FAA Electrical Systems Electrical Energy study

By: *M. Walz J. Russotto*

Date: *Oct. 2019*

Rechargeable Lithium Batteries and Battery Systems for Aerospace Applications

Fuel Cells for Aircraft

Initial Lithium Battery Program

•This project involves a layering of effects: (1) a new thermal management solution, our CIM, comprised of a refractory layer, a robust, thermally conductive backing layer and a fire-retardant/rated intumescent layer, to reduce the cell-to-cell “domino” effect, which can be combined with (2) an external cooling loop/thermal load management system(s) to further mitigate thermal runaway risks in future designs. A key to the proposed solution is optimizing the combination of these elements to maximize safety while maintaining battery performance

•This proposed program will use the testing and validation of a novel energy storage systems (ESS) design with thermal runaway cascading protections and early failure prognostics demonstrate enhanced aviation ESS safety, and the data and results from the program will be presented to standards bodies to aid in regulatory development and rule update considerations. **Sponsored by UAS**

This proposal pursues three complementary improvements to enhance the safety of higher specific-energy Lithium Ion cells when coupled with the existing monitoring and control of EaglePicher’s Battery Management System and its independent and dissimilar backup protections that avoid cell abuse that could lead to potential failure. While DO-311 serves as a viable guide for this design implementation

•This project will investigate a novel packaging technology for Lithium-ion cells that substantially prevents the cascading effect of cell-to-cell failure propagation inside a battery, without sacrificing the power and energy density

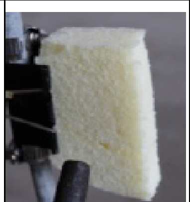
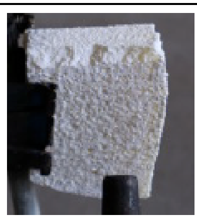
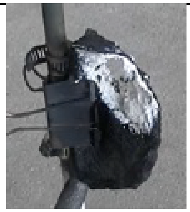
•This project will study the design of a thermal and dendrite proof, early electrical short detectable, multifunctional electrolyte separator to

• (i) enhance electrochemical performance of Li-ion battery (LIB), (ii) stop thermal runaway, (iii) with advanced diagnostics arrangement to achieve early detection of cell shorting ensuring complete battery safety for aviation applications.

FAA Lithium Battery Cell Separation Material

Purpose- The design proposed in this project involves a layering of effects: (1) a new thermal management solution, our CIM, comprised of a refractory layer, a robust, thermally conductive backing layer and a fire-retardant/rated intumescent layer, to reduce the cell-to-cell "domino" effect, which can be com[...] with (2) an external cooling loop/thermal load management [...]tem[...] to further mitigate thermal runaway risks in future designs[...] key to the proposed solution is optimizing the combination of th[...]e elemen[...] [...]aximize safety while maintaining battery performance. [...]fe[...]vene[...] [...]pproach will be demonstrated in Year 1 through emp[...] [...]v[...]ati[...] a[...] [...]he lab-scale using simulated battery failure conditions. [...] Y[...] 2, [...]e w[...] demonstrate cell isolation demonstration(s) under battery pac[...] [...]ai[...]e conditions

Completed

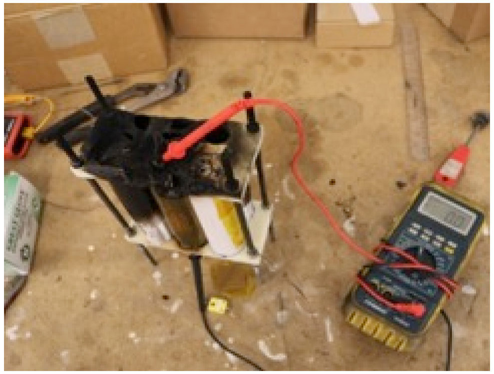
	Uncoated / Unloaded	Refractory Coated / Unloaded	Uncoated / Ceramic Loaded	Refractory [...]ated / Ceramic Loaded
Before				
After				

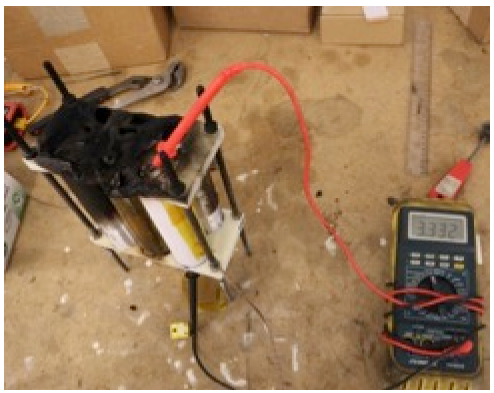
Before

After 15 min

Burn through

No Cascading Failure With CIM

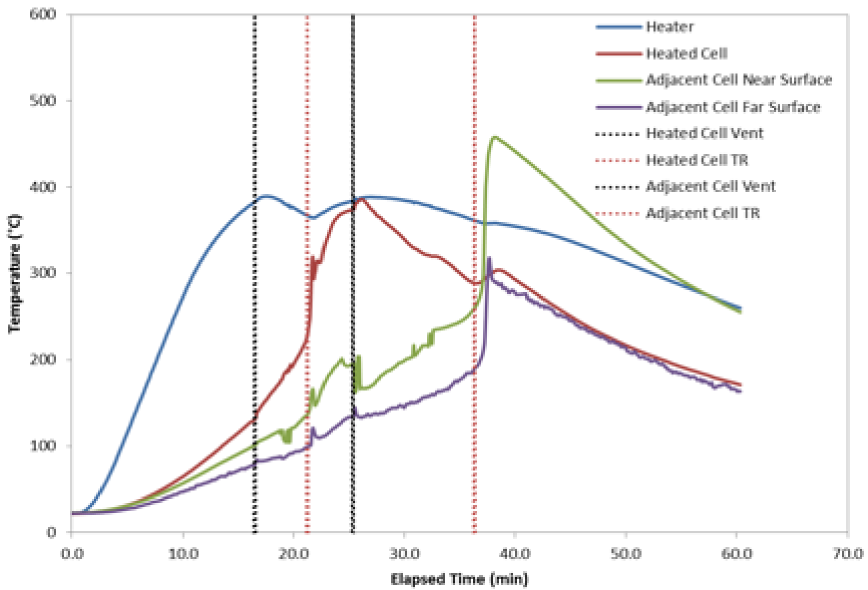




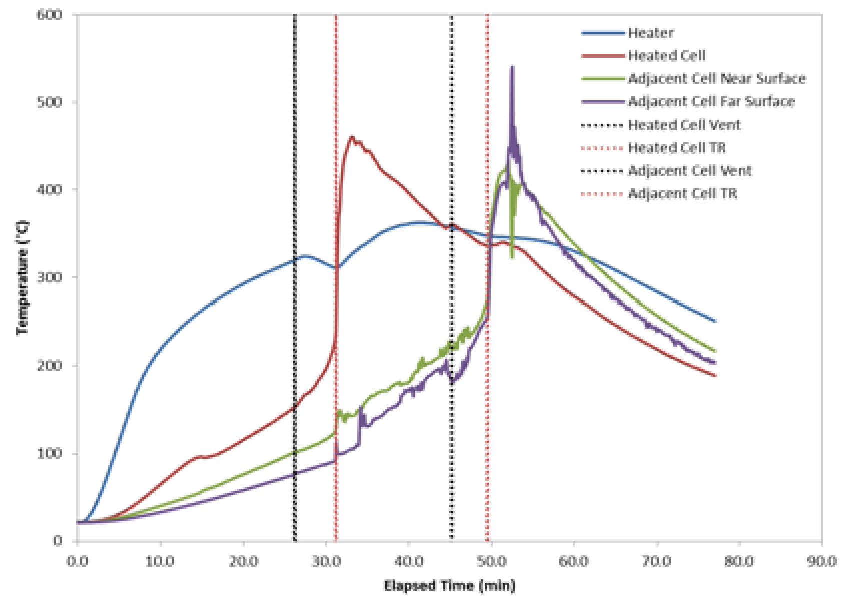
- Module is melted and charred
- Heated cell has substantial charring, no voltage. Adjacent cell has minor melting of shrink wrap, still has charge. CIM has little damage.

