Thermal Runaway Comparison between Pressurized Gas vs Standard Electrolyte in 2.7Ah 18650 Cells

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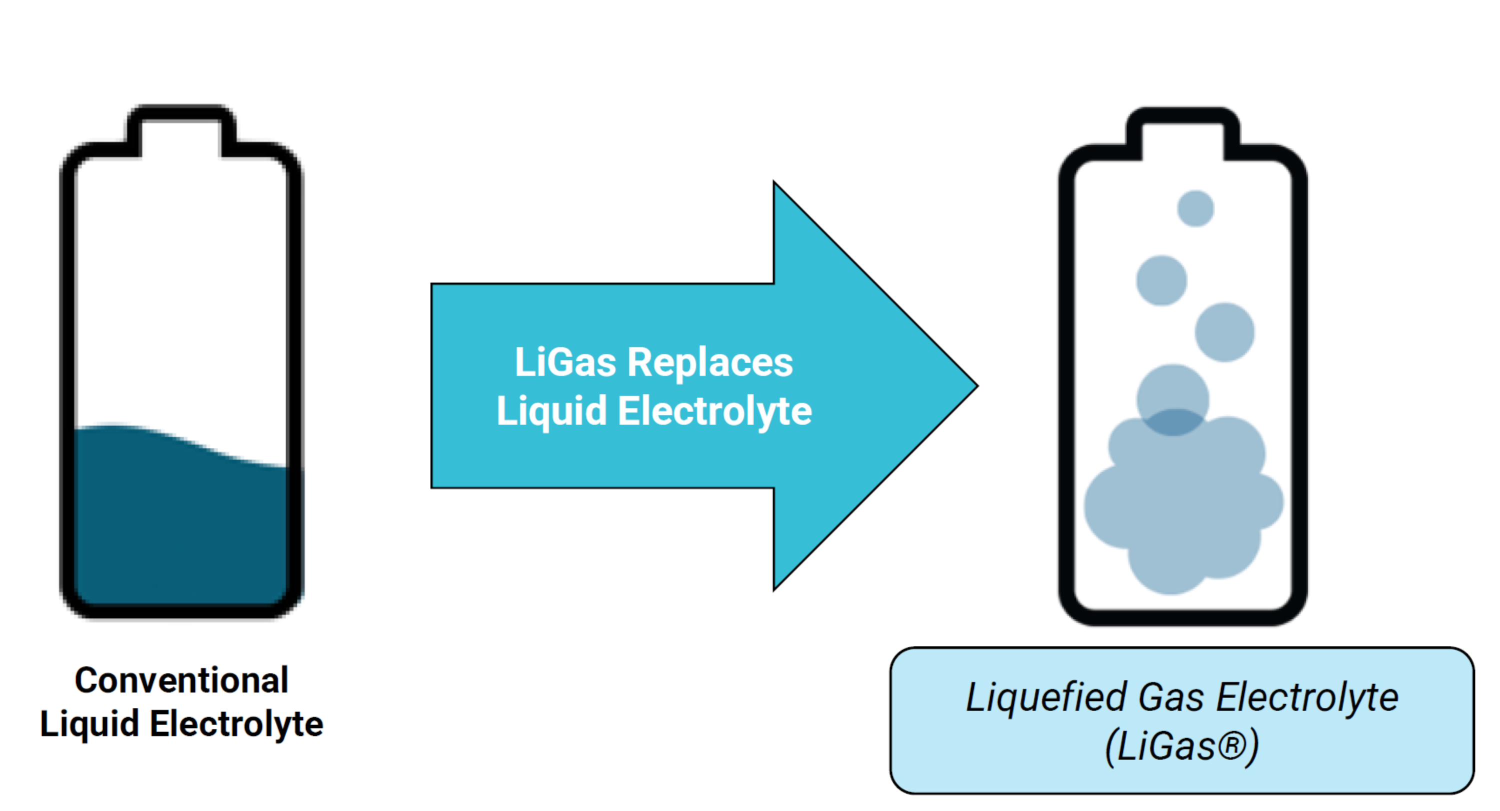

Team Effort with Many Contributors

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Acknowledgements

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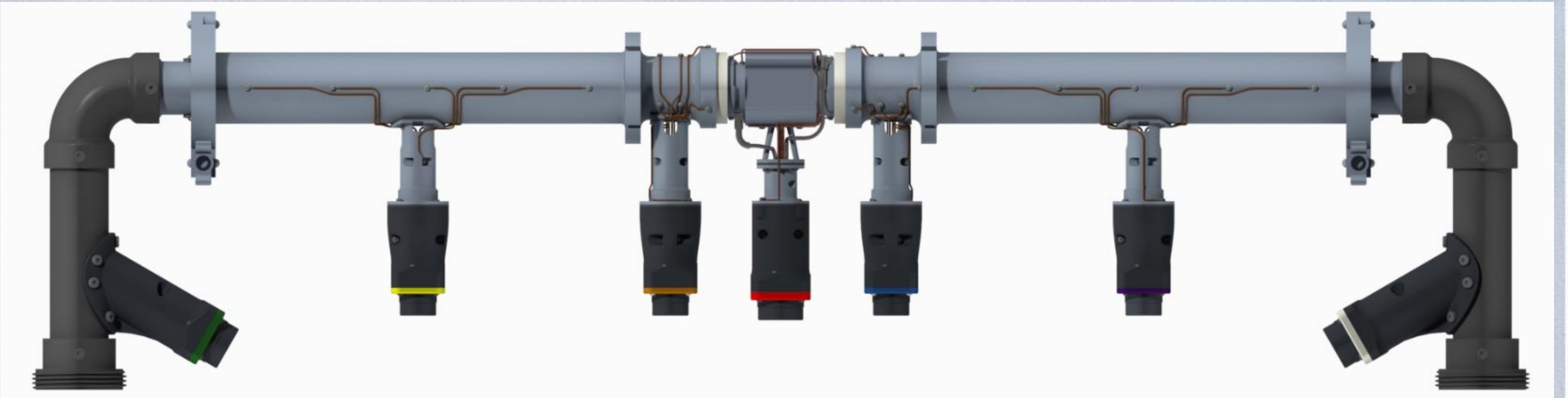
- Orion, CCP, HLS, and NAVSEA

Fractional Thermal Runaway Calorimeter



Objective, Motivation, and Team

Objectives

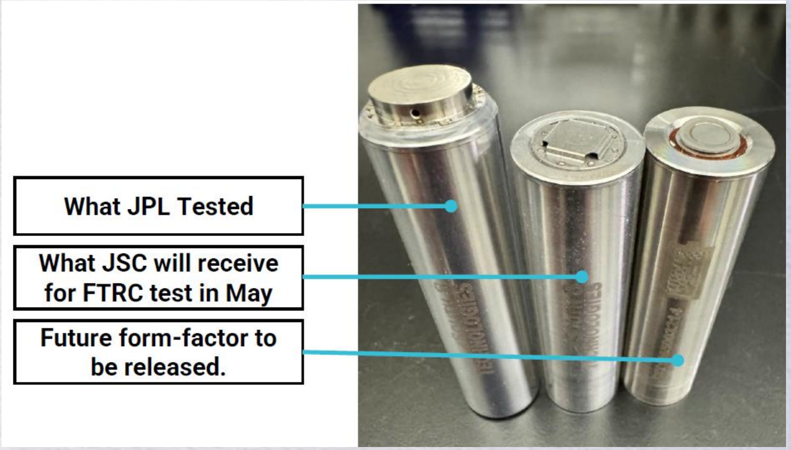
- Determine the safety impacts of the LiGas electrolyte with 2.7Ah 18650 cells vs standard liquid electrolyte.
  - FTRC with nail and heater
  - High speed radiography

Motivation

- Pressurized gas electrolyte is liquified at 300 psi and its very low viscosity enables charge/discharge operation down to -60°C
- Endothermic venting of this electrolyte mitigates severity of thermal runaway
  - Lower maximum temperatures
  - Faster cool down
  - Lower thermal mass of TR ejecta
  - Lower parasitic mass in battery design to protect adjacent cells and achieve PPR

Team

- South 8 Technology (San Diego, CA) to provide all Li-Gas cells
  - 2.7Ah LiGas 18650
  - 2.7Ah liquid electrolyte cell design
- NASA to provide cell testing
  - With NREL, Oxford University, and ESRF for radiography
  - 8-person team with 96 hrs of beamtime



