CHARACTERIZATION OF THE GS YUASA 134 AH CELL THERMAL RUNAWAY EVENTS WITH LARGE FORMAT FRACTIONAL THERMAL RUNAWAY CALORIMETRY (L-FTRC)

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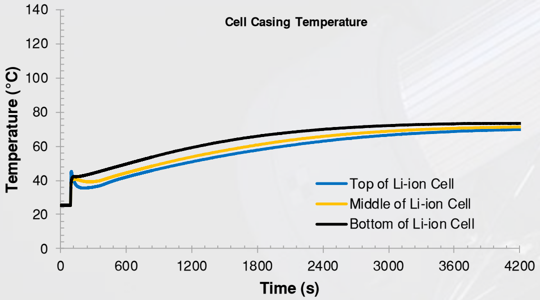
GETTING STARTED

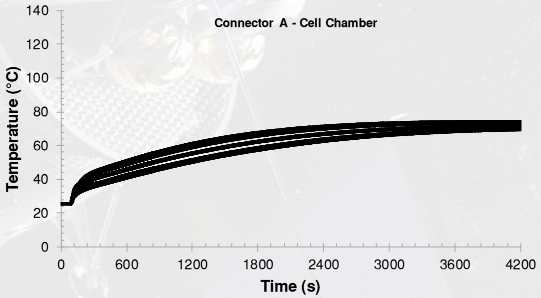
- **After the success of the small format fractional thermal runaway calorimeter (S-FTRC), there was a desire to develop similar capability for larger format lithium-ion (Li-ion) cells:**
  - A recent NESC assessment was initiated in early 2018 to develop a large format fractional thermal runaway calorimeter *(L-FTRC)* capable of supporting cell formats with capacities greater than 100 Ah.
  - The NESC led assessment, which concluded in April 2020, involved collaboration between the NESC, NASA Johnson Space Center, NASA Glenn Research Center, SAIC®, and USRA.
  - The completed L-FTRC was designed trigger the 134 Ah GS Yuasa Li-ion cell *(LSE-134)* used by the International Space Station *(ISS)* into thermal runaway via nail penetration.
  - An extensive test series was conducted at the conclusion of the assessment at the test facilities provided by the JSC Energy Systems Test Area *(ESTA)* where 13 LSE-134 Li-ion cells were triggered into thermal runaway via nail penetration.
- **A preliminary status of the L-FTRC results was presented at the NASA Aerospace Battery Workshop 2019; this presentation serves as presentation of the final results.**

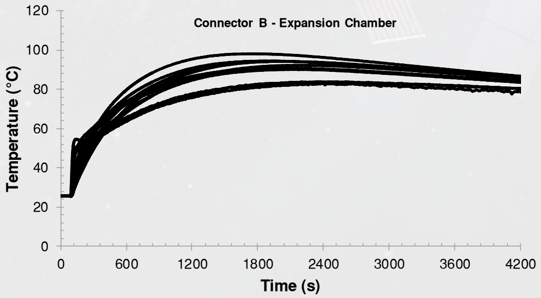
GETTING STARTED

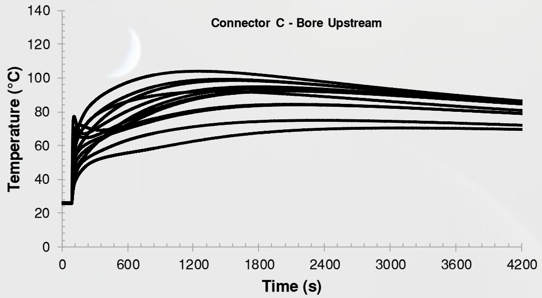
CALCULATING ENERGY YIELD

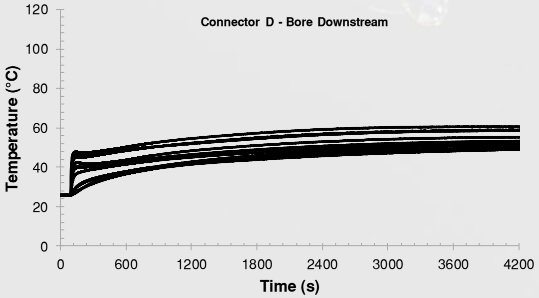
- **The primary goal for the L-FTRC was to characterize both the total thermal runaway energy release and the fractions of the energy released through the cell casing vs. the ejected electrode winding vs. the ejected gases and effluents:**
  - This is accomplished by calculating the $\sum m_i C_{p_i} dT_i$ of the calorimeter components *(cannot disclose images at this time)* as a whole and then by dividing said energy calculations based on sub-assembly.
  - Plots below provide example of the L-FTRC thermal response to a LSE-134 cell thermal runaway event *(Run 2)*.

