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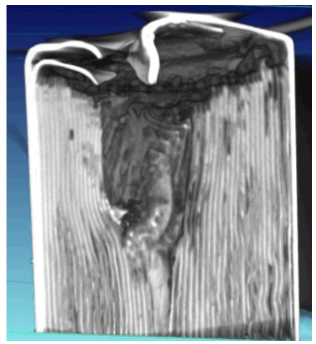
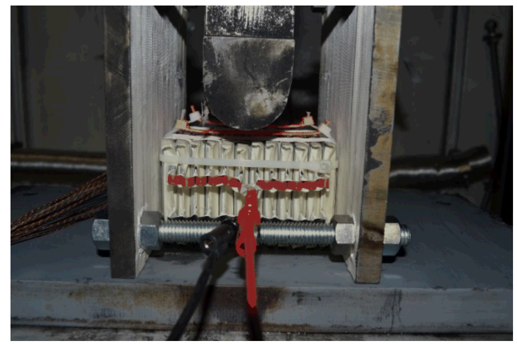


Understanding Lithium Ion Battery Fires

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U.S. DEPARTMENT OF ENERGY
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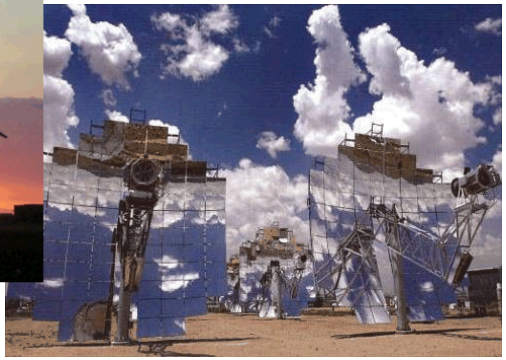
Increased Use of Lithium-ion Battery Technology

Larger batteries in larger quantities:

- **EV and PHEV battery packs are much higher energy (15-50 kWh)**
- **Increasing consideration for lithium-ion cells for utility storage (MWh systems*)***

6 cells, 50 Wh battery

7000 cells, 50 kWh battery



??? cells, MWh battery

Increased # of cells and higher energy batteries leads to greater impact during failure

- ***Field Failure***
  - **Manufacturing defects**
    - Separator damage, foreign debris
    - Can develop into an internal short circuit
- ***Abuse Failure***
  - **Mechanical**
  - **Electrical**
  - **Thermal**

Energy Storage Safety/Reliability Issues Have Impact Across Multiple Application Sectors

2006 Sony/Dell battery recall 4.1 million batteries

2010 FedEx Cargo Plane Fire, Dubai

2011 NGK Na/S Battery Explosion, Japan (two weeks to extinguish blaze)

2011 Chevy Volt Latent Battery Fire at DOT/NHTSA Test Facility

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

2012 GM Test Facility Incident, Warren, MI

2013 Storage Battery Fire, The Landing Mall, Port Angeles, (reignited one week after being "extinguished")

2013 Boeing Dreamliner Battery Fires, FAA Grounds Fleet

2013 Tesla Battery Fires, Washington, resulting from a highway accident

2013 Fisker Battery Fires, New Jersey, in the wake of Super Storm Sandy

Quantification of Lithium Ion Battery Fires

- **Gaseous byproducts/quantities** generated during battery fire
- **Heat Release Rate (HRR)** is the rate at which fire releases energy (i.e. power measure using oxygen consumption calorimetry)
- **Heat flux** is the rate of heat energy transferred per surface unit area - kW/m^2 (Estimates Fire Intensity)

Heat Flux (kW/m^2)	Example
1	Sunny day
2.5	Typical firefighter exposure
3-5	Pain/burns to skin within seconds
20	Threshold flux to floor at flashover (ignition of most of the directly exposed combustible material in an enclosed area)
84	Thermal Protective Performance Test (NFPA 1971)
60 - 200	Flames over surface

- **Fire fighting techniques** based on battery chemistry/size

Goal: model lithium ion battery fires and validate results with abuse initiated battery fires

Ribiere et.al., Energy Environ. Sci., 2012, 5, 5271
Long, R., et.al., Fire Protection Research Foundation, 2013
http://www.nist.gov/fire/fire_behavior.cfm

Approach: Fires Resulting from Battery Abuse Testing

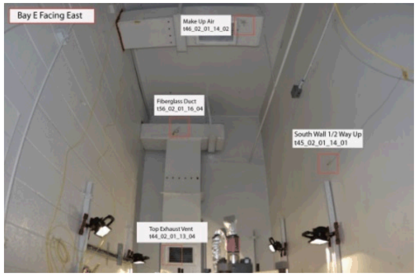
Part 1) Model: Fire Sciences Department at Sandia (Department 1532) use Fire Dynamics Simulator (FDS), a computational fluid dynamics code developed by NIST

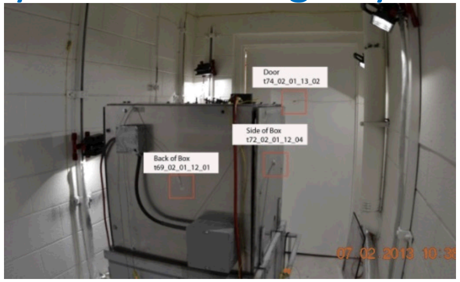
- Simulations using 1.1 kWh and 264 Wh (nominal) lithium ion battery fire
- Fire confined to abuse test bays

Part 2) Validation: Battery Abuse Testing Lab (BATlab)

- Electrical, thermal, and mechanical testing capabilities
- Validation testing done using mechanical testing on lithium ion batteries (222 Wh to 11 kWh)

