INNOVATIVE MANUFACTURING AND MATERIALS FOR LOW COST LITHIUM ION BATTERIES

Prepared for:	U.S. DOE/NETL
Award No.:	DE-EE0005433
Report/Product Number:	DOE-OPTO-05433-1
Grant Period:	10/01/2011 through 9/30/2015
Submission Date:	December 29, 2015
Reporting Period End Date:	09/30/2015
Report Frequency:	Final
Author, PD/PI:	Dr. Steve Carlson President & CEO 617-569-5059 scarlson@optodot.com
Submitting Official:	Same as Author above
Contractor:	Optodot Corporation 100 TradeCenter, Suite G-700 Woburn, MA 01801
DUNS Number:	020801929

Subcontractors:

Madico, Inc., 64 Industrial Parkway, Woburn, MA 01801
XALT Energy, 2901 NE Hagan Road, Lee's Summit, MO 64064
University of Rhode Island, 51 Lower College Road, Kingston, RI 02881
Ashland Inc., 1361 Alps Road, Wayne, NJ 07470

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This project demonstrated entirely new manufacturing process options for lithium ion batteries with major potential for improved cost and performance. These new manufacturing approaches are based on the use of the new electrode-coated separators instead of the conventional electrode-coated metal current collector foils. The key enabler to making these electrode-coated separators is a new and unique all-ceramic separator with no conventional porous plastic separator present. A simple, low cost, and high speed manufacturing process of a single coating of a ceramic pigment and polymer binder onto a re-usable release film, followed by a subsequent delamination of the all-ceramic separator and any layers coated over it, such as electrodes and metal current collectors, was utilized.

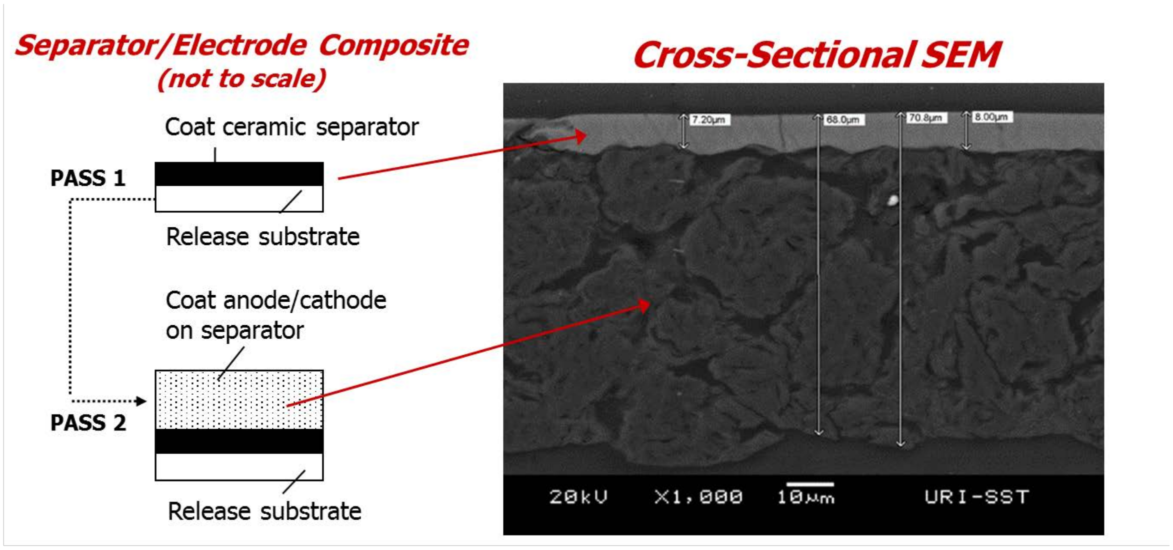
A suitable all-ceramic separator was developed that demonstrated the following required features needed for making electrode-coated separators: (1) no pores greater than 100 nanometer (nm) in diameter to prevent any penetration of the electrode pigments into the separator; (2) no shrinkage of the separator when heated to the high oven heats needed for drying of the electrode layer; and (3) no significant compression of the separator layer by the high pressure calendering step needed to densify the electrodes by about 30%. In addition, this nanoporous all-ceramic separator can be very thin at 8 microns thick for increased energy density, while providing all of the performance features provided by the current ceramic-coated plastic separators used in vehicle batteries: improved safety, longer cycle life, and stability to operate at voltages up to 5.0 V in order to obtain even more energy density.

The thin all-ceramic separator provides a cost savings of at least 50% for the separator component and by itself meets the overall goal of this project to reduce the cell inactive component cost by at least 20%. The all-ceramic separator also enables further cost savings by its excellent heat stability with no shrinkage at up to 220^{o}C. This allows vacuum drying of the dry cell just before filling with the electrolyte and thereby can reduce the size of the cell assembly dry room by 50%. Once the electrode-coated separator is produced, there are many different approaches for adding the metal current collector layers and making and connecting the tabs of the cells. These approaches include: (1) laminating the electrode side of the electrode-coated separator to both sides of a metal current collector; and (2) making a full coated electrode stack by coating or depositing a current collector layer on the electrode side and then coating a second electrode layer onto the current collector. Further cost savings are available from using lower cost and/or thinner and lighter current collectors and from using a separator coating manufacturing process at widths of 1.5 meters (m) or more and at high production line speeds of up to 125 meters per minute (mpm), both of which are well above the conventional coating widths and line speeds presently used in manufacturing electrodes for lithium ion batteries.

GOALS AND ACCOMPLISHMENTS

A number of significant accomplishments were made during this project, including many first-of-its-kind technology demonstrations based on a novel electrode-coated separator manufacturing approach to achieve lower cost batteries. The most important breakthrough was demonstrating the ability to coat the electrodes directly onto the separator as shown in Figure 1.

Figure 1.



NOTE: Release substrate was removed prior to cross-sectional SEM

The project demonstrated the major technology foundations for the electrode-coated separators and their assembly into lithium ion cells, but was not able to build the electrode-coated separators into high performance 2 Ah cells due partly to limitations on the availability of coating equipment and personnel over the last 2 years by the subcontractor, XALT Energy, responsible for doing the electrode coatings onto the all-ceramic separator and the subsequent 2 Ah cell building and formation cycling. In November 2013, Dow Chemical discontinued its participation in Dow Kokam and transferred its ownership to a minority owner, named Townsend & Associates, who renamed the company, XALT Energy. Eventually, XALT Energy closed its R&D facility in Lee’s Summit, MO, in August 2015, which included its only small scale, pilot coating capability for making electrode-coated separators.

At a project review meeting with the DOE in August 2015, the decision was made to finish the project on September 30, 2015, and make the best effort with the small existing inventory of anode-coated separators to make a laminated design of the 2 Ah cells of this project. More details on this will be described later in this report, but the overall result was that Optodot only received 15 working cells from XALT Energy in November 2015. Although these cells cycled, they were not acceptable in performance. The cells cycled at about a C/10 rate with a capacity of about 1.2 Ah, were not extremely high in cycling efficiency, and did not generally show excellent voltage stability in stand tests.

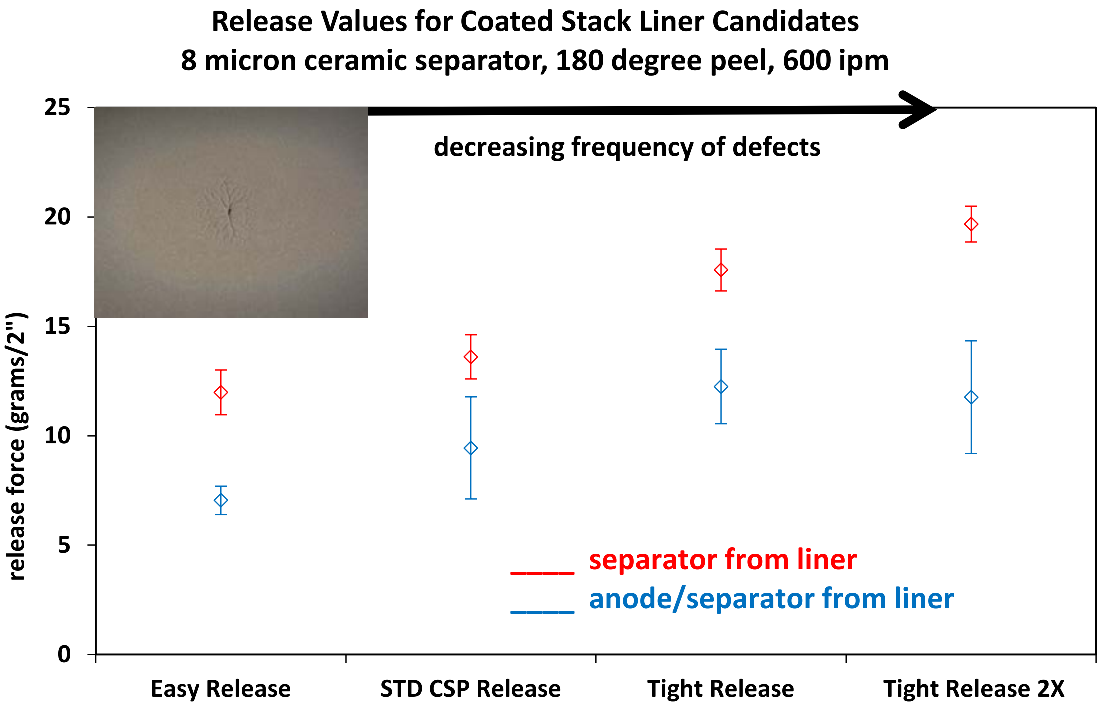
Optodot is confident in its electrode-coated separator technology for manufacturing lithium ion cells and is committed to building 2 Ah cells which demonstrate the cost and performance features of this technology. To accomplish this, Optodot is currently negotiating a development project on this electrode-coated separator technology with one of the major lithium ion cell manufacturers, who has a strong interest in this technology for next generation lithium ion cells.