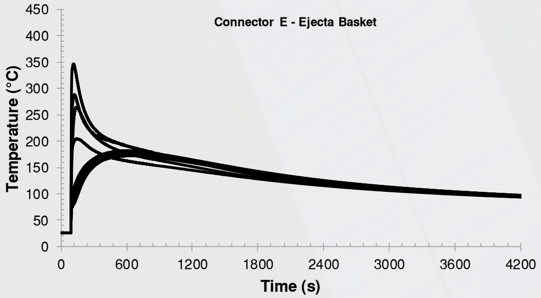


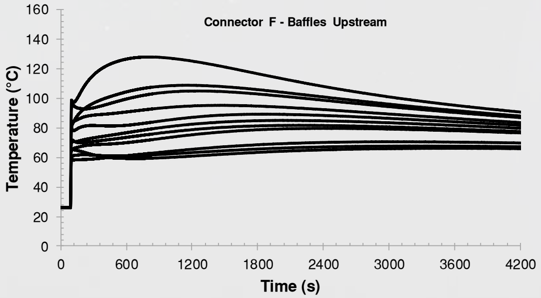


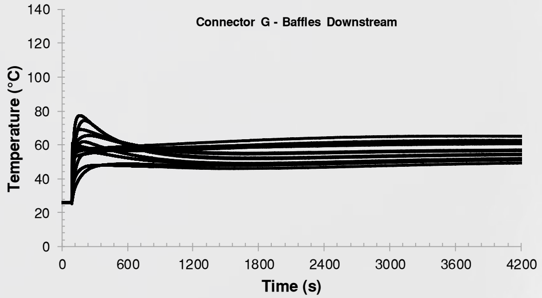






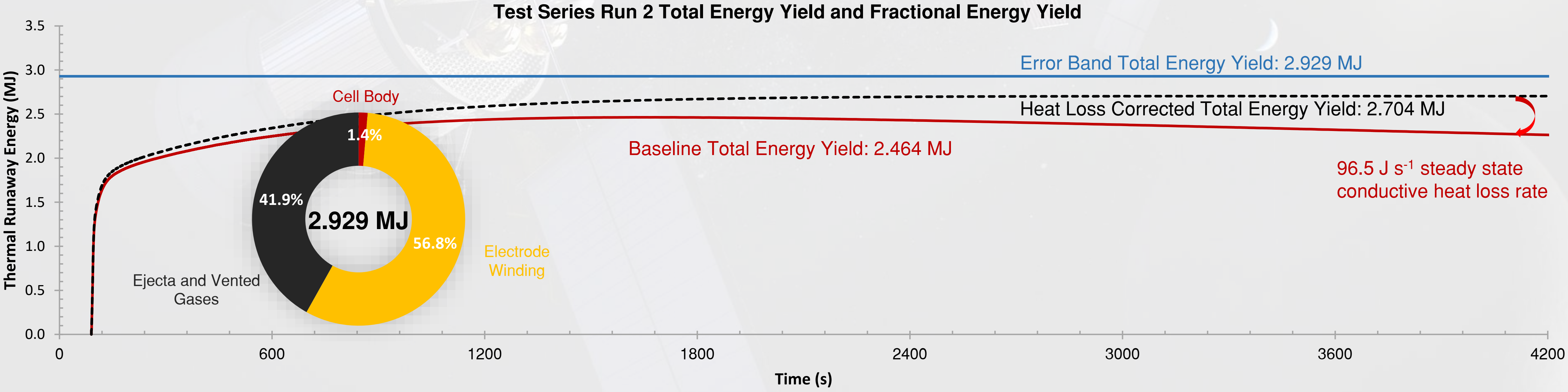






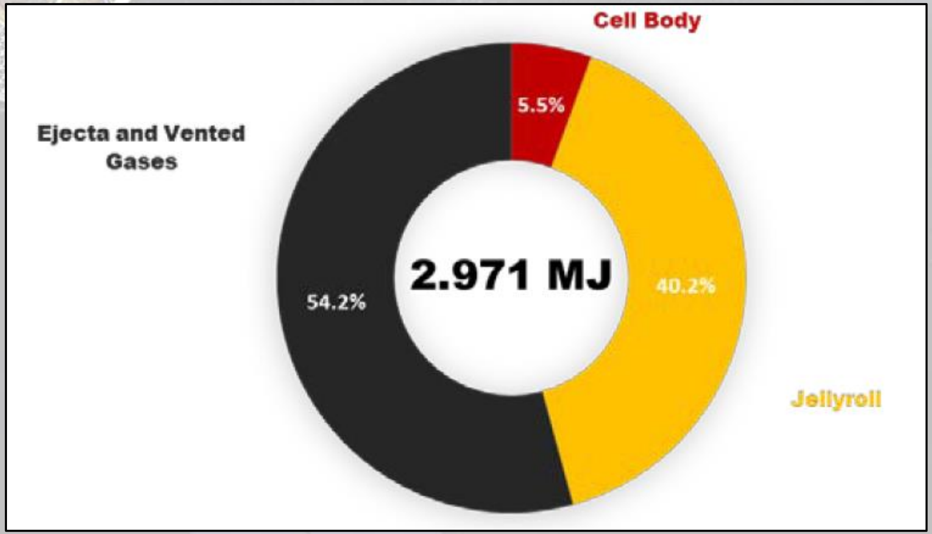
CALCULATING ENERGY YIELD

- **Using $\sum m_i C_{p_i} dT_i$, the total energy yield as a function of time from trigger is calculated:**
  - Approximately 1500-2000 s are required for the total energy to be "realized" by the system *(this is a function of the thermal mass of the system and how the heat of the explosion is distributed through the system)*.
  - The energy fractions are determined based on the state of the L-FTRC system after 15 s from trigger.
