Advanced Drying Process for Lower Manufacturing Cost of Electrodes

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Project ID: ES246

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Overview

Timeline

- Project Start: October 1, 2014
- Project End: September 30, 2016
- Completed To Date: 90%

Budget

- ***Total project funding***
  - ***$1,011,453 (DOE)***
  - ***$288,547 (Lambda)***
- ***$701,965*** *received in FY15*
- ***$76,205*** *received so far in FY16*

Project Goals / Barriers

- Higher electrode loading for high energy density batteries
- Rapid drying of higher loading electrodes using ADP
- Build and test ADP prototype for anticipated 30% - 50% cost reduction of Li-ion battery as compared long convection ovens

Partners

- ***Navitas Systems, LLC***

NAVITAS SYSTEMS

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Relevance and Project Objectives

- Drying of electrode slurries is a slow and high cost operation for lithium ion batteries.
  - Convection oven can hence be up to 40 meter long.
  - ADP/VFM prototype is shorter at 1/5 in length.
  - ADP/VFM system can be added inline with existing oven to increase throughput.
- Advanced Drying Process (ADP) for 30%-50% lower cost manufacturing of electrodes utilizes unique Variable Frequency Microwave (VFM), which can process metal electrodes and is being successfully used for production processes in semiconductor electronics.
- Microwaves penetrate the electrode slurry and interact with polar water or solvent molecules and rapidly drives them out of thick coatings.
- The Advanced Drying Process is expected to reduce the cost of manufacturing of lithium ion batteries used in Electric Vehicles.

Milestones

Date	Milestone & Go/No Go	Status
Start + 2 months	**Milestone 1:** Evaluate Static to Dynamic Processing Parameters	Complete
3 months	**Milestone 2:** Microwave Choke Prototype Testing	Complete
6 months	**Milestone 3:** Final Design Review	Complete
12 months	**Go/No-Go 1:** Lambda Factory System Acceptance	Complete
13 months	**Milestone 4:** Tool Integration at Navitas	Complete
18 months	**Milestone 5**: Prototype cell fabrication	Complete
24 months	**Milestone 6**: Cycle life demonstration and final report	Ongoing

Approach/Strategy

- Electrodes slurries, especially thicker coatings are slow to dry because of the surface heating by convection or infrared radiation (IR frequency is much higher than microwaves).
- Use Variable Frequency Microwaves (VFM) to penetrate the thickness of the thick slurry electrode coatings.
- Water and other solvent molecules are polar. Microwaves selectively target these polar molecules and sets these molecules into rotation.
- The enhanced mobility rapidly drives the water or solvent vapors out of the thick electrode coatings.
- The hot air flowing over the electrode carries these solvent vapors away through the exhaust ports on the equipment.
- The result is a rapid drying cycle which saves drying time and cost.

Variable Frequency Microwaves (VFM)

- With Variable Frequency Microwaves (VFM), a bandwidth (5.85-6.65GHz) of frequencies is rapidly swept in a fraction of second (0.1s).
- The standing wave pattern for any single frequency rapidly changes allowing 4096 frequencies in the bandwidth to sweep in 0.1s, thereby providing electronic stirring of the modal patterns.
- As a result heating is much more uniform than fixed frequency microwaves processes.
- The rapid sweep allows the resident time of only 25 micro-seconds for standing wave pattern for each frequency. Thus there is no charge build up, hence no need potential to discharge (or arc as with fixed frequency) and no damage.
- This unique feature has allowed processing on metal foil as well as semiconductor electronics. VFM used in high volume electronics manufacturing since 2002.