LiGas 18650 Cell Design

Document Number: D-820-012 **Rev:** D
Document Title: S8T18650-27E Product Data Sheet (Preliminary)

SOUTH 8 TECHNOLOGIES

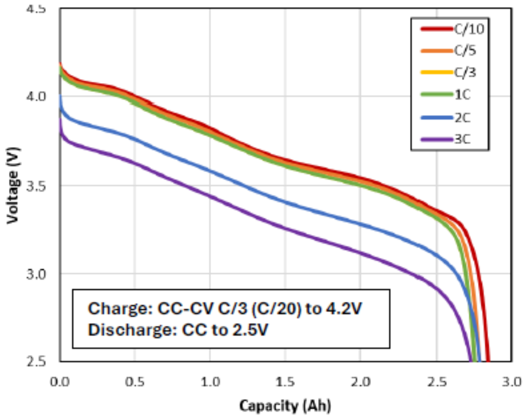
Cell Characteristics

Capacity	Typical	2.70 Ah
	Minimum	2.60 Ah
Voltage	Nominal	3.60 V
	Maximum	4.20 V
	Minimum	2.50 V
Charge Current	Standard	0.90 A
	Maximum	2.70 A
Discharge Current	Standard	0.90 A
	Maximum	5.40 A
Temperature	Charge[1]	-20 °C to +60 °C
	Discharge	-60 °C to +60 °C
	Storage	-60 °C to +60 °C
	Venting[2]	+105 °C[3]
Impedance (AC 1 kHz)	Typical	35 mΩ
	Maximum	40 mΩ

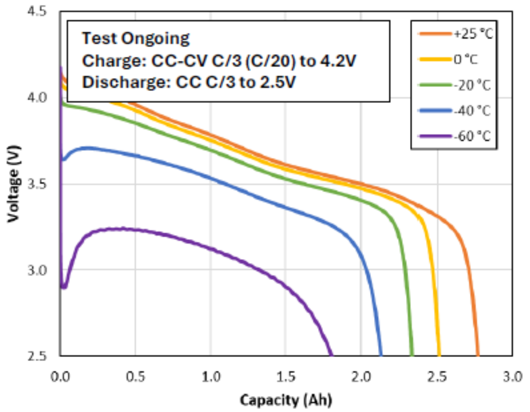
Notes

1. Charge current ≤ 0.90A. Charging at lower temperatures at lower rates is possible, contact South 8.
2. Upon venting, gas volume released will be 1.26 ± 0.2 l (+20 °C, 14.7 psia).
3. ± 10 °C.

Discharge Rate Map at +23 °C



Discharge Temperature Map



Physical Characteristics

Shape	Cylindrical
Can	Steel
Diameter	≤ 18.6 mm
Height	≤ 66.0 mm
Weight	≤ 50.0 g

Average mass 46.1g, specific energy 210 Wh/kg

Liquid Electrolyte Control Cell Design

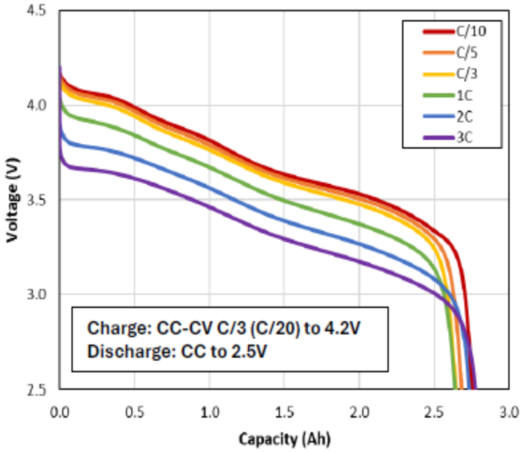
Document Number: D-820-003 **Rev:** B
Document Title: CON18650-27A Product Data Sheet (Preliminary)

SOUTH 8 TECHNOLOGIES

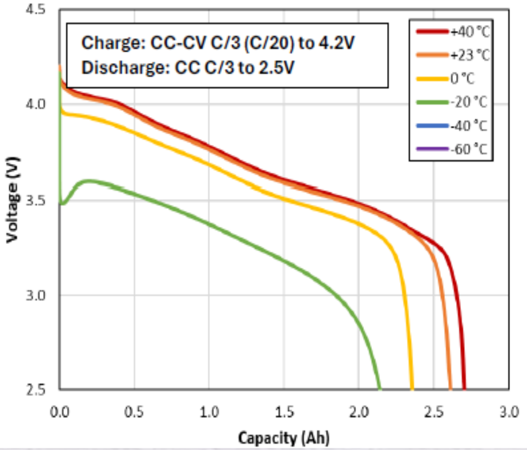
Cell Characteristics

Capacity	Typical	2.70 Ah
	Minimum	2.60 Ah
Voltage	Nominal	3.60 V
	Maximum	4.20 V
	Minimum	2.50 V
Charge Current	Standard	0.90 A
	Maximum	2.70 A
Discharge Current	Standard	0.90 A
	Maximum	5.40 A
Temperature	Charge	-0 °C to +60 °C
	Discharge	-20 °C to +60 °C
	Storage	-30 °C to +60 °C
	Venting	N/A
Impedance (AC 1 kHz)	Typical	35 mΩ
	Maximum	40 mΩ