Delayed Cascading Failure With CIM

•Without CIM



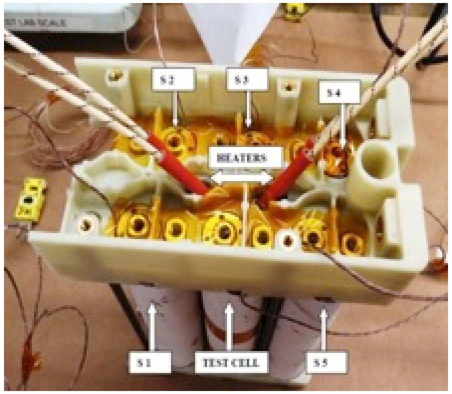
•With CIM



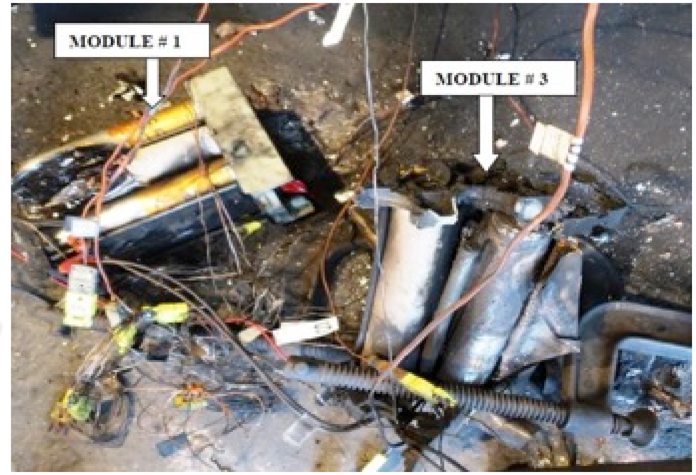
	Cascading Failure Without CIM	Cascading Failure With CIM
Heated Venting to Adjacent Venting	8.8 min	19.0 min
Heated TR to Adjacent Venting	4.0 min	14.0 min

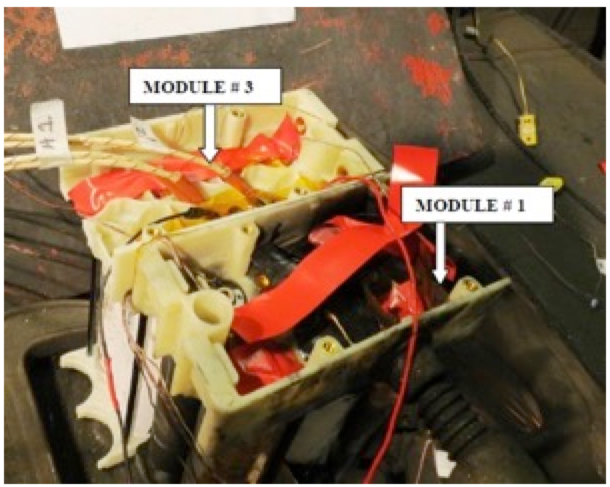
- In this experimental setup, cascading failure difficult to avoid due to large thermal mass of the hot plate; therefore, cascading failure occurs with CIMs present.
- When cascading failure occurs, CIMs significantly delay the cascading failure event.
- Greater than two fold increase in time between heated cell venting and adjacent cell venting. Over three fold increase in time between heated cell thermal runaway (TR) and adjacent cell venting.

Thermal Runaway Aftermath with and without ADA CIMs



- Cells wrapped in ADA CIM





- No CIM

Comparison of Cell Peak Temperatures with and without CIMs

Cell Peak Temperature (^{o}C)	*Module 3 w/ CIM*	*Module 4 w/o CIM*
Overheated	441	529
S1	442	unknown
S2	390	961
S3	650	986
S4	190	1137
S5	332	791
Ave Cell Peak Temp	408	881

•50% lower

- Temperature data shows cell temperature is much lower with ADA’s CIM present.
- Average peak temperature with CIM present less than half without CIM present.
- During this test two cells exploded with ADA CIM present, while all six cells exploded without CIM protection.

Summary

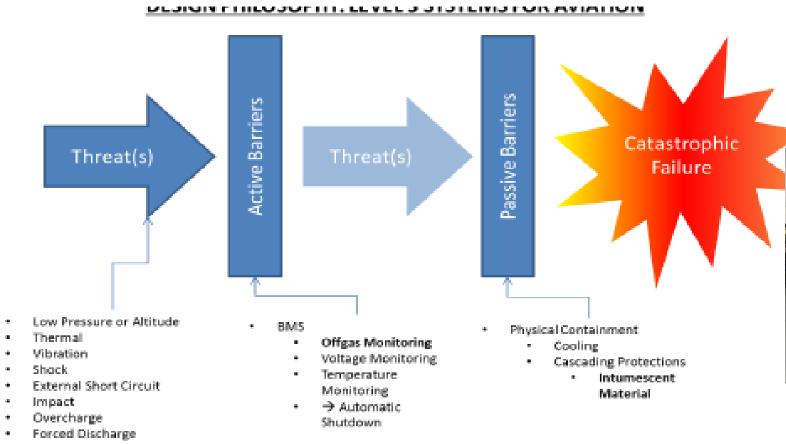
- Cell failure is highly probabilistic
- Cylindrical cells and pouch cells undergo failures through different mechanical failure procedures
- Cell-to-cell isolation technology has to be incorporated in different formats for cylindrical vs. prismatic configurations
- Depending on configuration, some battery applications will require sprayed on multilayer CIMs, in addition to or instead of CIM “wraps” fabricated on a coater
- **CIMs with only one side coated with multilayer refractory/intumescent binder configuration will be adopted for cylindrical and prismatic/pouch cells**
- **NASA and AF have started mandating cell-to-cell or pack-to-pack thermal deflagration prevention technologies for space and aerospace applications**

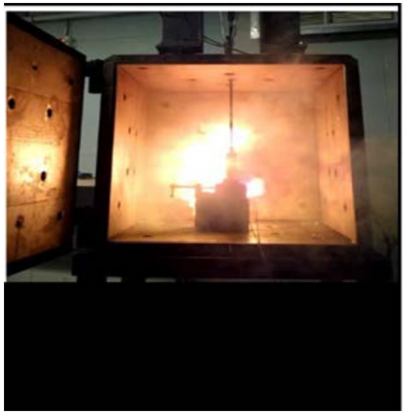
FAA Lithium Battery UAS

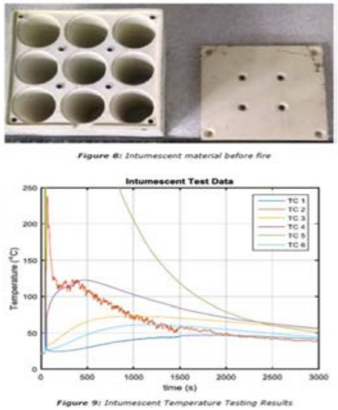
DNV·GL

Purpose- This proposed program will use the testing and validation of a novel energy storage systems (ESS) design with thermal runaway cascading protections and early failure prognostics demonstrate enhanced aviation ESS safety, and the data and results from the program will be presented to standards bodies to aid in regulatory development and rule update considerations.

An aviation battery solution needs both active and passive barriers to battery cell failure and can do so by adopting methodologies that have already been established in automotive, marine, and stationary ESS designs. DNVGL proposes to test and validate a battery system that mitigates cascading thermal runaway and provides early warning of failure.





