University of Science and Technology – China (USTC) and Boeing Test Results of Li-ion and Li-metal Batteries

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USTC and Boeing Lithium Battery Fire Research

Purpose of research:

- Understand and characterize key parameters for fires involving lithium ion and lithium metal batteries.
- Evaluate various mitigation strategies for carrying lithium batteries as cargo on aircraft with this understanding.

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Test Goals:

- Establish a baseline set of measurements that characterize specific quantities of lithium ion and lithium metal batteries involved in an unsuppressed fire.
- Determine if there are critical differences between manufacturers of similar battery types.
- Simultaneously measure thermal and pressure characteristics of burning lithium batteries.

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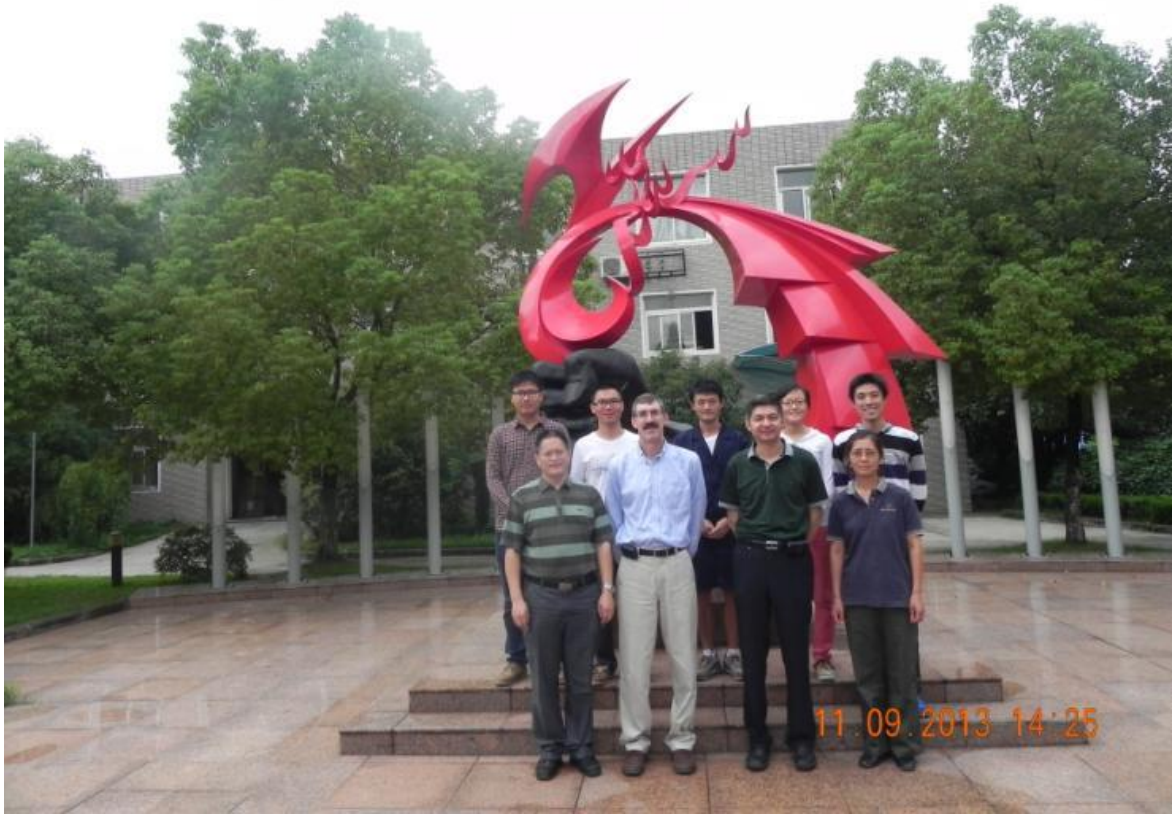
中国科学技术大学
University of Science and Technology of China

Boeing and the University of Science and Technology of China (USTC) have been collaborating in lithium battery fire research



Special thanks to
Mary Xing (Boeing)
Joe Yin (Boeing)
Prof. Jian Wang and his research team (USTC)

BOEING

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Lithium Battery Fire Characterization

Configuration	Primary		Secondary	
	Primary #1	Primary #2	Secondary #2	Secondary #1
2 x 2	5 tests	5 tests	5 tests	5 tests
2 x 4	5 tests	5 tests	5 tests	5 tests
6 x 6	3 tests	--	--	3 tests
10 x 10	3 tests	--	--	3 tests

Measurements:

Mass loss, Heat Release Rate (HRR), Total Heat Release, Side Heat Flux, Pressure Pulse, Centerline Temperatures, Side Temperatures

Primary batteries: CR123A, 1.55Ah, 100% State of Charge (SOC)
Secondary batteries: 18650, 2.6 Ah, 80% SOC