Discharge Rate Map at +23 °C



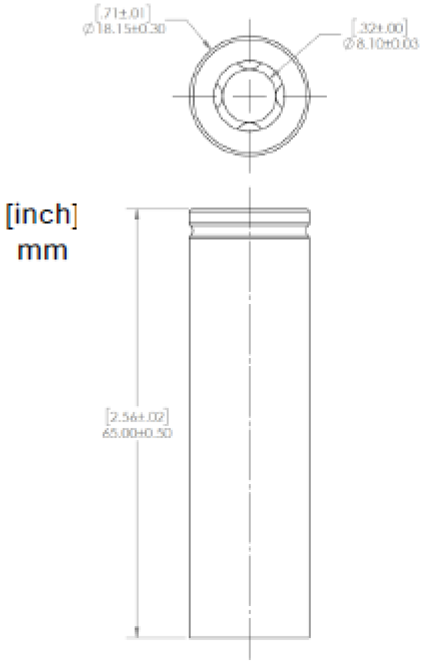
Discharge Temperature Map



Physical Characteristics

Same jellyroll as in LiGas cell design

Physical Characteristics



Shape	Cylindrical
Can	Steel
Diameter	≤ 18.2 mm
Height	≤ 65.5 mm
Weight	≤ 50.0 g

Average mass 44.3g, specific energy 219 Wh/kg

Text Matrix Plan – Spring 2025 ESRF

Run	Cell General Design	P/N Model	Cell Serial/ID	Charging Protocol	State of Charge	Cell Pre-Test Mass(g)	Charged OCV (V)	Trigger
60	S8T LiGas Electrolyte	S8T18650	3257	0.9A to 4.2V w/ 50mA taper	100%	46.31	4.193	Nail
61	S8T LiGas Electrolyte	S8T18650	3251	0.9A to 4.2V w/ 50mA taper	100%	45.89	4.195	Nail
62	S8T LiGas Electrolyte	S8T18650	3259	0.9A to 4.2V w/ 50mA taper	100%	45.75	4.184	Nail
63	S8T LiGas Electrolyte	S8T18650	3260	0.9A to 4.2V w/ 50mA taper	100%	45.99	4.195	Nail
64	S8T LiGas Electrolyte	S8T18650	3258	0.9A to 4.2V w/ 50mA taper	100%	46.26	4.195	Nail
65	S8T LiGas Electrolyte	S8T18650	3261	0.9A to 4.2V w/ 50mA taper	100%	46.14	4.193	Nail
66	S8T Liquid Electrolyte	CON18650	140	0.9A to 4.2V w/ 50mA taper	100%	44.3	4.192	Nail
67	S8T Liquid Electrolyte	CON18650	146	0.9A to 4.2V w/ 50mA taper	100%	44.24	4.191	Nail
68	S8T Liquid Electrolyte	CON18650	137	0.9A to 4.2V w/ 50mA taper	100%	44.34	4.193	Nail
69	S8T Liquid Electrolyte	CON18650	138	0.9A to 4.2V w/ 50mA taper	100%	44.23	4.195	Nail
70	S8T Liquid Electrolyte	CON18650	139	0.9A to 4.2V w/ 50mA taper	100%	44.35	4.194	Nail
71	S8T Liquid Electrolyte	CON18650	142	0.9A to 4.2V w/ 50mA taper	100%	44.2	4.191	Nail
105	S8T LiGas Electrolyte	S8T18650	3264	0.9A to 4.2V w/ 50mA taper	100%	46.37	4.196	Heater
106	S8T LiGas Electrolyte	S8T18650	3263	0.9A to 4.2V w/ 50mA taper	100%	46.03	4.183	Heater
107	S8T LiGas Electrolyte	S8T18650	3262	0.9A to 4.2V w/ 50mA taper	100%	46.09	4.181	Heater
108	S8T LiGas Electrolyte	S8T18650	3265	0.9A to 4.2V w/ 50mA taper	100%	46.18	4.182	Heater
109	S8T LiGas Electrolyte	S8T18650	3252	0.9A to 4.2V w/ 50mA taper	100%	46.22	4.183	Heater
110	S8T LiGas Electrolyte	S8T18650	3248	0.9A to 4.2V w/ 50mA taper	100%	45.97	4.208	Heater
111	S8T Liquid Electrolyte	CON18650	136	0.9A to 4.2V w/ 50mA taper	100%	44.12	4.194	Heater
112	S8T Liquid Electrolyte	CON18650	144	0.9A to 4.2V w/ 50mA taper	100%	44.3	4.195	Heater
113	S8T Liquid Electrolyte	CON18650	145	0.9A to 4.2V w/ 50mA taper	100%	44.28	4.194	Heater
114	S8T Liquid Electrolyte	CON18650	141	0.9A to 4.2V w/ 50mA taper	100%	44.55	4.195	Heater
115	S8T Liquid Electrolyte	CON18650	143	0.9A to 4.2V w/ 50mA taper	100%	44.36	4.182	Heater
116	S8T Liquid Electrolyte	CON18650	147	0.9A to 4.2V w/ 50mA taper	100%	44.44	4.185	Heater

One prior test at JSC with heater and open casket FTRC achieved TR in 26 minutes.

- Heater power was dialed down from 1kW (for ~3min) to levels that achieved ~7°C rise per minute.
- Higher heating power risks causing cell venting without TR
- Lower heater power = long heating times = high heating losses = poorer calorimetry

Max Cell Can & Ejecta Temperatures

			Cell Can Wall				Ejecta		
Run	Design	Trigger	Max T1 (°C)	Max T2 (°C)	Max T (°C)	Time to Max T (s)	Max T (°C)	Time to Max T (s)	Sensor
60	LiGas	Nail	229	56	229	6	374	4	TC99
61	LiGas	Nail	444	417	444	1	303	7	TC56
62	LiGas	Nail	47	49	49	178	263	3	TC56
63	LiGas	Nail	197	120	197	1	381	5	TC56
64	LiGas	Nail	73	37	73	1	250	41	TC56
65	LiGas	Nail	171	434	434	4	385	3	TC56
108	LiGas	Nail	288	364	364	4	219	5	TC56
109	LiGas	Nail	79	87	87	4	366	5	TC56
110	LiGas	Nail	208	222	222	1	409	2	TC56
			192.9	198.4	Average	St Dev	Average	St Dev	
				Average	233.2	151.8	327.8	69.8	
			Cell Can Wall				Ejecta		
Run	Design	Trigger	Max T1 (°C)	Max T2 (°C)	Max T	Time to Max T (s)	Max T (°C)	Time to Max T (s)	Sensor
66	Liquid E	Nail	260	348	348	16	246	2	TC56
67	Liquid E	Nail	706	49	706	2	187	3	TC48
68	Liquid E	Nail	422	211	422	3	203	3	TC56
69	Liquid E	Nail	389	464	464	2	174	2	TC49
70	Liquid E	Nail	313	468	468	6	185	3	TC48
71	Liquid E	Nail	452	346	452	2	268	2	TC56
111	Liquid E	Nail	365	487	487	5	208	3	TC48
112	Liquid E	Nail	404	587	587	3	159	5	TC48
113	Liquid E	Nail	507	311	507	5	232	2	TC44
114	Liquid E	Nail	469	568	568	1	228	3	TC48
115	Liquid E	Nail	425	407	425	2	298	3	TC56
116	Liquid E	Nail	251	463	463	6	196	3	TC44
			413.6	392.4	Average	St Dev	Average	St Dev	
				Average	491.4	92.8	215.3	40.6	

After 3 unsuccessful heater triggers with LiGas cells, only nail triggers were used thereafter

- **LiGas reduces cell can max Temp by 53% (258°C)**
- **LiGas increases cell ejecta max Temp by 52% (112°C)**

FTRC Results With Nail Trigger

Test ID	Cell Description	Trigger Method	Total Energy	Cell Body Energy	Negative Ejecta Energy	Positive Ejecta Energy	Mass Ejected (g)
ESRF Spring 2025_RUN060	S8T LiGas Electrolyte S8T18650	Nail	64.06	8.83	54.87	0.36	25.69
ESRF Spring 2025_RUN061	S8T LiGas Electrolyte S8T18650	Nail	66.31	11.44	54.09	0.78	30.4
ESRF Spring 2025_RUN062	S8T LiGas Electrolyte S8T18650	Nail	56.82	5.61	50.87	0.34	29.31
ESRF Spring 2025_RUN063	S8T LiGas Electrolyte S8T18650	Nail	67.34	8.00	58.95	0.40	30.31
ESRF Spring 2025_RUN064	S8T LiGas Electrolyte S8T18650	Nail	60.64	6.70	53.60	0.33	29.15
ESRF Spring 2025_RUN065	S8T LiGas Electrolyte S8T18650	Nail	67.16	14.63	52.12	0.41	23.72
ESRF Spring 2025_RUN105	S8T LiGas Electrolyte S8T18650						
ESRF Spring 2025_RUN108	S8T LiGas Electrolyte S8T18650	Nail	62.30	16.85	44.75	0.70	20.84
ESRF Spring 2025_RUN109	S8T LiGas Electrolyte S8T18650	Nail	70.12	5.57	64.28	0.27	30.76
ESRF Spring 2025_RUN110	S8T LiGas Electrolyte S8T18650	Nail	62.09	8.38	53.13	0.58	29.41

Test ID	Cell Description	Trigger Method	Total Energy	Cell Body Energy	Positive Ejecta Energy	Negative Ejecta Energy	Mass Ejected (g)
ESRF Spring 2025_RUN066	S8T Liquid Electrolyte CON18650	Nail	61.56	14.46	46.13	0.97	18.07
ESRF Spring 2025_RUN067	S8T Liquid Electrolyte CON18650	Nail	62.56	22.56	39.06	0.95	17.18
ESRF Spring 2025_RUN068	S8T Liquid Electrolyte CON18650	Nail	64.03	22.04	41.05	0.93	17.82
ESRF Spring 2025_RUN069	S8T Liquid Electrolyte CON18650	Nail	63.12	23.57	38.82	0.73	17.32
ESRF Spring 2025_RUN070	S8T Liquid Electrolyte CON18650	Nail	62.81	25.07	36.78	0.96	16.66
ESRF Spring 2025_RUN071	S8T Liquid Electrolyte CON18650	Nail	62.59	22.44	39.13	1.02	17.55
ESRF Spring 2025_RUN111	S8T Liquid Electrolyte CON18650	Nail	62.00	23.64	37.37	0.99	17.88
ESRF Spring 2025_RUN112	S8T Liquid Electrolyte CON18650	Nail	62.70	26.66	35.19	0.85	16.34
ESRF Spring 2025_RUN113	S8T Liquid Electrolyte CON18650	Nail	61.69	22.28	38.77	0.65	18.54
ESRF Spring 2025_RUN114	S8T Liquid Electrolyte CON18650	Nail	66.40	19.17	46.58	0.65	21.09
ESRF Spring 2025_RUN115	S8T Liquid Electrolyte CON18650	Nail	64.96	20.20	44.06	0.70	20.3
ESRF Spring 2025_RUN116	S8T Liquid Electrolyte CON18650	Nail	62.11	24.46	36.70	0.94	18.52

Three attempts with the heater trigger yield only 1 successful TR and it took 49 minutes

- The other two heater runs resulted in venting without TR

Thereafter we decided to revert back to nail trigger and got 21 nail runs done in total