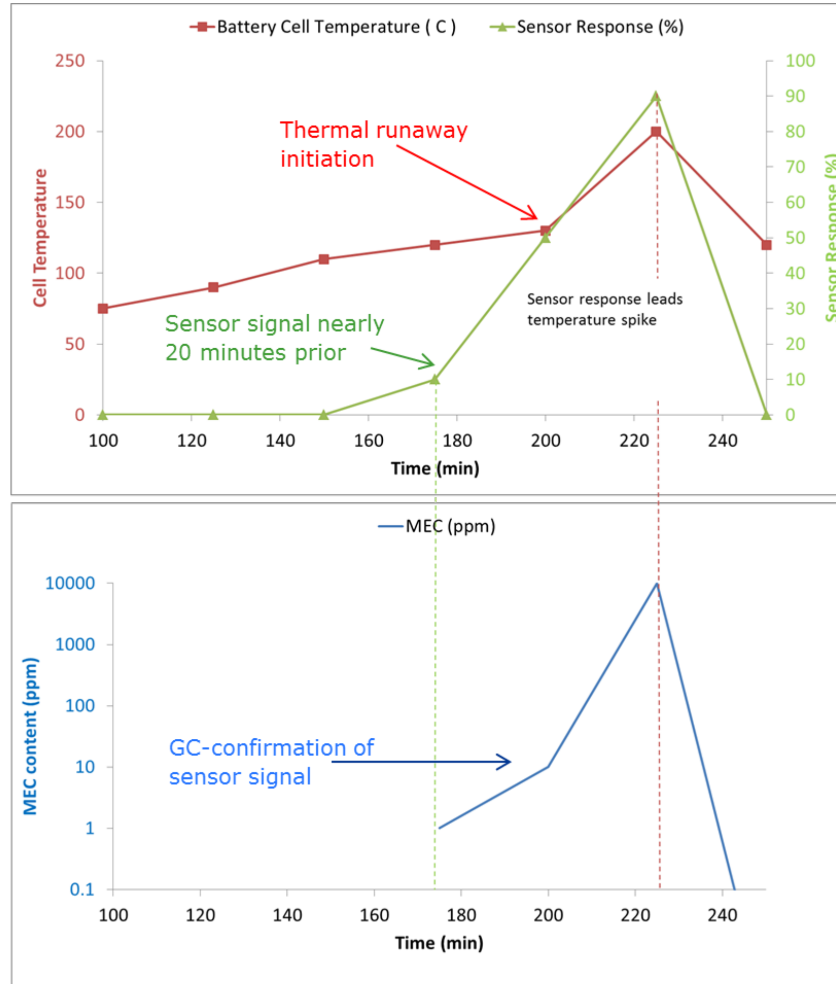


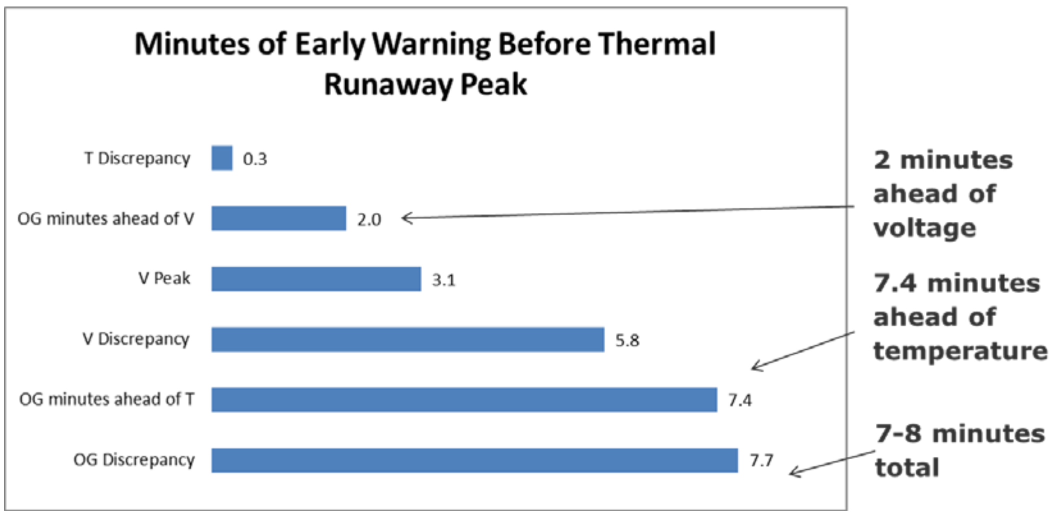
ARPAe AMPED Testing

Advanced Research Projects Agency-Energy (ARPA-E)

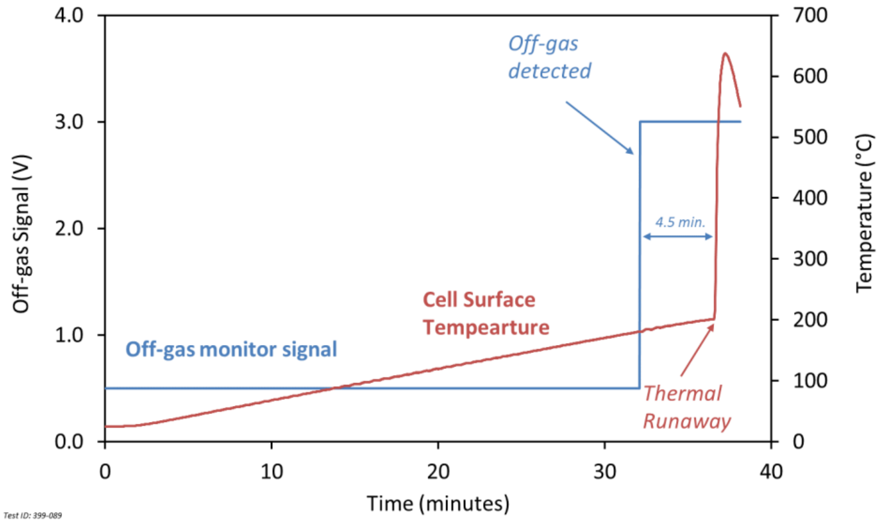
Advanced Management and Protection of Energy Storage Devices (AMPED)

Prime takeaway from the testing was that offgassing from the battery may give indication of pending cell failure several minutes before thermal runaway. Coupled with intelligent BMS monitoring, potentially troublesome cells may be spotted and isolated several minutes before TR

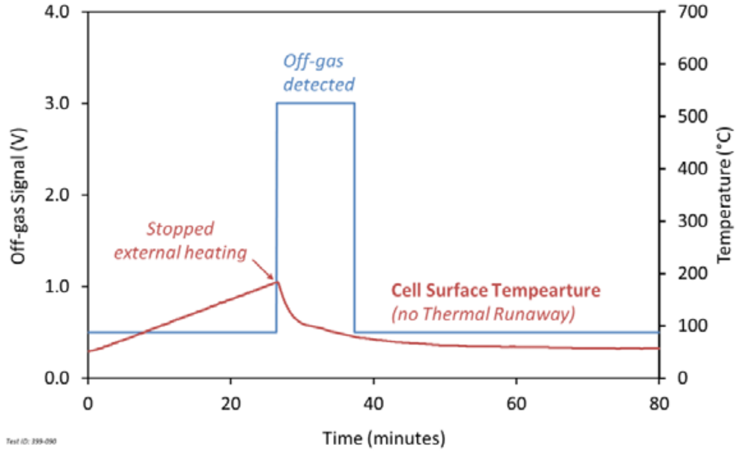




Off-gas detection in Action



The binary output from the algorithm within the off-gas monitor can then be used to signal shutdown of a battery to mitigate the risk of thermal runaway. The following examples show test data for how the binary output can both provide indication of cell venting as a precursor to thermal runaway



The signal can be used to trigger shutdown to prevent thermal runaway

Both examples were thermal abuse tests performed on 18650 cells. In the first test, the off-gas detector was used to monitor the cell for off-gas while the cell was thermally abused until it entered thermal runaway. This is a demonstration of the binary function of the output which provided the on/off indication of off-gas when the cell vented 4.5 minutes prior to thermal runaway. The same test procedure with the exception that the binary output of the off-gas monitor was used to trigger the shutdown of the test. Thermal runaway was prevented when the abuse condition was removed.