Although the builds of high performance 2 Ah cells could not be accomplished before the project end date, Optodot did carry out a detailed cost analysis on electrode-coated separators and cells built from it. This cost analysis, using the Argonne cost model, did show that the project goal of at least a 20% cost reduction for the inactive components of the cell was met and that process savings would likely contribute further cost reductions due to these new inactive components, particularly the very low cost all-ceramic separator with its ability to enable vacuum drying of the dry cells at very high temperatures just before filling the cells with electrolyte.

PROJECT ACTIVITIES, RESULTS, AND KEY OUTCOMES

The first significant problem encountered in this project was the presence of small random coating defects when the anode or the cathode layers were coated onto the all-ceramic separator layer on a release substrate. It took some time and experimentation to determine that these coating defects were caused by premature delamination of the ceramic separator layer from the release substrate due to too easy a release force for the delamination (see Figure 2). This problem and its solution delayed the timetable of the project by about one year. Three commercial silicone-coated release film substrates were evaluated with one of them that provided a much higher release force being selected for future work. The release force for delamination of the separator layer was in the range of 5 to 12 grams per 2 inch width with the original release film used that resulted in coating defects by premature delamination during the electrode coating. The higher release force commercial film was used for making the final set of anode-coated separators for the cell build in September 2015. It had a release force for delamination of about 30 to 40 grams per 2 inches. After overcoating with the electrodes and calendering, the cathode-coated separator was too difficult to delaminate from the release substrate.

Figure 2.



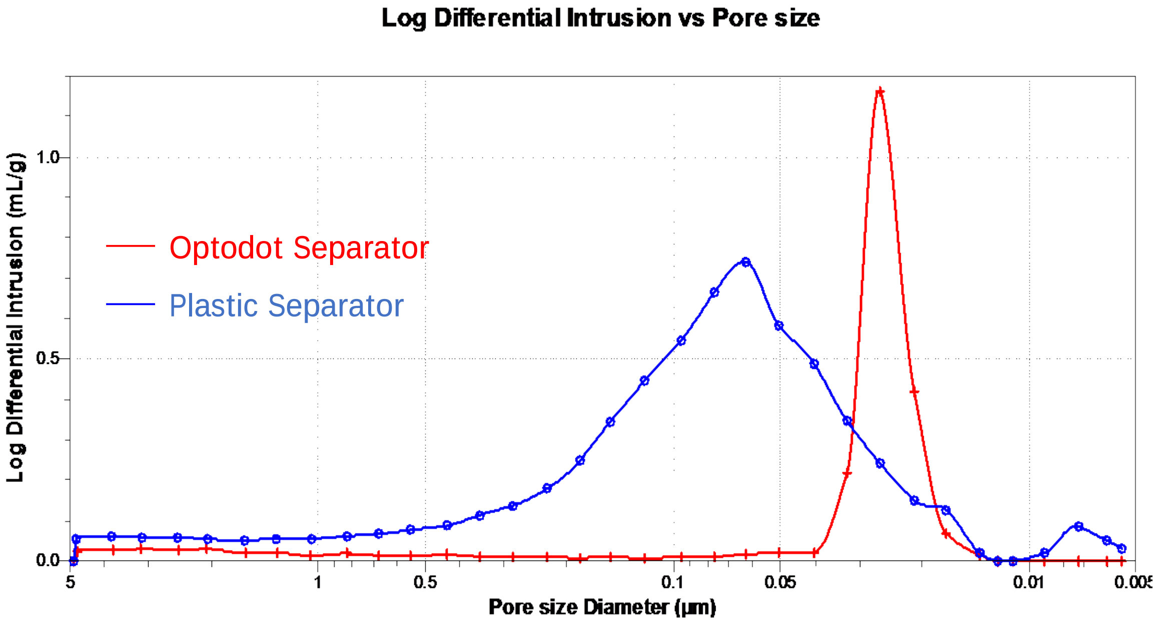
The needed release force for the electrode-coated separators of this project needed to be in the intermediate range of release force for delamination of 15 to 25 grams per 2 inches. The combination of the lack of commercial release films with this level of release force and the observation that the N-methyl pyrrolidone (NMP) solvent in the electrode coatings was penetrating into the polyester (PET) film of the release substrate led to a decision to develop an in-house production-made release film that had the right release force and provided a good barrier to diffusion of the NMP into the PET substrate. This was accomplished by developing a highly cross-linked release coating with the right level of silicone material to achieve the desired release force for delamination. It is estimated that this in-house release film with its highly crosslinked solvent barrier layer could be reused for at least 15 times before needing to be refurbished by recoating the release layer with a fresh release coating. For the cost analysis for this project, a more conservative number of 10 reuses before re-coating was used.

Samples of this new in-house release film at two different release force levels (Tight Release and Tight Release 2X as shown in Figure 2) were made on a production coater at Madico and then coated with an 8 micron thick all-ceramic separator layer. XALT Energy was not able to provide pilot coating time for doing anode and cathode coatings on this all-ceramic separator in order to choose the preferred release force level from the two release film candidates and to provide cathode-coated separator and new anode-coated separator that could be efficiently delaminated and could be used to build 2 Ah cells. As a result, Optodot only had some anode-coated separator made in 2014 to use in the 2 Ah cell builds in September 2015.

Although there was a problem encountered with coating defects from premature delamination from the release layer, the other requirements for manufacturing electrode-coated separators that were in the original plans for the project turned out to not present a problem.

First, the all-ceramic separator had pore size diameters in a narrow range centered around 35 nm and had no significant pores above 100 nm in diameter (see Figure 3). This prevented any penetration of the conductive carbon pigments and other pigments from the electrode coating into the all-ceramic separator layer. Figure 3 also has the pore size distribution for a 9 micron thick plastic separator from Toray Tonen. It can be seen that the pore sizes for the plastic separator include many pores above 100 nm, and even up to 500 nm. As a result, the carbon black pigments in the electrode easily penetrate the pores of the plastic separator and are able to diffuse over to the opposite electrode layer during the cycling of the cell. The all-ceramic separator layer of this project provides an ultrafiltration barrier to any penetration of conductive carbon pigments and other pigments into and through the separator layer. Optodot also did considerable work with a larger ceramic particle which provides a narrow pore size distribution around 75 nm, but was still small enough to be useful in the electrode-coated separators of this project.

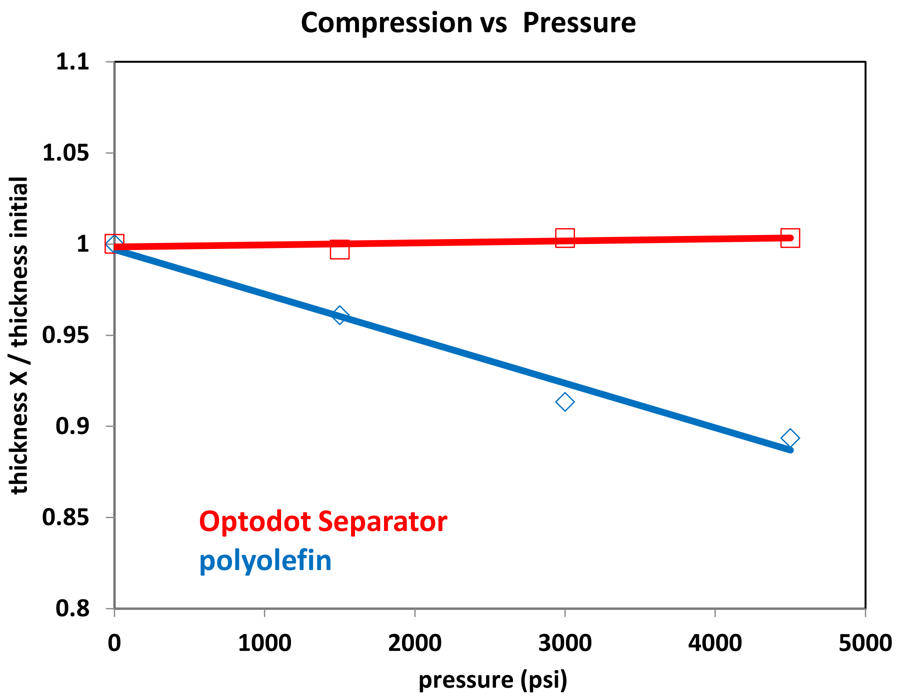
Figure 3.



Second, the all-ceramic separator layer had exceptional heat stability with shrinkage of only 0.5% or less when heated at 220^{o}C for 1 hour. There was no distortion or disruption of the all-ceramic separator layer when it was coated with a NMP solvent-based anode or cathode coating and then heated at a high temperature to dry the electrode layer. Part of this resistance of the all-ceramic separator layer to NMP solvents and to high drying temperatures is thought to be due to the sol gel or xerogel nature of the all-ceramic separator with its 3-dimensional inorganic oxide porous layer reinforced with polyvinylidene difluoride (PVdF) polymer binder of one of the high performance grades also used in battery electrode coatings. The ceramic pigments of boehmite or AlOOH are nearly cubic in shape and form a 3-dimensional porous network with the pore sizes similar to the size of the primary particle of the boehmite.