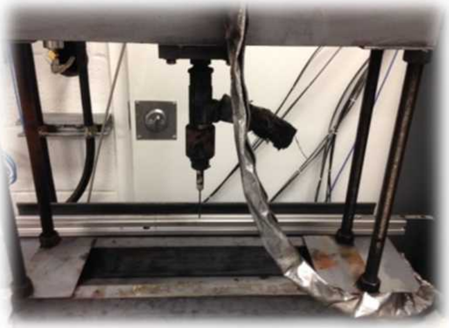
Destructive Battery Abuse Testing Bays

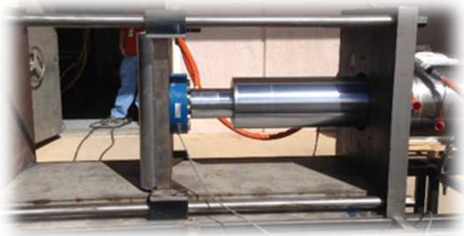




Medtherm Heat Flux Gauges

Mechanical Testing





Part 3) Refine model using data collected during validation tests

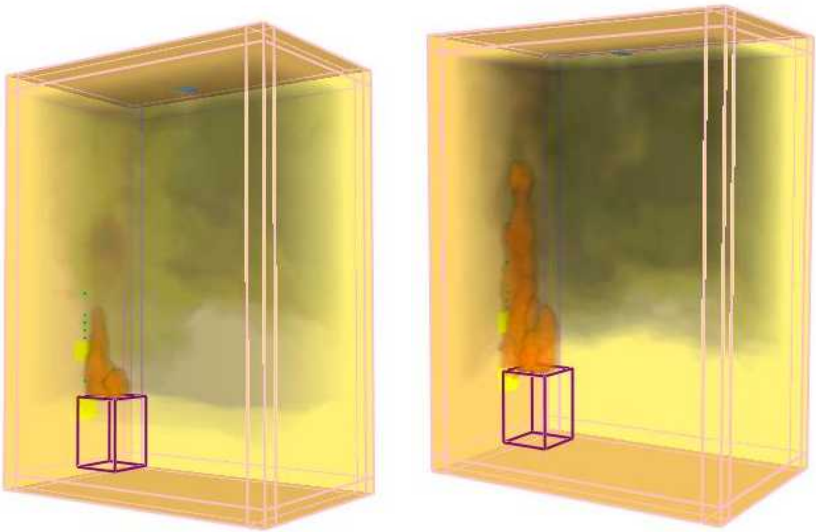
Simulations for 1.1 kWh and 264 Wh Li-ion Battery

Assumptions:

- Two heat release rates per unit area were explored: 2.5 MW/m^2 and 10 MW/m^2 for an area of .042 m^2 or .0105 m^2 (1/4 area of the 1.1 kWh fire)
  - Liquid fuels typically have HRR values of 2.0 – 2.5 MW/m^2.
  - HRR (heat release rate) measurements from Ribiere, et al. indicate that a 2.9 Ah Li-ion battery provides a normalized HRR of 1.7 MW/m^2
- Burn time of 180 seconds (1.1 kWh pack) or 113 seconds (264 Wh)
  - based on electrolyte/mass ratio battery

Description of Simulation Cases (1.1 kWh Li-ion)

Case	Table Placement	Exhaust Vent Status	Heat Release Rate (MW/m^2)
1	8” from wall	open	2.5
2	8” from wall	open	10
3	8” from wall	closed	2.5
4	8” from wall	closed	10
5	center of floor	open	2.5
6	center of floor	open	10



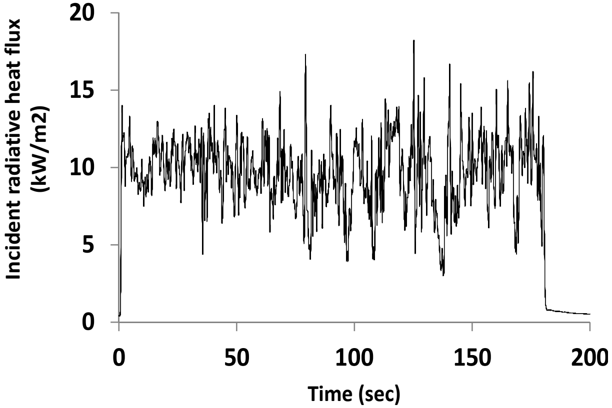
Case 1 and 3: a) low HRR fire, b) high HRR fire
Test bay : 2.18 m x 3.45 m with 4.88 m ceiling

Ribiere et.al., Energy Environ. Sci., 2012, 5, 5271

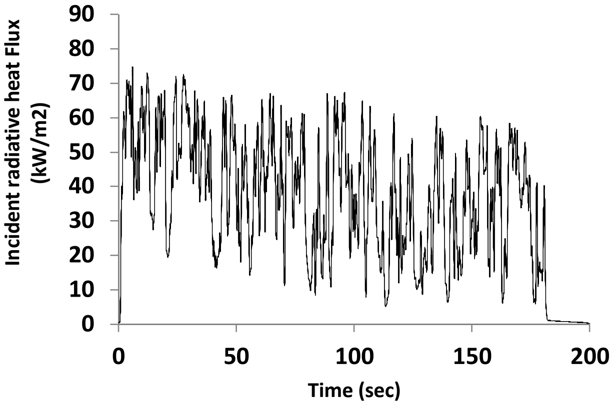
Fire Simulations for 1.1 kWh Li-ion Battery