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2X2

2X4

Primary battery

6X6

10X10

Secondary battery

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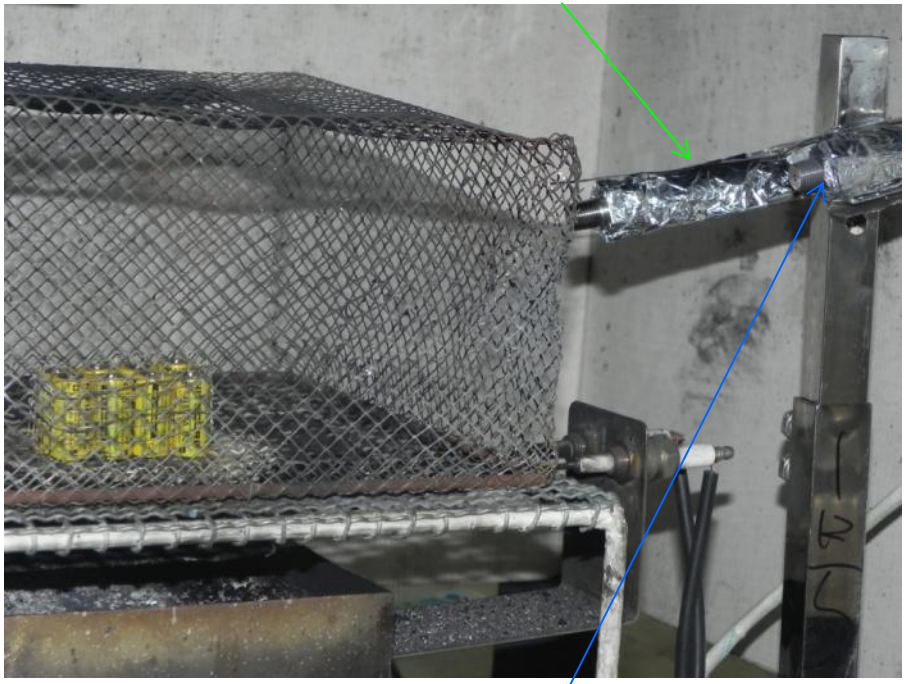
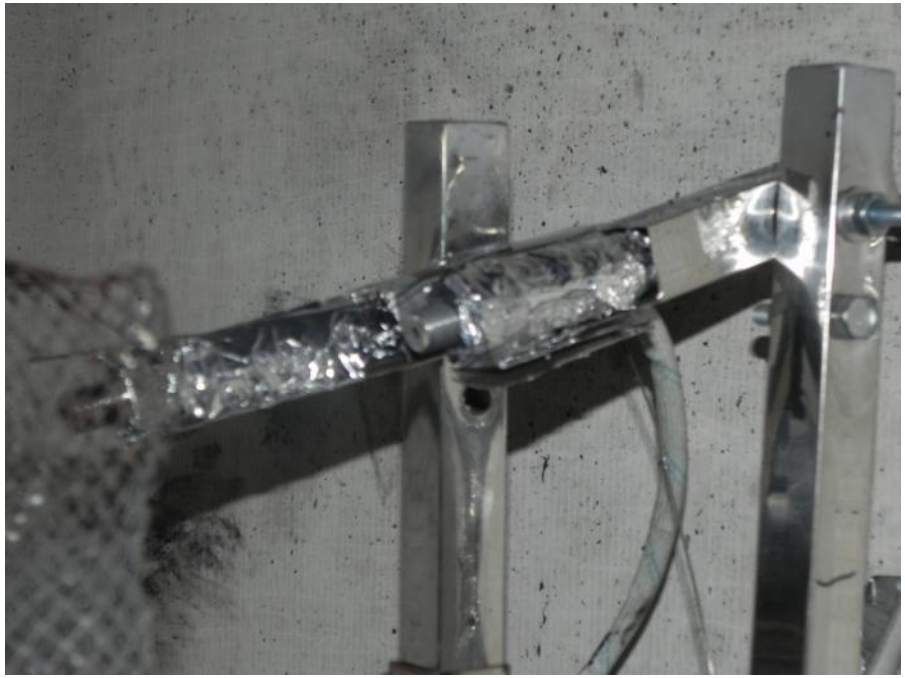
Goal: Capture pressure pulses in an open volume

Pressure at 20cm from the center at Right





Pressure at 30cm from the center at Right

Two OMEGA pressure sensors at the right side

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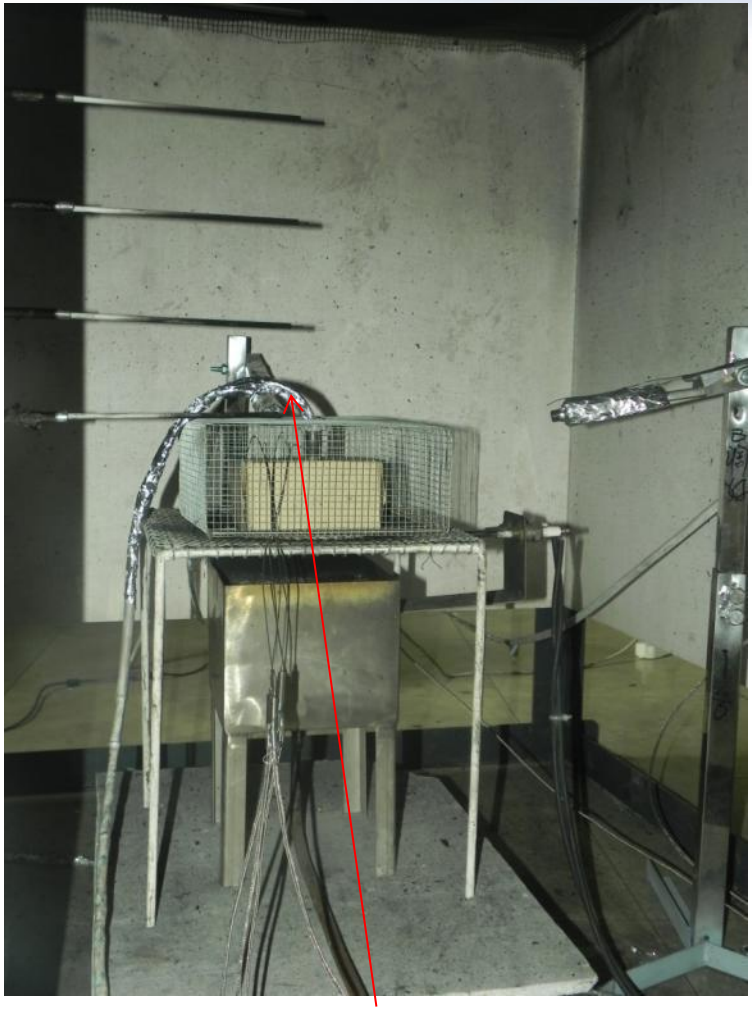
Flame Exposure:
Propane heater



Propagation thermal runaway test:
Electric heater

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Purpose: Capture the temperature field around the batteries

Thermocouples located at:

- *Center line*
- *Right side*
- *Right corner*
- *Left corner*
- *Back side*
- *Left at Heat flux*