Drying Rate Comparison

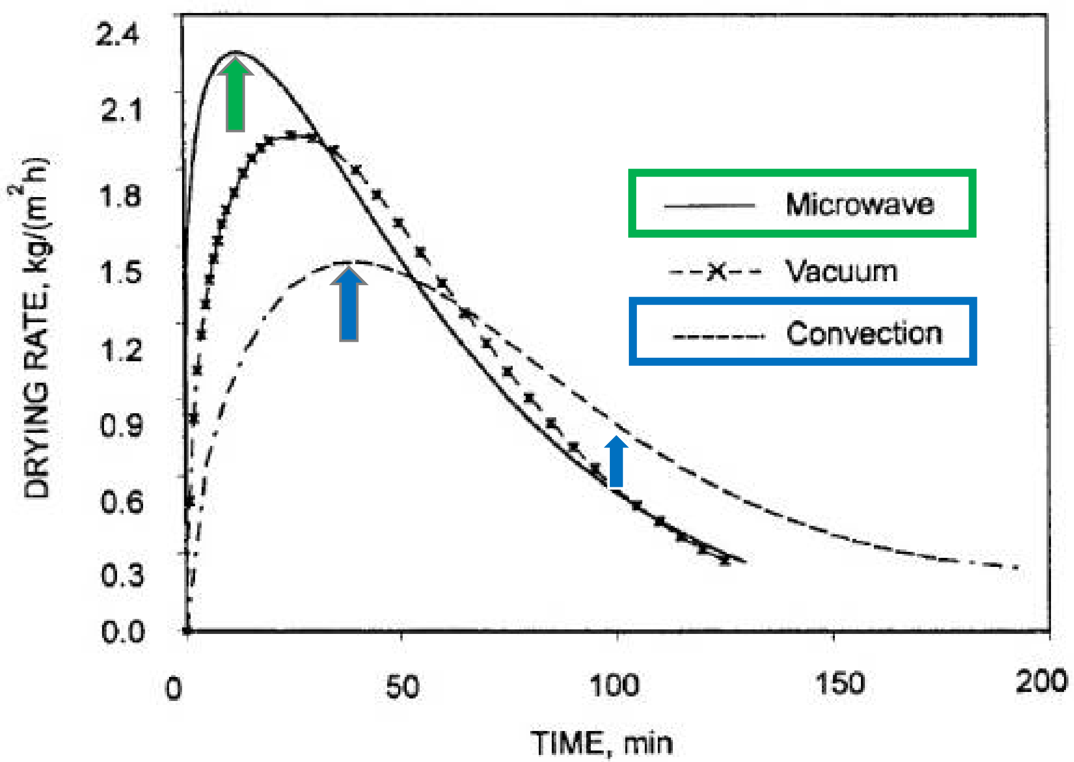
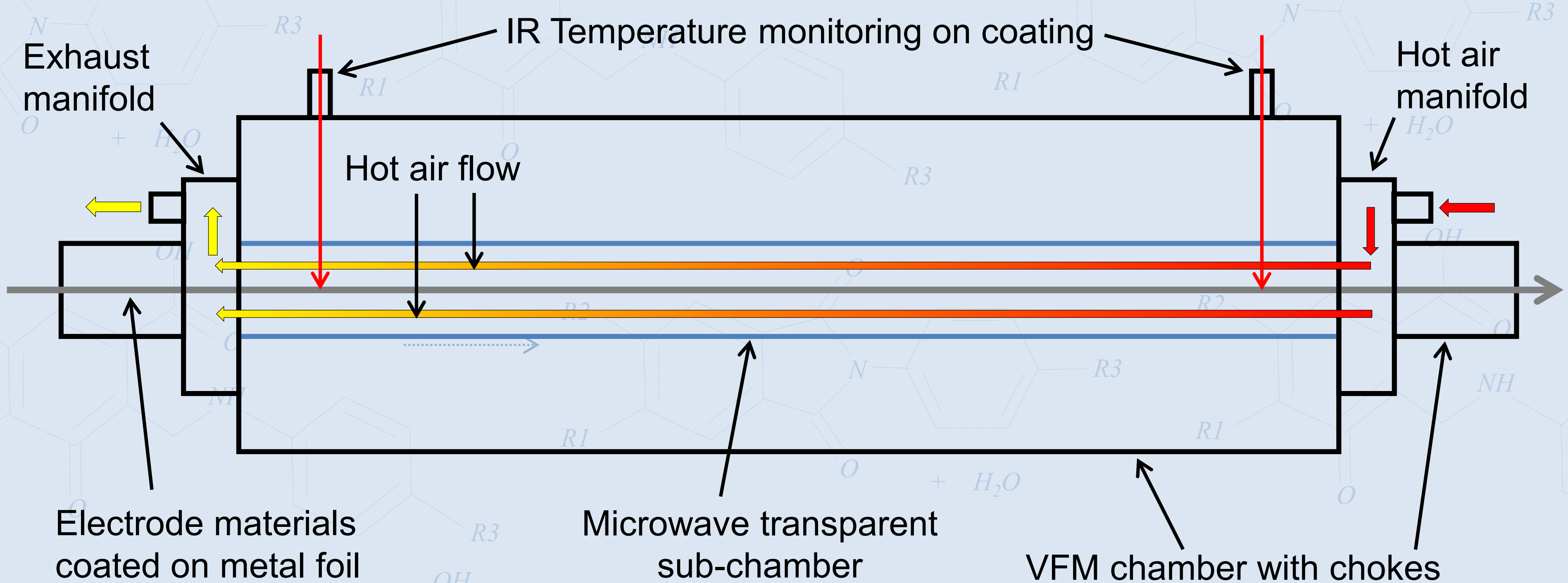