Representative incident radiative heat flux to wall closest to battery fire (8” to 3’ away)

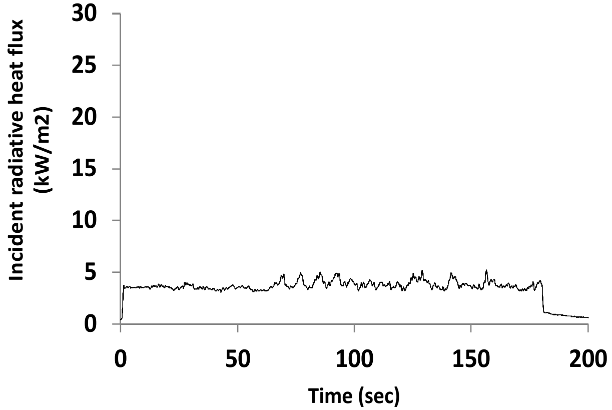
Case 1 (8” from wall): low HRR



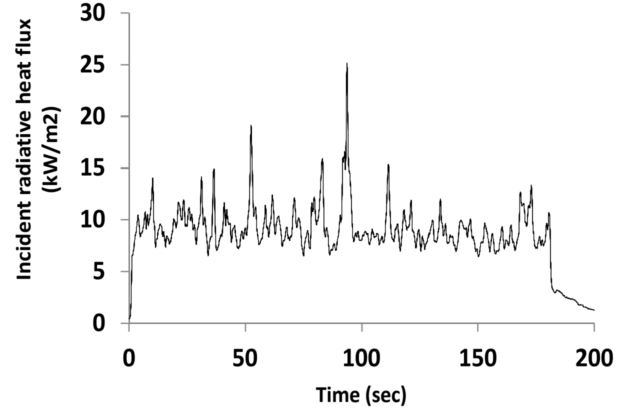
Case 2 (8” from wall): High HRR



Case 5 (3’ from wall): low HRR



Case 6 (3’ from wall): high HRR



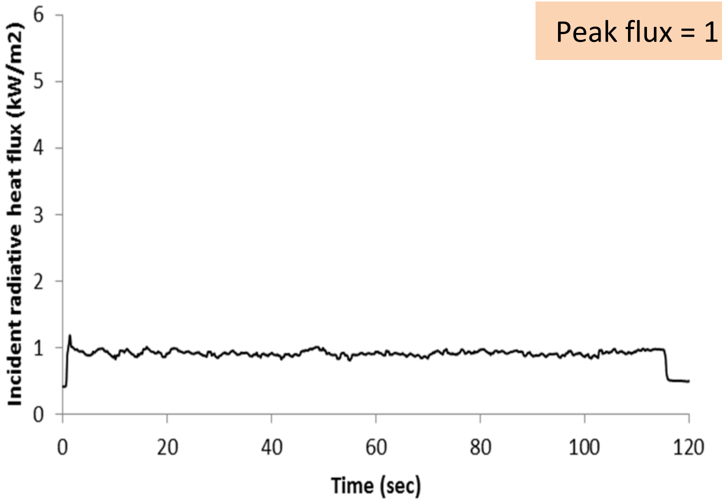
Case	Peak wall surface temp. (C)	Peak wall temp. in-depth at 0.0254 m (C)	Peak heat flux kW/m^2
1	156	42	15
2	364	77	70
3	94	33	12
4	226	56	80
5	41	24	5
6	75	30	25

- Higher HRR results in greater flux and peak temperatures for all cases
- Wall further from the fire (case 5 and 6) is exposed to lower temperatures and flux
- For all cases, flux ranges between 4 and 70 kW/m^2 = pain/burns to skin to flames directly on surface (NIST chart)

Fire Simulations for 264Wh Li-ion Battery

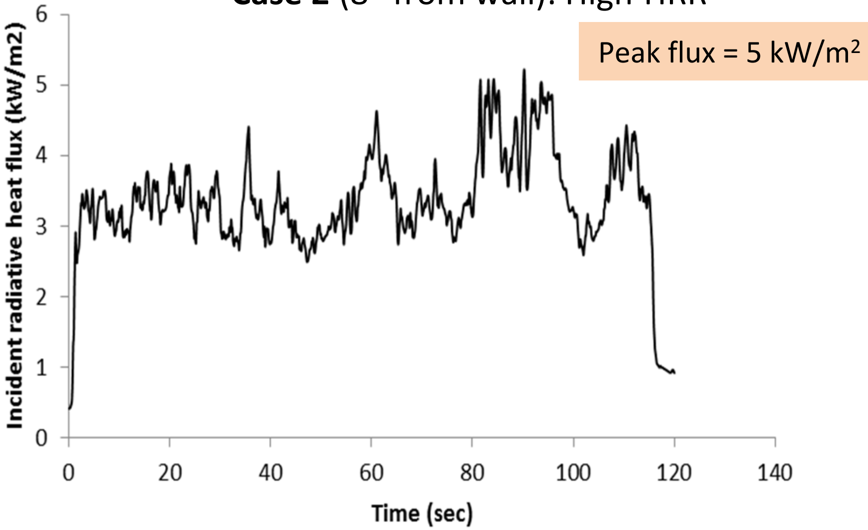
Representative incident radiative heat flux to wall closest to battery fire (8 in. away)

Case 1 (8" from wall): low HRR



Time (sec)	Peak wall surface temperature (C)	Peak wall temperature in-depth at 0.0254 m (C)
30	22	20
60	23	21
90	24	21
113	24	22