Third, the all-ceramic separator layer has very high compression strength (see Figure 4), which enables it to be calendered under high pressure when the electrode is densified by about 30% without any collapse or degradation of the pores of the separator. Typically, calendering only densifies the all-ceramic separator layer by about 5%, instead of the 30% compaction for the electrodes. The ability of the all-ceramic separator layer to be calendered without degradation was one of the key potential problems identified at the start of this project. It proved not to be a problem. Instead of a negative effect which would have made this project very difficult or impossible to do, the calendering had a beneficial effect on the all-ceramic separator by making it about 5% thinner while increasing its tensile strength by about 15%.

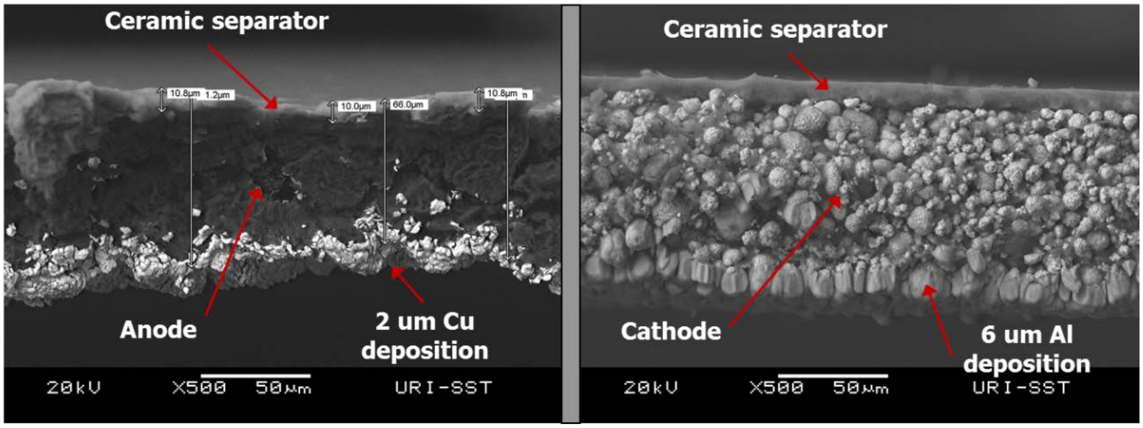
Figure 4.



The all-ceramic separator layers of this project have a porosity of about 40% and showed excellent cycling efficiency and rate capability when evaluated in coin cells. If a higher rate capability is needed for power cells, the % porosity can be increased by lowering the amount of polymer binder in the all-ceramic separator layer to boost the % porosity to 45% or higher. These all-ceramic separator layers also contribute to long cycle life, probably by scavenging the degradation products of the electrolyte such as HF and POF_3. They also appear to improve the temperature stability of $LiPF_6$-based electrolytes such that, for example, heating cells with the all-ceramic separator showed very little degradation in capacity after heating at 150°C for 1 hour. As a consequence, the decision was made to continue to use conventional $LiPF_6$-based electrolytes in this project, rather than working to develop a lower cost electrolyte with improved performance.

With the development and demonstration of acceptable electrode-coated separators in this project, the next problem area encountered was how to provide a low cost current collector layer and how to tab and connect it to the external circuit. As a first step to evaluate feasibility, metal current collector layers were sputtered onto the electrode side of the electrode-coated separators (Figure 5). Copper metal layers were deposited for the anode-coated separator. Aluminum metal layers were deposited for the cathode-coated separator. This was the first demonstration of a coated stack of metal current collector/electrode/separator and provided acceptable performance in coin cells. This result, which was jointly done with The University of Rhode Island (URI), was presented in a poster session at an Electrochemical Society Meeting in November 2013 and published in the Journal of Power Sources in 2014.

Figure 5.



The next step in providing the current collection and tabbing was to evaluate various design options for adding the current collector layer to the electrode side of the electrode-coated separator. To provide the desired rate capability in large vehicle cells, it became clear that the current collection layer needed to be a highly conductive metal layer, such as a copper metal layer for the anode.

A promising new approach for doing a copper metal layer was found in 2013 and further developed in 2014. This approach involved coating an ink of copper oxide nanoparticles on the anode side of the anode-coated separator and then exposing this ink layer to xenon flash lamp sintering to form a thin conductive copper metal layer of 3 to 6 microns in thickness. A special process to create a copper metal layer on an electrode-free area of the separator next to the coated lane of anode and to use this copper metal layer on the separator layer to adhere to a nickel-clad copper tab to provide tabbing, was developed. The very positive feature of the all-ceramic separator layer of adhering strongly to adjacent layers, including any metal layers, in the presence of the carbonate solvents of the electrolyte was used to advantage to adhere the tab.

In order to pursue this coated current collector approach, electrode-coated separator using the improved in-house release film needed to be coated so Madico could coat the precursor ink for the sintering to form copper metal layers. This needed to be subsequently followed by coating a lane of a second electrode layer over the copper metal layer. Since XALT Energy was not able to do any more electrode coatings for this project after late 2014 and with the decision at the DOE project review in August 2015 not to do any extension of the project beyond September 30, the project focus changed to using the existing inventory of anode-coated separators and laminating them to both sides of a conventional copper foil with the use of a conductive graphene-based adhesive tie coat coated on the anode surface.

Optodot had repeatedly observed an unexpected finding that using the all-ceramic separator layer as the adhesive tie coat in the laminated stack approach seemed to provide excellent adhesion and excellent electrical conductivity properties. This was unexpected since the all-ceramic separator layer is a very good insulator between the anode and the cathode layers. It may be that the very conductive copper layer and the fairly conductive anode layer can still have a good electrical connection when separated by a fairly thin 8 micron thick, or thinner if needed, all-ceramic tie coat. Since there was a very limited quantity of anode-coated separators for the cell builds, it was necessary to focus on only laminating the anode stacks using the graphene-based conductive tie coat. For reasons unknown, this approach did not provide high performance cells. When possible, Optodot would like to evaluate the all-ceramic separator layer as the adhesive tie coat for laminated stacks.

This laminated stack approach was the original electrode-coated separator process for making lithium ion cells that was invented in 2009 and became an issued U.S. patent in 2015. It was generally compatible with the punching, tabbing, and cell assembly process at XALT Energy for 2 Ah cells, where the lamination left about a 12 mm width of electrode-free copper foil on one side of the stack which could be punched out to provide the tab.

Although Optodot provided enough anode-coated separator laminated to both sides of copper foil to XALT Energy to make at least 50 2-Ah cells, XALT only did formation cycling on 38 cells and then provided only 17 cells to Optodot in mid-November. Of these 17 cells, two of them were dead so that there were only 15 working cells received by Optodot. XALT could offer no details on why many of the 38 cells that went through formation cycling and had some of the better formation cycling data were not shipped to Optodot and said that these cells had been discarded. XALT did say that they had not put insulating tape in key areas of the 2 Ah cells and had later realized that this was a mistake and started to use insulating tape on some of the last cells. However, XALT could not identify which cells had insulating tape in them.

XALT Energy did say that, if they had had more time, that it would have been better to have a special punch die and new assembly rig made for the doing the cell builds with the laminated anode stacks because they were not an exact drop-in to their conventional anodes. Combined with the lack of using insulating tapes, this may be the cause for the lack of voltage stability observed in extended stand tests of the 15 working cells received by Optodot.

XALT Energy uses a very fast formation cycling protocol. The formation cycling capacities and efficiency on the cells of this project were very scattered. This is not surprising because, when the cells were cycled at Optodot, they had a low rate capability of about C/10.

It should be noted that it is possible that the adhesion between the anode and the copper foil was lost in part or wholly in the presence of electrolyte and the charging and discharging process. This could also explain the low cycling rates. The low capacity of about 1.2 Ah for the cells could have been the result of thinner anodes and cathodes giving a lower cell capacity being used.

All in all, there are too many variables, unknowns, and questions about the cell build at XALT Energy at the end of September 2015 to draw any conclusions. As stated earlier in this report, Optodot plans to make cells using electrode-coated separators using both the laminated anode stack approach and the full coated anode stack approach with sintered metal current collectors and is negotiating with a major cell manufacturer to partner with Optodot in making these cells.

