – Voltage and temperature of test 5-2

A.2.2.2 Tests on cell C and cell D

A.2.2.2.1 Test with type 2 indenter

The tests from 6-1 to 6-5 in Table A.1 are conducted according to Clause 5 using type 2 indenter on Cell C (pouch cell for BEV application). The voltage data are shown in Figure A.13.

The tests from 7-1 to 7-5 in Table A.1 are conducted according to Clause 5 using type 2 indenter on Cell D (pouch cell for HEV application). The voltage data are shown in Figure A.14.

The results of comparison test according to 6.4.4.2.1 of IEC 62660-3:2016 (FISC) are also shown as tests 10-1 and 10-2 in Table A.1, and Figures A.13, A.14, A.18 and A.19. In comparison with the FISC test, the tests 6 and 7 resulted in higher value in voltage drop, temperature rise, and number of short circuited layers.

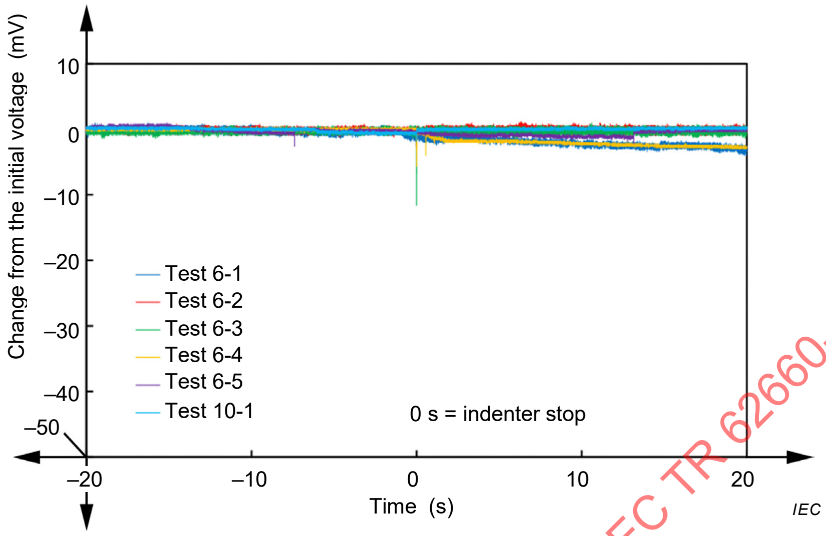

Figure A.13 – Voltage data of tests 6

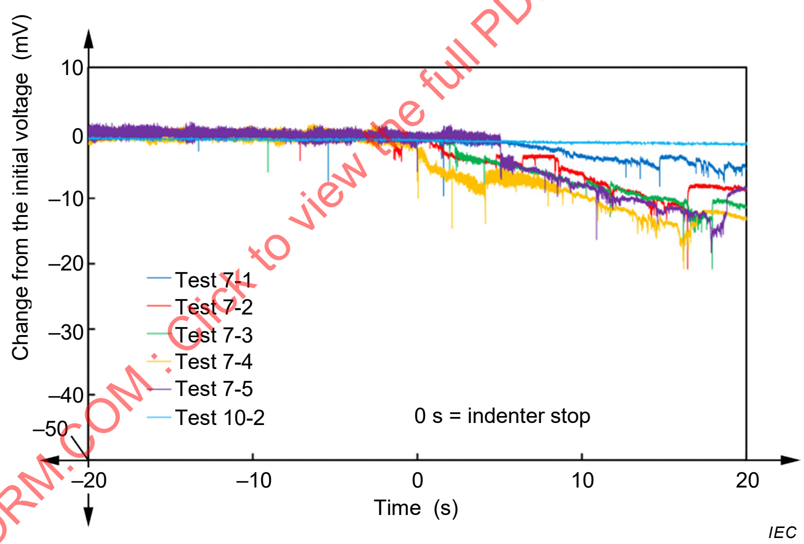

Figure A.14 – Voltage data of tests 7

A.2.2.2.2 Test with Type 1 indenter and comparison with different nail tip angle

The tests from 8-1 to 8-5 in Table A.1 are conducted on cell C, according to Clause 5 using type 1 indenter and a ceramic nail with 3 mm diameter and 20° angle. The voltage data are shown in Figure A.15.

The tests from 9-1 to 9-5 in Table A.1 are conducted on cell D, according to Clause 5 using type 1 indenter and a ceramic nail with 3 mm diameter and 20° angle. The voltage data are shown in Figure A.16.

