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Data Article

Experimental data of lithium-ion batteries under galvanostatic discharge tests at different rates and temperatures of operation

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ABSTRACT

In this paper, we report data from lithium battery cells from: Panasonic NCR-18650B (3350 mAh), LG Chem INR21700-M50 (4850 mAh) and A123 Systems ANR26650m1-B (2500 mAh). They own the same anode composition, graphite-based, and different cathode chemistry: lithium-nickel-cobalt aluminum-oxide (NCA), lithium-nickel-manganese-cobalt-oxide (NMC) and lithium-iron-phosphate (LFP), respectively. In this study, six cell samples were tested for each chemistry. The experiments consist in fully discharging the cells from 100% state-of-charge until the cell cutoff discharge voltage. The discharge is performed under controlled temperature conditions, namely 5 °C, 25 °C and 35 °C, and subjecting the battery cells to galvanostatic discharge rates ranging from C/20 to 5C, for NCA and NMC, and from C/20 to 20C, for LFP chemistry. The IncuMax IC-500R thermal chamber provides the reference temperature to the cell. The input current profiles are configured via the MITS Pro-software, and transmitted through the TCP/IP connection to the Arbin measurement system and the Arbin LBT21024. Voltage, current and cell surface temperature are measured on each cell and for each experiment to characterize the cells in terms of discharge capacity, discharge efficiency, thermal robustness, specific energy and specific power. A comprehensive analysis of the data is found in [1].

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Specifications Table

Subject	Electrical and Electronic Engineering
Specific subject area	Characterization of lithium-ion batteries
Type of data	Table
How data were acquired	Hardware: • Arbin Instruments LBT21024 and Arbin measurement system; • IncuMax IC-500R thermal chamber Arbin Instruments LBT21024; • T-type thermocouple sensor, Omega. Software: • MITS Pro-software and Data Watcher.
Data format	Raw data of battery voltage, current and surface temperature.
Parameters for data collection	Each battery is firstly fully charged through CC-CV protocol, then subjected to galvanostatic discharge at various controlled temperatures (5 °C, 25 °C and 35 °C) and discharging rates: C/20, 1C, 2C, 3C, 5C for NCA and NMC; C/20, 1C, 2C, 3C, 5C, 10C, 15C, 20C for LFP. According to manufacturer specification, the Arbin Instruments LBT21024 guarantees a control accuracy $< \pm$ 0.02%.
Description of data collection	The Arbin system supplies the user-defined current to the battery and measures voltage and surface temperature responses. Once the battery is fully charged (after the CC-CV protocol), a galvanostatic discharge profile is applied until the voltage cutoff limit is reached (2.5 V for NCA and NMC, 2 V for LFP chemistry). The type-T thermocouples are placed at the center location and measure the battery skin temperature. The ambient temperature is controlled by the user via the thermal chamber.
Data source location	Institution: Stanford Energy Control Laboratory, Energy Resources Engineering Department, Stanford University. City, State: Stanford, California. Country: United States of America. Latitude and longitude for collected samples/data: (37.426666918636386, −122.17397631867011).
Data accessibility	Electronic data set is provided as a .zip file including Microsoft Excel Worksheet files for each experiment (cell chemistry type and sample, discharge rate and reference temperature). The Dataset is fully available online https://data.mendeley.com/datasets/kxsbr4x3j2/2
Related research article	E. Catenaro, D. M. Rizzo and S. Onori, “Experimental analysis and analytical modeling of enhanced-Ragone plot,” Applied Energy, 2021, Accepted, https://dx.doi.org/10.1016/j.apenergy.2021.116473, https://authors.elsevier.com/tracking/article/details.do?aid=116473&jid=APEN&surname=onori

Value of the Data

- The data provide the characterization of three lithium-ions battery cells, NCR-18650B, INR21700-M50 and ANR26650m1-B, respectively, under different discharge rates and reference temperatures.
- The data are used to compare different lithium-ion battery chemistry based on metrics such as specific power, specific energy and discharge efficiency which are key to evaluate feasibility and adaptability of given chemistry to a particular application.
- Data provide granular information when plotted on the Ragone plot.

