Measurement of the Effective Radial Thermal Conductivities of 18650 and 26650 Lithium-Ion Battery Cells

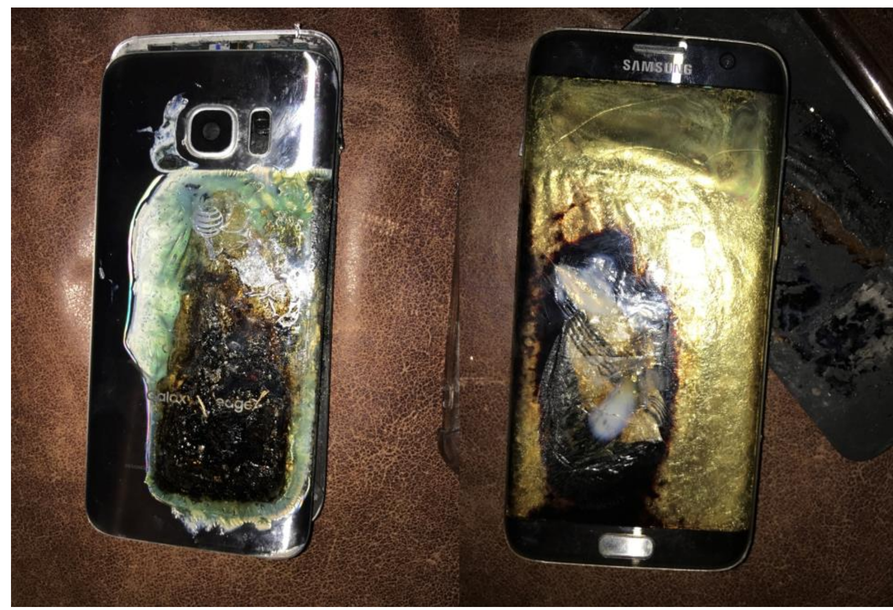
Harsh Bhundiya and Melany Hunt
Division of Engineering and Applied Science, Caltech
Bruce Drolen
Engineering Consultant

Presented By
Harsh Bhundiya

Thermal & Fluids Analysis Workshop
TFAWS 2018
August 20-24, 2018
NASA Johnson Space Center
Houston, TX

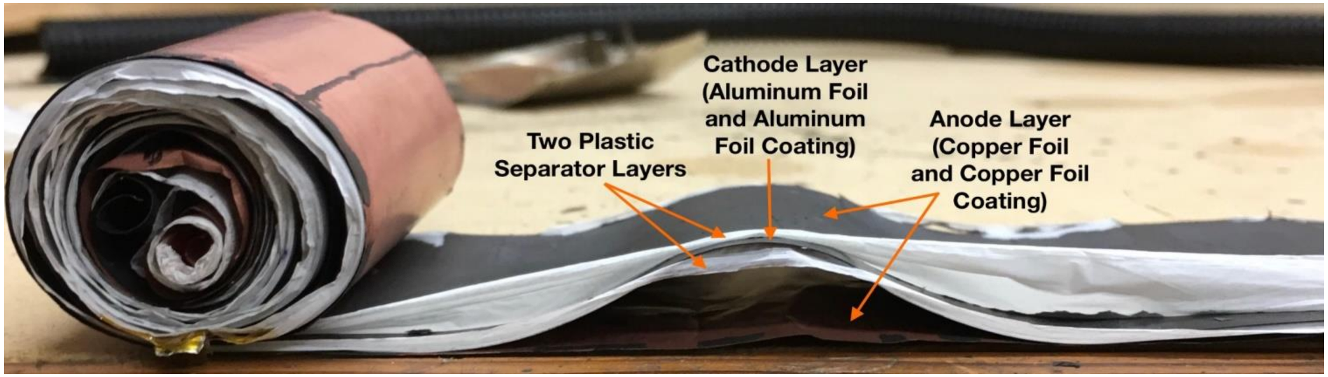
Introduction

- Recent harmful fires: Boeing 747-400F cargo plane, Samsung Galaxy S7 phones
- Cause: thermal runaway
- Important to understand thermal runaway and its propagation