The test data show that the difference in nail tip angle has little impact on the test results, at least for cell C and cell D.

In comparison with the FISC test, the tests 8 and 9 resulted in higher value in voltage drop, temperature rise, and number of short circuited layers.

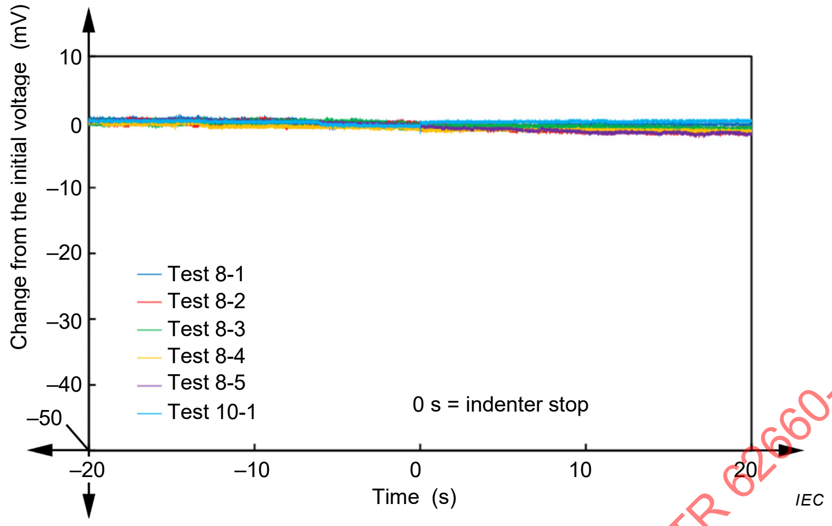

Figure A.15 – Voltage data of tests 8

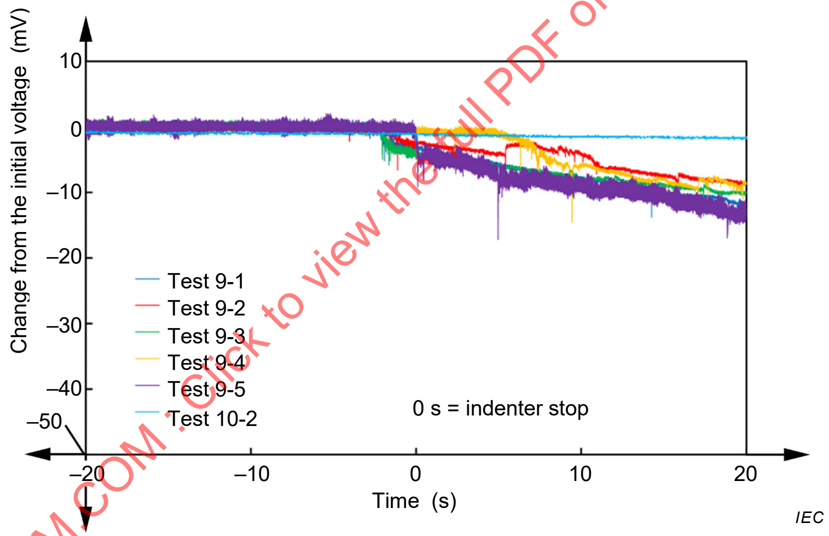

Figure A.16 – Voltage data of tests 9

A.2.2.2.3 FISC test results on cell C and cell D

The tests 10-1 and 10-2 in Table A.1 are conducted according to 6.4.4.2.1 of IEC 62660-3:2016, with one sample of cell C and cell D. The voltage data are shown in Figure A.17 and Figure A.18.