  - The corresponding total energy curves and energy fractions for the previously shown temperature profiles *(from Run 2)* are given below.



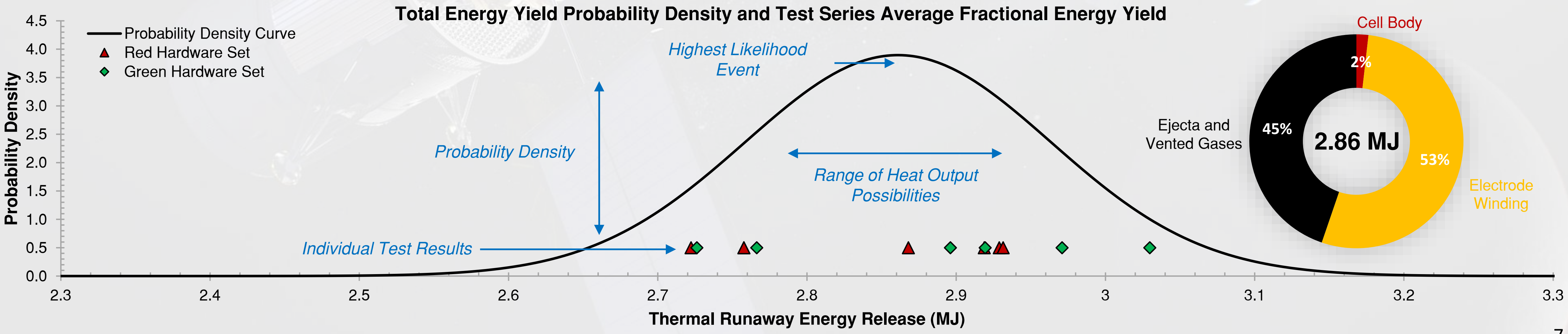
CALCULATING ENERGY YIELD

- **The majority of the experiments, including Run 2 as discussed on the previous slides, resulted in a complete electrode winding ejection:**
  - This resulted in energy fractions similar to what is shown on the previous chart where only 1-2% of the total energy yield was released through the cell body.
  - The remaining 98% to 99% was released through the electrode winding and ejecta materials.
- **One experiment in the test series, Run 5, did not have a complete jellyroll ejection, which resulted in the fractional distribution shown in the image below.**