The following process was used to build the 2 Ah cells in September 2015:

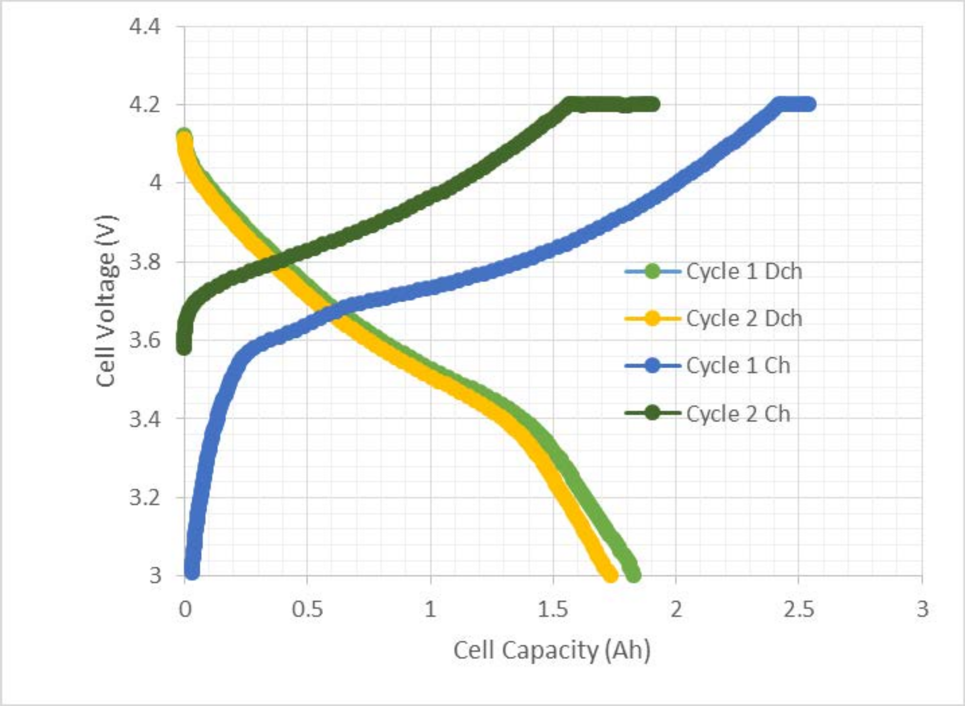
- Coat a conductive adhesive tie coat onto the anode surface of the lane of anode coating on 8 micron ceramic separator on a release film. Coat this tie coat to the edge of the anode lane but not onto the adjacent anode-free separator surface. The lane of anode was wide enough to punch out the anode for two 2 Ah cells.
- Delaminate the coated anode separator from the release film and cut it to have about a 5 mm border of anode-free ceramic separator on each side of the anode lane. This separator area is useful for insulating the edges around the anode from the cathode when the cell stacking is done.
- Cut the copper foil sheet to be used in the heat lamination to provide about 12 mm of extra copper on each side for an anode-free area for conventional tabbing and termination.
- Position two anode separator stack cut pieces on each side of the copper foil cut piece and heat laminate them to make the anode ready for punching for cell builds.
- Punch these anode stacks into the cut size for cell builds with the existing 2 Ah anode cell punch at XALT Energy.
- Note that the anode stacks after punching were vacuum dried at XALT at 130^{o}C for 4 hours, since the ceramic separator is very heat stable and it was

found that this vacuum drying significantly improved cycle life and, with some lithium ion battery chemistries, also improved the rate capability.

- Build up the 2 Ah cell stack with 17 punched anode sheets and the equivalent punched cathode sheets, weld the anode and cathode tabs, place the cell stack in the pouch, fill the pouch with electrolyte, and seal as done in conventional cell manufacturing.

An example of the data on the 2 Ah cell builds at XALT Energy is shown below (Figure 6) in the formation cycling curve for one of the 2 Ah cells built.

Figure 6.



This cell, along with about 18 others, was discarded by XALT Energy and not shipped to Optodot in mid-November 2015 for further testing.

A cost analysis using the Argonne cost model was done on the all-ceramic separator and on cells of different sizes according to the Argonne cost model and for the laminated anode stack approach. This analysis was done mainly by Eric Dix of Innovation Associates in St. Louis, MO, working as a consultant to Optodot. The cost analysis is in Appendix 1 of this report.

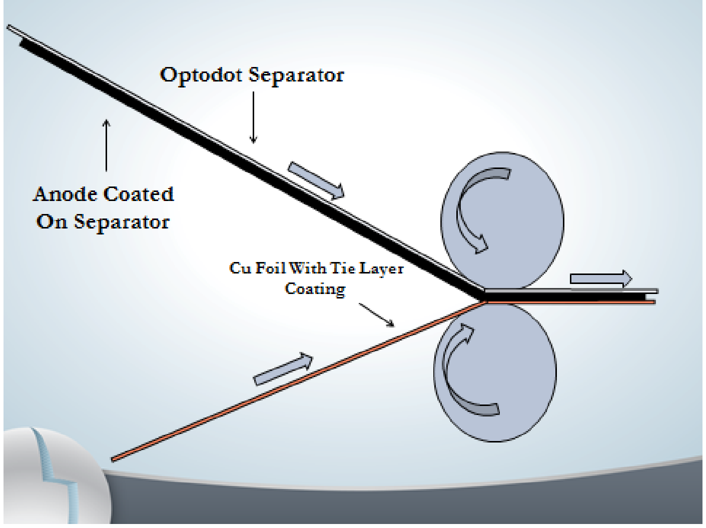
The baseline cost model developed at Argonne was used with the exception of the use of the Optodot ceramic separator and of the novel fabrication concepts specific to the coated stack cell of this project. In the Argonne model of 2012, the separator cost is assumed to be \$2.00/m^2.

Optodot continues to closely monitor the selling prices of ceramic-coated plastic separators on a quarterly basis and has only seen pricing so far getting as low as \$1.50/m^2 with pricing of the wider widths of separator used for vehicle batteries still being \$2.00/m^2 or higher. Also, Optodot is not aware of ceramic-coated plastic separators providing all of the desired safety features, such as passing nail penetration tests on fully charged batteries especially as the cell designs move to higher energy density and voltages.

In this cost analysis, switching to the re-usable release film for making the separator with its in-house manufacture by Madico or another company, its continued re-use by re-coating, and the option of making it on both sides of the release film in a “simultaneous” single pass or a tandem two-station pass through the coater further reduced the cost. This, combined with the high volume throughput of the separator coating at a 1.5 meter width and at a line speed of 125 meters per minute, resulted in the costing of \$0.39/m^2 to be used as the input for the separator cost in the ANL cost model.

Across the range of cell energy capacities in the ANL cost model, this separator cost results in a cost reduction of 25 to 35% of the total cost of the inactive materials of the cell. Analysis of the potential added cost of about \$0.40/m^2 for the conductive adhesive tie coat applied to the copper foil as shown in the figure below (Figure 7), combined with the net cost savings of the manufacturing process with its potential for a 50% reduction in the size of the dry room because of the ability to vacuum dry the electrode stacks at high temperatures just prior to electrolyte filling, and because of the roll-to-roll nature of the electrode separator stacks using 1.5 meter widths and with a lamination process step that can be combined with calendering, shows that greater than this 25 to 35% cost savings is possible in this project.

Figure 7.



Two new technical factors were learned which should enable more cost savings. First, Lambda in North Carolina is working on variable microwave frequency drying under a DOE project and with two of the leading coating equipment manufacturers to increase the oven drying speed for NMP-based battery electrode coatings by up to three times. This should work even better with the release film substrate, which doesn't interfere with the microwave-enhanced drying efficiency as do the conductive metal foils of the conventional electrode coatings. Second, a two side coated copper on PET film can be ultrasonically welded with at least 60 layers into a single high quality tab for battery termination. This could provide a lighter and lower cost alternative to using copper metal foil for the heat lamination of the anode stack.

PRODUCTS

Publications

One scientific publication was published from work done on this project. It covered the first demonstration of a current collector/anode-coated separator stack for lithium ion cells. The details of this publication are: M. Lazar, B. Sloan, S. Carlson, and B. Lucht, Analysis of integrated electrode stacks for lithium ion batteries, Journal of Power Sources, Vol. 251, 1 April 2014, Pages 476-479

Website or other Internet Sites that Reflect the Results of this Project

The Optodot website at www.optodot.com has information relating to this DOE project.

Collaborations fostered by this Project

This project fostered relationships and collaborations between Optodot and several of the largest lithium ion cell manufacturers. Due to confidentiality agreements, Optodot is not able to disclose the names of these cell manufacturers.

New Technology and Techniques

The overall technology of making electrode-coated separators and their use in assembling lithium ion cells are novel and useful. In order to practice this technology, a number of first-of-its-kind technologies and techniques were developed in this project, including new release films, improved all-ceramic separator layers, and laser flash lamp sintering for making copper current collector layers on anodes. A more complete list of these new technologies will be published in late 2016 and in 2017, as the 6 to 10 national patent applications from the two US provisional patent applications filed in 2015 to cover the work on this project, become in the public domain.

Inventions and Patent Applications

Two U.S. provisional patent applications were filed in 2015 for work done on this project. The first was titled "Separator/Electrode Coated Stacks for

Batteries" and was filed on April 15, 2015. This invention was reported on the iEdison.gov website on January 18, 2016 as DOE "S" No. T-108764 and assigned Invention Report Number 10040938-16-0001. Its Patent Docket Number is OP01.747P, and its US Provisional Patent Application Serial Number is 62/178,633. The second was titled "Separators for Electrochemical Cells" and was filed on July 9, 2015. This invention was reported on the iEdison.gov website on January 18, 2016 as DOE "S" No. T-108766 and assigned Invention Report Number 10040938-16-0002. Its Patent Docket Number is OP01.748P, and its US Provisional Patent Application Serial Number is 62/231,530. It is estimated that these two provisional patent applications will be divided into a total of 6 to 10 different national patent applications to cover the major inventions under this project.