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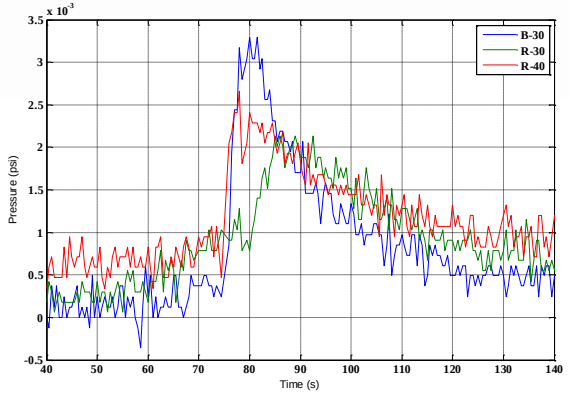
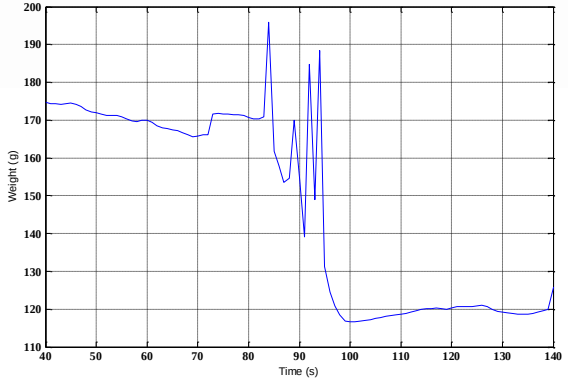
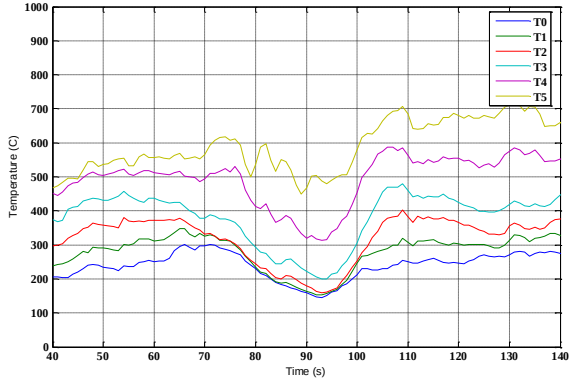
Data example for 2 x 2 Secondary Battery test



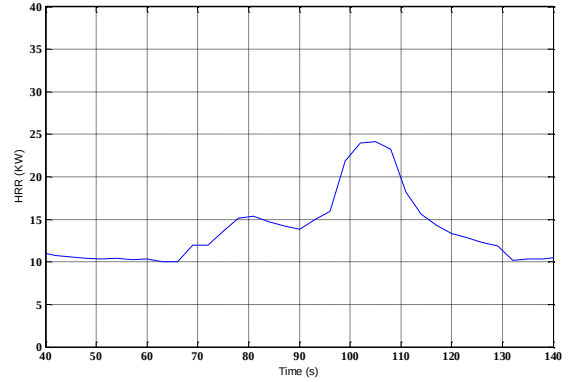
Pressure at back and right



Weight loss



Temperature at the centerline



Raw HRR

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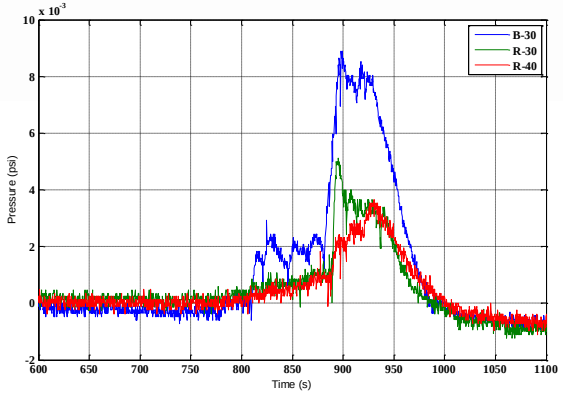
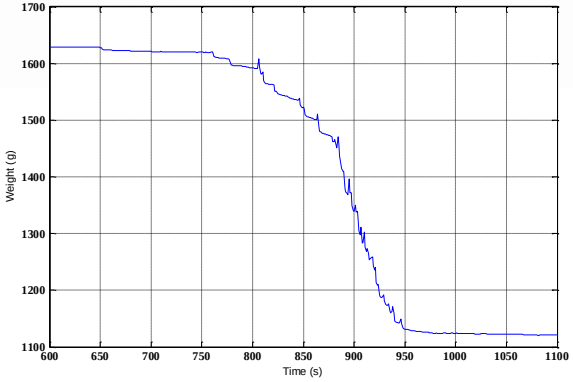
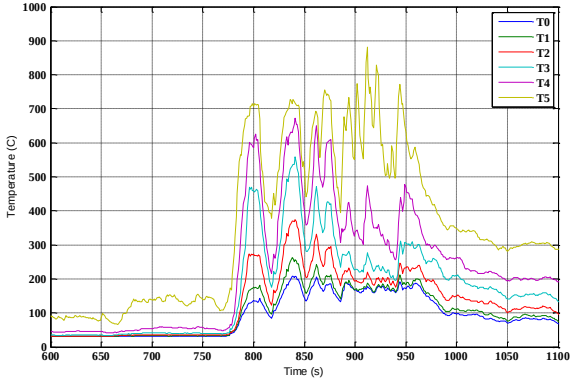
Data example for 6 x 6 Secondary Battery test