Case 2 (8" from wall): High HRR



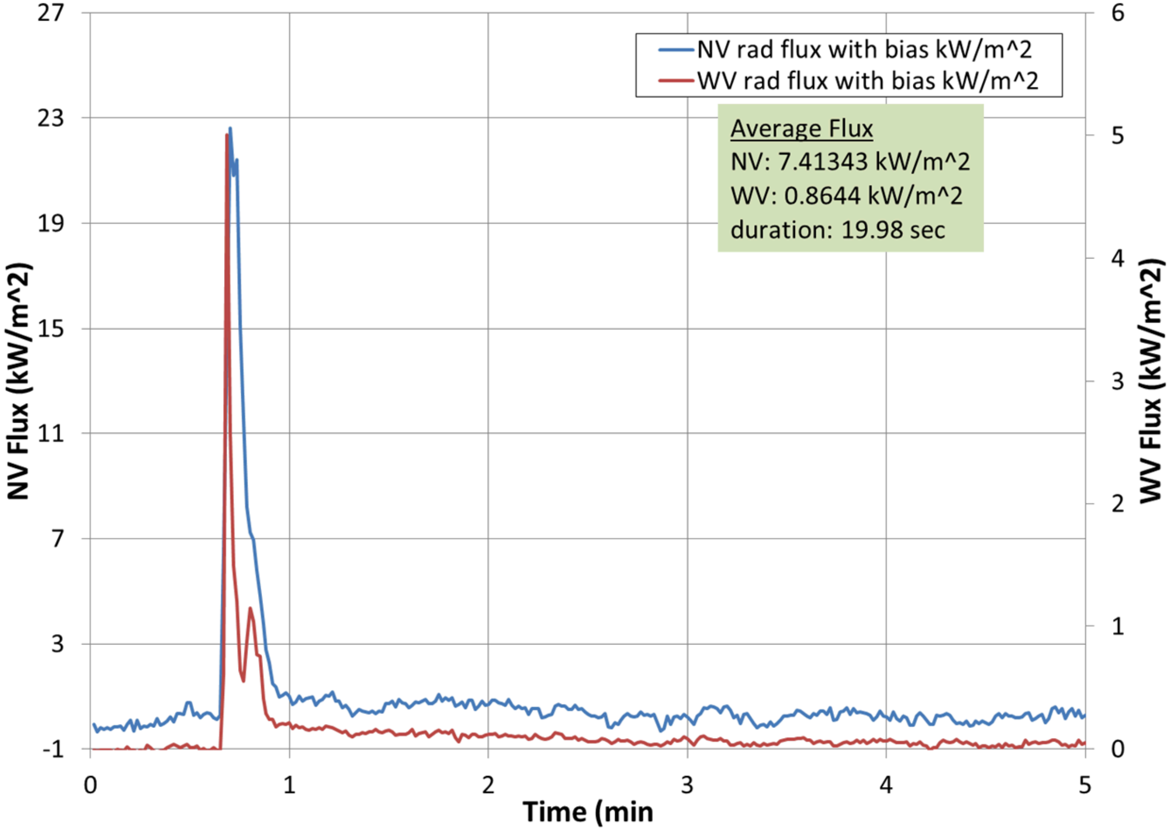
Time (sec)	Peak wall surface temperature (C)	Peak wall temperature in-depth at 0.0254 m (C)
30	27	21
60	30	22
90	34	24
113	35	25

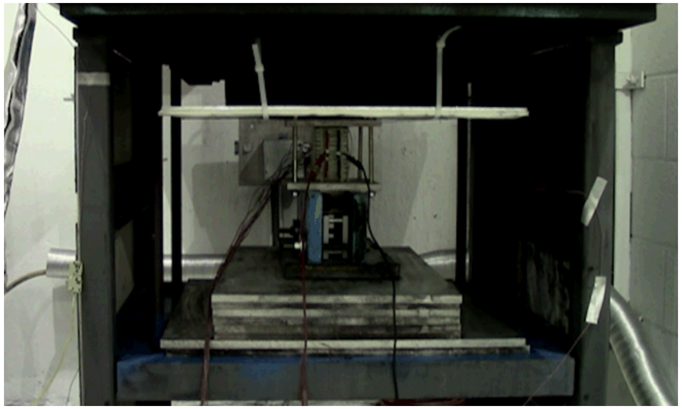
- Average heat flux 1-3 kW/m^2 = sunny day to pain to skin (NIST chart)
- Peak temperatures at wall closest to fire below 35^{o}C throughout the entire burn (113 sec)