- Research dealing with lithium-ion batteries modeling can benefit from these data for experimental identification and validation.

1. Data Description

In this work, we investigate three different Lithium-ion battery cells whose cathode, anode and electrolyte chemical composition are listed in Table 1. For each battery chemistry, six samples are tested. In the following, we refer to the specific chemistry by the variable b, $b = \{\text{NCA, NMC, LFP}\}$, and the given sample by the index k, $k = \{k_1, k_2, \ldots, k_6\}$. Manufacturer specifications for the NCA, NMC and LFP are described in [2,3] and [4], respectively. A cell sample for each battery is showed in Fig. 1.

The experimental testing procedure is described in Table 2. Before each galvanostatic test, the battery cell is left to reach the reference temperature as set in the chamber for at least one hour (Step 1). In Step 2 and 3, the standard charging protocol CC-CV [5] is applied. During the CC phase the cell is subject to constant current, as specified by the manufacturer, until the voltage reaches the charging cutoff value. In the CV phase the cell is kept at constant voltage equal to the charging cutoff value. One-hour rest time is enforced in Step 4 to ensure the cell be fully charged and thermally stable. In Step 5, a given discharge current value, specified in terms of C-rate, x, is commanded until the voltage reaches the discharge cutoff value. In case the cell surface temperature hits the thermal limit of 75 °C the discharge phase is immediately stopped. Finally, one hour resting time is planned in Step 6 after the discharge phase.

We univocally refer to each experiment as $(b, k, \ x, T_{amb})$, where b refers to the LIB chemistry (namely, NMC, NCA or LFP), k to the cell sample, x to the applied C-rate and T_{amb} to the reference temperature. The possible allocations for $b, k, \ x$ and T_{amb} are summarized in Table 3.

The overall structure of the dataset is outlined in Fig. 2. In the parent folder, *galvanostatic_discharge_test*, one can find 1) a sub-folder named *table_datasheet*, which contains a single file, *manufacturer_specifications.xlsx*, including the manufacturer data for the three

Table 1
Cathode, anode, and electrolyte chemical composition for the NCA [2], NMC [3] and LFP [4] batteries.

	NCA	NMC	LFP
Cathode chemistry composition	LiNiCoAlO2	LiNiMnCoO2	LiFePO4
Anode chemistry composition	graphite	graphite	graphite
Electrolyte	LiPF6 in an organic solution	LiPF6 in an organic solution	LiPF6 in an organic solution

Fig. 1. Cell sample of NCA, NMC and LFP battery (from left to right) used in this work.

Table 2
Steps, actions and exit conditions implemented in the test procedure.

Step	Action	Exit condition
1	Resting: no current applied	Synchronization between cell surface temperature and setpoint temperature T_{amb}
2	CC phase: charging current applied	Voltage reaches the cell maximum voltage
3	CV: charging voltage applied	Current reaches the cutoff current, for NCA and NMC chemistry; 1 h for LFP chemistry.
4	Resting: no current applied	1h
5	Galvanostatic discharge: Discharge current applied according to the C-rate	Voltage hits the cutoff value
6	Resting (up to 1 h): no current applied	Synchronization between cell surface temperature and reference temperature T_{amb}

Table 3
Allocations for cell samples, k, C-rates, x, and reference temperature, T_{amb}, for each LIB chemistry, b.

b	k	x	T_{amb}
NCA	$k_1, k_2, ..., k_6$	$C/20,\ 1C,\ 2C,\ 3C,\ 5C$	$5°C,\ 25°C,\ 35°C$
NMC	$k_1, k_2, ..., k_6$	$C/20,\ 1C,\ 2C,\ 3C,\ 5C$	$5°C,\ 25°C,\ 35°C$
LFP	$k_1, k_2, ..., k_6$	$C/20,\ 1C,\ 2C,\ 3C,\ 5C, 10C,\ 15C,\ 20C$	$5°C,\ 25°C,\ 35°C$