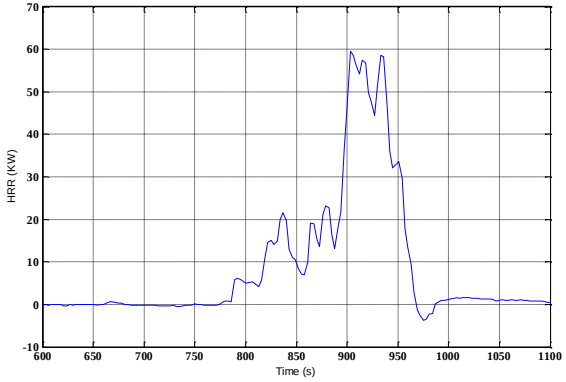
Pressure at back and right



Weight loss



Temperature at the centerline



Raw HRR

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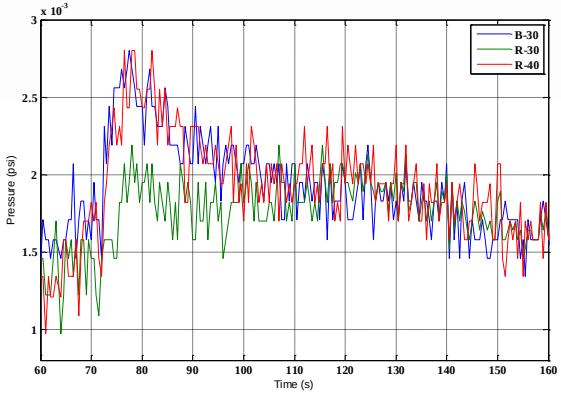
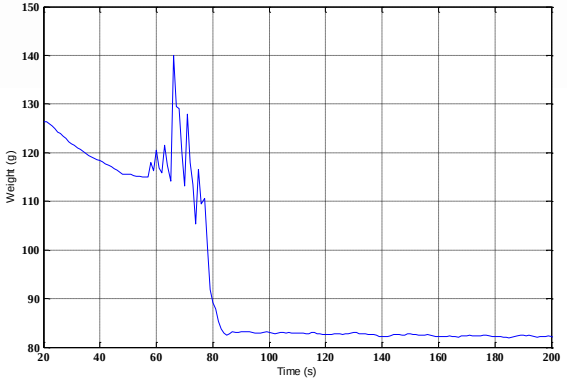
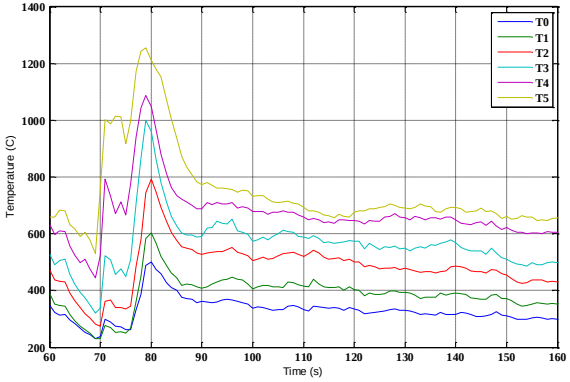
Data example for 2 x 4 Primary Battery test



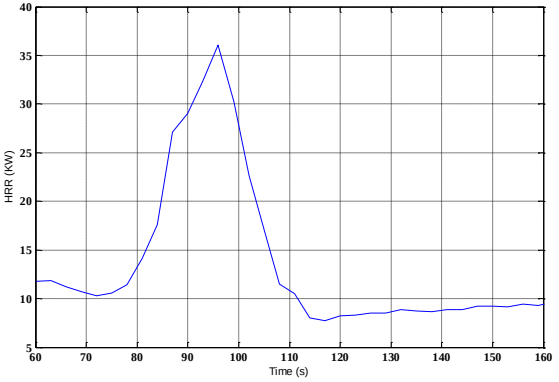
Pressure at back and right



Weight loss



Temperature at the centerline



Raw HRR

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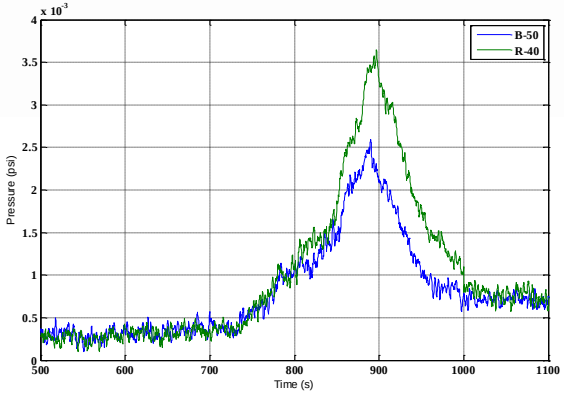
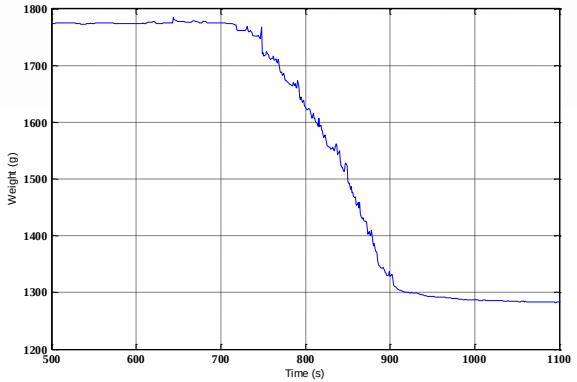
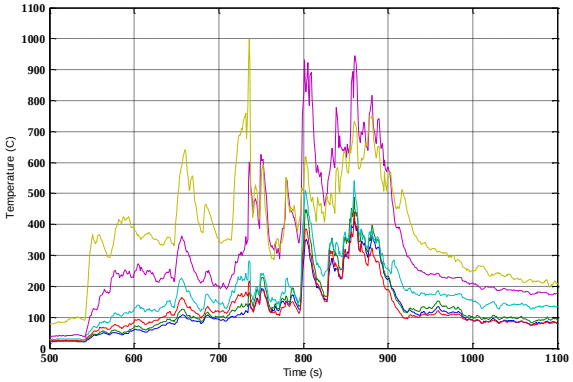
Data example for 10 x 10 Primary Battery test