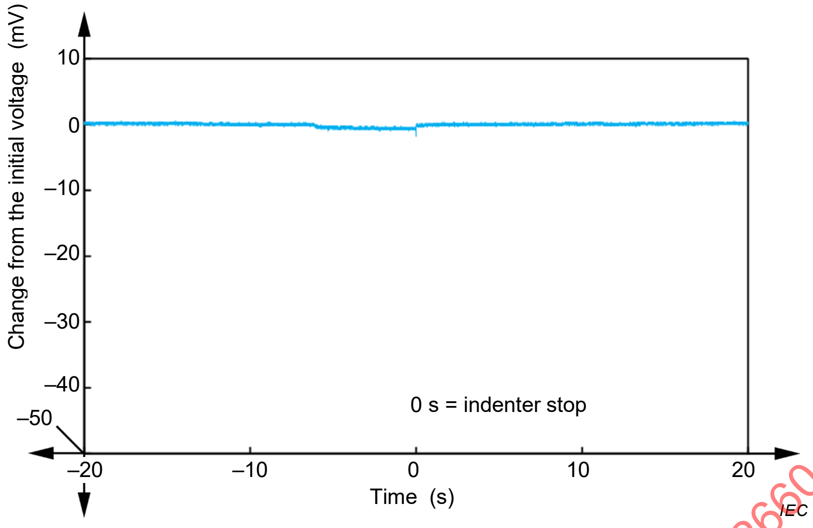

Figure A.17 – Voltage data of tests 10-1

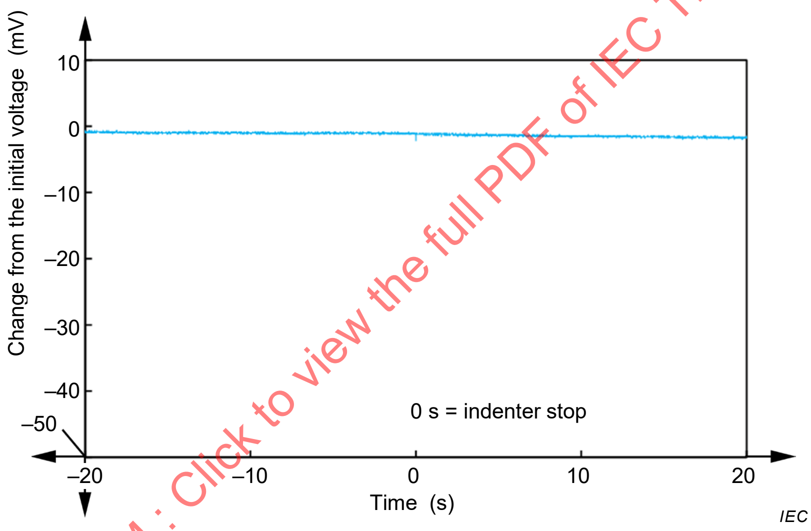

Figure A.18 – Voltage data of tests 10-2

A.2.2.3 Tests on cell E and cell F

A.2.2.3.1 FISC test result

The tests 11-1 and 11-2 in Table A.1 are conducted according to 6.4.4.2.1 of IEC 62660-3:2016, with cell E (graphite/MNC, 21,5 Ah, for PHEV application) and cell F (graphite/NCA, 5 Ah, for HEV application), respectively. The voltage data are shown in Figure A.19 and Figure A.20. Figure "a" of each figure shows the voltage change of cell within 500 s, and "b" is the magnified figure showing the voltage change when the short circuit occurs.

Both cells passed the acceptance criteria. Number of short circuited layers in both tests is no positive electrode and one negative electrode.