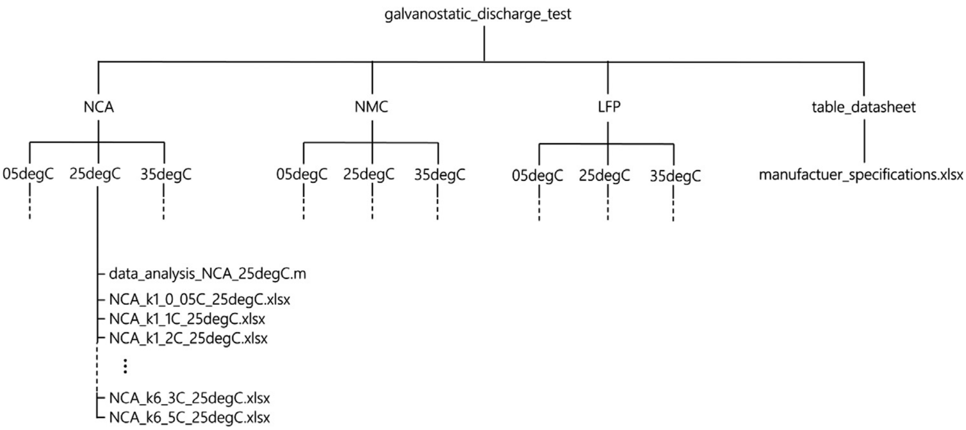

Fig. 2. Dataset files structure.

batteries under study, and 2) three sub-folders, one for each LIB (*NCA, NMC* and *LFP*), where the experimental data are saved. Inside each of these sub-folders, data are grouped in folders by the reference temperature of operation:

- T_amb_05degC
- T_amb_25degC
- T_amb_35degC

In each of these folders, the following files are found

- Multiple *b_k_x_Tamb.xlsx* file (Microsoft Excel Worksheet), where b, k, x and T_{amb} indicate the battery chemistry, cell sample, C-rate and reference temperature of testing;
- the *data_analysis_b_Tamb.m* file (Matlab2019b script), with b either NMC, NCA or LFP and *Tamb* the reference temperature.

Table 4
File structure providing a full description of the experimental test in terms of time information and measured signals (voltage, current and surface temperature). The table is structured in such a way to separate the rows of data related to the same "step_index" value.

Date_Time(s)	Test_Time(s)	Step_Time(s)	Step_Index	Voltage(V)	Current(A)	Surface_Temp(degC)
08–29–2019 15:29:32.927	1.0004	1	1	3.35597014	0	25.06369019
08–29–2019 15:29:33.927	2.0004	2	1	3.35598421	0	25.06300163
⋮	⋮	⋮	⋮	⋮	⋮	⋮
08–29–2019 16:29:32.976	3601.04	1.001	2	3.54099965	1.625183105	25.19890976
08–29–2019 16:29:33.976	3602.04	2.001	2	3.54407310	1.62515831	25.19890976
⋮	⋮	⋮	⋮	⋮	⋮	⋮
08–29–2019 17:56:59.967	8848.040	1	3	4.20009136	1.628015876	26.53018761
08–29–2019 17:57:00.968	8849.040	2.0007	3	4.20015716	1.625107646	26.54776207
⋮	⋮	⋮	⋮	⋮	⋮	⋮
08–29–2019 19:13:44.802	13452.875	0.9998	4	4.19420099	0	25.25404167
08–29–2019 19:13:45.803	13453.876	2.0007	4	4.19414138	0	25.25404167
⋮	⋮	⋮	⋮	⋮	⋮	⋮
08–29–2019 20:13:44.851	17052.923	1.001	5	4.16415691	−0.160017133	25.6257682
08–29–2019 20:13:45.851	17053.924	2.0012	5	4.16398668	−0.160015762	25.62577057
⋮	⋮	⋮	⋮	⋮	⋮	⋮
08–30–2019 17:05:49.125	92177.195	1.0002	6	2.53500270	0	25.45355034
08–30–2019 17:05:50.126	92178.195	2.0004	6	2.54768657	0	25.45355034
⋮	⋮	⋮	⋮	⋮	⋮	⋮

The structure of the experimental data file is shown in Table 4. The rows of the file refer to the time sample (sampling time is 1 s), and columns are (from left to right): *Data_Time(s)*, indicating the date (mm-dd-yyyy format) and time of the test; *Test_Time(s)*, describing the elapsed time from the beginning of the procedure; *Step_Time(s)*, providing the time passed from the beginning of each step; *Step_Index*, indicating the step number within the procedure; *Voltage(V), Current(A)* and *Surface_Temp(degC)*, indicating the voltage, current and surface temperature values at each sampling time.