Prior to submitting the proposal for this project in February 2011, Optodot had filed 4 PCT patent applications and an earlier US provisional patent application in May 2009 covering the electrode-coated separator technology and its application to new ways of manufacturing lithium ion cells. From these filings, four U.S. patents issued in 2015 with a number of equivalent foreign patents having been issued starting in 2013. Many patents from this series are pending worldwide.

Appendix 1: Cost Model

Study Overview

Cost Models are presented for a range of Lithium Ion Electric Vehicle Battery Packs which incorporate the 8 micron ceramic Optodot separator in combination with three innovative cell assembly process concepts. The specifics of these innovations are discussed in a later section.

The Optodot models presented have been developed by use of a Cost/Performance model developed at Argonne National Labs. They are then each compared to a conventional Baseline Model constructed by the same Argonne National Labs model with a set of standard assumptions. This methodology provides for the direct comparisons of cost estimates of the Optodot separator and advanced cell design concepts to the assumed Argonne standards.

This report is an update to a previous analysis produced in December 2012. The scope of this 2015 analysis has been expanded to include a broader matrix of battery packs and electrochemical couples. Specifically, wherein the 2012 analysis focused solely upon the PHEV application and the LMO-G electrochemical couple, here we explore four end use vehicle configurations (Micro HEV, HEV-HP, PHEV and EV) and three electrochemical couples (NCA-G, LMO-G, LFP-G). This broader scope allows for the important investigation of potential advantages and interactions across Vehicle platforms and electrochemical couple comparisons.

As in the 2012 analysis, there are 7 battery pack energies explored within a vehicle configuration (i.e. 7 each for Micro HEV, HEV-HP, PHEV, and EV) with an incremental energy level between each of 2 kWh as shown below in Table 1. This analysis is then extended to each of the three electrochemical couples.

Table 1 – Battery Pack Energy within Each Vehicle Type

Pack Design #	**1**	**2**	**3**	**4**	**5**	**6**	**7**
kWh	**4.0**	**6.0**	**8.0**	**10.0**	**12.0**	**14.0**	**16.0**

The largest factor of interest, beside innovations in process, is the advantage the Optodot separator cost has relative to the standard separator technology assumed in the standard Argonne model. Specifically, Optodot has developed a chemical formulation and fabrication technology which, with fully loaded costs and profit assumptions enters the battery factory at \$0.39/sqm as compared to the standard cost of \$2.00/sqm.

Finally, part of the standardized cost assumption in the Optodot model includes the use of a negative current collector with an adhesive promoting coating on both sides of the copper foil. This format assumes a cost of \$2.20/sq. meter while the standard Argonne model assumes a cost of \$1.80/sq. meter. Since the costs are projected to 2020, it is quite possible that Optodot will be able to bring this higher cost configuration to the standard model cost.

Therefore we also repeat one of the electrochemical couples in the Optodot model at the standard $1.80/sq. meter as a benchmark for the two different costs.

Executive Summary of Results

The expanded scope of the study encompasses a total of 175 unique battery pack designs. Consequently the most efficient method of the presentation of results is graphically with an emphasis on net economic benefits (data files with full tables of the data are supplied separately).

The central economic parameters of interest are the total cost of cell materials/pack and $/kWh at the pack level. Since our interest is of a comparative basis to standard the results are generally presented in percentage differences to the Argonne benchmark but we will also look at savings in absolute $s on an annualized basis for a limited number of cases just to get a feeling for scale.

We begin by comparing % decreases in $/kWh per pack obtained by the Optodot design.

Figure 1 - % Decrease $/kWh (NCA-G)

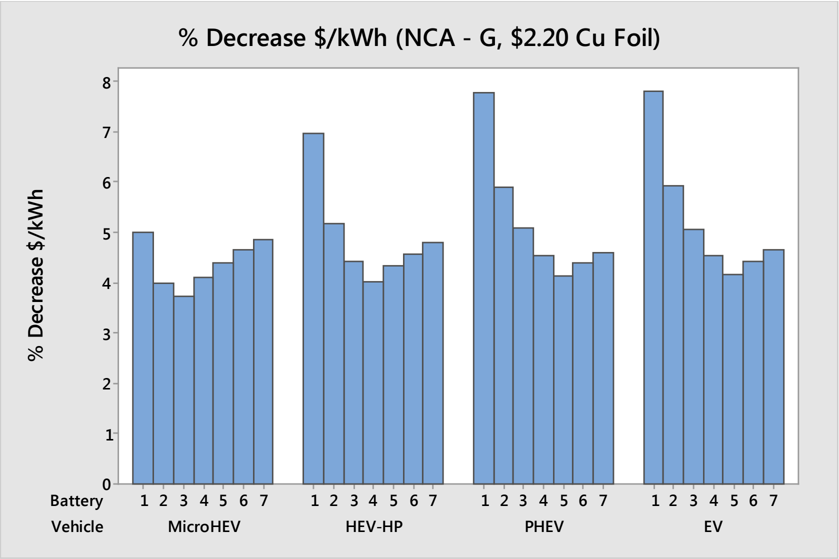


Figure 2 - % Decrease $/kWh (LMO-G)

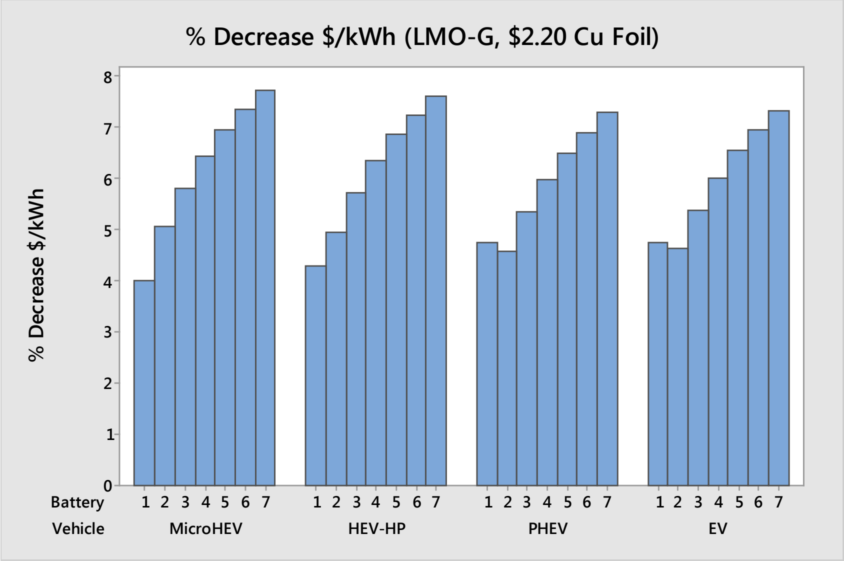
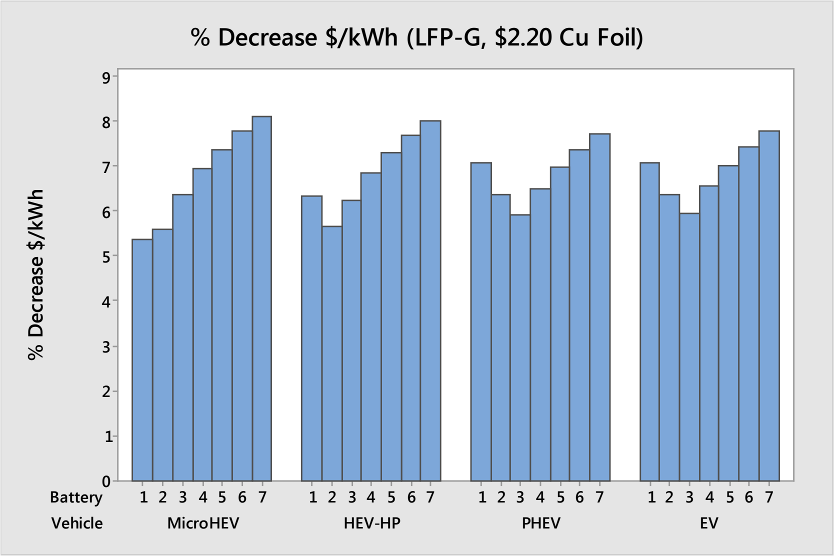


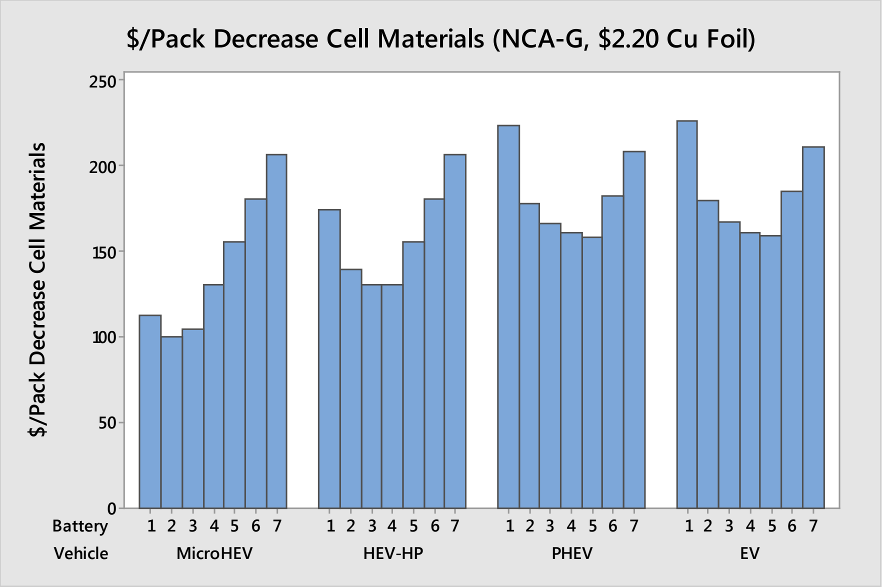
Figure 3 - % Decrease $/kWh (LFP-G)



Across the three electrochemical couples, a net maximum benefit of an 8% decrease in $/kWh at the pack level is observed. Having said this, of interest is the difference in the pattern of behavior across the 7 pack energies within each electrochemical couple. Specifically, the maximum cost advantage within the NCA – G couple is found at the lowest pack energy levels while this maximum advantage is found at the highest pack energy levels within the LMO – G couple. The LFP couple also demonstrates the greatest advantage at the higher pack energy levels but has a more complex relationship across the full seven pack energy levels.