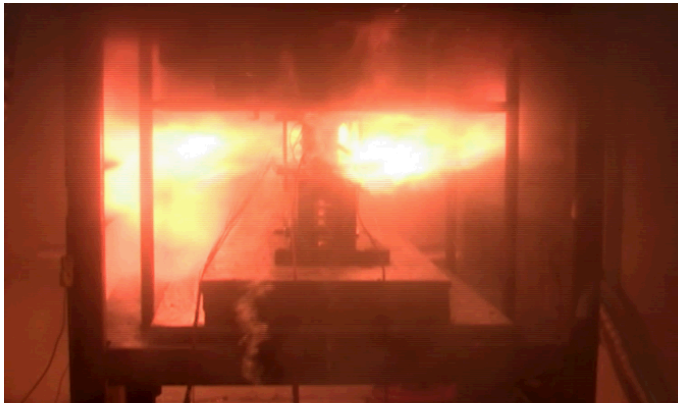
Validation: 222 Wh Pack Crush: unit 3

12 cells in a 1s12p configuration

Heat flux





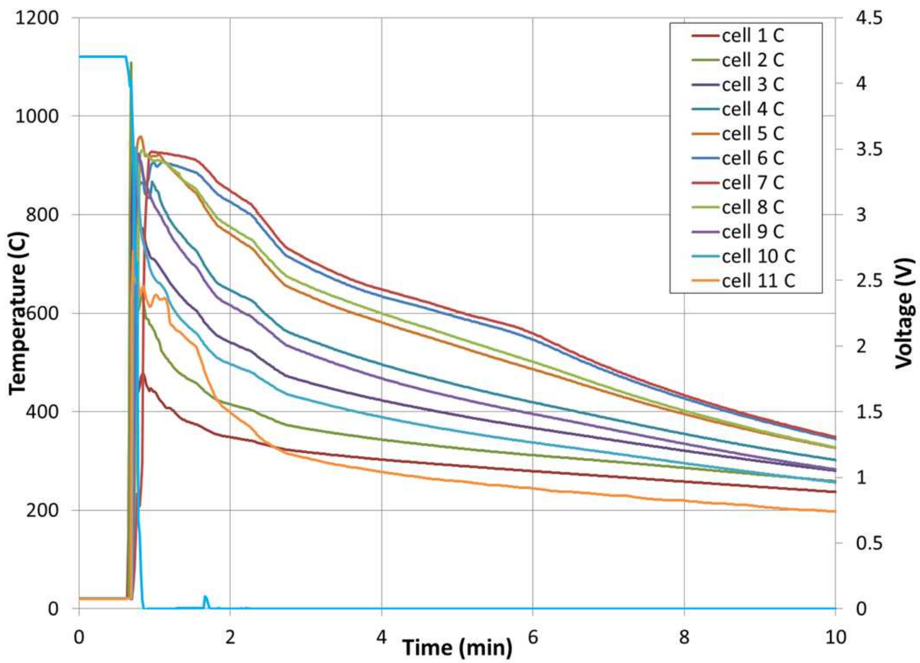


Unit 3: video

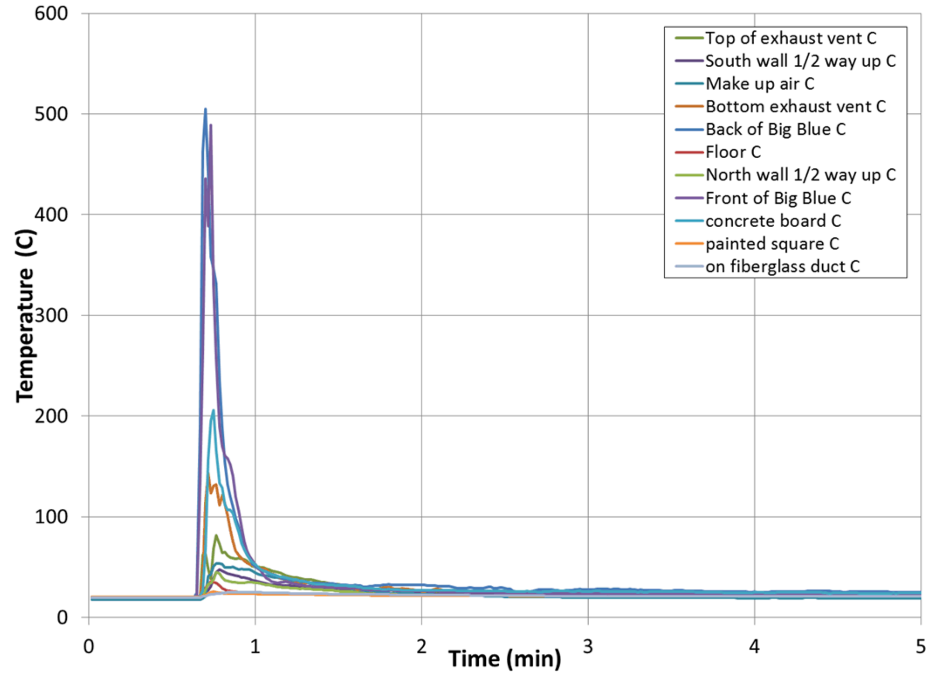
- Heat flux gauge 7 ft. standoff distance
- NV: 5.5^{o} view; WV: 150 ^{o} view
- Peak Flux: NV= 22.63 kW/m^2; WV= 5.01 kW/m^2