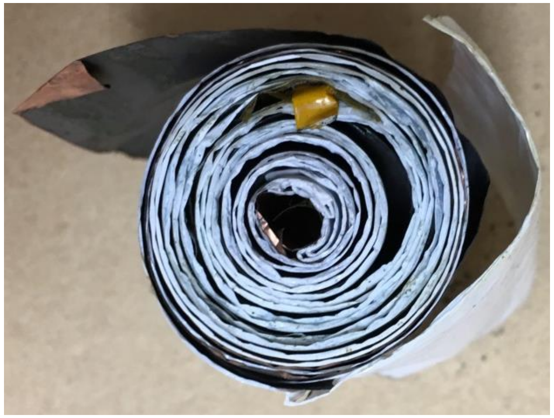
Disassembly

- Discharged cells using 13.1 ohm and 5.6 ohm resistors
- Disassembled ten cells: 8 INR18650-25R cells (made by Samsung) and 2 LFP26650P (K226P01) cells (made by K2 Energy Solutions, Inc.)
- Not all cells were manufactured in the same way


Cathode Layer
(Aluminum Foil
and Aluminum
Foil Coating)
Two Plastic
Separator Layers
Anode Layer
(Copper Foil
and Copper Foil
Coating)

~34 in.

~66 in.



Previous Modeling

- Key consideration in previous thermal models: Effective Radial Thermal Conductivity
- Dr. Tanaka (2014) and Coman et al. (2016) used values in the 1 – 4 W/m-K range (assuming perfect thermal contact in "sheet")
- Drake et al. (2014) used an analytical model and theoretically determined these values: 0.20 $\pm$ 0.01 W/m-K for 18650 cell, 0.15 $\pm$ 0.01 W/m-K for 22650 cell
- No other experimental values in literature