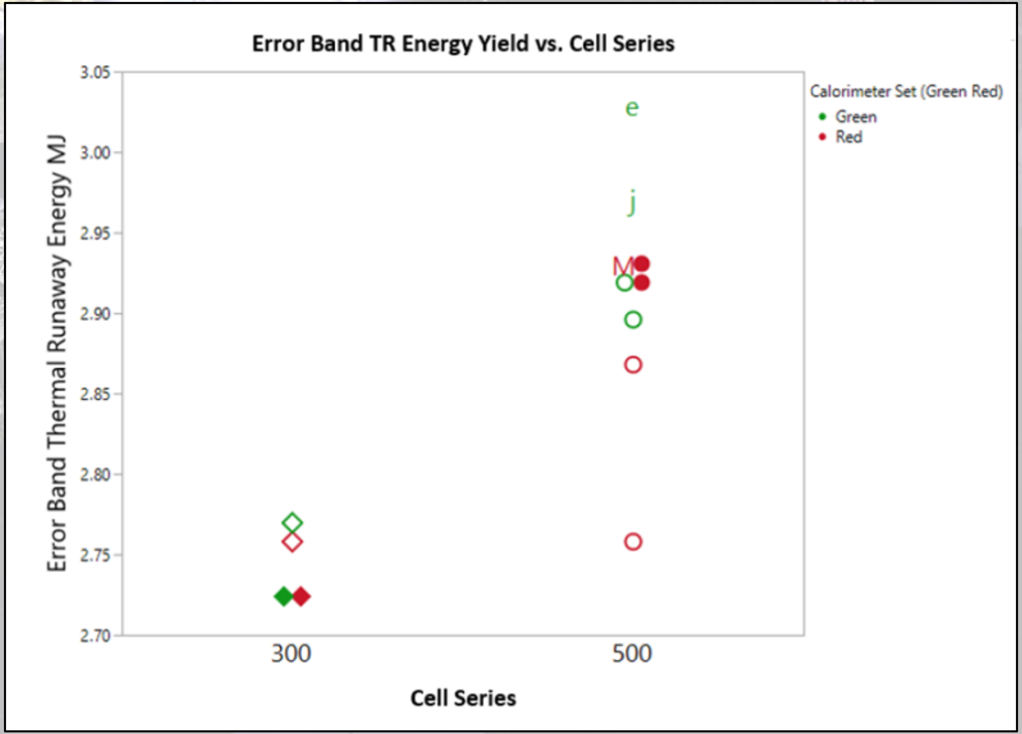
ADDRESSING VARIABILITY

- **Since no two thermal runaway events are the same, test-to-test variability must be taken into consideration for any scientific effort that seeks to characterize the overall range of behavior.**
- **It is helpful to consider the variability of thermal runaway energy yield as a statistical distribution to help answer the following questions:**
  - What is the highest probability energy release? What is the lowest?
  - What is the absolute maximum energy release? Minimum?



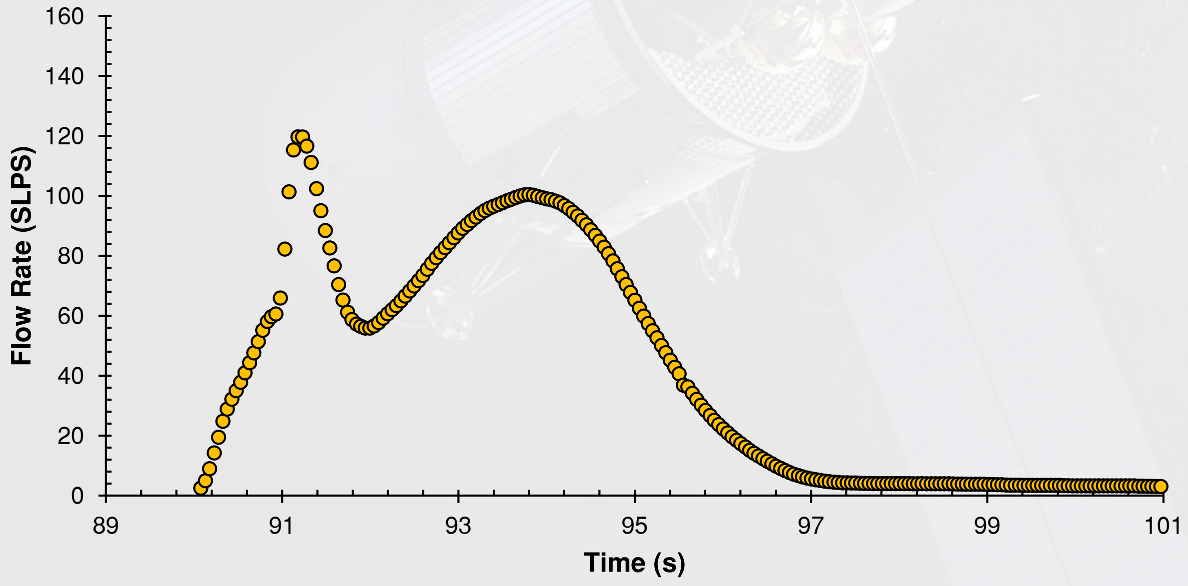
ADDRESSING VARIABILITY

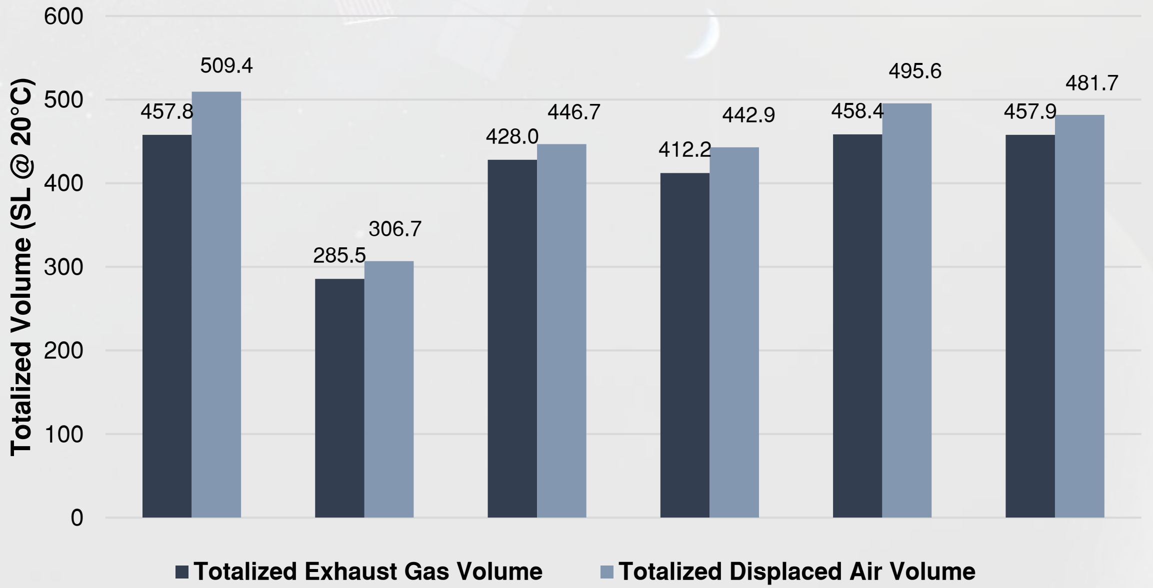
- **Further analysis revealed lot-to-lot variability in thermal runaway response, even for a cell as highly controlled as the LSE-134:**
  - The plots below show the Total Energy Yield as a function of the cell lot *(300 series vs. 500 series)*.
  - Additional comparisons, beyond Total Energy Yield, as a function of cell lot are described in the NESC Report.