Only data (voltage, current and temperature) related to the battery discharge galvanostatic test (Step 5 from the testing procedure described in Table 2) are extracted and analyzed in Matlab2019b Script named *data_analysis_b_Tamb.m*.

For instance, Matlab2019b script *data_analysis_NCA_25degC.m*, corresponding to the NCA cell under controlled temperature of 25°C, outputs the following figures:

- voltage versus time for the six NCA cell samples;
- voltage and surface temperature to discharge capacity for the six NCA cell samples (Fig. 3);
- measured discharge capacity, discharge efficiency,[1] specific energy and specific power averaged across the six cell samples as a function of the applied C-rate (Fig. 4).

2. Experimental Design, Materials and Methods

The equipment at Stanford Energy Control Laboratory used to collect the data and shown in Fig. 5 includes a (1) host computer used to program test profiles and real-time data monitoring through the MITS Pro-and Data Watcher software; (2) the Arbin measurement system; (3) the

[1] The discharge efficiency defined in this paper is related to the Peukert-like effect [7] where the discharge energy at a given C-rate is measured against the discharge energy at C/20.

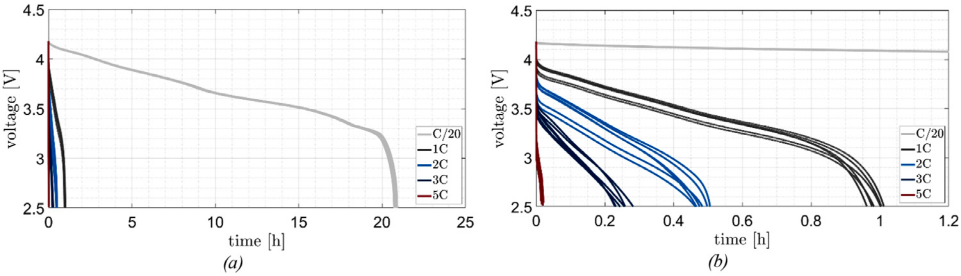

Fig. 3. (a) Voltage versus time of six NCA cells at ambient temperature $T_{amb} = 25$ °C and for different discharge rates: C/20, 1C, 2C, 3C and 5C. A zoom in of the voltage response is showed in (b), where the slowest discharging rate is partially omitted.

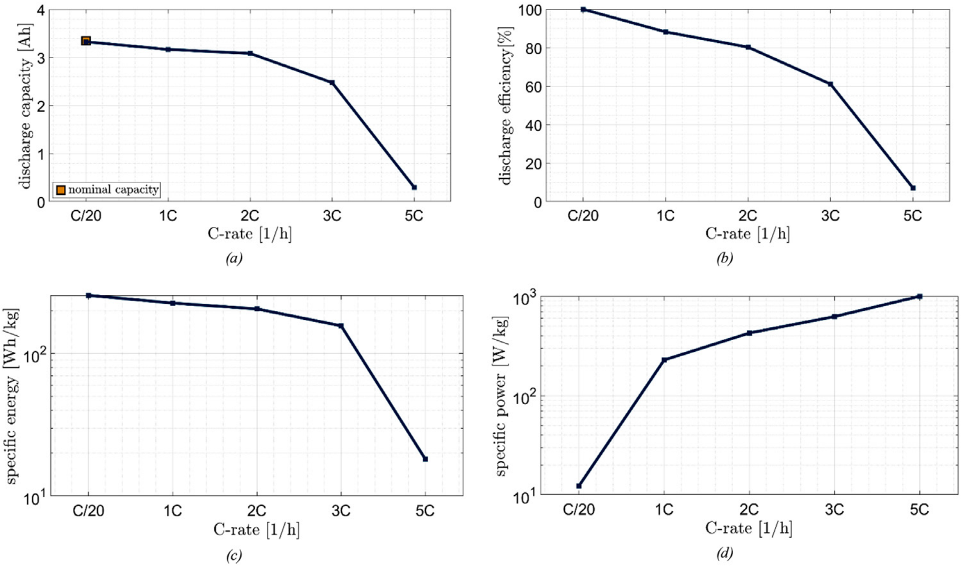

Fig. 4. (a) Discharge capacity, (b) discharge efficiency, (c) specific energy, and (d) specific power averaged across all NCA cell samples at 25 °C controlled temperature and subjected to various discharge rates (C/20, 1C, 2C, 3C and 5C).