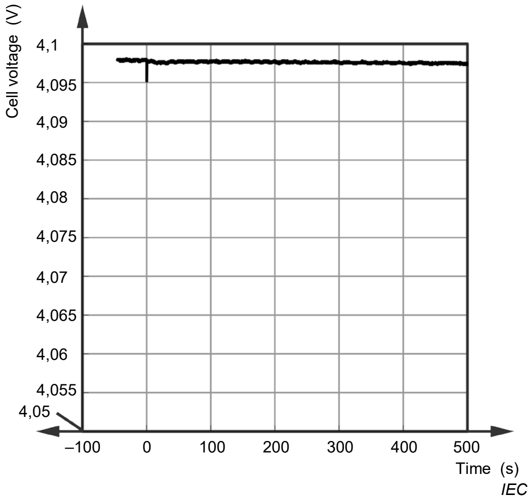

Figure A.19a

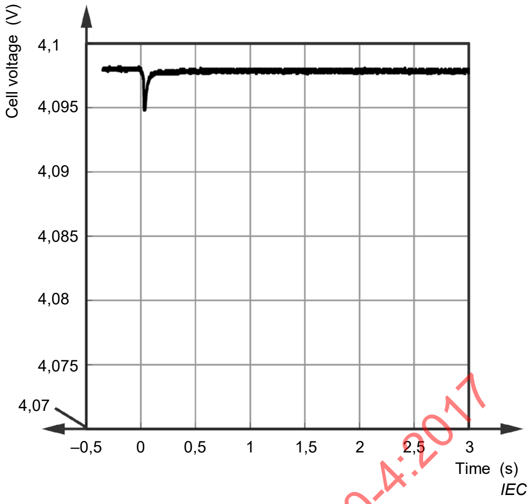

Figure A.19b

Figure A.19 – Voltage data of test 11-1

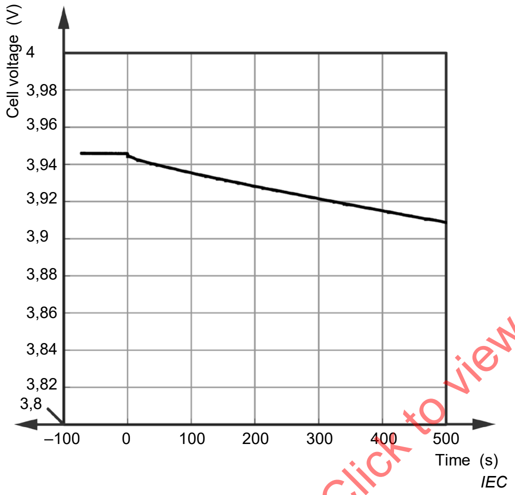

Figure A.20a

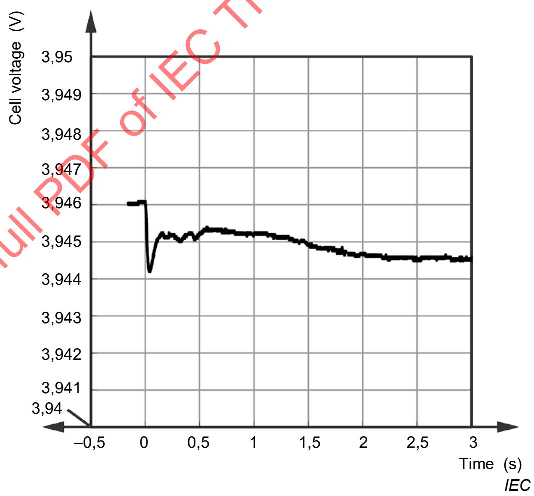

Figure A.20b

Figure A.20 – Voltage data of test 11-2

A.2.2.3.2 Tests with type 2 indenter and comparison of indenters with different size

The tests from 12-1 to 12-7 in Table A.1 are conducted on cell E according to Clause 5 using type 2 indenter and different sizes of ceramic nails with Ni tip. The voltage data are shown from Figure A.21 to Figure A.27. The indenters are ceramic nails having a diameter of 1 mm and 3 mm, with a Ni tip of 0,35 mm or 1 mm in height. The angle of the Ni tip is 30°, 45° or 60°. Press speed varies from 0,001 mm/s to 0,1mm/s.

The test 13 in Table A.1 is conducted on cell F, according to Clause 5 using a ceramic nail having a diameter of 3 mm with a Ni tip of 1 mm in height, and 30° angle. The voltage data are shown in Figure A.28.