DETERMINATION OF EXPELLED GAS VOLUME

- **A secondary goal for this assessment was to determine the volume, composition, and energy fractions of the gas that is expelled from the cell during thermal runaway:**
  - Our system allows us to measure the flow rate of gases as they exit through a specialized exhaust path.
  - The flow rate is integrated over time to calculate the total volume of expelled gases.
  - A sample flow rate plot *(for Run 2)* is shown to the bottom left and a plot showing the total expelled gases *(for the experiments which used the gas collection system)* is shown to the bottom right.





GAS COMPOSITION

- **The gas constituents were similar to those observed in other thermal runaway events recorded in literature, with the exception that other tests normally detected carbon monoxide:**
  - The largest component detected in our experiments was carbon dioxide in the range of 42% to 58%.
  - The table below shows all detected gas constituents from the gas samples collected during the final test series after adjusting for air and normalizing to 100%.

Exhaust Gas Component	Run #1	Run #2	Run #3	Run #4	Run #5	Run #6	Run #7	Run #8
Carbon Dioxide, mole%	45%	*Insufficient Sample*	42%	42%	48%	41%	51%	52%
Hydrogen, mole%	35%		30%	35%	28%	33%	41%	35%
Oxygen, mole%	3%		2%	3%	1%	2%	3%	3%
Ethane, mole%	16%		15%	17%	15%	16%	2%	
Methane, mole%	1%		5%	4%			4%	
Additional HCs +/- 1%	< 1%		< 1%	< 1%	< 1%	< 1%	< 1%	
Dimethyl Carbonate, mole %	*	*	1.732%	*	1.457%	1.356%	*	1.618%
Ethyl Methyl Carbonate, mole %	*	*	5.096%	*	5.935%	7.149%	*	8.754%
Diethyl Carbonate, mole %	*	*	0.0249%	*	0.0323%	0.0394%	*	0.0511%
Total Mole% (Volume%)	100%		100%	100%	100%	100%	100%	100%