Validation: 222 Wh Pack Crush: unit 3

Battery Temperatures and Voltage



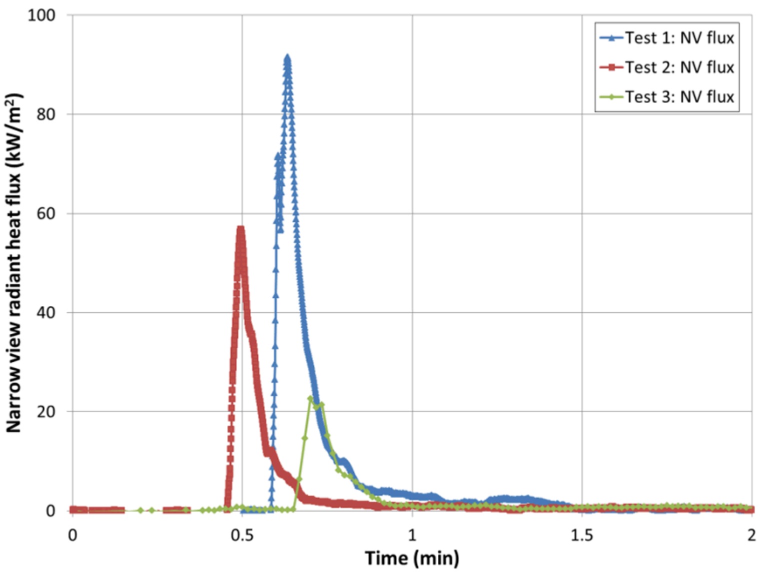
Test Bay Temperatures



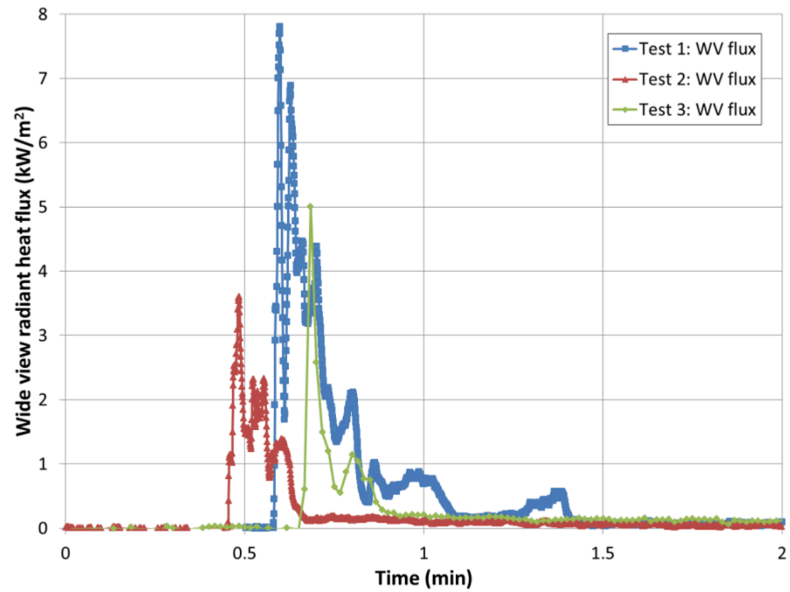
- Peak battery temp: ~900^{o}C
- Peak test bay temp: ~500^{o}C (TC on crush fixture)
  - measured temperatures in bay are higher than model but for less duration

Heat Flux Summary for 222 Wh pack

NV flux for tests 1-3



WV flux for tests 1-3

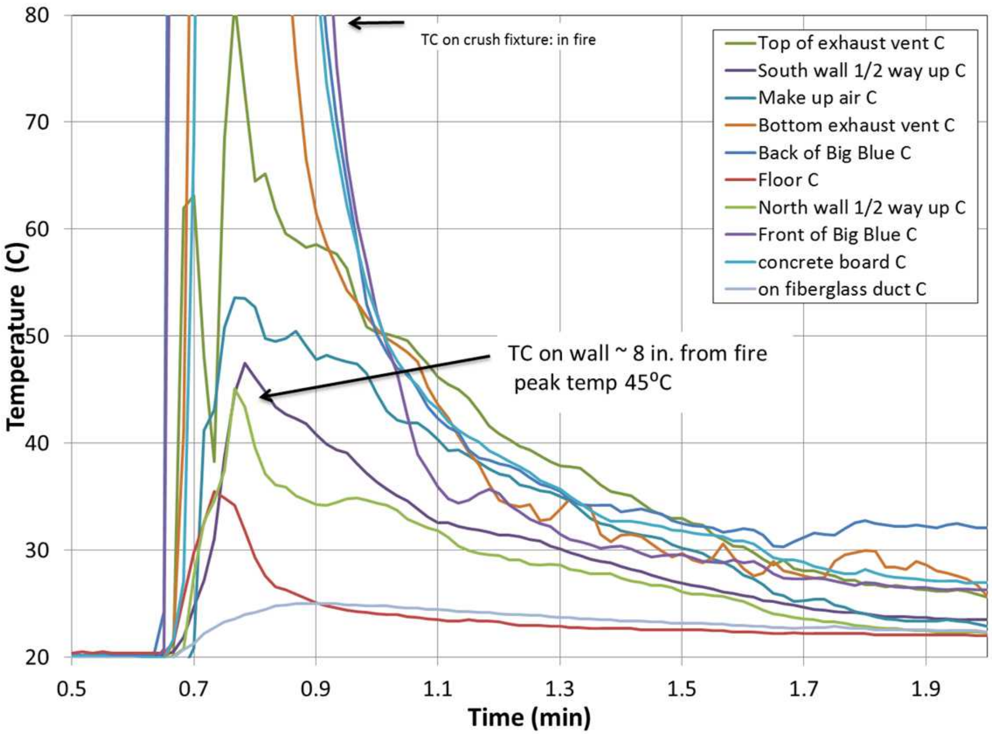


#	Pack size (nominal)	NV flux avg. (kW/m²)	WV flux avg. (kW/m²)	Duration (min)	Duration (sec)	Peak NV flux (kW/m²)	Peak WV flux (kW/m²)
1	222 Wh pack	7.41343	**0.8644**	0.333	19.98	22.63	5.01
2	222 Wh pack	13.1782	**0.9058**	0.355	21.3	56.76	3.61
3	222 Wh pack	10.5858	**1.0822**	0.932	55.92	91.57	7.8

- Wide view (~150^{o} viewing angle) heat flux is most comparable to FDS simulation (describes fire area)
- Flux data correlates better with the lower HRR (2.5 MW/m^2) model example
  - average flux 264 Wh model = 1 kW/m^2