FIGURE 25.1 Convective, vacuum, and microwave drying of chlorpropamide: $T = 60^{\circ}C$, $P = 0.1$ atm, $u = 5.4$ m/s, $P' = 385$ W/kg. (From Kardum et al., 2001.)

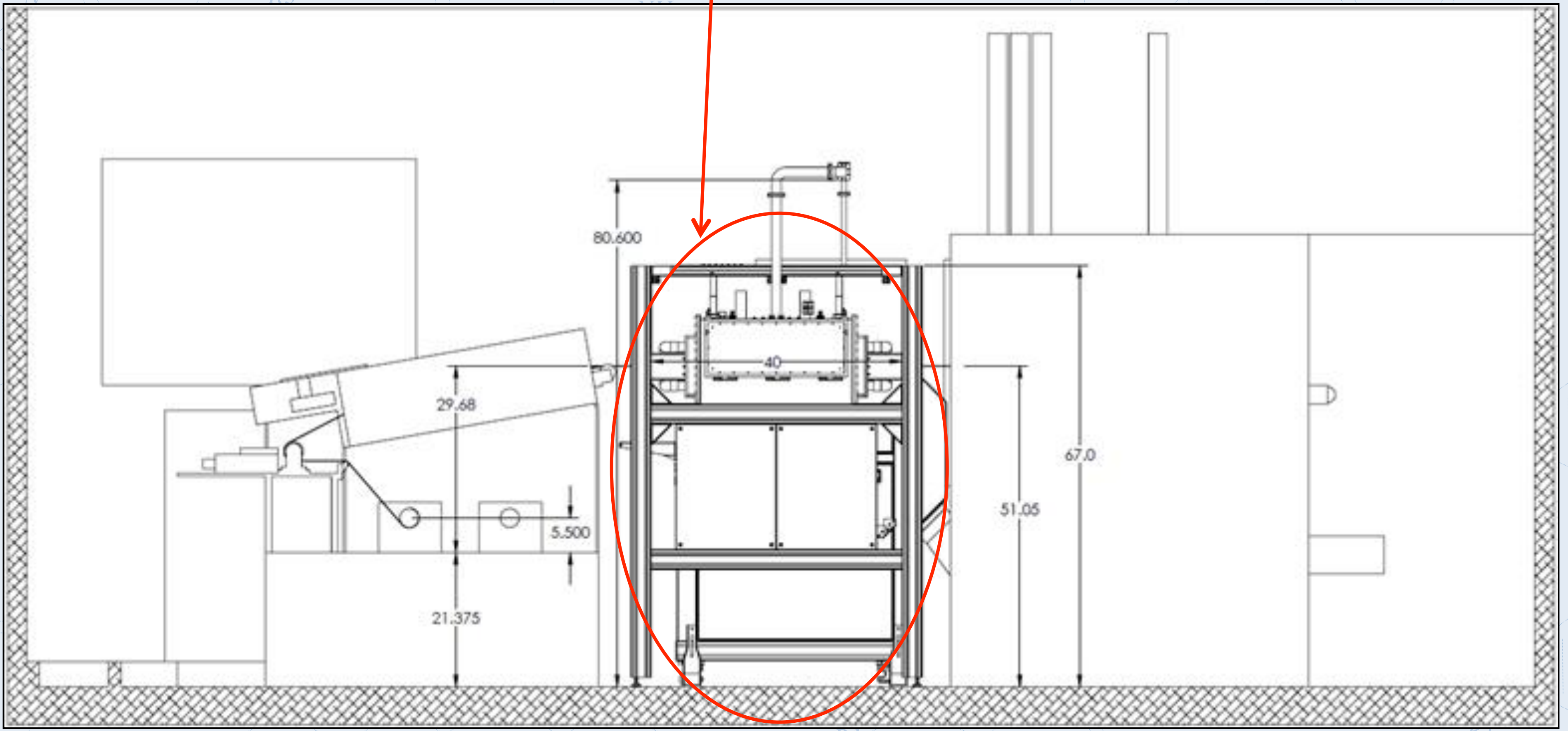
- ***Advanced Drying Process (ADP) employs both the higher microwave drying rate earlier in the process followed by the higher convection drying rate as illustrated in following slide.***