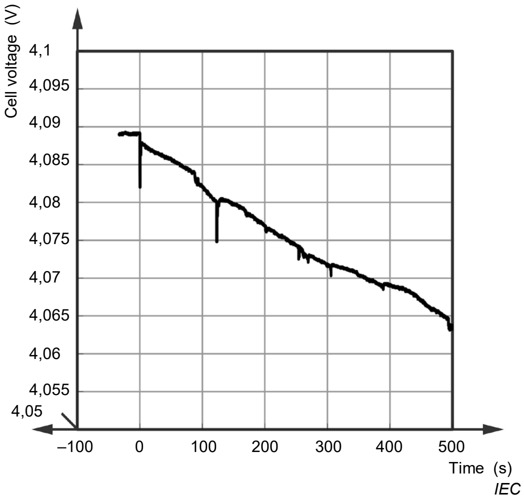

Figure A.21a

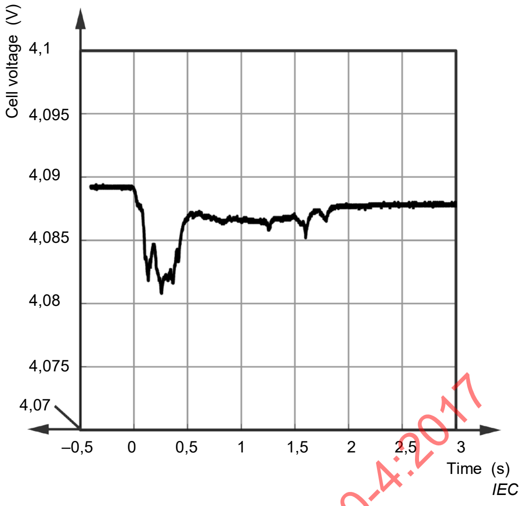

Figure A.21b

Figure A.21 – Voltage data of test 12-1

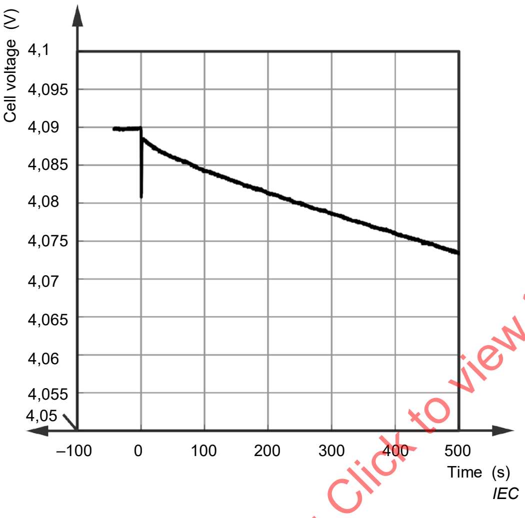

Figure A.22a

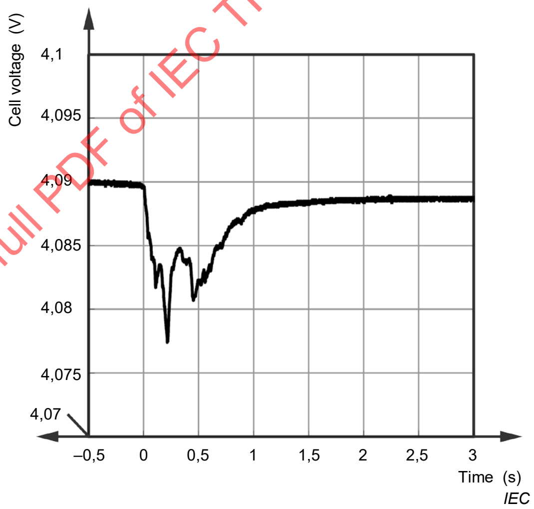

Figure A.22b

Figure A.22 – Voltage data of test 12-2

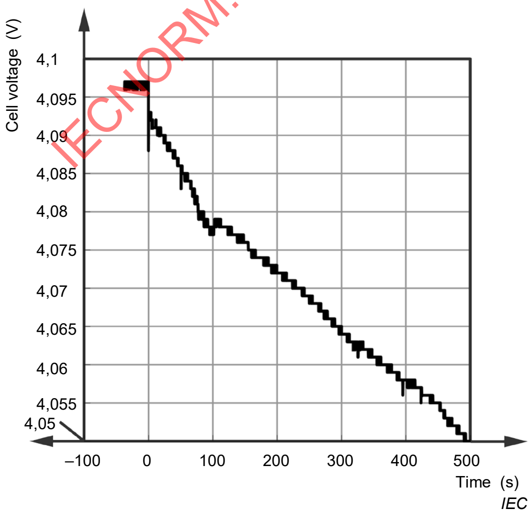

Figure A.23a

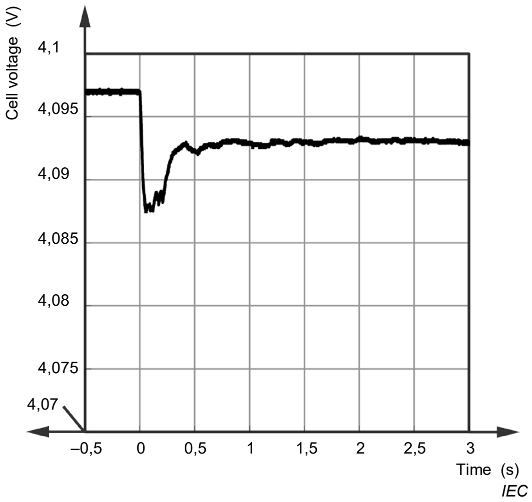

Figure A.23b

Figure A.23 – Voltage data of test 12-3