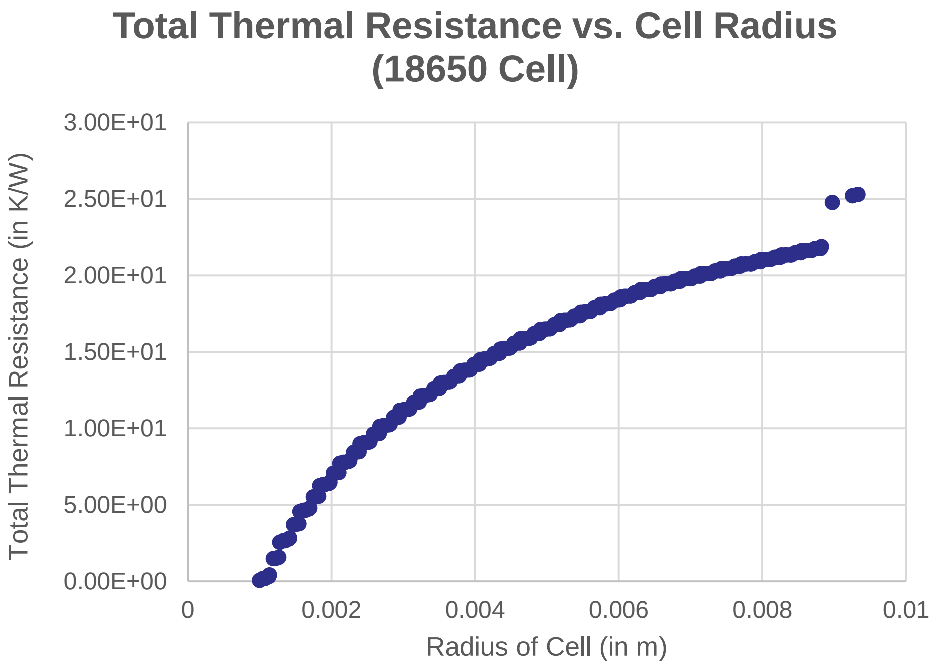
Modeling

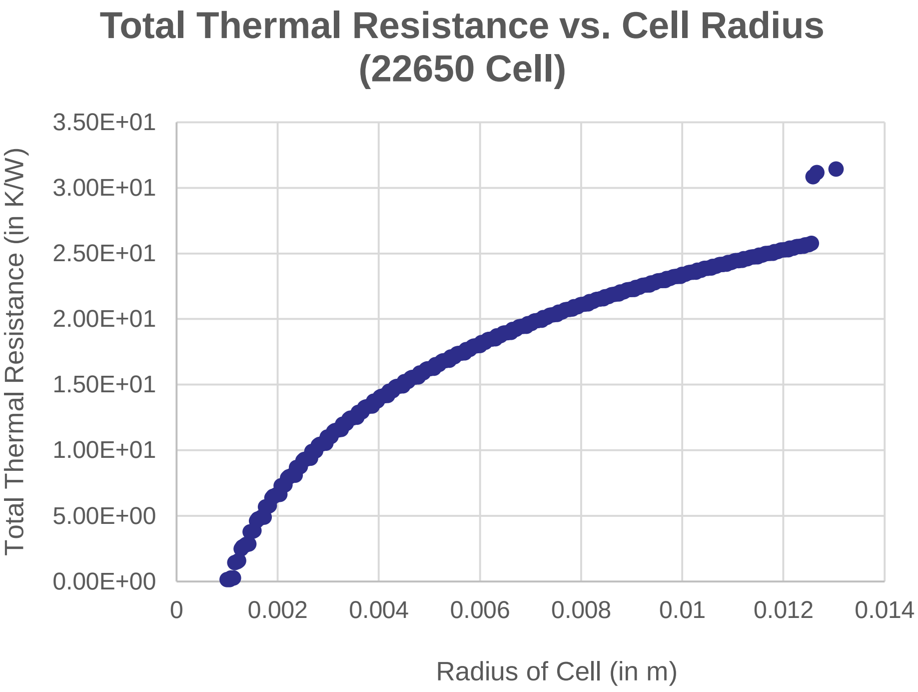
- Created thermal models of cells using equation for thermal resistance of a cylindrical layer from Fourier's Law:

$$R_{cyl} = \frac{\ln\left(\frac{R_2}{R_1}\right)}{2\pi k_1 L}$$

- 18650 cell: 28 "sheets"; 22650 cell: 38 "sheets"
- Included contact resistances between each "sheet" layer calculated by previous researchers
- Were able to predict thermal conductivity values:

  18650 cell: 0.27 W/m-K; 22650 cell: 0.22 W/m-K
- Disregarding contact resistances, model predicted 1.4 W/m-K for 18650 cell


Total Thermal Resistance vs. Cell Radius
(18650 Cell)
Total Thermal Resistance (in K/W)
3.00E+01
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
0
0.002
0.004
0.006
0.008
0.01
Radius of Cell (in m)