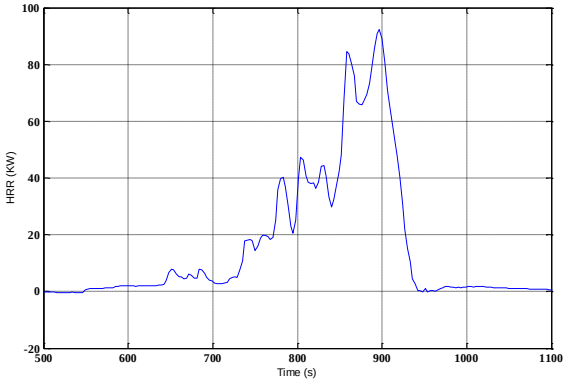
Pressure at back and right



Weight loss



Temperature at the centerline



Raw HRR

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Batteries after the tests












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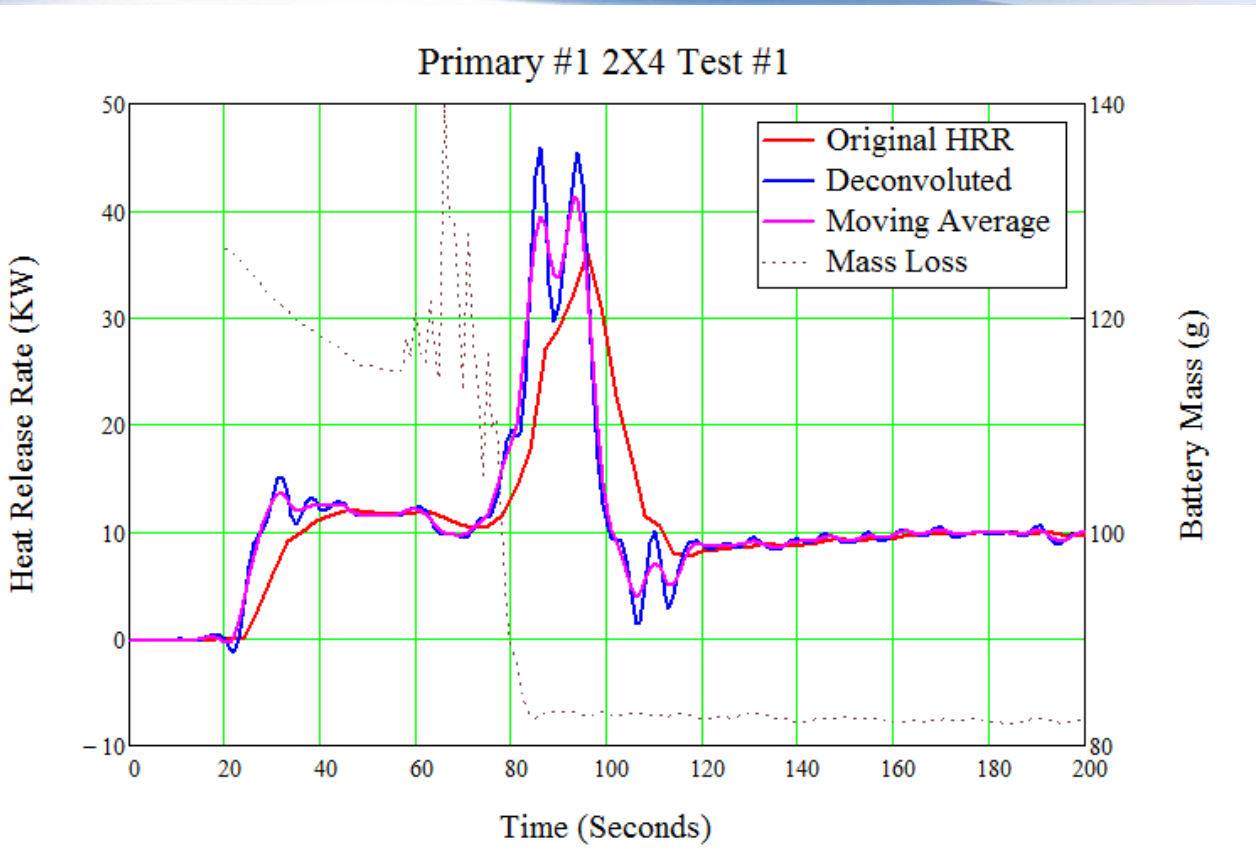


Example of Deconvolution of Heat Release Data for "Net" Data

References:

"Heat Release Rates of Objects Burning In Compartment" by Richard E. Lyon and David Blake

"Heat release rate measurements of thin samples in the OSU apparatus and the cone calorimeter" by Robert Filipczak, Sean Crowley, Richard E Lyon, Fire Safety Journal 40 (2005) 628-645