* No electrolyte data for these runs

TEST SERIES SUMMARY

Item	Units	Experiment												
Experiment ID	-	Run2	Run3	Run4	Run5	Run6	Run7	Run8	Run9	Run10	Run11	Run12	Run13	Run14
Date of Experiment	-	10/24/2019	10/25/2019	10/25/2019	10/28/2019	10/29/2019	10/29/2019	10/30/2019	10/30/2019	10/30/2019	10/31/2019	10/31/2019	10/31/2019	11/4/2019
Time of Trigger	-	1:06PM	10:15AM	3:04PM	11:22AM	8:14AM	2:13PM	7:30AM	10:35AM	2:21PM	7:56AM	11:15AM	3:18PM	2:34PM
Calorimeter Set (Green Red)	-	Red	Green	Red	Green	Red	Green	Red	Green	Red	Green	Red	Green	Red
Cell Serial Number	-	S/N 0558	S/N 0549	S/N 0563	S/N 0569	S/N 0385	S/N 0397	S/N 0538	S/N 0560	S/N 0388	S/N 0562	S/N 0552	S/N 0384	S/N 0553
Cell Charged Voltage	V	4.092	4.090	4.090	4.090	4.080	4.080	4.080	4.090	4.080	4.080	4.100	4.090	4.060
Initial Cell Mass	kg	3.607	3.690	3.590	3.590	3.560	3.560	3.560	3.580	3.560	3.570	3.590	3.570	3.570
DPA Cell Mass	kg	0.377	0.345	0.387	1.150	0.336	0.377	0.339	0.353	0.354	0.364	0.528	0.370	0.343
DPA Jellyroll Mass	kg	1.801	1.542	1.851	0.526	2.056	2.046	1.959	1.964	2.026	1.705	1.016	2.054	1.953
DPA Cu Mesh 1 Soot Mass	kg	0.013	0.023	0.008	0.052	0.009	0.022	0.014	0.011	0.010	0.033	0.099	0.011	0.015
DPA Cu Mesh 2 Soot Mass	kg	0.011	0.026	0.013	0.080	0.016	0.021	0.018	0.018	0.013	0.029	0.072	0.012	0.021
DPA Cu Mesh 3 Soot Mass	kg	0.027	0.063	0.017	0.118	0.018	0.032	0.027	0.030	0.021	0.065	0.113	0.029	0.055
DPA Bore/Baffle Soot Mass	kg	0.453	0.490	0.294	0.586	0.378	0.330	0.380	0.362	0.325	0.432	0.547	0.307	0.467
Exhaust Gas Mass	kg	0.637	0.397	0.596	0.574	0.638	0.637	*0.616*	*0.616*	*0.616*	*0.616*	*0.616*	*0.616*	*0.616*
Ejected (Unrecovered) Mass	kg	0.288	0.804	0.428	0.505	0.108	0.094	0.209	0.228	0.190	0.326	0.596	0.166	0.098
Baseline Total Energy Yield	MJ	2.464	2.503	2.468	2.511	2.319	2.261	2.451	2.396	2.334	2.408	2.590	2.279	2.324
Conductive Heat Loss Rate	$J\ s^{-1}$	96.500	116.800	83.500	105.000	65.000	67.500	79.900	79.500	65.200	77.500	75.500	65.000	89.000
Exhaust Gas Heat Loss	MJ	0.035908	0.020370	0.019357	0.029475	0.030972	0.017969	*0.023288*	*0.021643*	*0.014086*	*0.024145*	*0.020971*	*0.015118*	*0.028885*
Ejected (Unrecovered) Mass Heat Loss	MJ	0.013390	0.038747	0.020112	0.025109	0.004689	0.003971	0.009783	0.010106	0.008447	0.015359	0.031925	0.007042	0.004330
Heat Loss Corrected Total Energy Yield	MJ	2.704	2.725	2.695	2.672	2.514	2.452	2.648	2.605	2.546	2.626	2.707	2.488	2.546
Distribution$_{\text{Cell Body}}$	MJ	0.037	0.045	0.043	0.148	0.011	0.036	0.025	0.031	0.024	0.035	0.095	0.033	0.048
Distribution$_{\text{Jellyroll}}$	MJ	1.535	1.296	1.684	1.075	1.622	1.212	1.481	1.399	1.431	1.264	1.372	1.369	1.411
Distribution$_{\text{Ejecta \& Vented Gas}}$	MJ	1.132	1.384	0.969	1.449	0.881	1.204	1.142	1.174	1.091	1.327	1.240	1.087	1.087
Percent$_{\text{Cell Body}}$	%	1.369	1.658	1.587	5.522	0.452	1.470	0.935	1.200	0.943	1.348	3.511	1.318	1.898
Percent$_{\text{Jellyroll}}$	%	56.758	47.556	62.473	40.244	64.516	49.438	55.943	53.716	56.198	48.135	50.671	55.008	55.427
Percent$_{\text{Ejecta \& Vented Gas}}$	%	41.873	50.786	35.940	54.234	35.033	49.092	43.121	45.084	42.859	50.517	45.818	43.675	42.676
Error Band Total Energy Yield	MJ	2.929	3.030	2.919	2.971	2.722	2.726	2.868	2.896	2.758	2.919	2.931	2.766	2.758
Updated Distribution$_{\text{Cell Body}}$	MJ	0.040	0.050	0.046	0.164	0.012	0.040	0.027	0.035	0.026	0.039	0.103	0.036	0.052
Updated Distribution$_{\text{Jellyroll}}$	MJ	1.662	1.441	1.823	1.196	1.756	1.348	1.604	1.556	1.550	1.405	1.485	1.522	1.529
Updated Distribution$_{\text{Ejecta \& Vented Gas}}$	MJ	1.226	1.539	1.049	1.611	0.954	1.338	1.237	1.306	1.182	1.475	1.343	1.208	1.177
Totalized Exhaust Gas Volume	SL @ 20 °C	457.8	285.5	428.0	412.2	458.4	457.9	*442.8*	*442.8*	*442.8*	*442.8*	*442.8*	*442.8*	*442.8*
Totalized Displaced Air Volume	SL @ 20 °C	509.4	306.7	446.7	442.9	495.6	481.7	*475.3*	*475.3*	*475.3*	*475.3*	*475.3*	*475.3*	*475.3*
Max Expansion Chamber Pressure	psid	12.5	10.0	11.0	11.6	3.6	7.0	0.9	8.5	1.5	11.7	1.3	5.6	1.9
Max Gas Collection System Pressure:	psid	0.6	0.8	0.4	1.2	0.4	0.3	-	-	-	-	-	-	-
Maximum Nail Temperature	°C	**BR**	**BR**	**BR**	834.5	761.7	720.2	741.4	795.7	710.3	796.3	793.4	**BR**	**BR**
Maximum Exhaust Gas Flow Rate	SLPS	119.6	129.49	138.96	131.4	90.356	97.809	*115.6*	*115.6*	*115.6*	*115.6*	*115.6*	*115.6*	*115.6*
Approximate Length of Flow Event	s	9	10	11	10	10	10	*10*	*10*	*10*	*10*	*10*	*10*	*10*

BR indicates "bad reading", recommend disregard.