Advanced Drying Process (ADP) VFM & Hot Air



Coated foil moves from the left to right, while hot air moves from the right to left. This arrangement provides higher temperature convection contribution where the foil exits and carries the solvent vapors towards the wet side at the entrance, where VFM contribution in directly heating the wet electrode material dominates the (relatively cooler) air temperature.

Advanced Drying Process (ADP) VFM & Hot Air



ADP/VFM processing chamber designed to fit in pilot coating line at Navitas

Technical Accomplishments

- The wider microwave chokes were designed, fabricated and tested to allow 170mm foil to pass through the ADP chamber without much microwave leakage (within OSHA and International Standards).
- ADP Prototype Tool designed to fit into available space (total of 40 inches) at existing pilot line at Navitas facility in Ann Arbor, MI.
- ADP fabricated and assembled which includes:
  - Microwave transparent quartz sub-chamber to contain hot air for solvent removal.
  - Blowers used with variable temperature control heater for hot air delivery and exhaust.
  - Hot air flow allows for exhaust of solvent and increase in metal foil temperature.
  - VFM works on internal bulk drying of slurry while hot air dries the surface of the slurry.
  - IR temperature devices monitoring electrode temperature at entrance and exit of foil.
- ADP provides a 5X advantage over conventional aqueous drying and 3X for NMP drying.
- Roll-to-roll dried electrode fabrication is complete and cycle life testing is ongoing.

System Acceptance & ADP Tool Integration at Navitas

- On fabrication and assembly of ADP, internal testing was performed for VFM power delivery, leakage and software debugging.
- Navitas personnel made a site visit to Lambda for System Acceptance and to verifying the continuous flow slurry drying.
- ADP Prototype successfully dried aqueous slurry continuously casted at 500mm/min.
- After acceptance the system was disassembled and shipped to Navitas, Ann Arbor, where it was integrated into the existing pilot coating line, as shown in the following slides.

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ADP Prototype Installed Process Module

Digital image of the ADP Prototype installed at Navitas. The Process Module shown is in front while the Power Module is placed behind the Process Module.

ADP Prototype Installed Power Module

Power Module delivers VFM power through waveguide to the Process Module.

Navitas Continuous coating/drying using Lambda Advanced Drying Process

Electrode	Drying Method	Loading (mg/cm^2)	Drying speed (mm/min)	Drying length (m)
Anode (graphite, water based binder)	Standard	10.4	500	2.5
	Advanced drying	10.6	500	0.5
	ADP Advantage	**5X**		
Cathode (NCM523, NMP based binder)	Standard	18.2	350	2.5
	Advanced drying	18.9	225	0.5
	ADP Advantage	**3X**		

- ✓ ***Electrodes were coated using Navitas pilot coating system and dried using either standard or advanced drying process (ADP)***
- ✓ ***Electrode testing at Navitas constituted: solvent content, adhesion, binder distribution experiments***
- ✓ ***Electrochemical validation included: full lithium ion electrochemical testing***
- ✓ ***Advantage of using ADP over conventional drying system was 5X for water based anodes and 3X for NMP based cathodes***