- 9 with LiGas and 12 with Liquid control cells)
- **Nearly identical total heat output (64 kJ for LiGas and 63 kJ for liquid electrolyte)**

Average Heat Output and Distributions Comparison

LiGas	Total Energy	Cell Body Energy	Negative Ejecta Energy	Positive Ejecta Energy	Mass Ejected (g)
Average	64.0953	9.5574	54.0736	0.4644	27.7322
sdev	4.0812	3.9762	5.3707	0.1799	3.5003
Normalized	100%	15%	84%	1%	
sdev%	6.367%	41.603%	9.932%	38.745%	12.622%
Min	56.8214	5.5704	44.7503	0.2723	20.8400
Max	70.1244	16.8516	64.2818	0.7813	30.7600
Range	13.3030	11.2812	19.5314	0.5090	9.9200
Range%	20.76%	118.04%	36.12%	109.60%	35.77%
-3sigma	51.8518	-2.3712	37.9616	-0.0754	17.2314
+3sigma	76.3388	21.4861	70.1856	1.0042	38.2330
6sRange	24.4870	23.8573	32.2240	1.0796	21.0016
6sRange%	38.204%	249.620%	59.593%	232.472%	75.730%
Low Outliers	0	0	0	0	0
High Outliers	0	0	0	0	0
Total Outliers	0	0	0	0	0
Count	9	9	9	9	9
Outliers%	0.00%	0.00%	0.00%	0.00%	0.00%

Li-ion control	Total Energy	Cell Body Energy	Positive Ejecta Energy	Negative Ejecta Energy	Mass Ejected (g)
Average	63.0437	22.2130	39.9701	0.8606	18.1058
sdev	1.4301	3.1695	3.7459	0.1403	1.3885
Normalized	100%	35%	63%	1%	
sdev%	2.268%	14.269%	9.372%	16.308%	7.669%
Min	61.5613	14.4606	35.1902	0.6451	16.3400
Max	66.3998	26.6565	46.5804	1.0219	21.0900
Range	4.8385	12.1958	11.3902	0.3768	4.7500
Range%	7.67%	54.90%	28.50%	43.78%	26.23%
-3sigma	58.7535	12.7046	28.7323	0.4396	13.9405
+3sigma	67.3340	31.7214	51.2080	1.2817	22.2712
6sRange	8.5805	19.0168	22.4757	0.8421	8.3307
6sRange%	13.610%	85.611%	56.231%	97.849%	46.011%
Low Outliers	0	0	0	0	0
High Outliers	0	0	0	0	0
Total Outliers	0	0	0	0	0
Count	12	12	12	12	12
Outliers%	0.00%	0.00%	0.00%	0.00%	0.00%

LiGas cell designed with (-) bottom vent

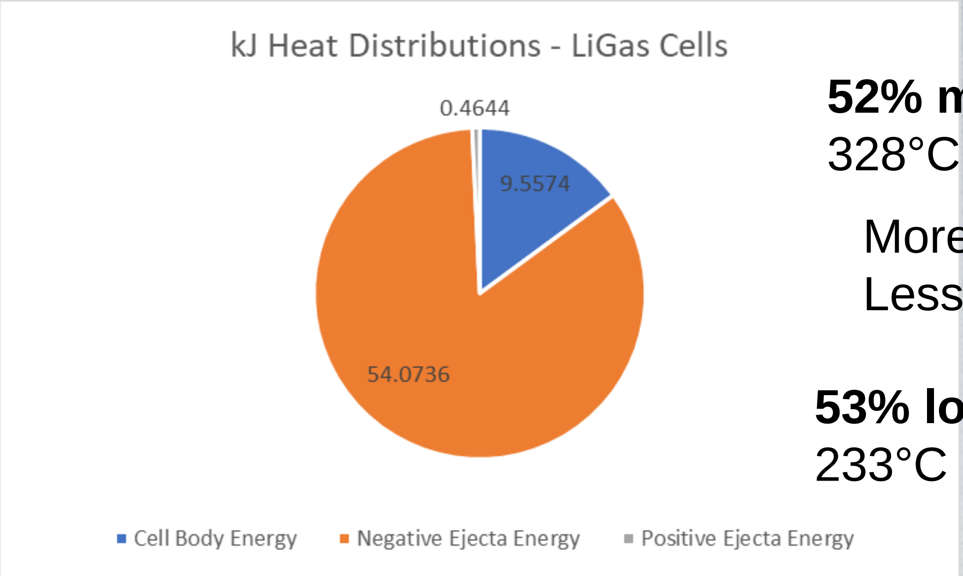
- More ejecta energy (84%)
- More mass ejected (28g)

Same total heat output
LiGas 64 vs 63 kJ

Li-ion control cells designed with (+) top header vent

- Lower ejected energy (63%)
- Lower mass (18g)

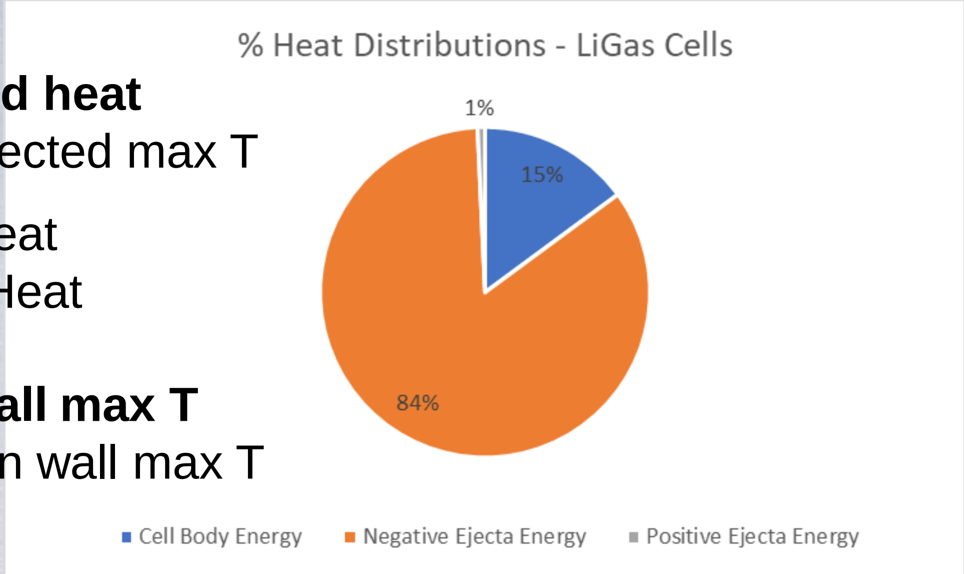
Nail Trigger Heat Distribution Comparison



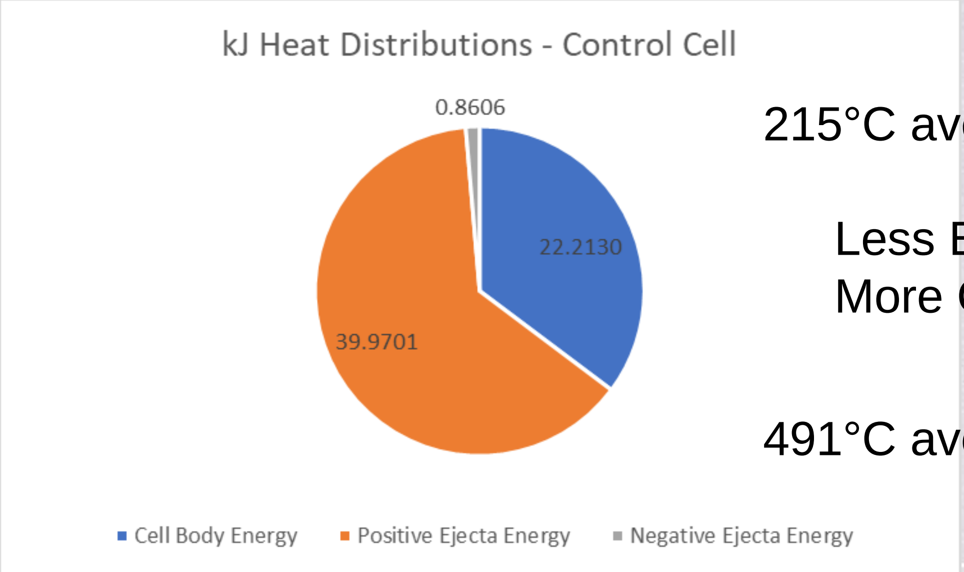
52% more ejected heat
328°C average ejected max T