Text indicates an estimated value used for calculations.

TEST SERIES SUMMARY

Item	Units	Global Avg	Global StDev	Red Hardware Avg	Red Hardware StDev	Green Hardware Avg	Green Hardware StDev
Cell Charged Voltage	V	4.085	0.010	4.083	0.013	4.087	0.005
Initial Cell Mass	kg	3.584	0.035	3.577	0.019	3.593	0.048
DPA Cell Mass	kg	0.433	0.221	0.381	0.068	0.493	0.322
DPA Jellyroll Mass	kg	1.731	0.463	1.809	0.361	1.640	0.582
DPA Cu Mesh 1 Soot Mass	kg	0.025	0.026	0.024	0.033	0.025	0.015
DPA Cu Mesh 2 Soot Mass	kg	0.027	0.022	0.023	0.022	0.031	0.025
DPA Cu Mesh 3 Soot Mass	kg	0.047	0.034	0.040	0.035	0.056	0.035
DPA Bore/Baffle Soot Mass	kg	0.412	0.093	0.406	0.088	0.418	0.107
Exhaust Gas Mass	kg	0.599	0.063	0.619	0.014	0.576	0.090
Ejected (Unrecovered) Mass	kg	0.311	0.217	0.274	0.181	0.354	0.263
Baseline Total Energy Yield	MJ	2.408	0.100	2.422	0.100	2.393	0.106
Conductive Heat Loss Rate	$J\ s^{-1}$	82.0	16.2	79.2	11.7	85.2	21.0
Exhaust Gas Heat Loss	MJ	0.026	0.007	0.025	0.008	0.021	0.005
Ejected (Unrecovered) Mass Heat Loss	MJ	0.015	0.011	0.013	0.010	0.017	0.013
Heat Loss Corrected Total Energy Yield	MJ	2.610	0.092	2.623	0.085	2.595	0.106
$\text{Distribution}_{\text{Cell Body}}$	MJ	0.047	0.036	0.040	0.027	0.055	0.046
$\text{Distribution}_{\text{Jellyroll}}$	MJ	1.396	0.165	1.505	0.115	1.269	0.117
$\text{Distribution}_{\text{Ejecta \& Vented Gas}}$	MJ	1.167	0.158	1.077	0.119	1.271	0.138
$\text{Percent}_{\text{Cell Body}}$	%	1.785	1.331	1.528	0.996	2.086	1.691
$\text{Percent}_{\text{Jellyroll}}$	%	53.545	6.430	57.426	4.646	49.016	5.254
$\text{Percent}_{\text{Ejecta \& Vented Gas}}$	%	44.670	5.565	41.046	3.999	48.898	3.912
Error Band Total Energy Yield		2.861	0.102	2.841	0.092	2.885	0.117
$\text{Updated Distribution}_{\text{Cell Body}}$		0.052	0.040	0.044	0.029	0.061	0.051
$\text{Updated Distribution}_{\text{Jellyroll}}$		1.529	0.166	1.630	0.124	1.411	0.130
$\text{Updated Distribution}_{\text{Ejecta \& Vented Gas}}$		1.280	0.185	1.167	0.129	1.413	0.154
Totalized Exhaust Gas Volume	SL @ 20 °C	416.6	67.1	448.1	17.4	385.2	89.3
Totalized Displaced Air Volume	SL @ 20 °C	447.2	73.7	483.9	32.9	410.4	91.9
Max Expansion Chamber Pressure	psid	9.3	3.4	9.1	4.8	9.5	2.3
Max Gas Collection System Pressure	psid	0.6	0.3	0.5	0.1	0.8	0.4
Maximum Nail Temperature	°C	769.2	43.1	751.7	34.9	786.7	47.9
Totalized Exhaust Gas Volume		17.4	2.8	18.7	0.8	16.1	3.7
Maximum Exhaust Gas Flow Rate		117.9	19.6	116.3	24.5	119.6	18.9
Approximate Length of Flow Event		10.0	0.6	10.0	1.0	10.0	0.0