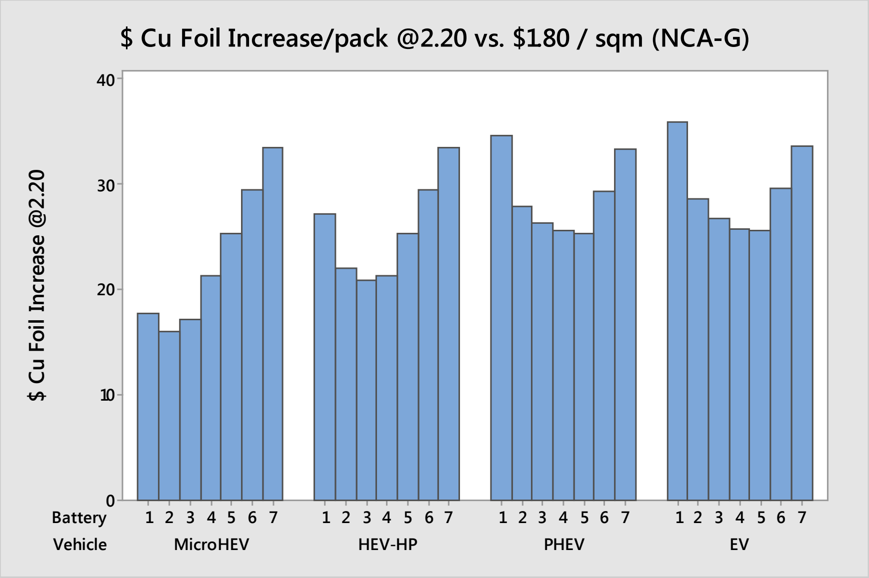
We now turn our attention from percentages to the absolute dollars involved for the battery factory producing at a rate if 100,000 net battery packs per year using the NCA-G example.

Figure 4 - $/Pack Savings Optodot vs. Standard (NCA–G)



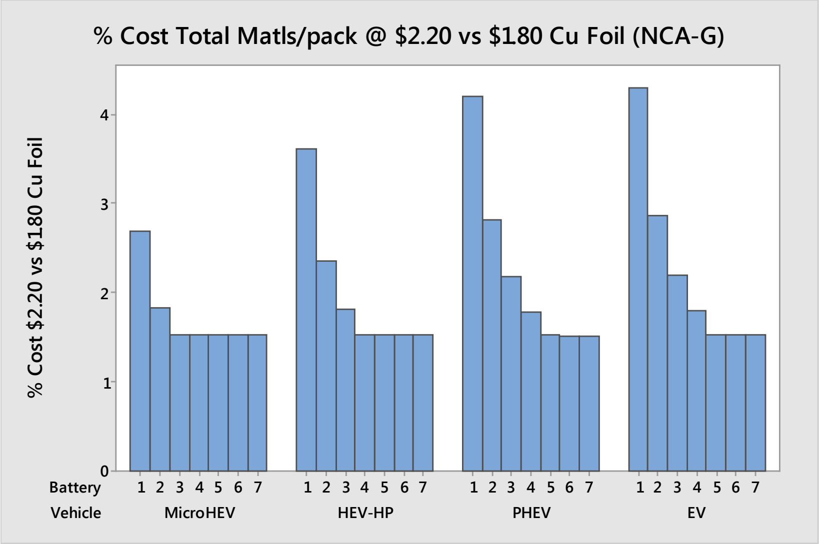
Again we see a complex relationship across the seven battery packs but using the greatest $/pack differences as examples we see approximately $200/pack savings. Extrapolating this to 100,000 net packs per year we have opportunities for annual saving of $20 million. This estimate is at the assumed $2.20/sqm Cu Foil cost. Should Optodot be successful in achieving parity with the Argonne assumption of $1.80/sqm we can calculate additional benefit.

Figure 5 – Impact of $2.20 vs $1.80 Cu Foil/Pack (NCA-G)



The maximum $ increase per pack at $2.20/sqm cost vs. $1.80/sqm is approximately $35. Applied to 100,000 packs/year there is a potential savings for Optodot meeting the Argonne standard for Cu foil of $3.5 million and a combined $23.5 million/year savings. Converting the $1.80/sqm cost to %, an additional 4% cost benefit is seen or net 12% per pack combined.

Figure 6 – % Impact of $2.20 vs $1.80 Cu Foil/Pack (NCA-G)



Modeling Reduction in Total Cost of Cell Materials/Pack

The cost behavior at the total Cell Materials level is the most direct analysis as it removes the costs in processes and materials subsequent to the cell level operations to arrive at the final pack, which are equal for both the Optodot and standard Argonne models. At this cell level of operations we will see a more leveraged benefit of the Optodot technology on a comparative basis to standard. As before we'll graphically view comparative percentage decreases in costs for a given electrochemical couple across the four vehicle platforms and the seven fixed pack energy levels within each.

Figure 7 - % Decrease Cell Materials/Pack (NCA-G)

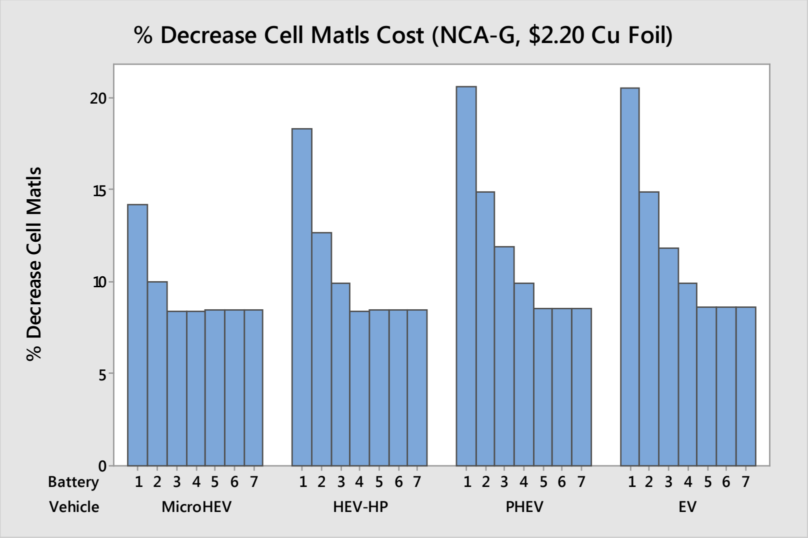


Figure 8 - % Decrease Cell Materials/Pack (LMO-G)

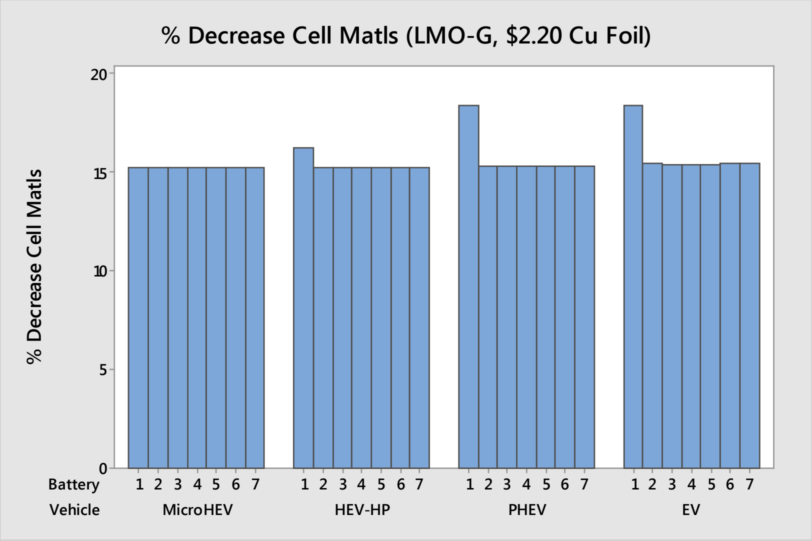
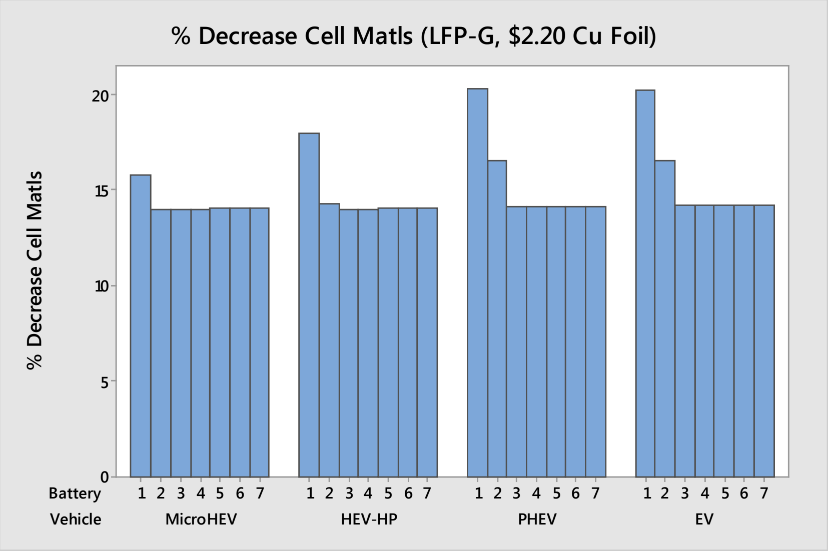


Figure 9 - % Decrease Cell Materials/Pack (LFP-G)



We see significant potential in cell material cost ranging up to 20% for the Optodot technology and this is seen in specific vehicle/battery pack configurations for each of the three electrochemical couples examined. We also see substantially different relationships in behavior between pack energies within the electrochemical couples than is previously seen in $/kWh at the pack level.