USTC and Boeing Lithium Battery Fire Research

Brand	Config	Net Total HR Smoothed (KJ)	Net HRR Peak (kW)	Net Peak Side Heat flux (kw/m2)	Peak Temp. (° C)	Peak Pressure (psia)	Mass Loss (g)	Total HR/Initial Battery Mass (KJ/g)	Total HR/Battery Mass Loss (KJ/g)	Total HR/Cell (KJ)	Total HR/ Capacity (KJ/Ah)
Primary #2	2X2	270.5	16.2	0.2	816	0.00239	43.7	4.2	6.2	67.6	43.6
Primary #2	2X2	314.0	19.1	0.7	1111	0.00378	37.7	4.9	8.3	78.5	50.6
Primary #2	2X2	322.9	18.6	0.7	1108	0.00199	34.1	5.0	9.5	80.7	52.1
Primary #2	2X2	288.2	24.1	4.1	969	0.00326	25.9	4.5	11.1	72.1	46.5
Primary #2	2X2	267.9	20.4	0.3	1004	0.00182	29.3	4.2	9.1	67.0	43.2
	Mean	292.7	19.7	1.2	1001.8			4.6	8.9	73.2	47.2
	Standard DEV	24.94	2.91	1.64	121.29			0.39	1.80	6.24	4.02
Primary #2	2X4	648.2	47.9	0.8	1007	0.00378	54.3	5.0	11.9	81.0	52.3
Primary #2	2X4	535.9	23.8	0.7	790	0.00341	66.1	4.2	8.1	67.0	43.2
Primary #2	2X4	626.1	47.1	1.1	776	0.00864	61.8	4.8	10.1	78.3	50.5
Primary #2	2X4	546.7	40.8	2.5	758	0.00402	63.1	4.2	8.7	68.3	44.1
Primary #2	2X4	628.6	52.7	1.5	1103	0.00232	68.5	4.9	9.2	78.6	50.7
	Mean	597.1	42.5	1.3	886.5			4.6	9.6	74.6	48.2
	Standard DEV	51.78	11.26	0.74	157.62			0.40	1.50	6.47	4.18
Primary #1	2X2	245.3	20.6	0.5	1044	0.00196	25.0	3.8	9.8	61.3	39.6
Primary #1	2X2	215.9	9.8	0.4	752	0.00171	26.8	3.6	8.1	54.0	34.8
Primary #1	2X2	205.2	11.8	0.3	945	0.00162	24.8	3.2	8.3	51.3	33.1
Primary #1	2X2	207.6	24.8	1.4	636	0.00332	35.4	3.4	5.9	51.9	33.5
Primary #1	2X2	241.7	16.7	0.2	874	0.00176	28.0	3.8	8.6	60.4	39.0
	Mean	223.1	16.7	0.5	850.2			3.5	8.1	55.8	36.0
	Standard DEV	19.04	6.20	0.48	160.14			0.27	1.44	4.76	3.07
Primary #1	2X4	455.3	31.3	0.3	1254	0.0028	47.9	3.5	9.5	56.9	36.7
Primary #1	2X4	391.7	38.0	1.1	956	0.00206	37.1	3.0	10.6	49.0	31.6
Primary #1	2X4	412.4	39.7	1.1	821	0.00255	37.4	3.2	11.0	51.6	33.3
Primary #1	2X4	416.8	34.0	0.7	1036	0.00207	39.7	3.2	10.5	52.1	33.6
Primary #1	2X4	508.6	37.9	0.6	1019	0.00219	43.2	3.9	11.8	63.6	41.0
	Mean	437.0	36.2	0.7	1017.3			3.4	10.7	54.6	35.2
	Standard DEV	46.17	3.43	0.33	157.31			0.35	0.83	5.77	3.72

Propane burner test results for Primary Batteries

USTC and Boeing Lithium Battery Fire Research

Brand	Config	Net Total HR Smoothed (KJ)	Net HRR Peak (kW)	Net Peak Side Heat flux (kw/m2)	Peak Temp. (° C)	Peak Pressure (psia)	Mass Loss (g)	Total HR/Initial Battery Mass (KJ/g)	Total HR/Battery Mass Loss (KJ/g)	Total HR/Cell (KJ)	Total HR/ Capacity (KJ/Ah)
Secondary #1	2X2	377.4	20.5	0.6	711	0.00329	53.4	2.1	7.1	94.4	45.4
Secondary #1	2X2	436.3	30.5	0.9	766	0.0042	58.8	2.4	7.4	109.1	52.4
Secondary #1	2X2	550.1	36.7	1.3	788	0.00359	58.7	3.1	9.4	137.5	66.1
Secondary #1	2X2	471.3	23.9	1.3	711	0.00499	63.6	2.6	7.4	117.8	56.6
Secondary #1	2X2	488.1	45.3	4.2	811	0.00362	51.8	2.8	9.4	122.0	58.7
	Mean	464.6	31.4	1.7	757.4			2.6	8.1	116.2	55.8
	Standard DEV	63.86	9.96	1.46	45.13			0.36	1.16	15.96	7.68
Secondary #1	2X4	689.4	47.3	3.0	863	0.00694	112.0	1.9	6.2	86.2	41.4
Secondary #1	2X4	694.0	51.8	1.6	893	0.00511	106.8	1.9	6.5	86.8	41.7
Secondary #1	2X4	410.5	20.2	1.3	824	0.00328	108.6	1.1	3.8	51.3	24.7
Secondary #1	2X4	649.1	29.1	1.0	756	0.00329	99.6	1.8	6.5	81.1	39.0
Secondary #1	2X4	652.5	45.2	0.6	747	0.00803	118.0	1.8	5.5	81.6	39.2
	Mean	619.1	38.7	1.5	816.8			1.7	5.7	77.4	37.2
	Standard DEV	118.41	13.43	0.92	64.52			0.33	1.14	14.80	7.12
Secondary #2	2X2	431.6	24.4	1.2	883	0.00316	47.5	2.4	9.1	107.9	51.9
Secondary #2	2X2	424.3	20.4	1.4	799	0.0045	32.0	2.3	13.3	106.1	51.0
Secondary #2	2X2	317.7	16.5	1.0	742	0.00475	57.6	1.7	5.5	79.4	38.2
Secondary #2	2X2	477.2	34.7	0.8	765	0.00462	37.3	2.6	12.8	119.3	57.4
Secondary #2	2X2	639.0	23.4	3.1	858	0.00268	51.4	3.5	12.4	159.8	76.8
	Mean	457.9	23.9	1.5	809.4			2.5	10.6	114.5	55.0
	Standard DEV	116.90	6.77	0.92	59.85			0.64	3.29	29.23	14.05
Secondary #2	2X4	725.1	21.1	0.5	809	0.0042	84.7	2.0	8.6	90.6	43.6
Secondary #2	2X4	869.0	37.6	1.9	760	0.0064	84.7	2.4	10.3	108.6	52.2
Secondary #2	2X4	823.7	23.6	1.3	795	0.00289	87.3	2.3	9.4	103.0	49.5
Secondary #2	2X4	780.7	25.1	1.5	882	0.00305	88.4	2.2	8.8	97.6	46.9
Secondary #2	2X4	842.3	19.7	0.8	779	0.00453	75.8	2.3	11.1	105.3	50.6
	Mean	808.1	25.4	1.2	805.2			2.2	9.6	101.0	48.6
	Standard DEV	56.49	7.13	0.55	46.79			0.16	1.05	7.06	3.40