Temperature Summary for 222 Wh pack

Test 3: Test Bay Temperatures



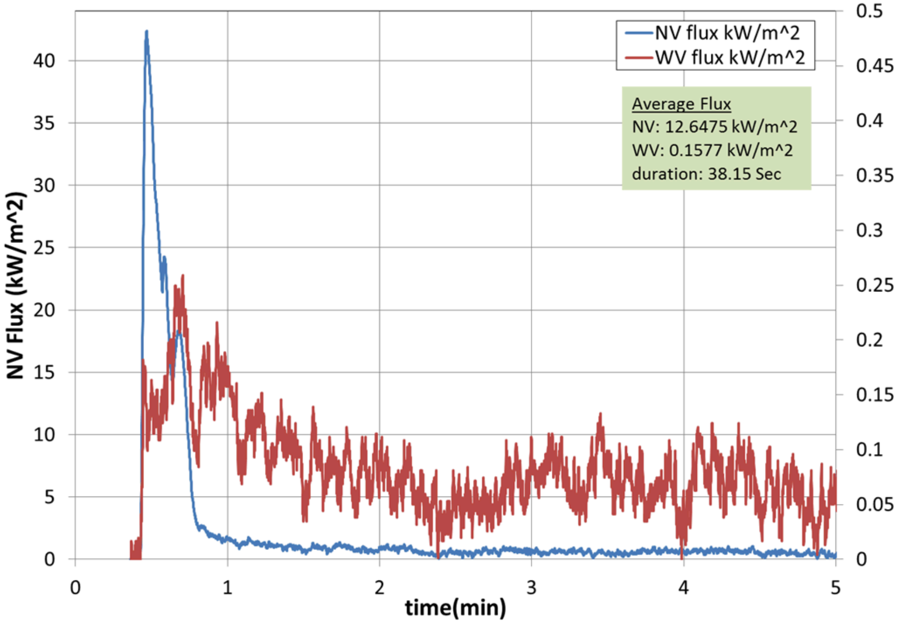
	Peak temp wall 8" from fire (°C)	Peak temp lower exhaust (°C)	Peak temp upper exhaust (°C)
Validation : 222 Wh (average)	50	145	80
Model: 2.5 mW/m^2	24	24	35
Model: 10 mW/m^2	35	72	95

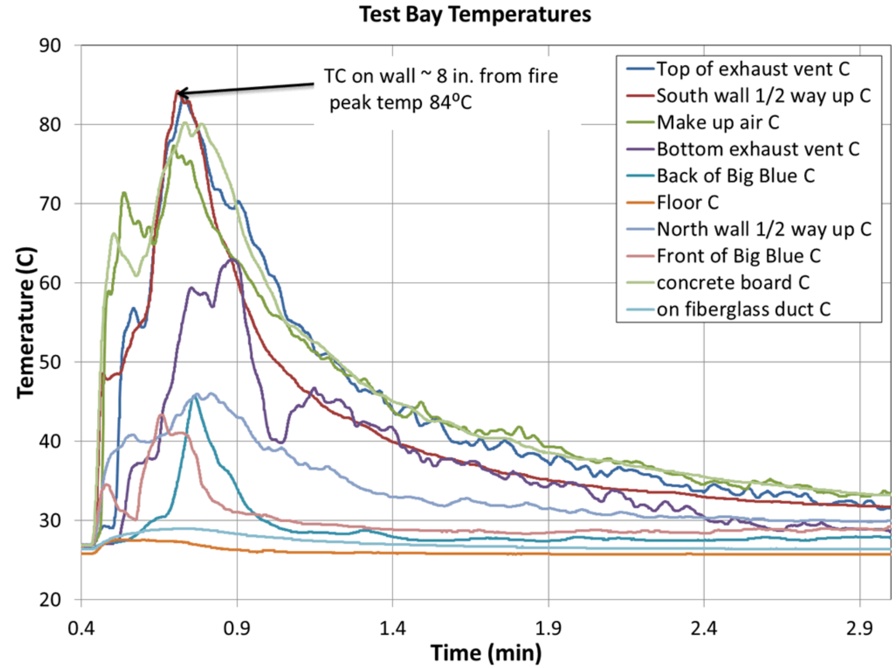
Note: there are some discrepancies between model and actual measurements

-Bay temperatures measured higher than model

-actual measurements will be added to model for refinement

Nail Penetration of 222 Wh Single Cell





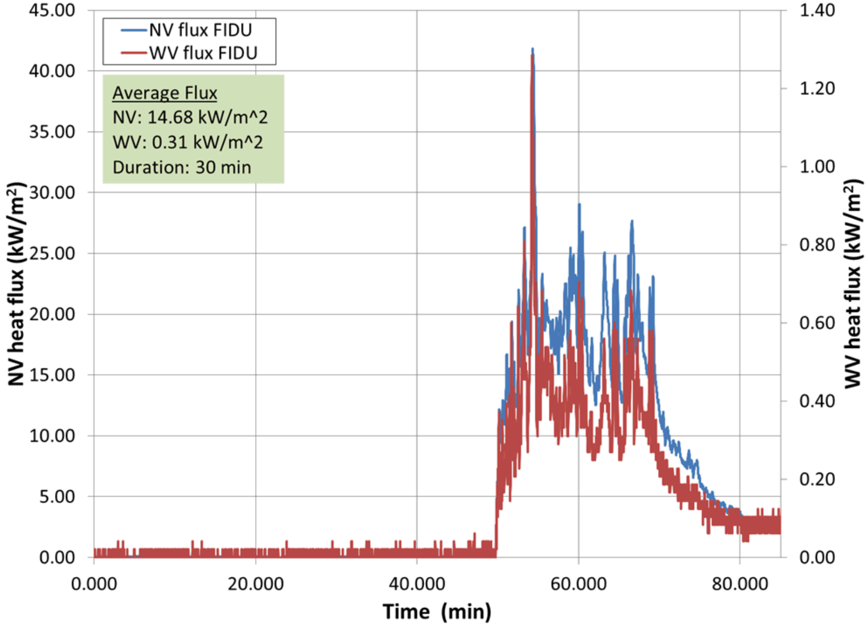
- Heat flux gauge 3 foot standoff distance
- Peak flux(kW/m^2) NV: 42.37; WV: 0.259