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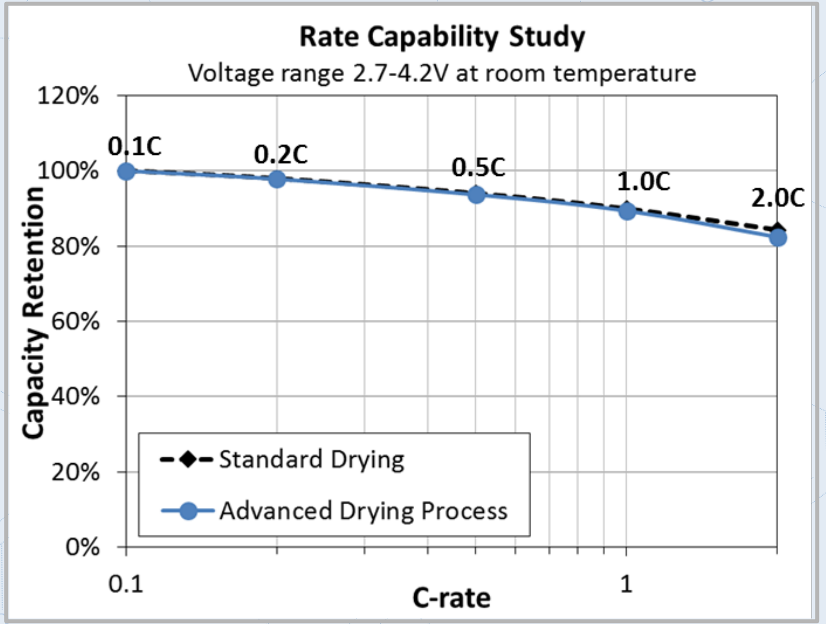
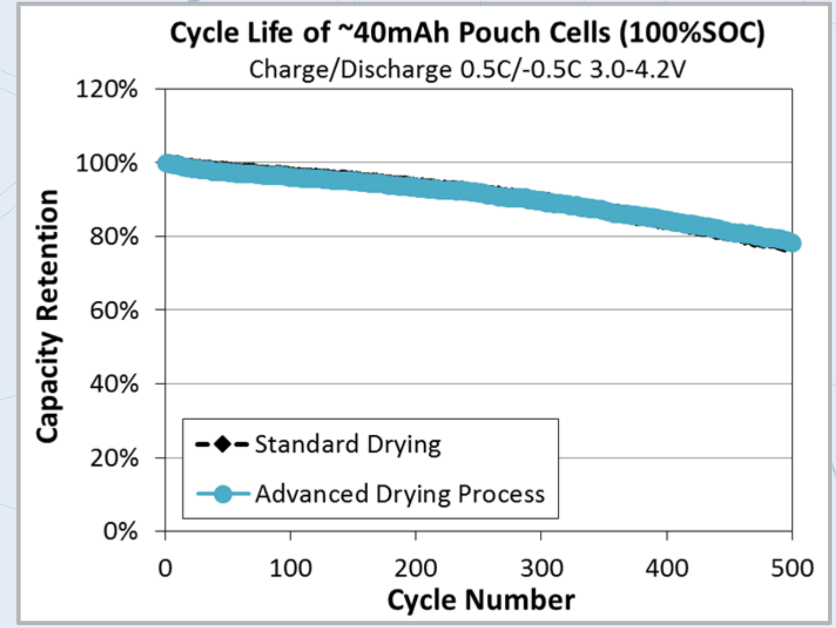
Navitas Continuous coating/drying : Binder Distribution

Electrode	Drying Method	Binder Solvent	Mass Loading (mg/cm^2)	Adhesion	Binder Distribution
Anode	Standard	Water	10.4	Pass	1.19
	ADP	Water	10.6	Pass	1.07
Cathode	Standard	NMP	18.2	Pass	1.09
	ADP	NMP	18.9	Pass	1.03

- ✓ ***Binder distribution ratio (electrode surface to near foil substrate) observed values were lower than target value (Navitas standard values <1.3)***
- ✓ ***Even though coating films were dried faster using ADP physical properties are similar or better than results using conventional drying***

Navitas Continuous coating/drying: validation using ~40mAh Li ion Cell





Drying Method		Loading (mAh/cm^2)	Initial Capacity (mAh/g)	# Life Cycles @ 100%SOC (C/2 rate)
Anode	Cathode			
Navitas	Navitas	3.1	**141.9**	**500**
ADP	ADP	3.1	**142.6**	**500**

✓ ***Pilot continuous drying using ADP confirms that the process does not sacrifice cell performance when compared to standard drying***

Responses to Reviewers Comments

2015 AMR comments	Responses
Energy related cost analysis for the drying processes	As shown in Milestone Timing in Reviewers only slides, detailed evaluation will be conducted in last few months of projects, but preliminary information shown here. (Standard drying equipment online information) Convection Equipment size : 3500×900×1300mm (L×W×H); Coating width:180mm Power = 20kW ADP = 6-7 kW
Effect of loading on drying time	The electrode fabrication has been completed. Experiments on increasing anode and cathode loadings will be carried out during the coming months of the no-cost extension period.
Binder distribution and adhesion	Binder distribution measurements (more details in the reviewers only section) were performed using elemental mapping (EDX) on 4 - 6 section of the film (anode, cathode) cross-section (from top to bottom). Adhesion test were performed using industrial standards (Navitas trade secret).