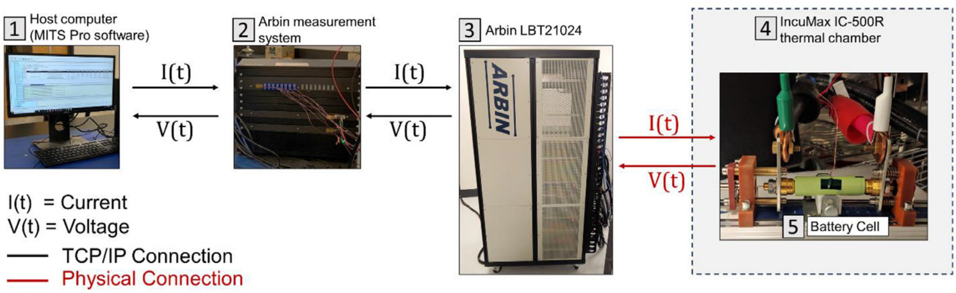

Fig. 5. Experimental setup and physical connections at the Stanford Energy Control Laboratory. Full description of the equipment is listed in [6].

Arbin LBT21024 with a programmable power supply; (4) the IncuMax IC-500R thermal chamber; (5) a battery cell positioned in a cylindrical cell holder. A type-T thermocouple sensor, manufactured by Omega, is positioned on the cell to measure the surface temperature. Data communication between different equipment components is also shown in Fig. 5 and described as follows. The input current profile is configured via the MITS Pro-software, which is transmitted through the TCP/IP connection to the Arbin measurement system and the Arbin LBT21024, before being sent- by physical connection - to the cell under test located in the IncuMax IC-500R thermal chamber. The electrical behavior of the cell is measured by the Arbin LBT21024 and Arbin measurement system in the form of voltage and surface temperature responses. The measured current, voltage and cell surface temperature signals are available to the Arbin measurement system and saved in the Microsoft Excel Worksheet file (*b_k_x_Tamb.xlsx*). The acquired data were not filtered.

The Matlab2019b script *data_analysis_b_Tamb.m*, performs the following tasks:

- it automatically loads the Microsoft Excel Worksheet data files related to the six cell samples into Matlab workspace;
- it extracts voltage, current and surface temperature during the galvanostatic discharge phase;
- it calculates the battery discharge capacity, discharge efficiency, specific energy and specific power, averaged across the six cell samples, for each discharging rate;
- it plots (1) the voltage versus time response; (2) the voltage and cell surface temperature as a function of the discharge capacity; (3) the discharge capacity, discharge efficiency, specific energy and specific power averaged across the six cell samples as a function of the applied C-rate under the controlled reference temperature.

Ethics Statement

Hereby, we Simona Onori and Edoardo Catenaro consciously assure that for the manuscript *Experimental data of lithium-ion batteries under galvanostatic discharge tests at different rates and temperatures of operation* the following is fulfilled:

1. This material is the authors' own original work, which has not been previously published elsewhere.
2. The paper is not currently being considered for publication elsewhere.
3. The paper reflects the authors' own research and analysis in a truthful and complete manner.
4. The results are appropriately placed in the context of prior and existing research.
5. All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
6. All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

Data Availability

Experimental data of three lithium-ion batteries under galvanostatic discharge tests at different C-rates and operating temperatures (Original data) (Mendeley Data).

CRediT Author Statement

Edoardo Catenaro: run experimental campaign, wrote the paper; **Simona Onori:** Conceived the experimental campaign, edited the paper.

Declaration of Competing Interest

The **authors** declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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