For example, 25 of the 28 configurations in the LMO-G couple are constant values at 15% at the cell level while at the $/kWh at the pack level exhibited a constantly increasing "stair-step" pattern as the battery pack energy is increased (Figure 2 vs. Figure 8).

% Cost Reduction in Cell Inactive Materials

One of the primary goals of our model is to quantify the extent to which the Optodot separator and process innovations may reduce the cost of the inactive materials at the cell level. To do this we want to again narrow our focus to the cost of the Total Cell Materials and subsequently partition this value into active material costs and inactive materials costs. We may then make comparisons between the inactive materials costs in the Argonne standard and the inactive material costs in the Optodot model. We choose the EV application and the NCA-G electrochemical couple for our modeling parameters.

Arguments may be made as to exactly how to define "active" and "inactive" materials. For the purposes of our model we are defining active materials as the entirety of those materials that make up the electrode coating matrix for both the anode and the cathode (note that in the assumed anode formulation there is no conductive carbon component).

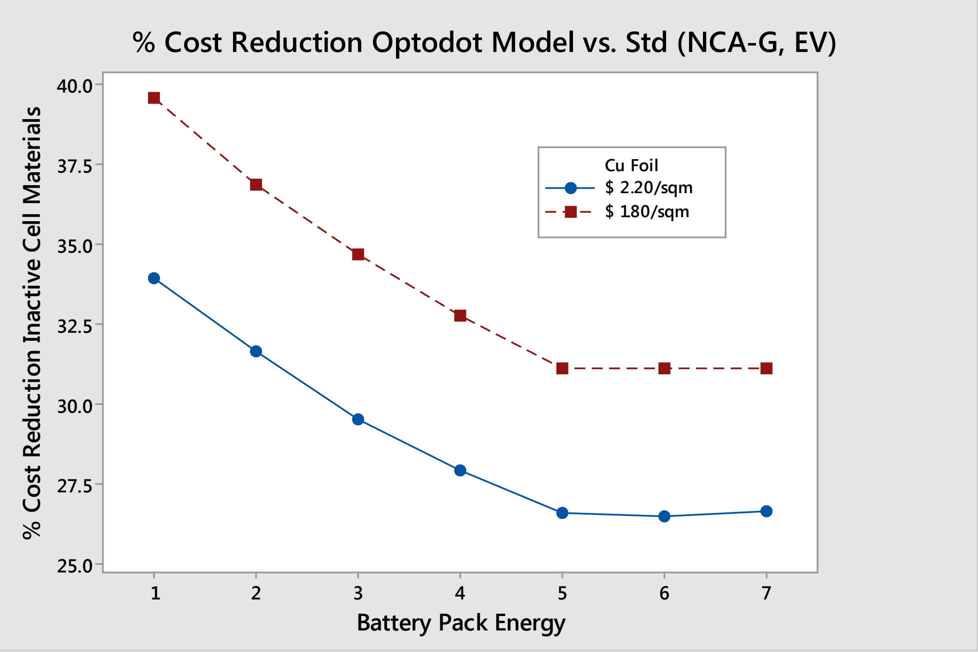
In Table 2 which follows, the seven battery pack energies outlined in Table 1 are listed in the first column. The remaining eight columns present parameters in both dollar units and percentages. Specifically, column two lists the dollar value for inactive materials in the standard model cell for each of the battery pack designs. Columns three and four list the same dollar values for the Optodot designs at two different Cu Foil cost assumptions (C3 with $2.20/sqm Cu foil, C4 with $1.80/sqm Cu Foil). The remaining three column are presented in percentage terms for the differences in inactive costs for Optodot to the standard as well as the % CC (current collector) isolating the opportunity % reducing the Cu Foil cost to the standard $1.80/sqm meter.

Table 2 – Inactive Material Component Costs Analysis (per Cell)

Battery	$ Inactive Std	$ Opto 2.20/sqm	$ Opto 1.80/sqm	$ CC 2.20/sqm	$ CC 1.80/sqm	% Reduced 2.20/sqm	% Reduced 1.80/sqm	% CC Cost
1	6.51	4.30	3.93	2.05	1.68	33.9	39.6	5.7
2	5.56	3.80	3.51	1.64	1.34	31.7	36.9	5.4
3	5.50	3.88	3.60	1.53	1.25	29.5	34.7	5.1
4	5.62	4.05	3.78	1.48	1.21	27.9	32.8	4.9
5	5.85	4.29	4.03	1.46	1.20	26.6	31.1	4.5
6	6.79	4.99	4.68	1.69	1.39	26.5	31.1	4.5
7	7.73	5.67	5.33	1.92	1.57	26.6	31.1	4.5

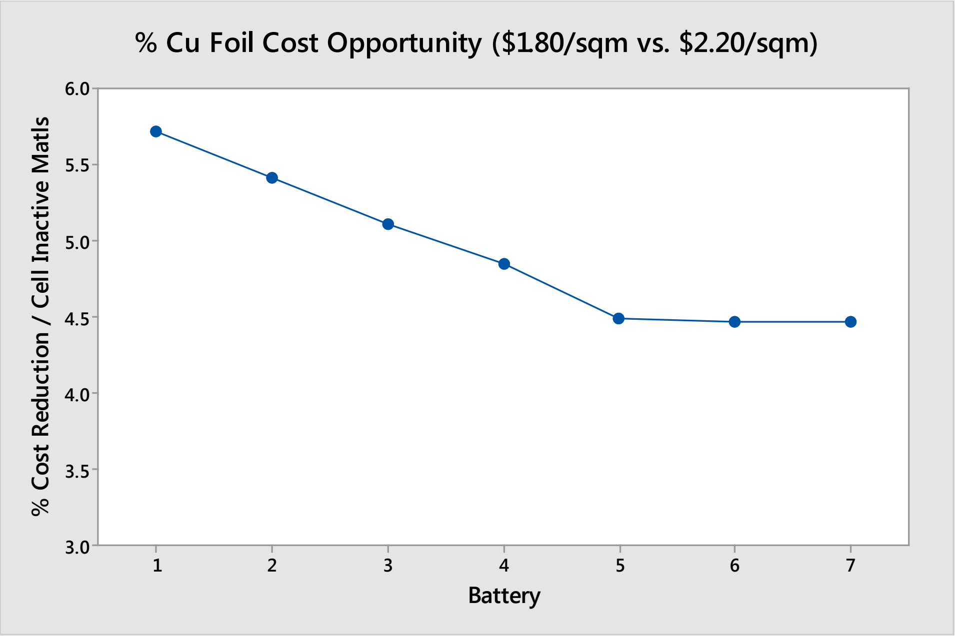
We can also view this information graphically. Since we are not working with multiple vehicles we may utilize a line plot in lieu of the clustered bar charts. Figure 10 presents the results for both the $2.20/sqm and $1.80/sqm Cu Foil current collector assumptions.

Figure 10 – Inactive Materials % Cost Reduction per Cell



Finally, Figure 11 graphically presents the isolated % inactive cost reduction opportunity of the two Cu Foil costs in the models as shown in the last column of Table 2.

Figure 11 – Cu Foil % Inactive Cost Reduction Opportunity ($2.20/sqm vs. $1.80/sqm)



Optodot & Standard Model Separator Comparisons

The Optodot ceramic separator is available in a range of thicknesses and widths. For the models in this report a nominal 8 micron thickness has been selected. This is compared to the base model's standard 20 micron thickness plastic separator.

The Optodot 8 micron ceramic separator is coated onto a Silicone Release Film and it has been demonstrated that release film may be reused in manufacturing 10 times before being replaced in the process. The standard separator is a porous membrane based on polypropylene (PP) and sometimes includes a polyethylene (PE) middle layer. PP and PE are very inexpensive raw materials and thus the cost assumption of $2.00/sqm is in large part due to the manufacturing process required to form the porous network in the membrane.