EaglePicher™ Technologies, LLC
A VECTRA Company

FAA Lithium Battery

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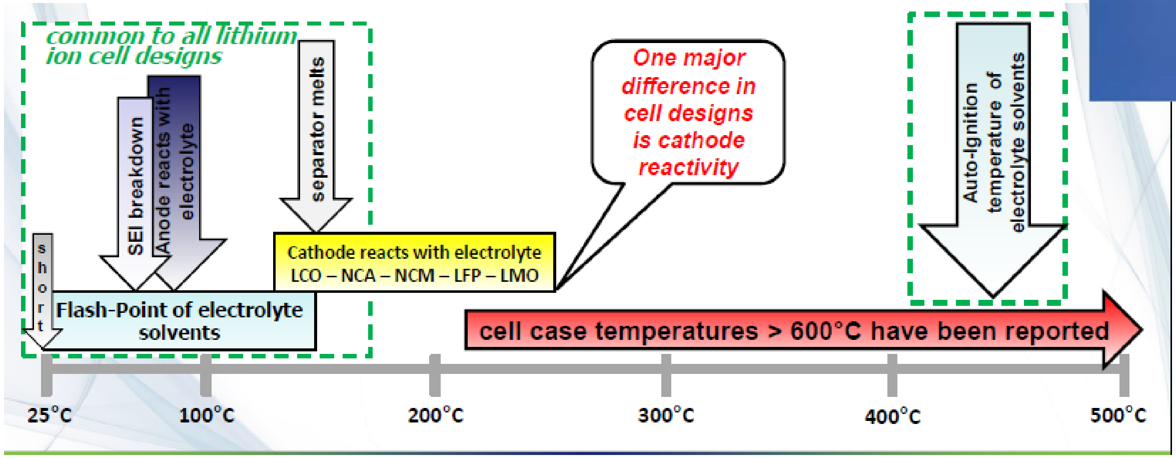
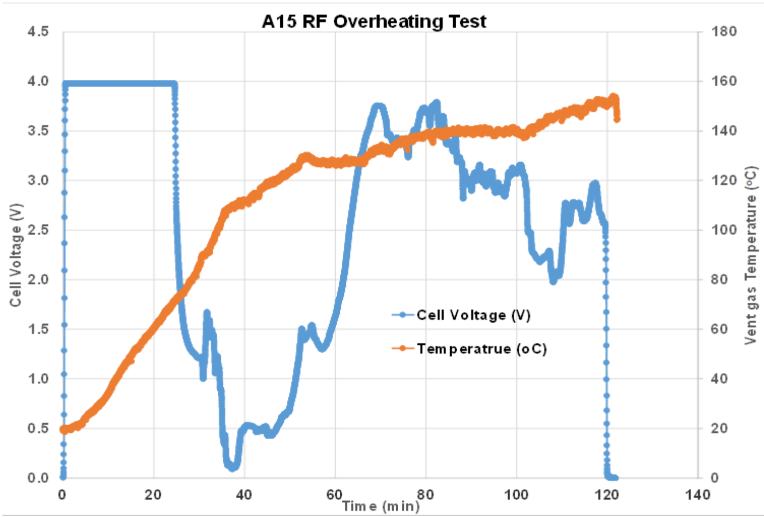
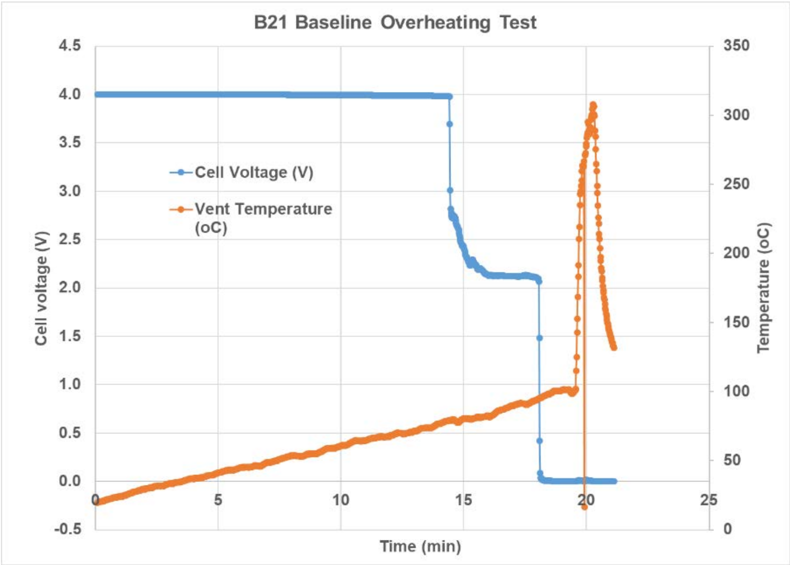
These include:

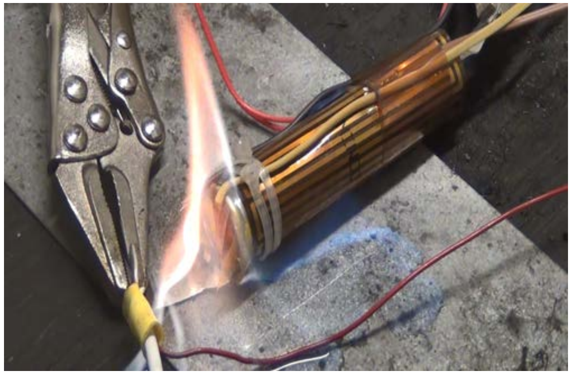
1. Reduced Flammability Electrolyte
2. Carbon-fiber Arrestor
3. Heat Dispersant Coating



Key Safety Tests – Overheating Test



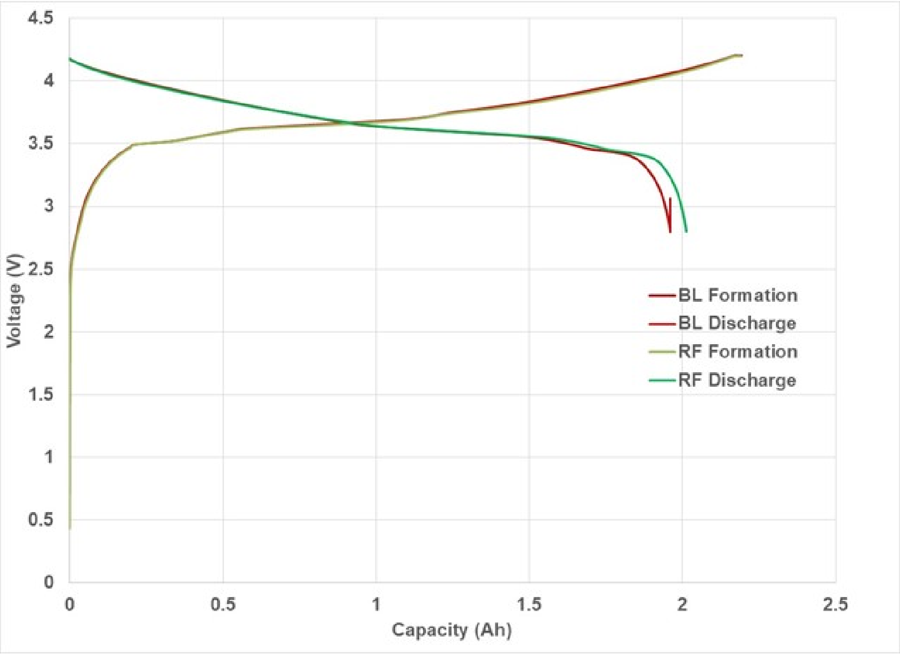




- 3 out of 5 ***BL cells tested in overheat caught fire***, leading to a large spike in temperature measured at the vent, while none of the tested "9 RF" cells produced flame.
- **Overheating test of 18650 cells showed the safety advantage of RF over BL**.