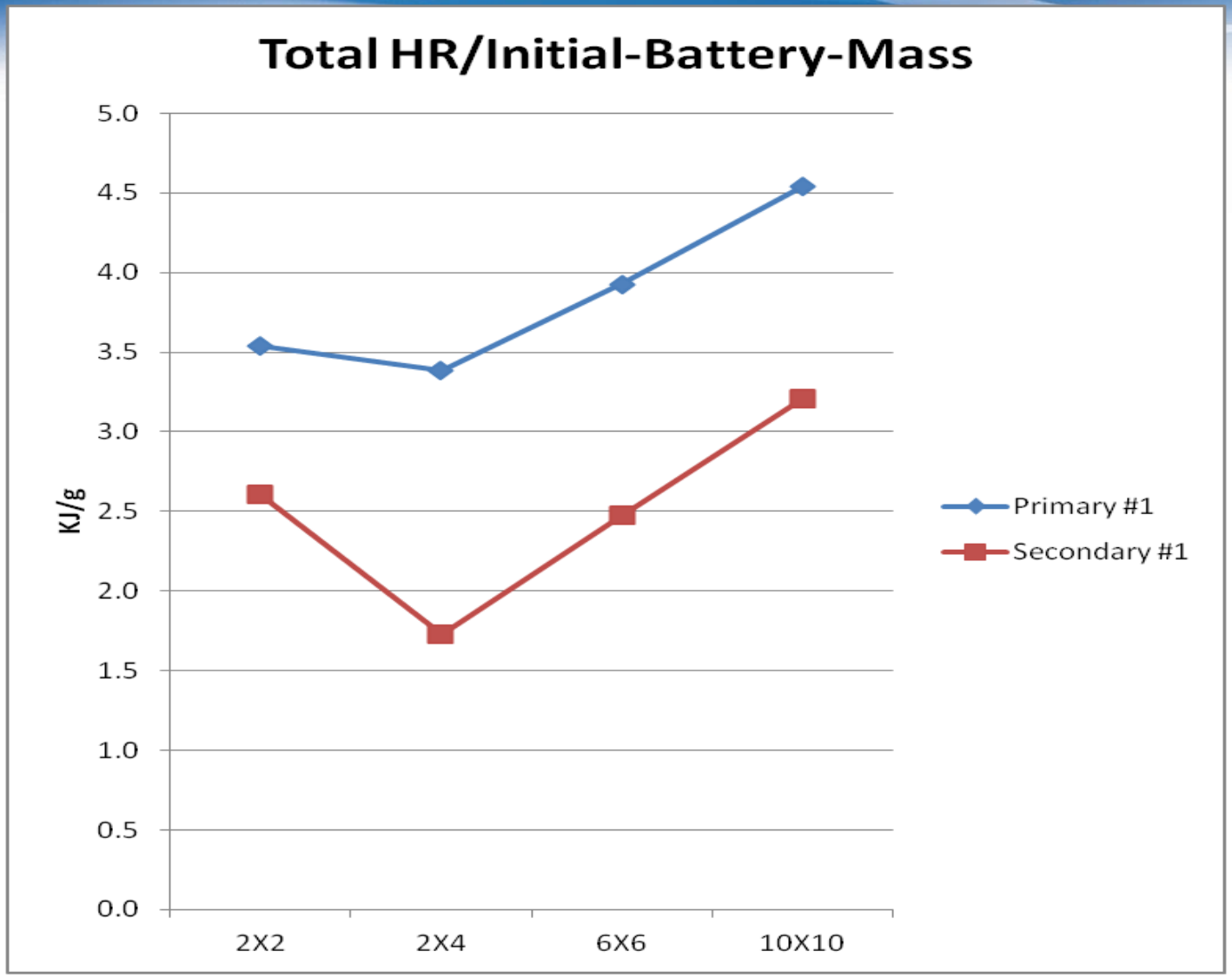
Propane Burner Test Results for Secondary Batteries