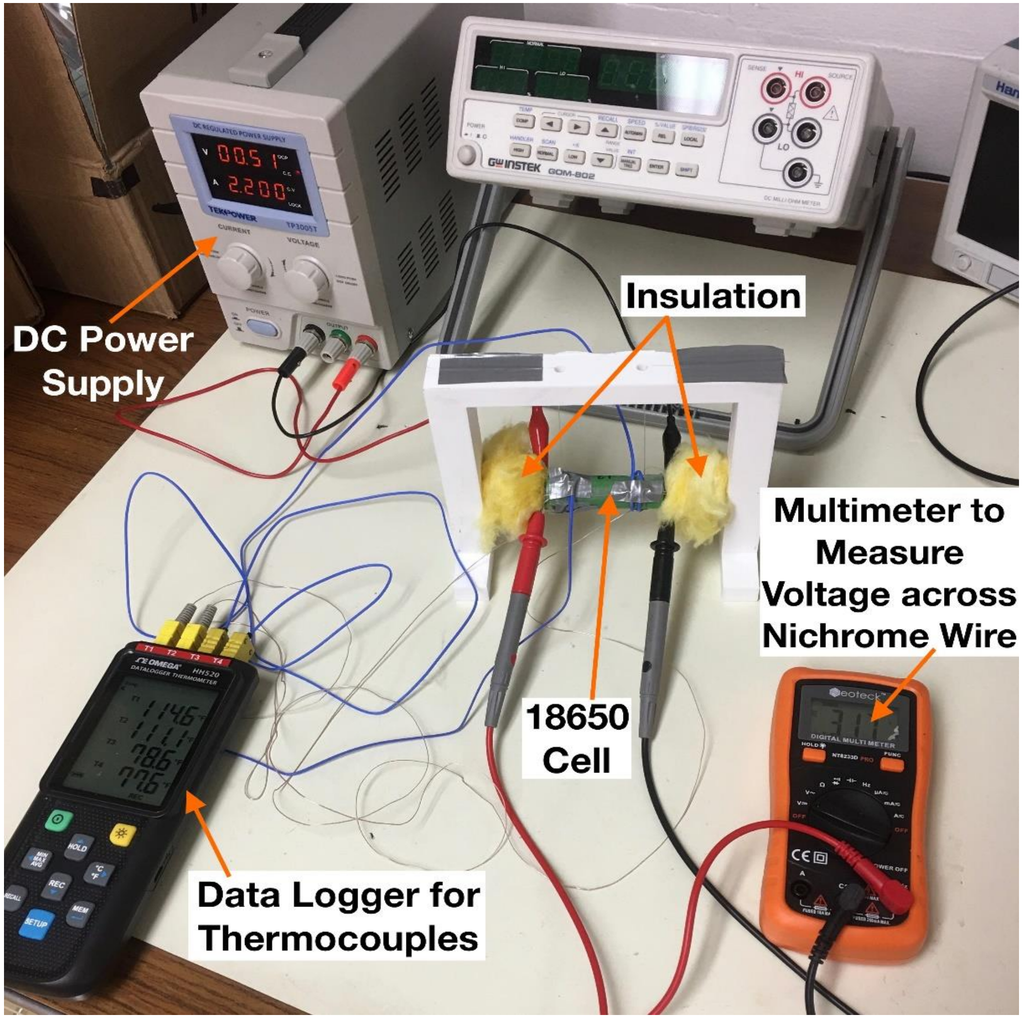

Total Thermal Resistance vs. Cell Radius
(22650 Cell)
Total Thermal Resistance (in K/W)
3.50E+01
3.00E+01
2.50E+01
2.00E+01
1.50E+01
1.00E+01
5.00E+00
0.00E+00
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Radius of Cell (in m)

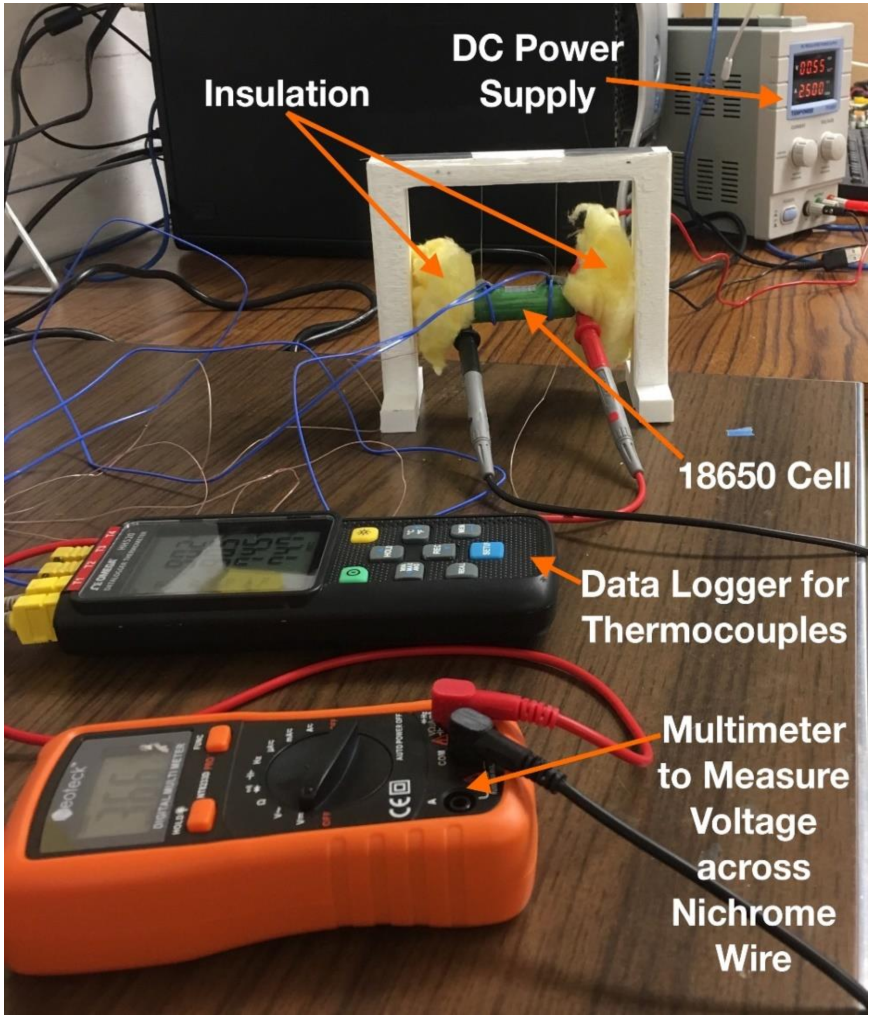
Experiment

- Inserted 20 AWG nichrome wire into center of the cell's winding and heated it using a DC power supply at varying currents
- Placed two Type K thermocouples (36 AWG) inside center of winding and two outside the case of the cell (20 AWG)
- Steady-state, one-dimensional heat conduction for cylindrical objects:

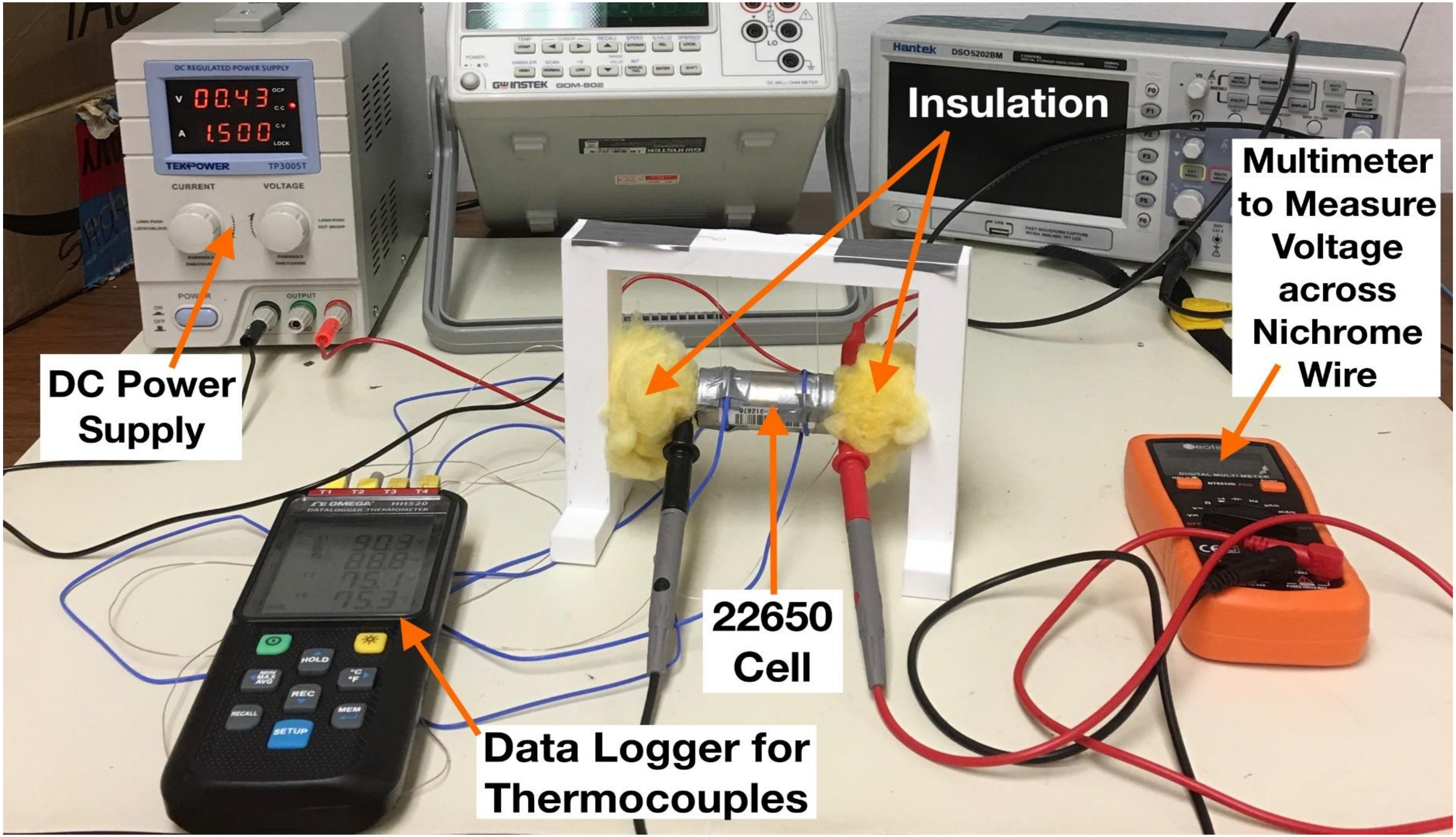
$$\dot{Q} = \frac{2\pi k_{eff} L\,(T_1 - T_2)}{\ln\left(\frac{R_2}{R_1}\right)}$$