More Ejected Heat
Less Can Wall Heat

53% lower can wall max T
233°C average can wall max T



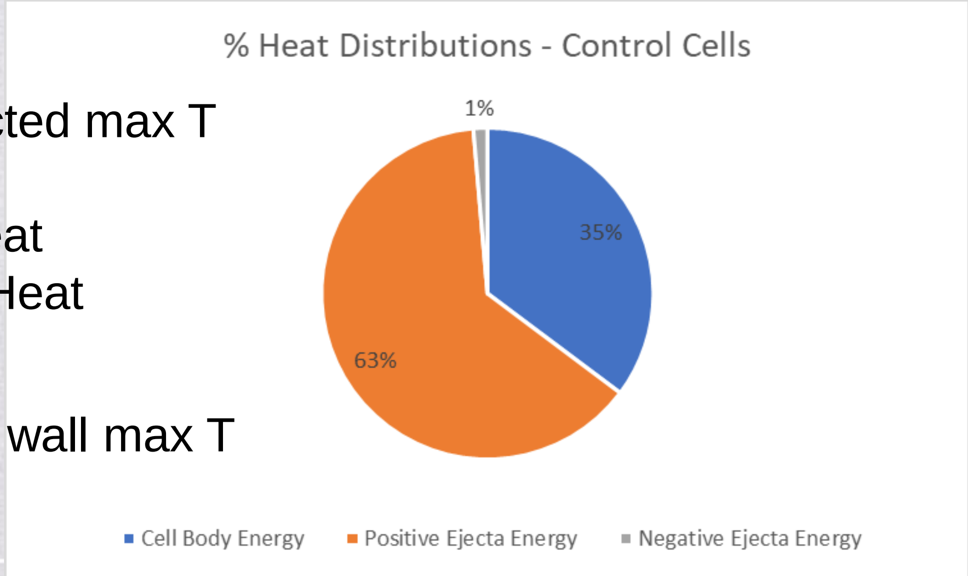
Same total heat output



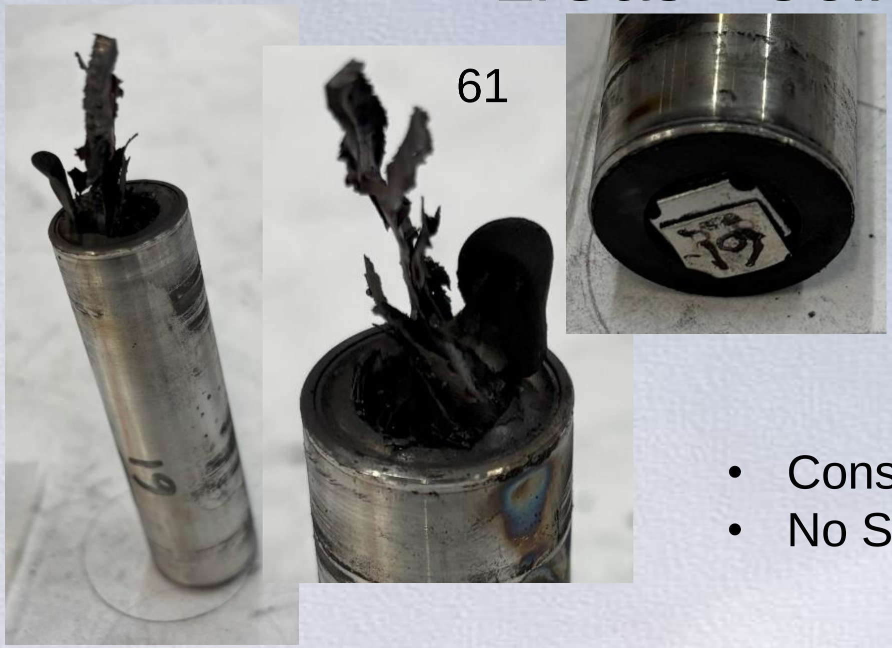
215°C average ejected max T

Less Ejected Heat
More Can Wall Heat

491°C average can wall max T



LiGas - Cell Carcasses - Nail