•Task 2.4 Cell Activation and Task 2.5 Formation

S.No.	Electrolyte	Cell Voltage (V)	Electrolyte wt
171101-1	BL	3.551	5.67
171101-2	BL	3.564	6.73
171102-1	RF	3.576	6.3445
171102-2	BL	3.554	6.789
171106-1	BL	3.438	6.09
171106-2	BL	3.592	6.37
171107-1	RF	3.585	6.9171
171107-2	RF	3.566	6.6379
171107-3	RF	3.578	6.539
171107-4	BL	3.592	6.8848
171107-5	BL	3.565	6.6229
171107-6	BL	3.522	6.18055
171109-1	BL	3.6	6.8461
171109-2	BL	3.6	7.0112
171109-3	BL	3.54	6.993
~~171113-1~~	RF	~~NA~~	~~0~~
~~171113-2~~	RF	~~NA~~	~~7.0374~~
171113-3	RF	3.453	6.758
171113-4	RF	3.507	7.024
171113-5	RF	3.431	6.782
171113-6	RF	3.52	6.922
171114-1	RF	3.575	6.97
171114-2	RF	3.593	6.802
171114-3	RF	3.585	6.918
171114-4	BL	3.574	6.751
171114-5	BL	3.578	6.685
171114-6	BL	3.583	6.916
171114-7	BL	3.584	6.817
171114-8	BL	3.585	7.017
171114-9	BL	3.58	6.799
171115-1	BL	3.596	7.172
171115-2	BL	3.59	7.074
171115-3	BL	3.593	6.974
171115-4	RF	3.597	7.139
171115-5	RF	3.597	7.285
~~171115-6~~	~~RF~~	~~NA~~	~~7.054~~
171206-9	RF	3.607	6.352
171206-10	RF	3.603	6.387
171206-11	RF	3.602	6.361



- ➢ NCM 18650 cells were manufactured and activated with RF and BL electrolyte.
- ➢ Formation profile shows good performance of cells made with both electrolytes.

TELEDYNE ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

FAA Lithium Battery Packaging

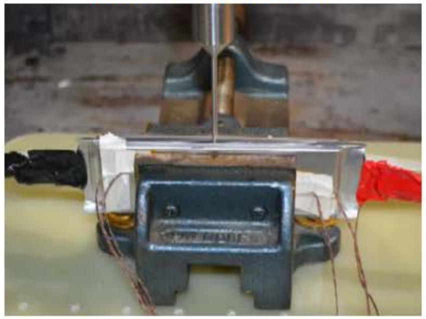
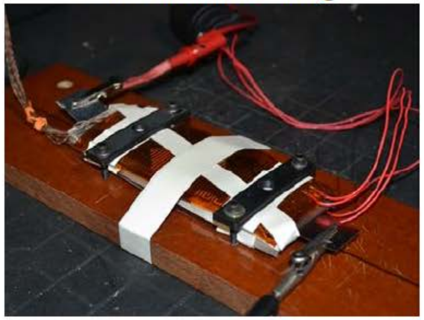
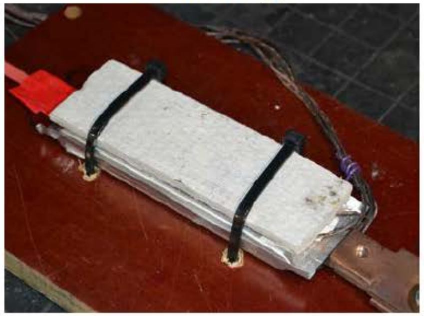
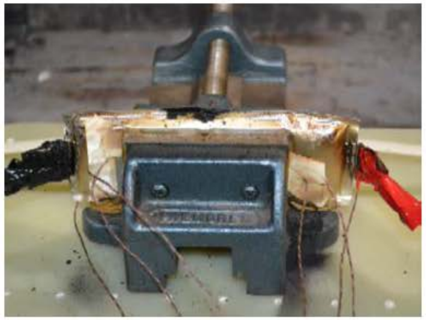
Purpose- This project will investigate a novel packaging technology for Lithium-ion cells that substantially prevents the cascading effect of cell-to-cell failure propagation inside a battery, without sacrificing the power and energy density. The uniqueness of the solution is its multi-functionality: ability to simultane[illegible]ddress the safety and thermal management (cycle life) aspe[illegible] the t[illegible] major bottlenecks of extensive deployment of Li-io[illegible]attery in a[illegible]tion and other vehicle and stationary application plat[illegible]ms.

Completed

- 7 highly energetic cells in series connection. How does the failure propagate to surrounding cells?

Cell Level Testing

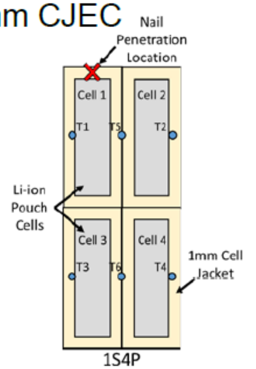
Single cell subjected to various abuse conditions

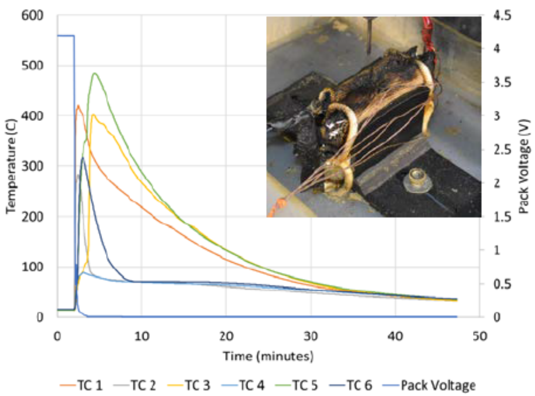
	Mechanical Abuse – Nail Penetration	Thermal Abuse – External Heating	Electrical Abuse – Overcharge
Before			
After			

Module Level Nail Penetration

Single cell in a module subjected to mechanical abuse – Propagation within a module and module-to-module