Partner/Collaborator

- The casting of the wet anode and cathode slurries, ADP and standard drying, as well as the characterization of the electrodes was all performed by our partner Navitas Systems.

- The comparison of the two drying methods, the drying speeds and their respective system lengths, show the advantage by ADP for aqueous (5X) and NMP (3X) based electrodes.
- The preliminary data for adhesion and binders distribution in anode and cathode show identical performance for both the standard and ADP
- The comparison of capacity retention of anode and cathode as well as cycle life testing performed on fabricated pouch cells are identical by standard and ADP method.

Proposed Future Work

- Cell fabrication at Navitas is complete.
- Cycle life testing is ongoing.
- Experiments on increasing anode and cathode loadings will be carried out during the coming months.
- Conduct energy related cost analysis for the ADP drying processes and compare it with conventional methods.
- Compile the data from cost analysis and cycle life testing.
- Write and submit final report in Fall of 2016.

Summary

Relevance

- Drying of electrode slurries is a high cost operation for lithium ion batteries.
- ADP/VFM can rapidly dry electrodes slurries on metal foils.
- ADP is expected to reduce the cost of manufacturing of lithium ion batteries used in Electric Vehicles.

Approach

- Microwaves target solvent molecules
- Use VFM to couple with polar solvent molecules.
- Use penetrating VFM to reach deep in thick coatings and drive solvent out.
- Use hot air to exhaust solvent vapors.

Technical Accomplishments

- Manufactured ADP prototype for drying 170mm wide anode and cathode electrodes on metal webs.
- ADP process had 5x advantage for aqueous anode and 3x for NMP yet providing equivalent properties.
- SLP full cell testing shows no difference in rate performance between standard and ADP dried electrodes.
- Cycle life testing is ongoing.

Future Work

- Carry out experiments on increasing anode and cathode loadings.
- Conduct energy related cost analysis.
- Prepare and submit final report.

Technical Back-Up Slides

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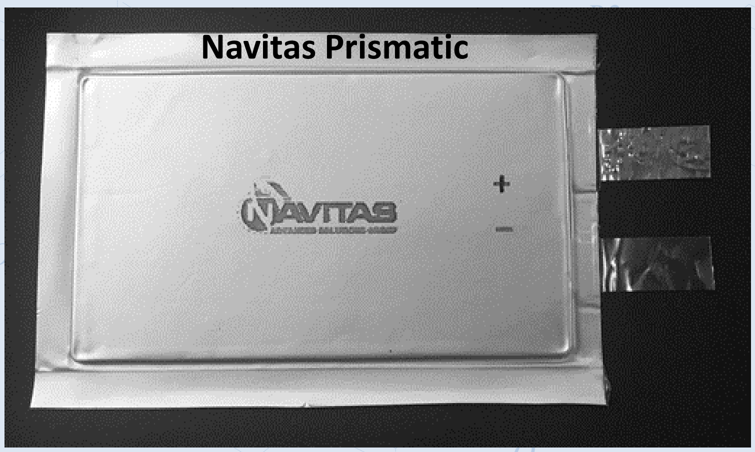
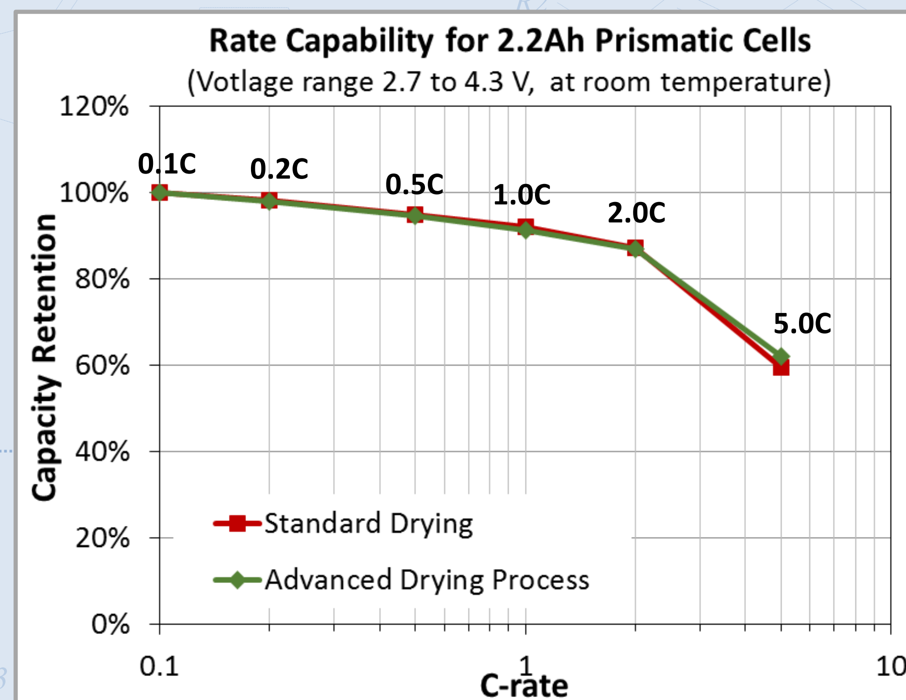
2Ah Prismatic Li ion Cell Testing: Formation and Rate Capability