- Consistent bottom vent opening
- No SWR or BR in all 9 nail runs

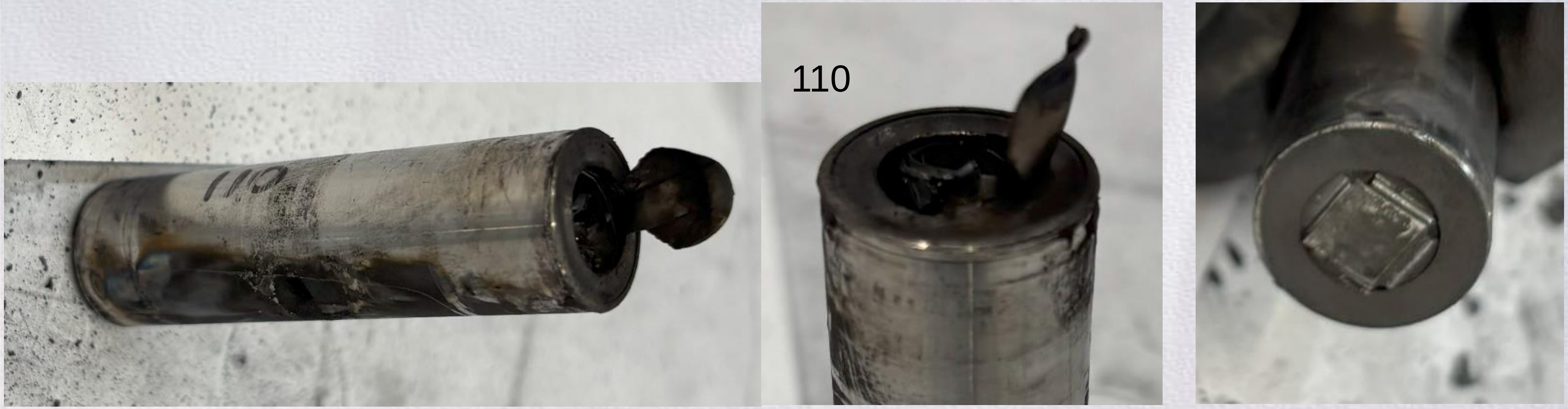
LiGas - Cell Carcasses - Nail

108

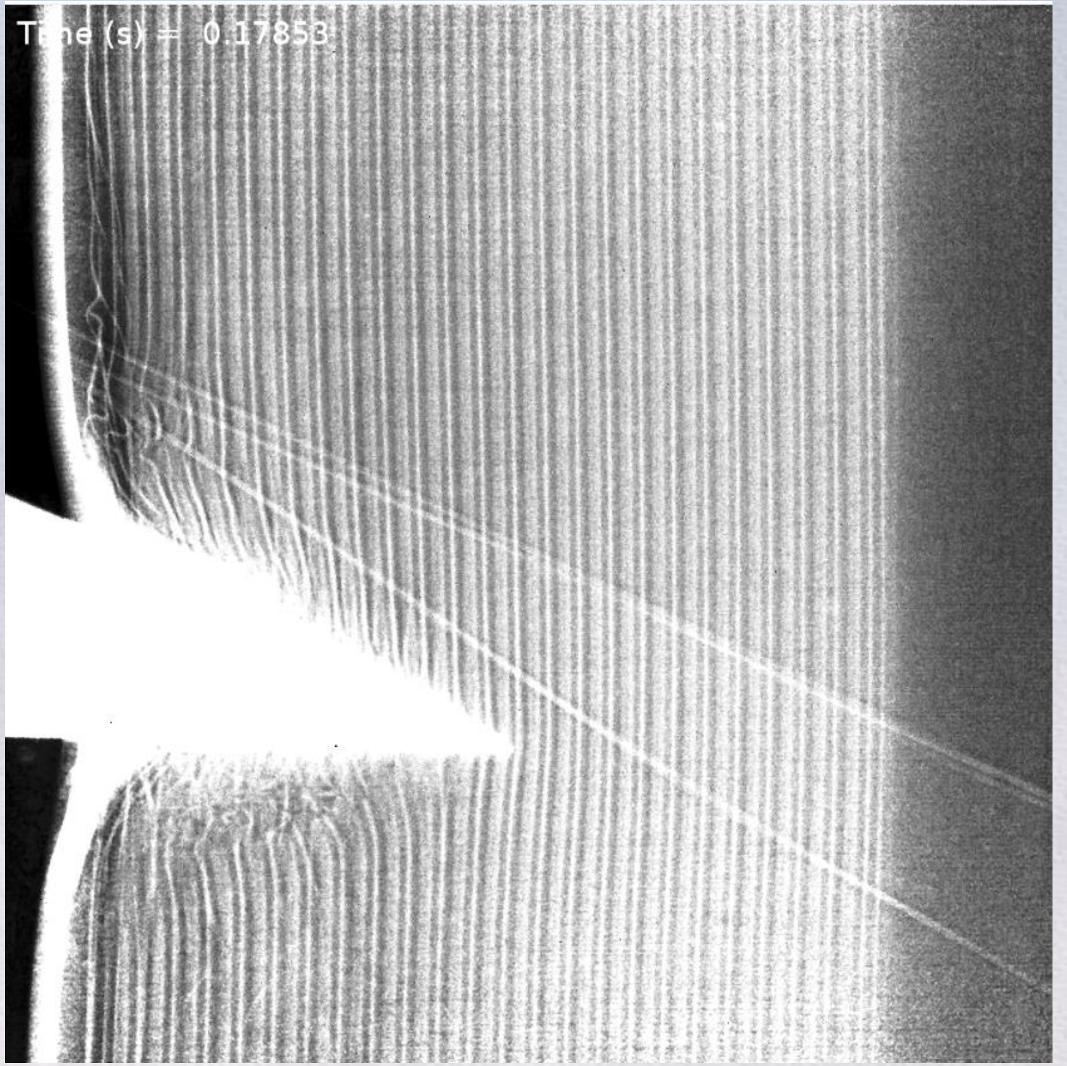
109

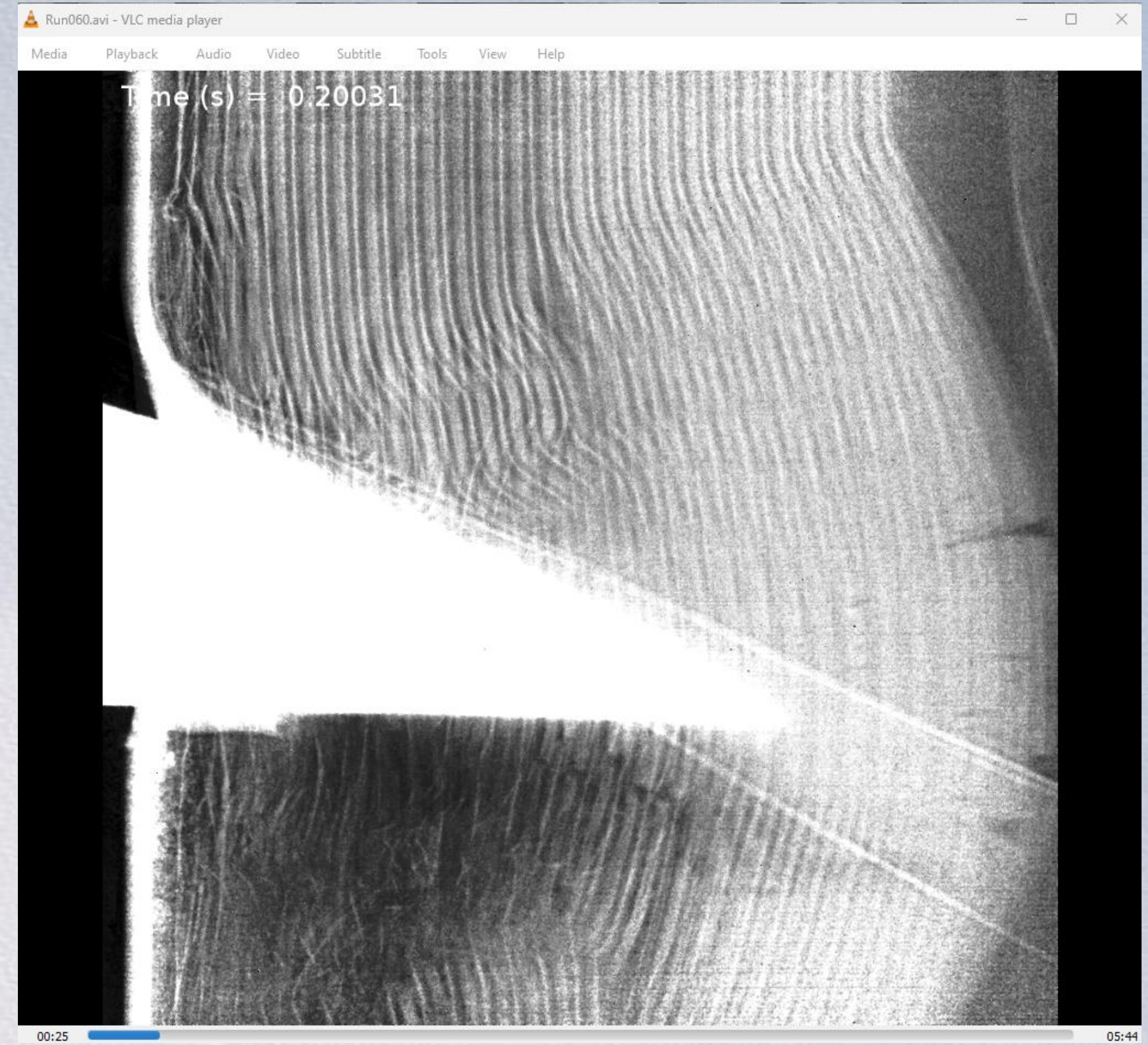
- Consistent bottom vent opening
- No SWR or top ruptures in all 9 nail runs