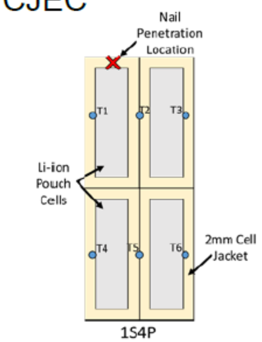
1S4P 1mm CJEC

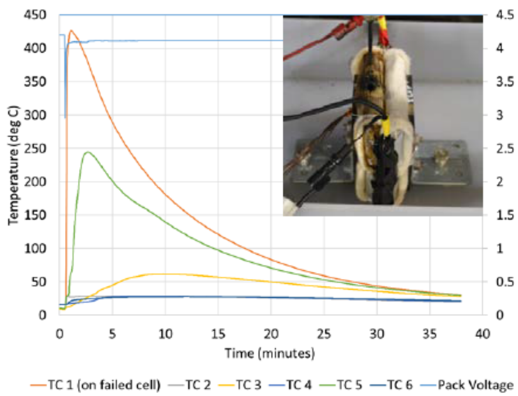




Propagation

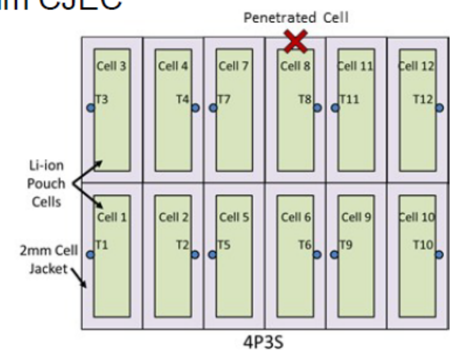
1S4P 2mm CJEC

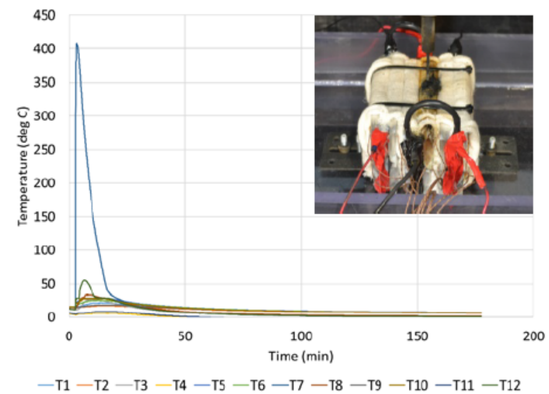




No Propagation

3S4P 2mm CJEC



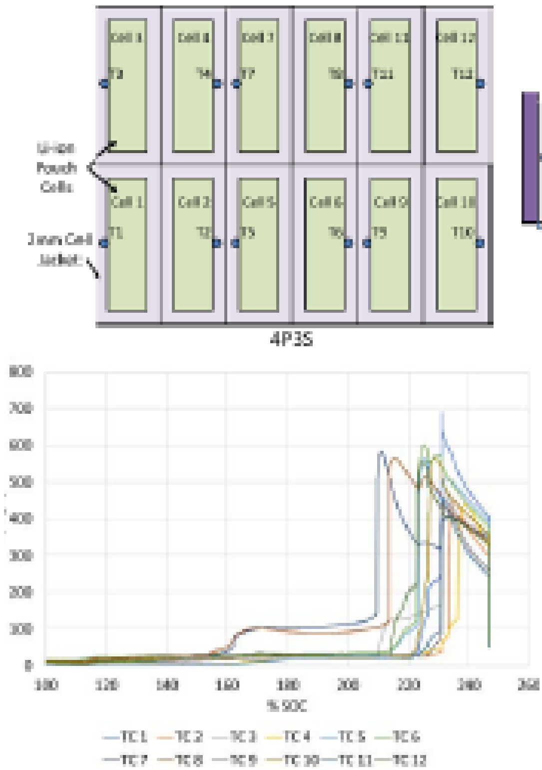


No Propagation

Module-Level Testing: An Entire Module

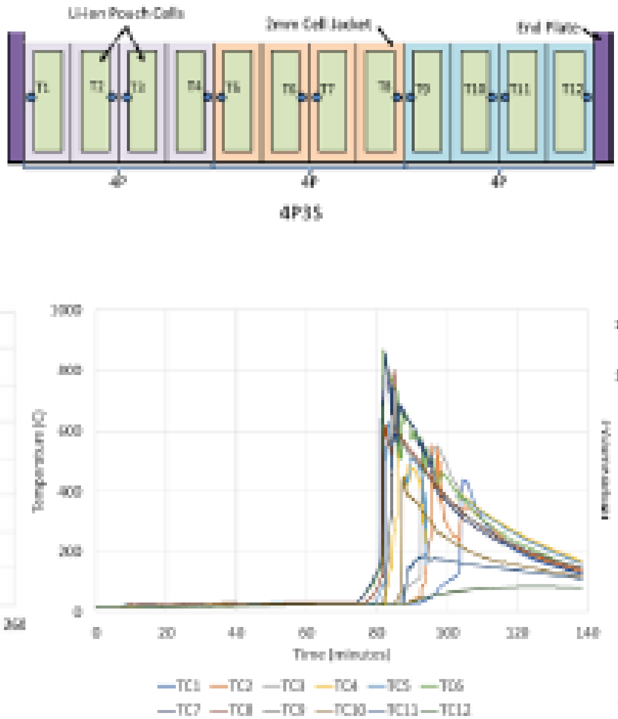
1S4P Module Overcharge and Propagation to Neighboring Modules

2 mm CJEC



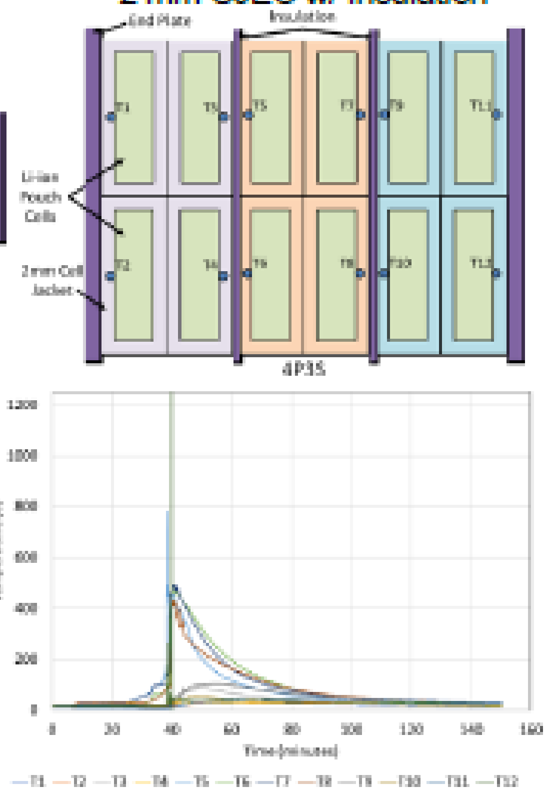
Propagation

2 mm CJEC Single Stacked



Propagation

2 mm CJEC w/ Insulation



No Propagation

FAA Lithium battery Cell Separator material

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- (i) enhance electrochemical performance of Li-ion battery (LIB),
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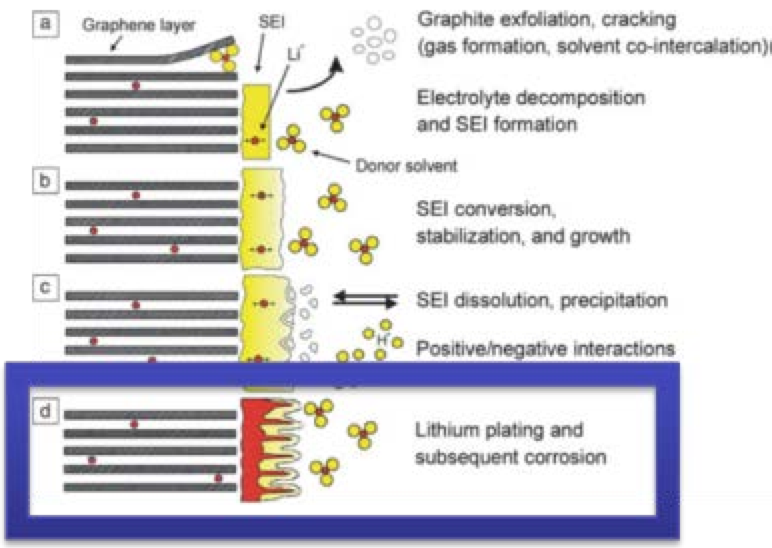
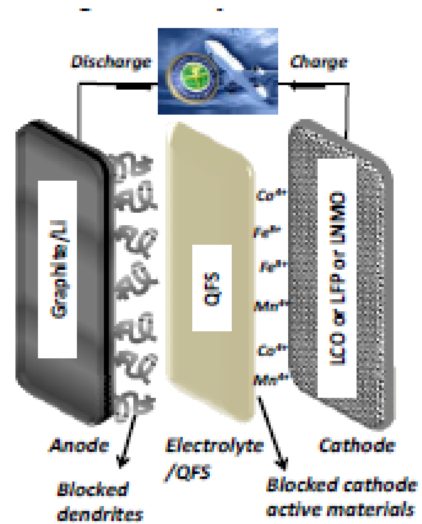
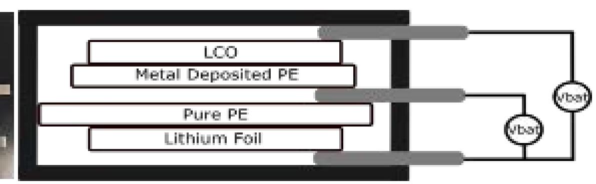
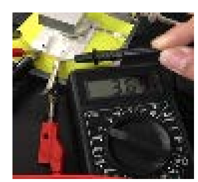


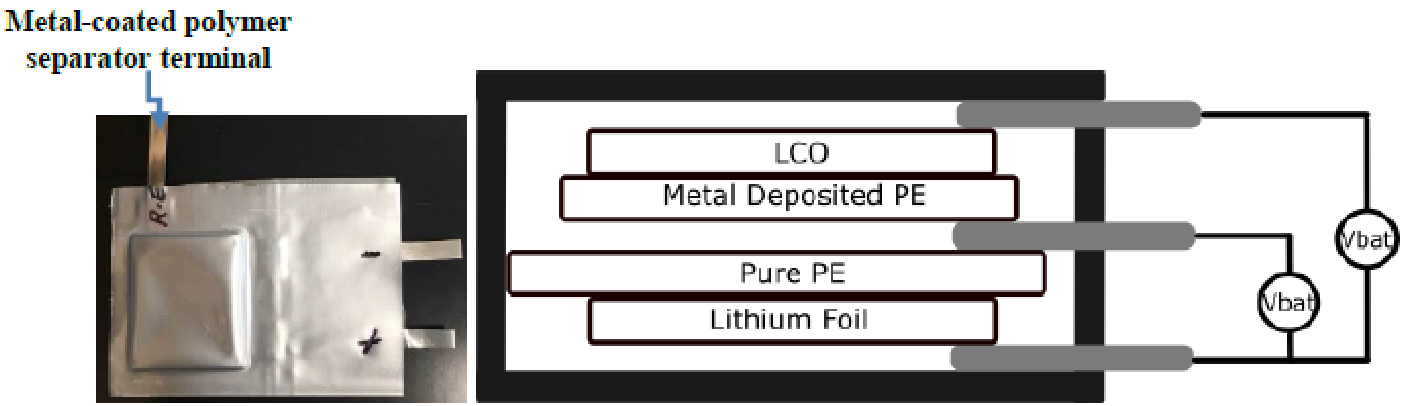
MRS Bulletin, 40, 1067-1076 (2015)