CONCLUSIONS

- **A large format fractional thermal runaway calorimeter (L-FTRC) for Li-ion cells with capacities greater than 100 Ah was developed and the testing capabilities were demonstrated:**
  - The completed device was designed to trigger the LSE-134 Li-ion cell into thermal runaway via nail penetration; additional cell formats could be accommodated with custom L-FTRC cell chambers.
  - The device supports the discernment of both total energy yield and the fractional energy yield.
  - A test series was conducted at the NASA JSC ESTA where 14 LSE-134 Li-ion cells were triggered into thermal runaway via nail penetration.
  - Thermal data, gas flow data, and gas samples were collected.
- **Of the 13 experiments, the average total energy release is 2.86 MJ with a standard deviation of 0.102 MJ; the corresponding average energy distribution is 1.8% through the cell casing, 53.5% through the electrode winding, and 44.7% through the ejecta and gases.**
- **Gas collection and flow rate measurement was conducted for 6 of the experiments; the totalized exhaust gas volume vented during thermal runaway ranged from 412.2 SL to 458.4 SL.**
- **All data given in this presentation is described in more detail in the final NESC report.**

ACKNOWLEDGEMENTS

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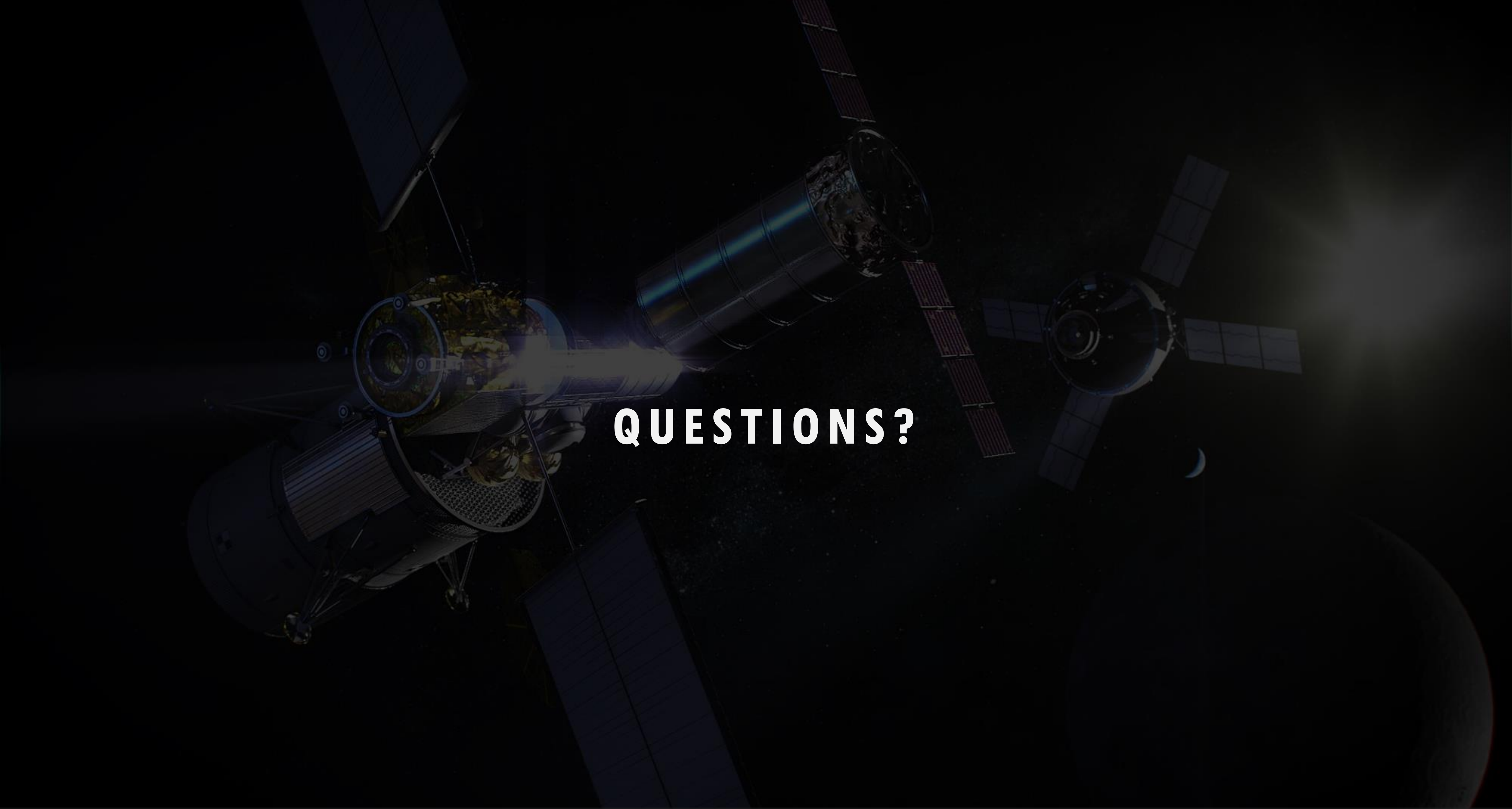
  - Steven Rickman, Kenneth Johnson, and Christopher Iannello, Ph.D.
- **NASA JSC Engineering Directorate (EA):**
  - Structural Engineering Division (ES).
  - Power and Propulsion Division (EP).
- **L-FTRC Team Members.**
- **NASA JSC Energy Systems Test Area (ESTA).**



QUESTIONS?