110



Radiography for LiGas with Nail Trigger

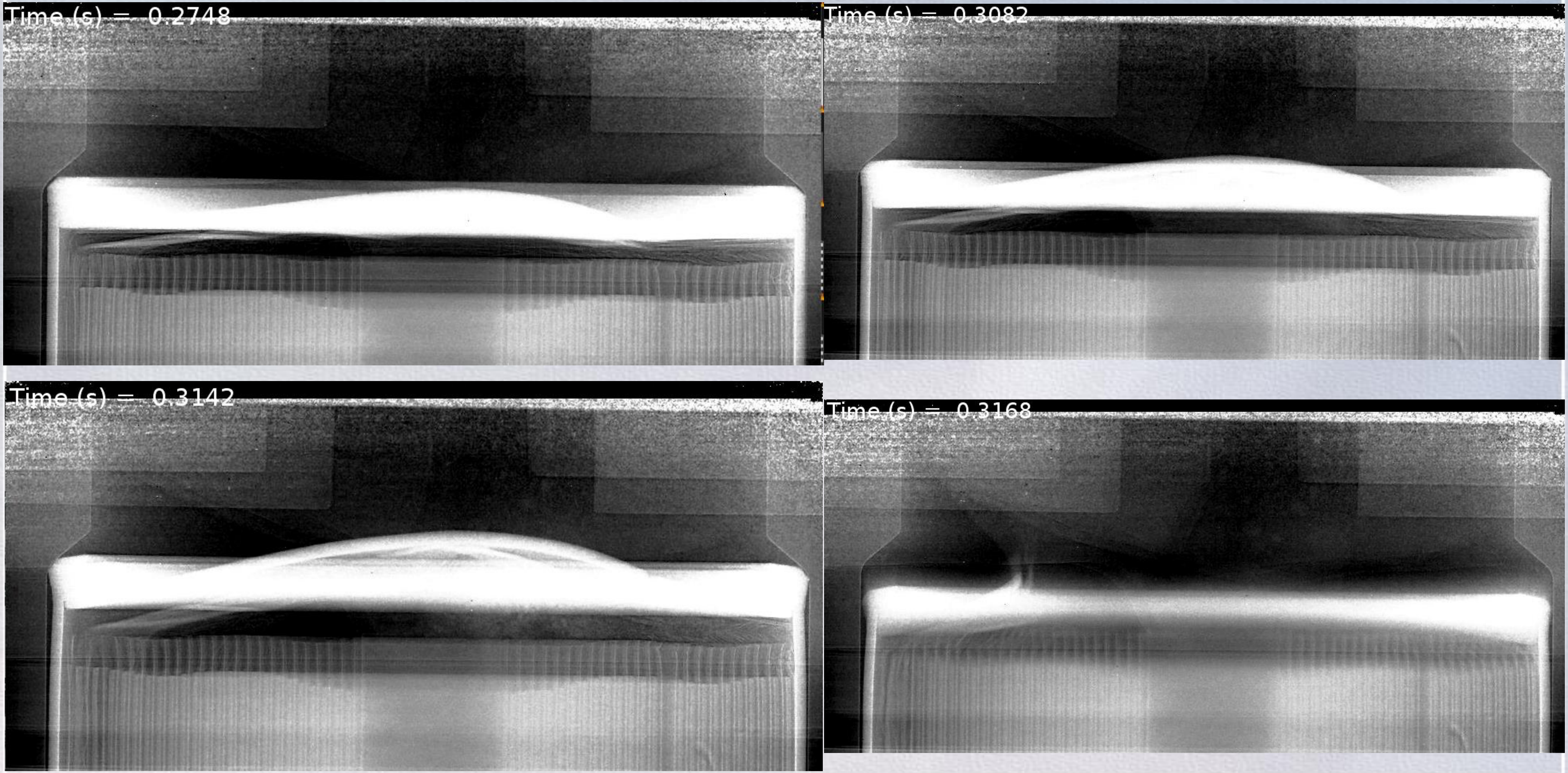




Run 60 - Immediate TR upon nail pen
Vent is on bottom of image

Radiographic Snapshots of Bottom Vent of LiGas Run 61

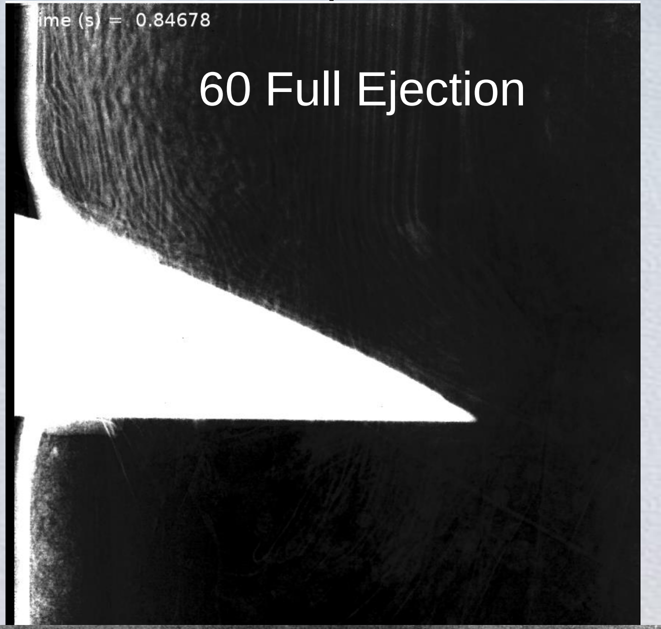
Cell inverted to allow FOV on bottom vent