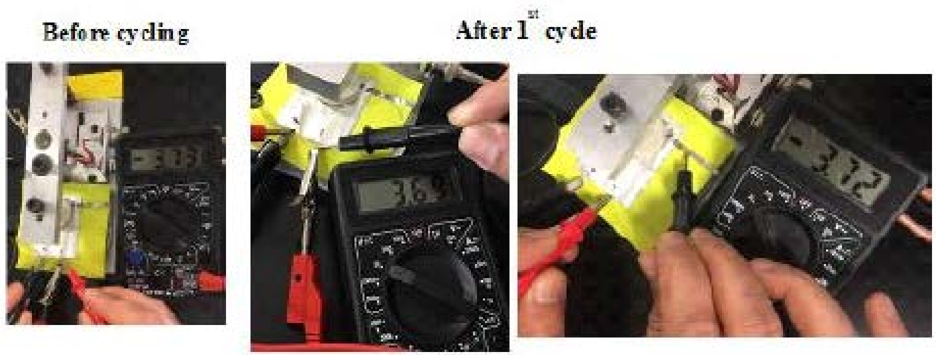




Pouch Cell Fabrication and Testing



Photographic image of pouch cell fabricated using the Ag-coated polymer separator dendrite sensing layer, and schematic of components placement inside pouch cell



Photographic image of pouch cell voltage after fabrication and before cycling (left), after 1 cycle between positive and negative terminals of cell (V1), and between negative terminal and reference metal electrode (Ag-coated polymer separator) (V2).

Lithium battery for Aircraft Propulsion

The purpose of the effort between the Federal Aviation Administration (FAA) and Battery Manufactures will be to provide a data driven process for the verification and validation of the safe installation of Lithium Ion Batteries used in Aerospace applications. This project will be a collaborative effort between the contractor and FAA personnel, OEMs , Li-Ion battery manufactures, and NASA. EP System will participate as a battery system manufacturer and share non-proprietary thermal run-away test data of Li-ion batteries at cell, modular and full battery system levels

Additional LI battery work

NASA

Collaborative research in collaborate and conduct research, exploratory development efforts, testing in the area of energy storage, aviation automation and systems safety, including but not limited to:

i. Development test methods for the Verification and Validation of design safety
ii. Safety and risk analysis;
iii. Systems engineering and analysis;
iv. aviation automation
v. Physic based models

ELECTRIC POWER SYSTEMS

TELEDYNE ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

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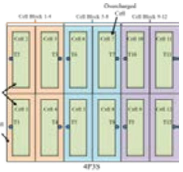
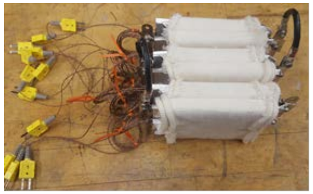
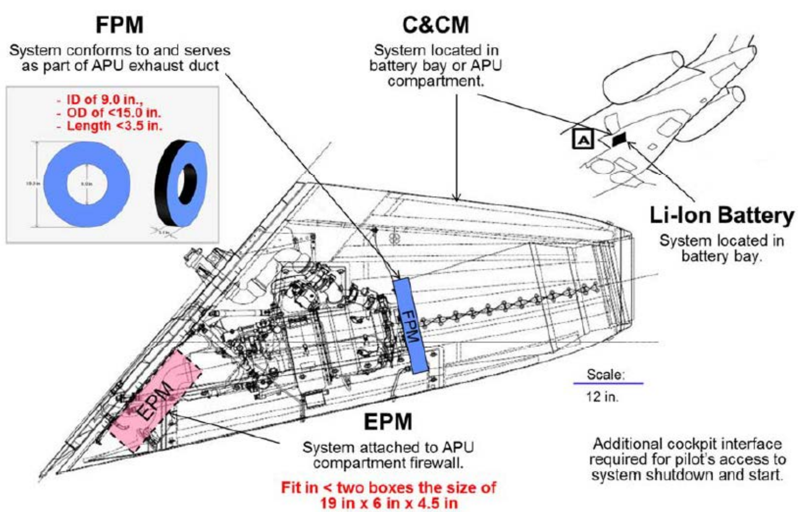




Honeywell FAA Fuel Cell Project

Purpose- The objective of this work will be to develop a Recommended Technical Standard Guidelines (RTSG) document. This RTSG is intended to serve as a basis for an industry standard, and eventually, support government issued certification requirements for fuel cell systems installed on aircraft. The initial step will be to create a set of requirements for this guideline. Honeywell envisions that this document will be based on a current federal standard, such as Technical Standard Order C77b which is used for the certification of Auxiliary Power Units on commercial air transport aircraft..

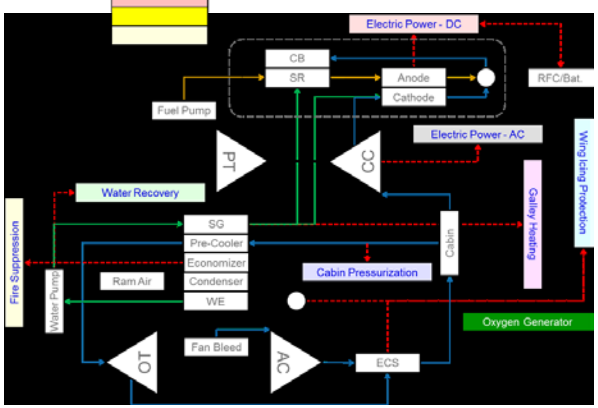


•Three implementation possibilities detailed in the Initial Detailed Research Plan

- •PEMFC APU Using Stored Compressed H_2.
- •SOFC Using Reformed Jet Fuel.
- •Self-Contained Regenerative Fuel Cell System

		Stored Pure H_2		Regenerative		Reformation	
Primary Functions	Legacy System	Stored Oxidant	Air	Stored Oxidant	Air	HTPEM	SO
Emergency Power	RAT						
Ground Operation Power	APU						
Takeoff/Climb Power Augmentation	ME Generator						
Cruise Electric Power	ME Generator						
Flight Idle Electric Power	ME Generator						
None Stop Power Supply	ME, APU, GP						
Battery Tender (V,T), Silent Watch	None						
Secondary Functions							
Anti-freezing, Thermal Management	None						
Cargo Bay Fire Supression	Halon						
Fuel Tank Inerting	ASM						
Water Recovery	Water						

Wide Body Intercontinental
Narrow Body Short - Mid Range
High End Biz-jet
Multiple Platform
Weak Proposition



Initial Fuel cell work

Honeywell

The objective of this work will be to develop a Recommended Technical Standard Guidelines (RTSG) document. This RTSG is intended to serve as a basis for an industry standard, and eventually, support government issued certification requirements for fuel cell systems installed on aircraft

Infinity

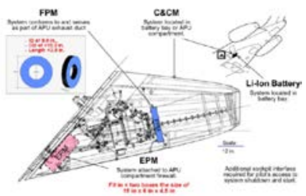
This project is proposing a fuel cell based power and energy system for high to low altitude unmanned aerial vehicles. This will be a lightweight and flexible fuel cell system with hydrogen and oxygen storage, providing long duration flight within and outside of demanding environments. **Sponsored by UAS**

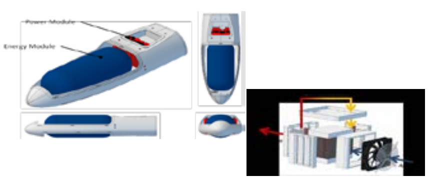
TELEDYNE ENERGY SYSTEMS, INC.
A Teledyne Technologies Company

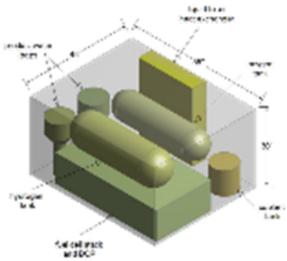
The project is proposing to evaluate two types of systems. Our preliminary assessment is to do one inside the cabin and one outside.