Experimental Setup (18650 Cell)





Experimental Setup (22650 Cell)



18650 Cell Experiments

- Conducted only on cells with spindles (dark green plastic covers): Cells 12 and 13
- Nichrome wire and thermocouples inside spindle (used conductive paste)
- No spindle; nichrome wire and thermocouples inside gap at center of winding
  - Give more accurate measurements because according to model, thermal resistance between spindle and winding is quite high
- Combinations of spindle/no spindle, green plastic cover, and case of cell

18650 Cell Experimental Data

	Spindle?	Green Plastic?	Case?	Power Input (in W)	Average ΔT (in K)	Average Cell Temperature (in ℃)	Average k_{eff} of Cell (in W/m*K)
Cell 13 Experiment (18650)	Y	Y	Y	0.34	9.8	32.5	0.21 ± 0.04
	Y	Y	Y	0.66	16.6	39.3	0.24 ± 0.03
	Y	Y	Y	0.70	22.2	43.2	0.19 ± 0.02
	Y	Y	Y	0.93	28.4	49.4	0.20 ± 0.01
	N	Y	Y	0.35	4.0	30.0	0.52 ± 0.14
	N	Y	Y	0.59	7.6	35.8	0.47 ± 0.08
	N	Y	Y	0.91	13.7	42.0	0.40 ± 0.06
	N	Y	Y	1.4	19.3	50.6	0.42 ± 0.05
	Y	N	Y	0.60	10.2	38.7	0.35 ± 0.09
	Y	N	Y	0.93	11.3	44.7	0.50 ± 0.10
	Y	N	N	0.77	21.3	44.8	0.22 ± 0.02
	Y	N	N	0.85	17.4	41.1	0.29 ± 0.05
Cell 12 Experiment (18650)	Y	Y	Y	0.36	6.9	32.6	0.31 ± 0.05
	Y	Y	Y	0.67	12.6	38.0	0.32 ± 0.04
	Y	Y	Y	0.80	14.7	41.6	0.33 ± 0.03
	N	Y	Y	0.73	11.2	39.7	0.39 ± 0.09
	N	Y	Y	1.0	14.8	42.8	0.41 ± 0.05
	N	Y	Y	1.5	21.7	51.7	0.41 ± 0.03
	N	N	Y	0.59	12.6	39.1	0.28 ± 0.04
	N	N	Y	0.92	20.4	48.0	0.27 ± 0.03

Uncertainty calculations were computed using a root-sum-square method

22650 Cell Experiments

- Cells do not contain spindle, so nichrome wire and thermocouples were put inside gap at center of winding
- Cardboard cover slides off easily
- Only Cells 8 and 15

22650 Cell Experimental Data

	Spindle?	Cardboard Cover?	Case?	Power Input (in W)	Average ΔT (in K)	Average Cell Temperature (in ℃)	Average k_{eff} of Cell (in W/m*K)
Cell 8 Experiment (22650)	N	N	Y	0.35	13.2	34.0	0.19 ± 0.02
	N	N	Y	0.58	22.7	41.8	0.18 ± 0.01
	N	N	Y	0.86	27.3	46.9	0.22 ± 0.02
	N	N	Y	1.0	32.6	51.6	0.23 ± 0.01
Cell 15 Experiment (22650)	N	N	Y	0.35	10.5	33.1	0.23 ± 0.04
	N	N	Y	0.61	21.8	42.0	0.20 ± 0.02
	N	N	Y	0.79	19.2	42.8	0.29 ± 0.02
	N	N	Y	0.98	38.3	55.6	0.18 ± 0.02