- Peak battery temp: 500 ^{o}C during failure
- Peak bay temperature: 85 ^{o}C nearest to fire
- Top exhaust peak temp: 85 ^{o}C
- Bottom exhaust peak temp: 65 ^{o}C

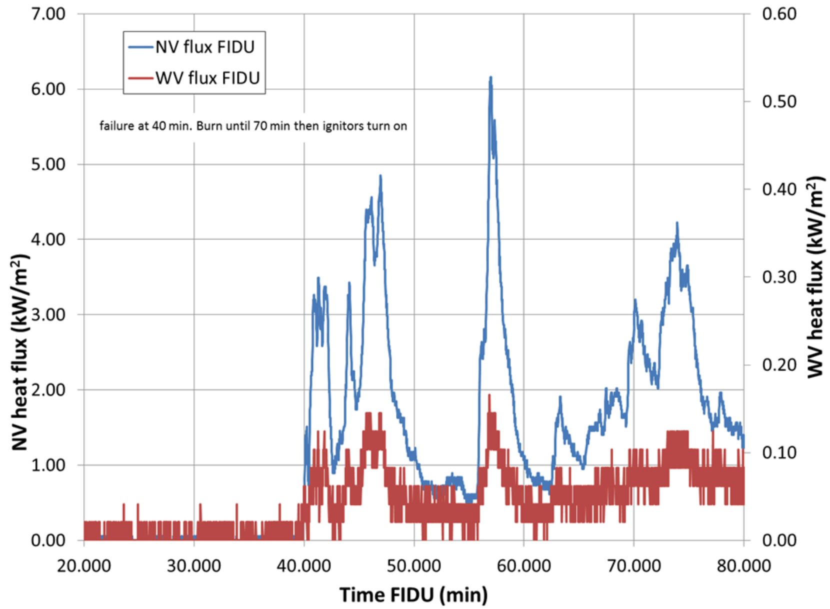
- WV heat flux is most comparable to FDS simulation (describe larger portion of fire area)
- Flux data is an order of magnitude lower than shown in model example
  - average flux low HRR :1 kW/m^2
- peak wall temperature 8" from fire measured to be ~ 50^{o}C higher than report in the model

Crushing of 11 kWh Test article: Heat Flux

Heat flux data for Test Article 5



Heat flux data for Test Article 7



#	Pack/battery size: Nominal	NV flux average (kW/m²)	WV flux average (kW/m²)	Duration (min)	Duration (sec)	Peak NV flux (kW/m²)	Peak WV flux (kW/m²)
5	~11 kWh pack	14.68	0.31	30	1800	41.87	1.28
6	~11 kWh pack	2.61	0.04	22	1320	6.79	0.23
7	~11 kWh pack	1.86	0.06	32	1920	6.16	0.17

- Wide view flux better representation of fire
- Peak WV flux between 0.2 and 1.3 kW/m^2 @ 15 ft. standoff
- Peak battery temperatures > 1200 ^{o}C

Heat Flux Summary for Tested Lithium-ion Batteries

Pack/battery size (nominal)	NV flux avg. (kW/m^2)	WV flux avg. (kW/m^2)	Duration (min)	Duration (sec)	Peak NV flux (kW/m^2)	Peak WV flux (kW/m^2)
222 Wh (averages)	10.96	0.75	0.56	33.84	43.33	4.17
11 kWh (averages)	6.38	0.13	28	1680	18.27	0.56

- Lower heat flux for longer durations collected for tests 5-7 (11kWh test articles)
    - pack had shielding (metal casing)
    - not all cells in pack ignited at once (propagation effect)
    - gauge at further standoff distance
- Wide angle flux measurements better represent entire battery fire
- Shorter standoff distances (3-7'): 222 Wh test had an average WV peak flux of 4.17 kW/m^2 = pain/burn to skin within seconds
- Longer standoff distances (14') with the larger battery tests had an average WV peak flux of 0.56 kW/m^2 = radiant heat from a sunny day
- Long et.al. report full HRR testing of a 16 kWh pack (vehicle size)
    - Peak flux (5 ft. standoff) 17.1-18 kW/m^2 and 3.7-4.7 kW/m^2 (10 ft. standoff)
    - Flux changes with distance

Long, R., et.al., Fire Protection Research Foundation, 2013

Summary

- **Preliminary modeling efforts were done to better understand lithium-ion battery fires**
  - fire assault on abuse testing lab infrastructure
  - possible HRR and heat fluxes of a battery fire
- **Validation of the model through battery abuse testing has begun**
  - mechanical abuse testing: heat flux and wall surface temperatures monitoring
- **Update fire models using flux/temperature data**
  - better prediction of fire properties for given battery size
  - compare heat flux and wall temperature profiles
  - assess HRR data collection capabilities at SNL
- **Continue to collect heat flux and temperature data during abuse testing**
  - range of battery sizes and chemistries
  - during other abuse scenarios for comparisons (electrical and thermal abuse)
- **Collect heat flux data at different standoff distances**
  - better predict effects on specific locations from a battery fire
- **Hope to compare results with literature values to better predict fire properties based on battery size and composition**