USTC and Boeing Lithium Battery Fire Research

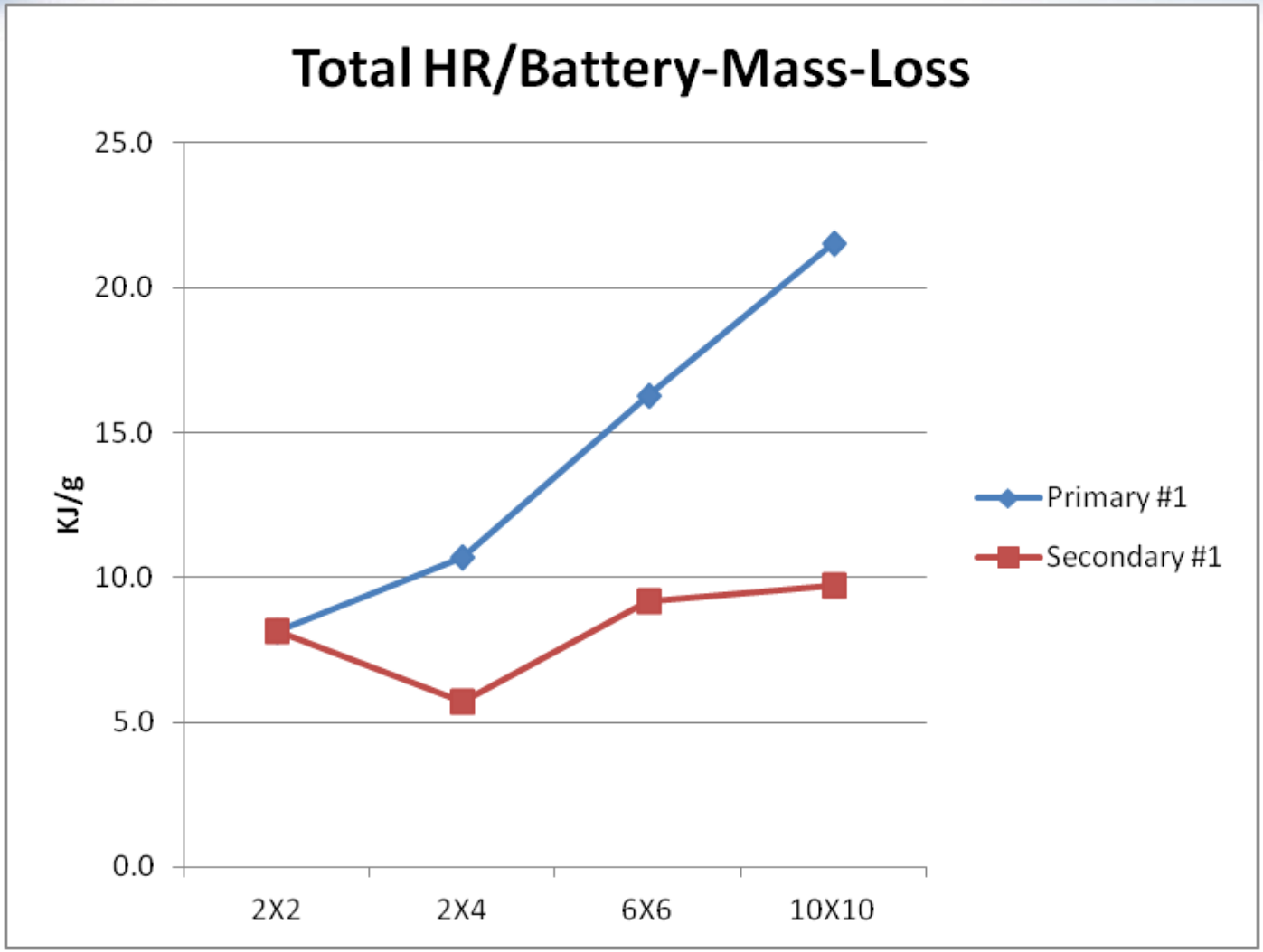
Brand	Config	Net Total HR Smoothed (KJ)	Net HRR Peak (kW)	Net Peak Side Heat flux (kw/m2)	Peak Temp. (° C)	Peak Pressure (psia)	Box Mass (g)	Mass Loss (g)	Total HR per Initial Battery Mass (KJ/g)	Total HR per Battery Mass Loss (KJ/g)	Total HR/Cell (KJ)	Total HR per Capacity (KJ/Ah)
Primary #1	6X6	2001.6	46.4	1.3	1029	0.00475	69.7	142.6	3.6	14.0	57.2	36.9
Primary #1	6X6	2388.5	41.9	2.4	842	0.00401	69.9	134.5	4.3	17.8	68.2	44.0
Primary #1	6X6	2178.8	36.5	3.2	1034	0.00378	69.6	128.1	3.9	17.0	62.3	40.2
	Mean	2189.6	41.6	2.3	968.5				3.9	16.3	62.6	40.4
	Standard DEV	193.69	4.97	0.91	109.39				0.33	1.97	5.53	3.57
Primary #1	10X10	7566.0	98.7	2.0	999	0.00365	148.7	333.8	4.7	22.7	76.4	49.3
Primary #1	10X10	7143.4	69.4	1.4	1166	0.00343	165.5	328.1	4.5	21.8	72.2	46.6
Primary #1	10X10	7189.5	69.4	1.4	1166	0.00343	163.1	357.9	4.4	20.1	72.6	46.9
	Mean	7299.6	79.2	1.6	1110.1				4.5	21.5	73.7	47.6
	Standard DEV	231.84	16.92	0.32	96.17				0.12	1.31	2.34	1.51
Secondary #1	6X6	3339.6	69.7	11.7	881	0.00889	74.2	437.6	2.1	7.6	95.4	45.9
Secondary #1	6X6	4281.5	137.5	5.9	1116	0.02301	73.7	417.4	2.7	10.3	122.3	58.8
Secondary #1	6X6	3981.7	108.3	5.9	1153	0.01108	73.6	414.2	2.5	9.6	113.8	54.7
	Mean	3867.6	105.1	7.8	1050.2				2.5	9.2	110.5	53.1
	Standard DEV	481.16	34.02	3.33	147.73				0.31	1.37	13.75	6.61
Secondary #1	10X10	14201.8	499.4	10.9	1018	0.04512	151.5	1319.2	3.2	10.8	143.5	69.0
Secondary #1	10X10	12883.4	283.6	4.8	929	0.01801	134.7	1239.3	2.9	10.4	130.1	62.6
Secondary #1	10X10	15444.8	748.6	8.8	992	0.04512	176.1	1934.2	3.5	8.0	156.0	75.0
	Mean	14176.7	510.5	8.2	979.9				3.2	9.7	143.2	68.8
	Standard DEV	1280.87	232.72	3.10	45.57				0.30	1.51	12.94	6.22

Heater Cartridge Test Results for Primary and Secondary Batteries

USTC and Boeing Lithium Battery Fire Research



USTC and Boeing Lithium Battery Fire Research



USTC and Boeing Lithium Battery Fire Research

Achievements

- Successfully captured the HRR for bulk tests of Lithium Ion Batteries and an indication of the pressure pulse simultaneously in an open space environment.
- Observed a correlation among HRR, Pressure, Mass loss rate and centerline temperature.

USTC and Boeing Lithium Battery Fire Research

OBSERVATIONS

- The total HR / initial battery mass from the primary lithium batteries was greater than the value for the secondary lithium batteries by 40% or more.
- The peak HRR increased with the number of batteries involved in the fire.
- During the heater cartridge testing, the total HR / initial battery mass increased with an increasing quantity of batteries.
- At the beginning of the explosions, the burning of propane was suppressed, aligning with the majority of CO2 vented.

USTC and Boeing Lithium Battery Fire Research

Next Steps?

- Testing of larger quantities of batteries by other organizations could be added to this data to build a model that would predict HRR for larger bulk quantities of batteries.
  - Improved measurement techniques are needed to capture the pressure pulses from random explosions coming from multiple directions.
  - Changes to the test setup allowing more airflow and greater sampling rate are needed to test larger quantities of batteries.
  - Containment of ejected materials and impact of pressure pulses will become more critical with greater quantities of batteries.

USTC and Boeing Lithium Battery Fire Research

THANK YOU

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