Uncertainty calculations were computed using a root-sum-square method

Discussion

18650 Cells:

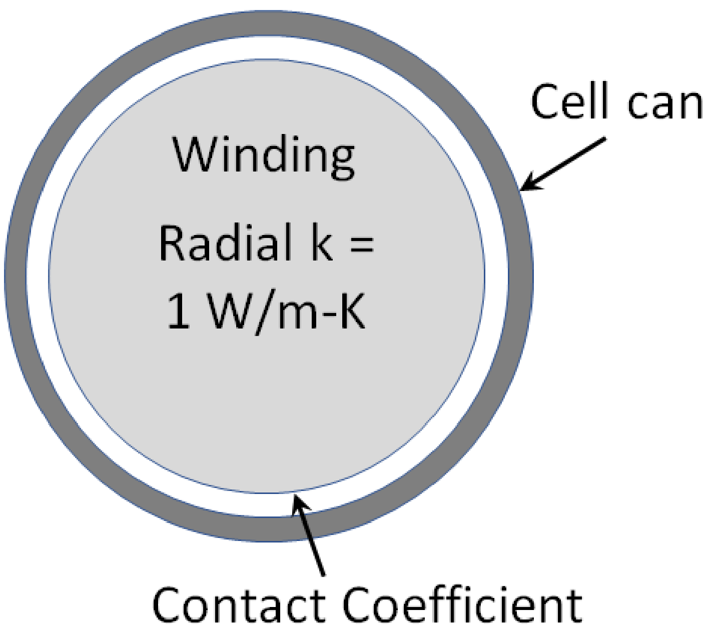
- Thermal resistance btw. spindle and winding is high, so experiments with NO spindles are preferred
- Last two trials from Battery 12 were ignored: 1) In event of thermal runaway propagation, heat would conduct through all parts of cell; 2) Bad thermocouple placement
- Averaging the values in red: 0.43 ± 0.07 W/m-K

22650 Cells:

- Experiments with highest power input give most accurate measurements (higher temp. difference)
- Averaging the values in red: 0.20 ± 0.04 W/m-K

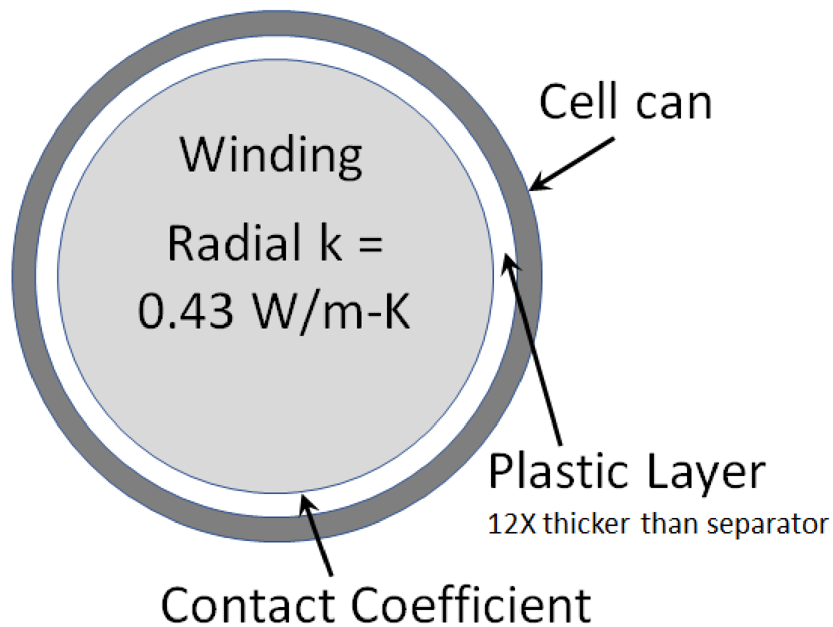
Comparisons with Prior Work

2016 NASA Model (Rickman, et al.)



- > Prof. Marconnett, Purdue value h=670 W/m^2-C
- > Correlated value in use was much lower, 50 W/m^2-C, to match model with Li-ion cell propagation test data

Caltech Study 2017



- > Gaitonde, et al. value: h=670 W/m^2-C
- > Thick layer (0.15 mm) of plastic surrounds winding
- > Effective contact coefficient including plastic layer and the reduced winding conductivity yields h_{eff} = 36 W/m^2-C in reasonable agreement with the correlated value

Conclusion

- For 18650 cell, we experimentally measured an effective thermal conductivity of 0.43 $\pm$ 0.07 W/m-K. For 22650 cell, we got a thermal conductivity of 0.20 $\pm$ 0.04 W/m-K
- Our values are greater than measured by Drake et al. so 18650 and 22650 cells can conduct heat better than previously thought
- Our model's predicted value for 22650 cell (0.22 W/m-K) is close to measured value. Predicted value for 18650 cell (0.27 W/m-K) isn't too close. One reason: contact resistance between cathode and plastic separator is greater than predicted

Acknowledgements

Many thanks to:

My mentors: Professor Melany Hunt and Dr. Bruce Drolen

Caltech SFP Office

The Tyson Family