BOEING

The SOFC power system will be assessed for possible safety hazards while identifying methods to contain potential failures or inhibit the propagation of failure effects



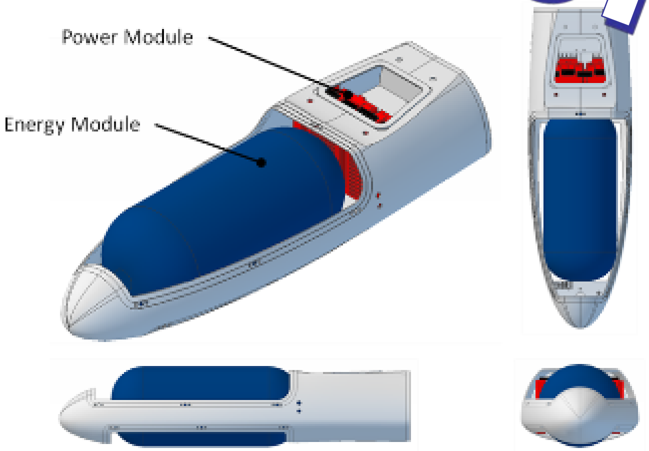


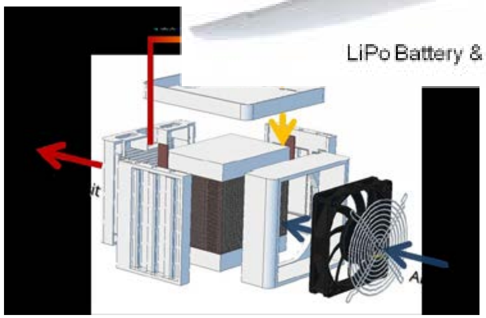


FAA UAS Fuel Cell Project

Purpose- This project is proposing a fuel cell based power and energy system for high to low altitude unmanned aerial vehicles. This will be a lightweight and flexible fuel cell system with hydrogen and oxygen storage, providing long duration flight within and outside of demanding environments. Building on the work of the Energy Supply Device Aviation Rulemaking Committee (ESD ARC) Infinity is mapping the ARC recommendations for applicable parts of the regulations as they apply both to a generic fuel cell system and to the UAV fuel cell system currently under development

Completed





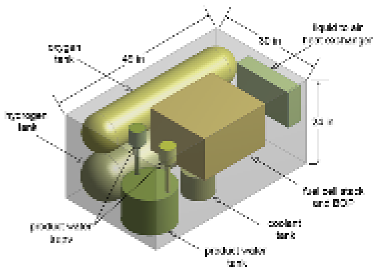
TELEDYNE ENERGY SYSTEMS, INC.

A Teledyne Technologies Company

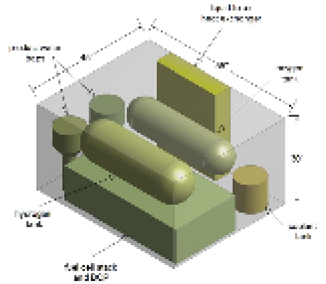
FAA PEM Fuel Cell Project

Completed

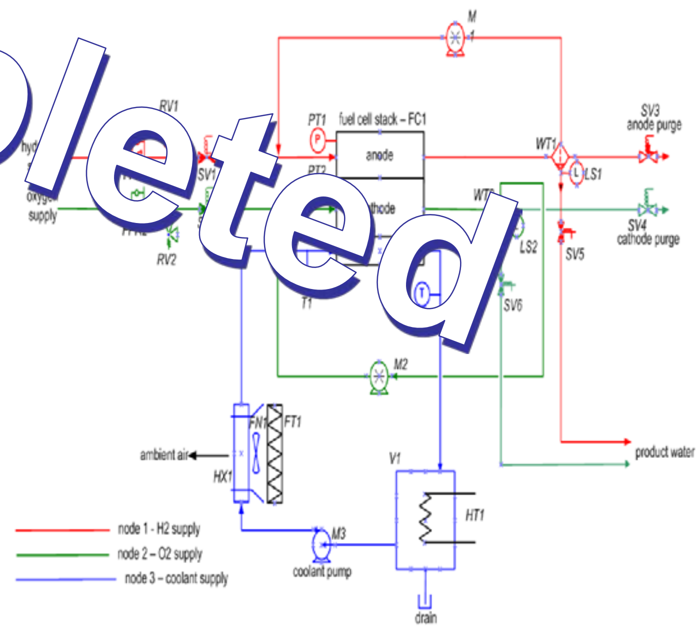
Purpose- The project is proposing to evaluate two types of systems. Our preliminary assessment is to do one inside the cabin and one outside. These are two environments with unique requirements. We also propose to look at one that is highly integrated into the aircraft and the [illegible] is very independent of the aircraft. For example, the emerg[illegible]y ai[illegible]aft power would be outside the cabin, but highly int[illegible]ated into aircraft system and critically important to safety. A g[illegible]ey c[illegible]rt w[illegible] minimally integrated into aircraft systems, bu[illegible]uld [illegible] ins[illegible] th[illegible]in. TESI proposes to review application options with [illegible]A [illegible]d [illegible] and determine at the start of the program which ap[illegible]cati[illegible] provides the most value to the FAA and to aviation OEMs.



•*Medevac Power System – MPS*



•*Emergency Power Systems – EPS*

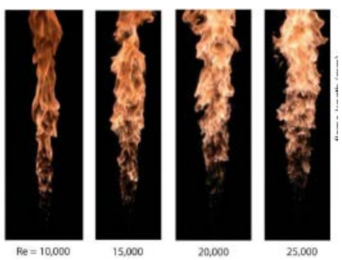


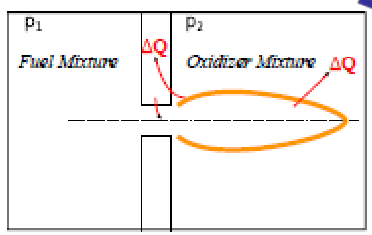
FAA SOFC Project

Purpose- The SOFC power system architecture developed for the NASA electric-flight initiative to develop a safety management approach for the FAA. The SOFC power system will be assessed for possible safety hazards while identifying methods to contain potential failures or inhibit the propagation of failure effects. Testing will be performed on an SOFC stack that undergoes a controlled failure, to evaluate containment of the hazards identified during analysis. Based on [illegible] data and analysis results, Boeing will provide the FAA with airplane [illegible] definitions that would assist the design integration and monitoring of SOFC power systems. Recommendations will also be provided for [illegible] of an SOFC power system for airborne applications in a [illegible] aircraft.

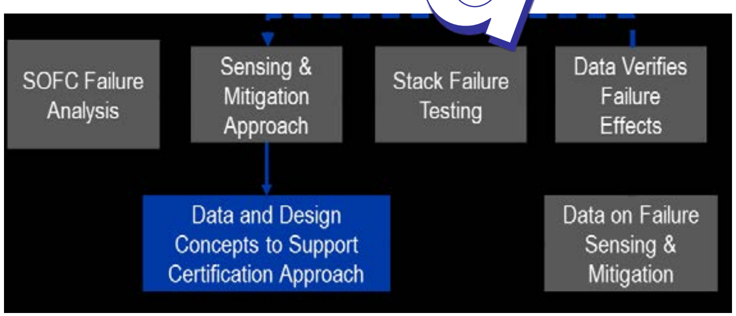
Completed

•Hot Fuel Gas Leakage:





- Flame length is mainly a function of
  - Orifice diameter
  - Fuel mix
  - Flow speed or pressure drop not as important
  - Helps prediction of hazard effects



This is a unique time in aviation which is providing us with an opportunity to help shape the future of Electric Aviation.

Questions?

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