✓ Formation data

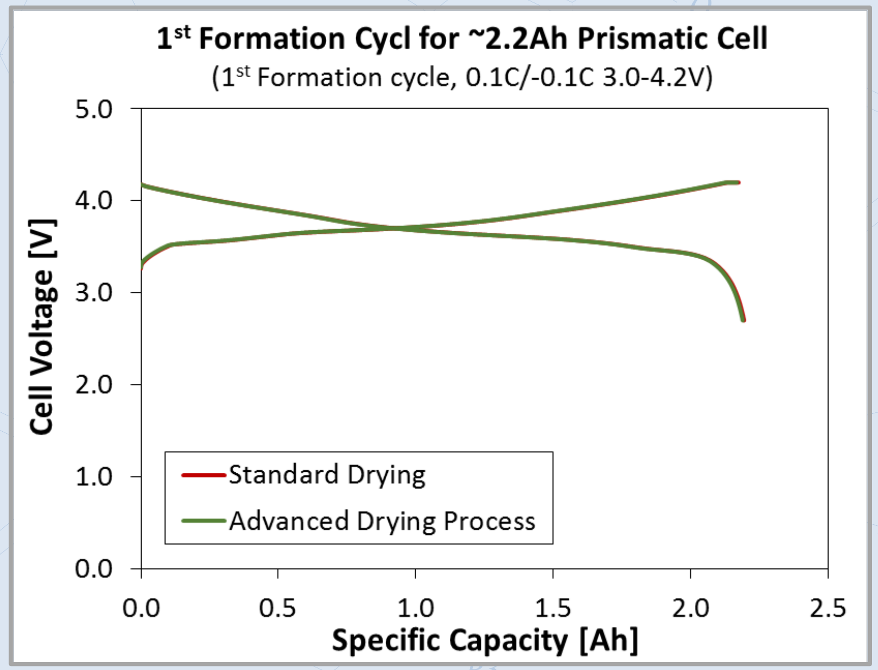
Drying method	Formation Capacities (Ah)		ICL (%)
	First Charge	Reversible	
Conventional	2.61	**2.19**	**15.9%**
ADP	2.61	**2.19**	**16.0%**

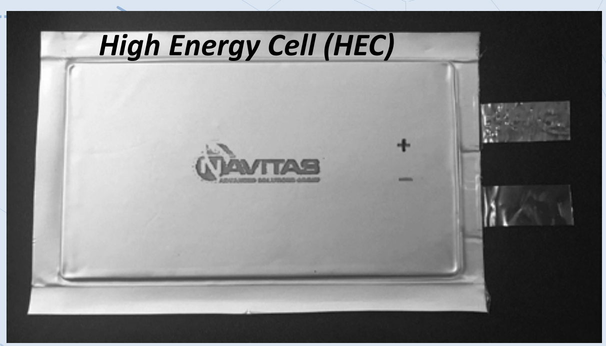




✓ Continuous coating/drying using ADP was used to fabricate electrodes for 2 Ah prismatic lithium ion cells

Navitas Continuous coating/drying: 2Ah Li ion cell fabrication testing





HEC cathode

HEC anode

Drying method	Cell format	Capacity (Ah)		ICL (%)
		FCC	Rev.	
Convectional	SLP	0.044	**0.038**	**13.4%**
	HEC	2.61	**2.19**	**15.9%**
ADP	SLP	0.043	**0.037**	**13.5%**
	HEC	2.61	**2.19**	**16.0%**