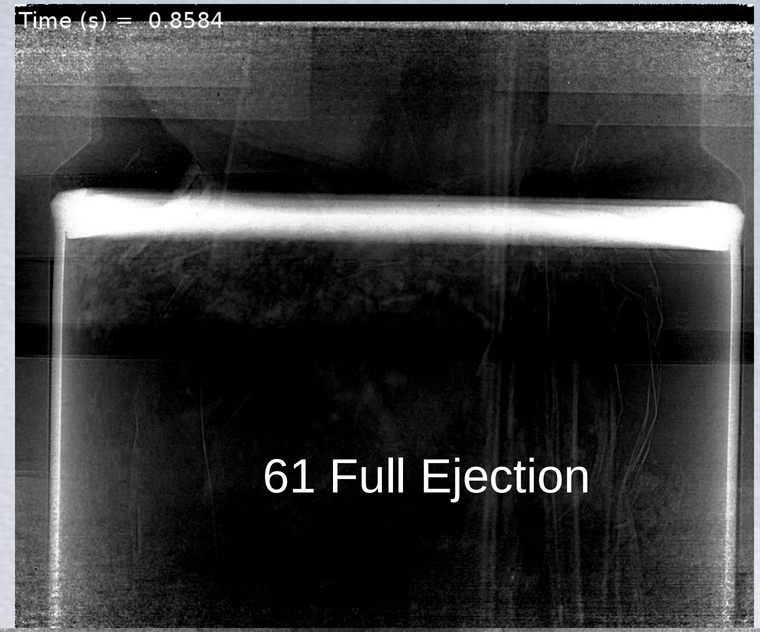


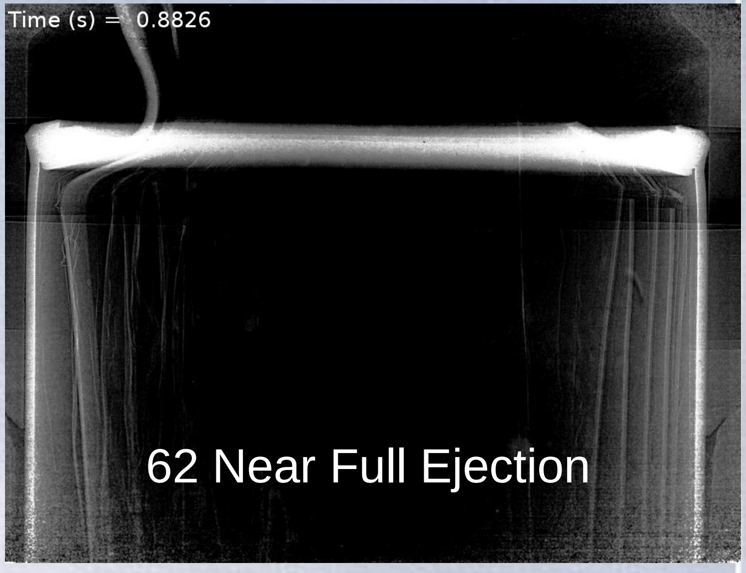
Radiography for LiGas with Nail Trigger

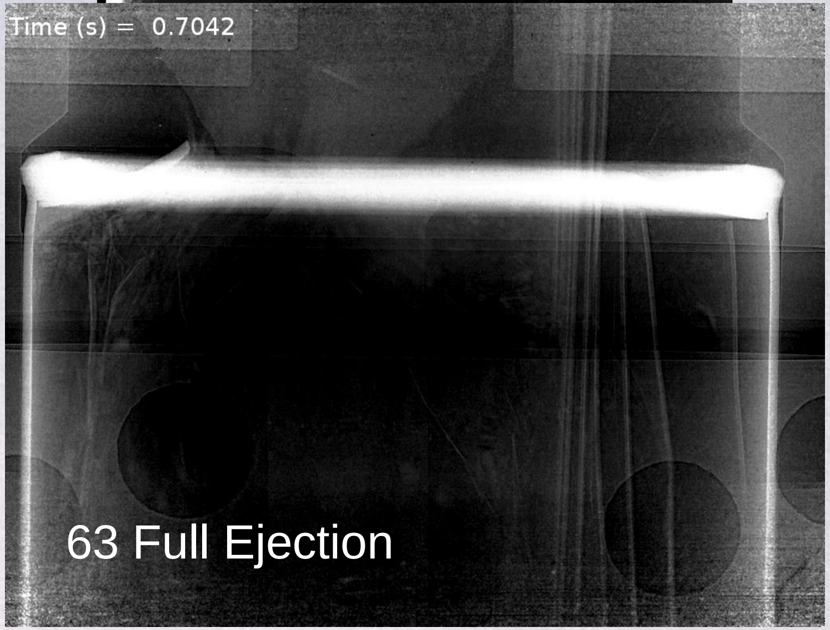
Top

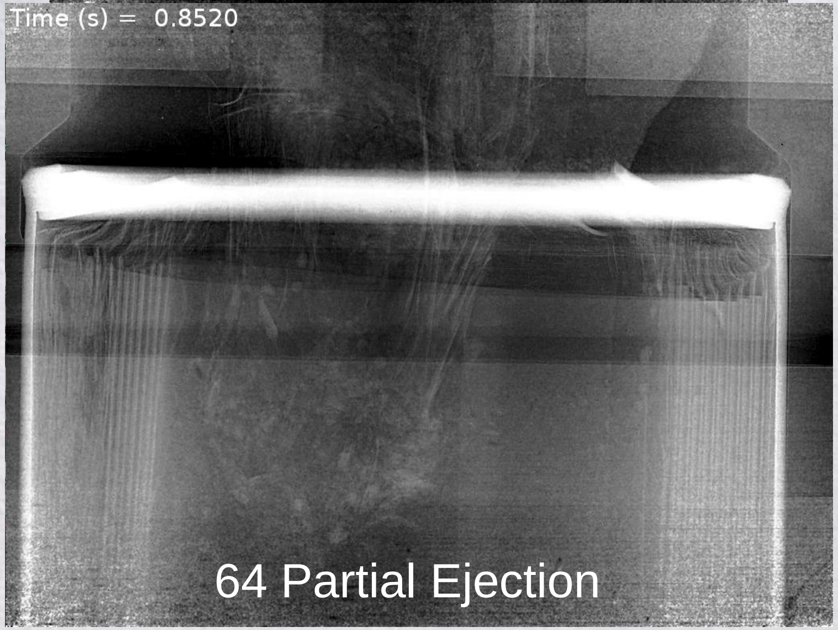
Bottom

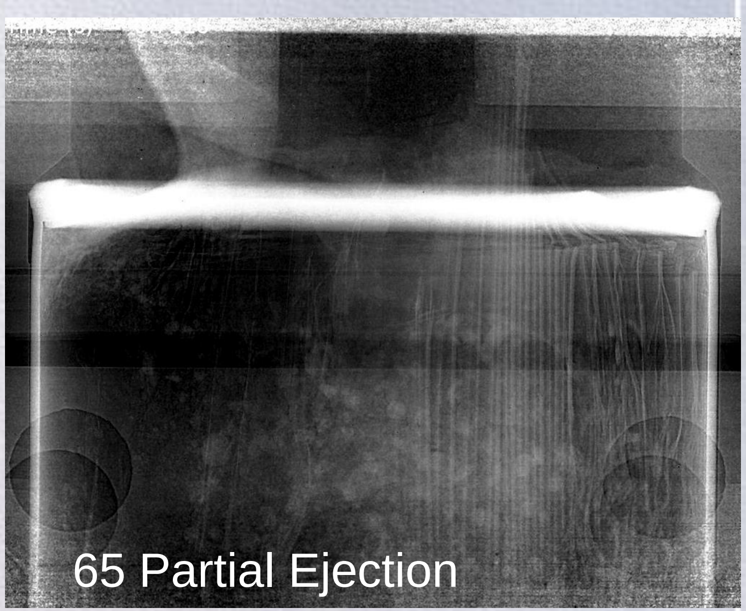




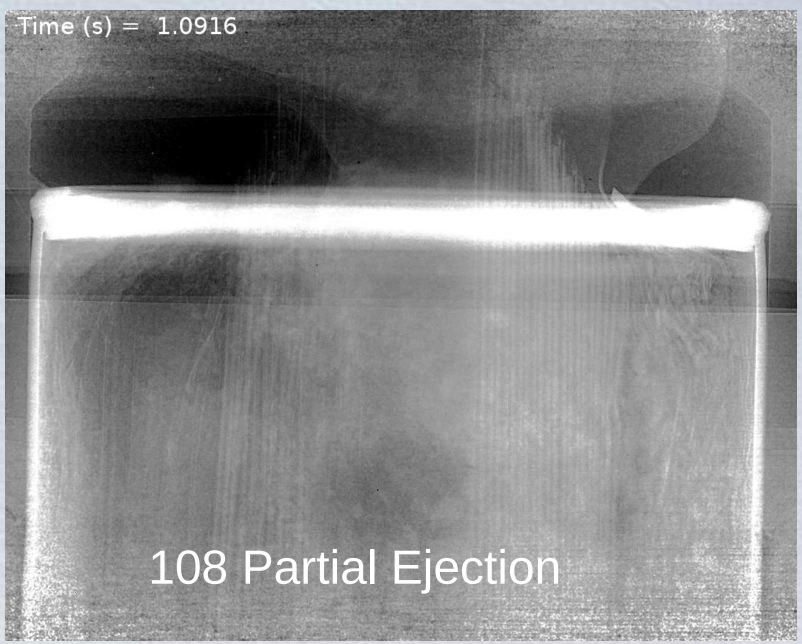




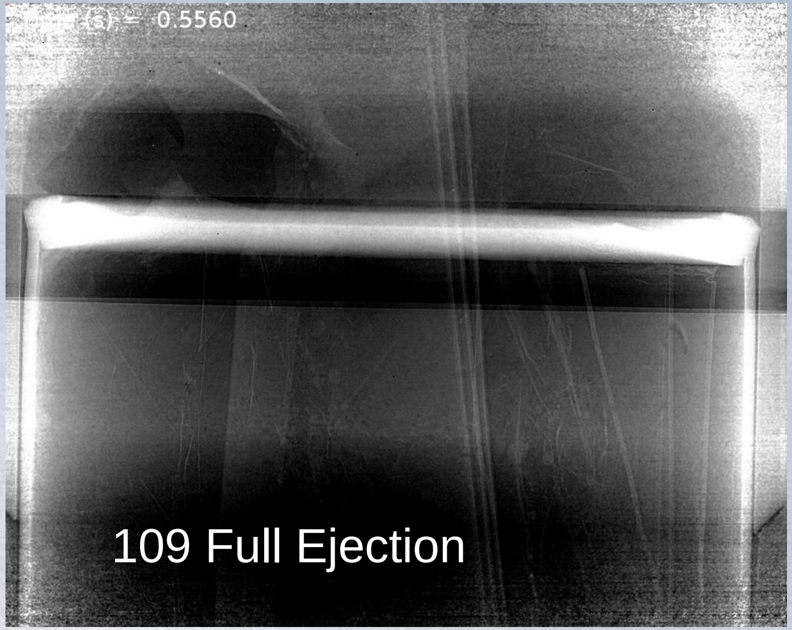




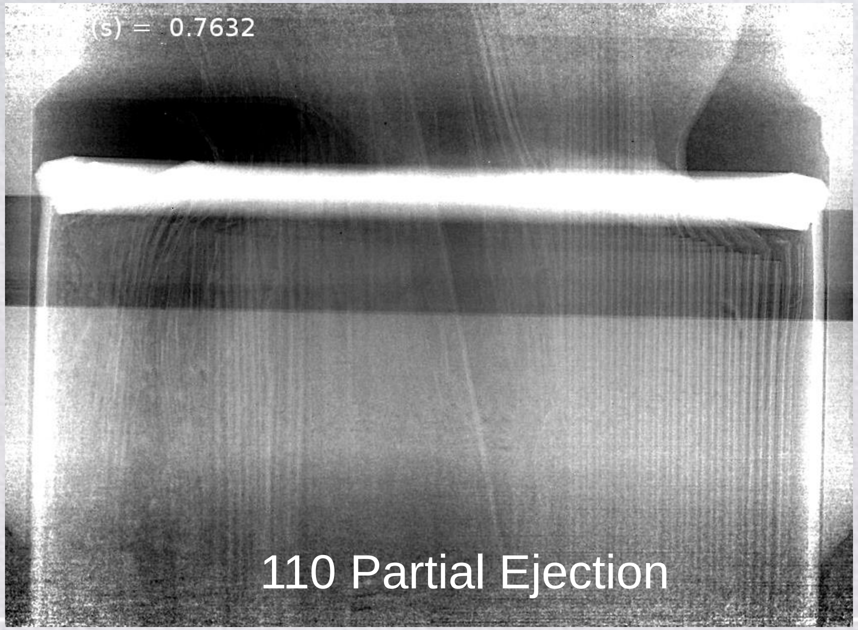
Radiography for LiGas with Nail Trigger



108 Partial Ejection



109 Full Ejection



110 Partial Ejection

Conclusions and Future Work

Conclusions

- LiGas doesn’t change total TR heat under nail penetration vs standard liquid electrolyte
  - **LiGas dramatically reduces conductive heat distribution through can wall**
    - **Cells can be brought closer together in PPR battery designs, reducing interstitial heat sink mass**
  - *LiGas ejected heat fraction is dramatically increased*
    - *Stronger blast plates and larger gaps may be needed in PPR battery designs*
- Bottom vent of LiGas cell design worked well for nail runs
- Heater trigger requires very slow heating to prevent venting prior to TR

Future Work

- >265 Wh/kg 18650 and 21700 LiGas development is underway & funded by TX Space Commission
- ISCD triggers cells will be included