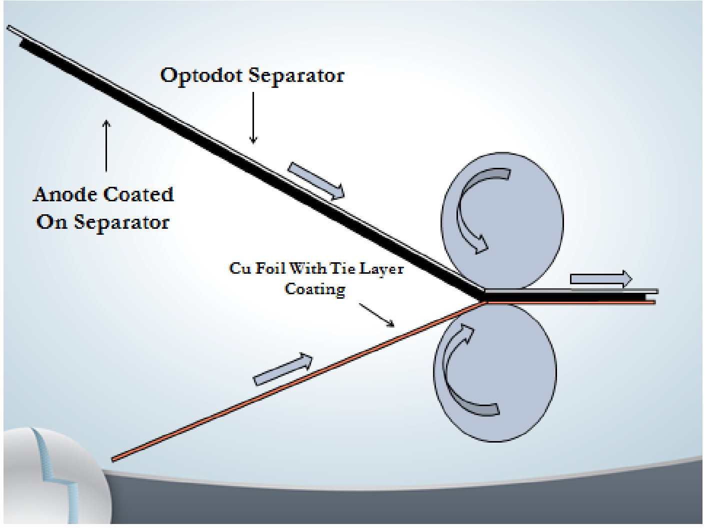
The cost of the Optodot separator is budgeted at $0.39 per square meter (details in Appendix C). This represents an approximate 80% reduction in separator cost and this percentage reduction is a constant across all the Vehicle Types, Chemical Couples and Battery Types analyzed.

The Optodot ceramic separator is approximately 3.4 times greater in density than the standard separator (1.56 g/cm^3 vs. 0.46 g/cm^3) while maintaining the same 50% void volume specification. The potential weight increase due to this higher density is substantially offset by the fact that the standard separator has 2.5 times the volume. Therefore the net increase in separator weight per square meter is only 35.6% as compared to the 3.4X higher density factor. Furthermore this 35.6% increase in weight per square centimeter of separator is reduced in practice to a net weight increase of only 5.5% due to the reduced quantity per square meter of electrolyte contained in the Optodot 8 micron separator (electrolyte density = 1.20 g/cm^3).

Optodot Process Innovations

As mentioned in the Study Overview section, the Optodot model employs three new innovations in electrode and cell assembly operations. Specifically, the negative electrode is coated directly onto the ceramic separator coating as supplied on the plastic release film (innovation one). This composite, two layer coating is subsequently calendered, then delaminated from the release film and finally laminated to the copper foil current collector which is coated with an adhesion promoting coating (innovation two). Figure 12 below portrays this lamination concept.

Figure 12 – Optodot Anode Composite Lamination Process Concept



In the standard Argonne Model the separator is processed as a single sheet that is folded back and forth as the electrodes are inserted. The electrodes are inserted so that all of the positive tabs extend beyond the separator sheet in one direction and the negative tabs extend in the opposite direction. In the Optodot concept this interface with the anode has already been fabricated and the cathode is the only component necessary for introduction at cell assembly greatly simplifying the operation at this stage.

Cell Assembly – Ambient vs. Dry Room Operations

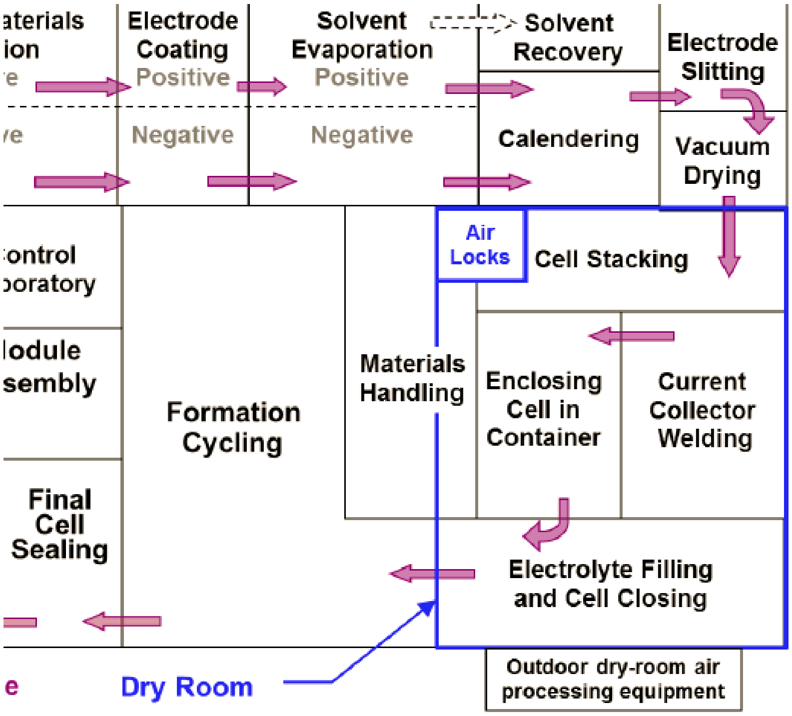
In the standard model the cell assembly process steps are completed in a dry room atmosphere which has a substantially higher cost/sqm. Optodot has demonstrated that the enhanced thermal stability of the ceramic separator allows for higher temperature vacuum drying conditions, thereby allowing the cell assembly, tabbing and tab welding operations to be performed in ambient conditions and vacuum dried as a composite (innovation three). This is in contrast to the much more expensive dryroom environment.

Net Economics of Optodot Process Innovations

The process innovations just presented increase costs in some respects (new lamination process) and decreases cost in other areas (ambient cell assembly operations). Therefore an estimate of any net economic impact of these innovative processes needs to be performed as we analyze the facilities, capital and process components.

Figure 13 is a section of the plant layout from the Argonne model which includes the proportional layout of the dryroom including the operations within. As mentioned, the Optodot model allows for the Cell Stacking and Current Collector Welding operations to be performed in ambient conditions.

Figure 13 – Dryroom Section of Plant Layout



Since the drawing in Figure 13 is to scale, we can estimate that these operations are approximately 50% of the square meters allocated to the dryroom. Therefore we can assume a reduction of one-half in our dryroom cost that will now be charged at the ambient square meters rate. The capital equipment costs, labor costs, etc. will remain the same.
The new lamination step is incremental to the standard model so full costing of this is a necessary addition. Since this process is essentially equivalent to a single electrode

calendering operation we may use the numbers provided by the standard model calendering operation to estimate this incremental cost.

On the next page there are two tables of information that have been extracted from the standard Argonne model which will allow us to estimate both the incremental cost of the new lamination step as well as the reduced cost of performing the cell level processes outside of the dryroom environment.

Table 3 outlines the dryroom costs. The incremental cost per square meter is substantially the capital equipment purchased for operating a -40 C maximum dew point environment and can be spread across the area to obtain a cost per square meter value.

Table 3 – Dryroom Cost

Dry Room Control (operating area, sq. meters)									
Volume ratio (volume/baseline volume)			1.334	1.338	1.356	1.371	1.386	1.400	1.412
Direct Labor, hours/year	14,400	0.4	16,159	16,179	16,263	16,339	16,408	16,472	16,533
Capital Equipment, million$	20	0.6	23.8	23.8	24.0	24.2	24.3	24.5	24.6
Plant Area, square meters	100	0.4	112	112	113	113	114	114	115

Table 4 outlines the costs for a single station calendering operation (i.e. our incremental lamination process).

Table 4 – Calendering Operation Cost

Calendering									
Positive materials (area/yr)									
Volume ratio (volume/baseline volume)			0.815	0.881	1.174	1.468	1.762	2.055	2.349
Direct Labor, hours/year	14,400	0.50	13,001	13,513	15,604	17,446	19,112	20,644	22,070
Capital Equipment, million$	1.0	0.70	0.9	0.9	1.1	1.3	1.5	1.7	1.8
Plant Area, square meters	225	0.60	199	208	248	283	316	347	376

The last seven columns of each table represent the seven battery pack energies we have been working with in our models.

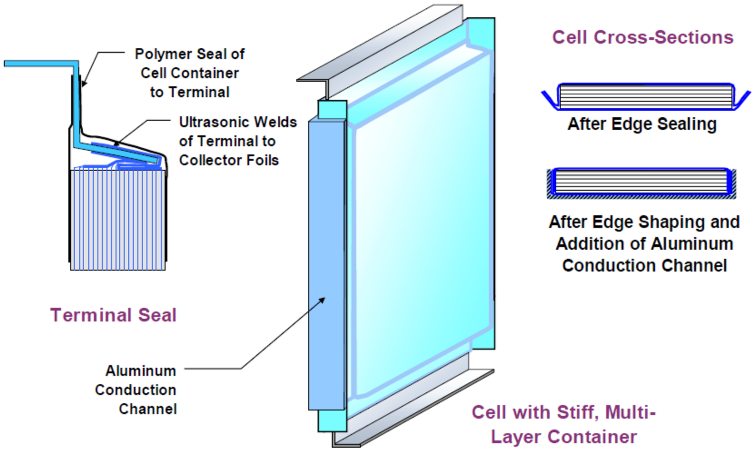
In the simplest, high level analysis we see that a 50% reduction in dry room area by performing cell assembly at ambient conditions will more than offset any incremental costs that may be experienced by the addition of a new lamination process including all CapEx, floor space and labor, etc.

Therefore, being conservative we will make the assumption here that we need not make any incremental increases in cost for Optodot process innovations and if a more in depth analysis is desired it is highly likely that we may argue for a net cost reduction.

Appendix A – Baseline Model Assumptions & Cell Type

Argonne has determined that the exact format of the battery (stacked plate prismatic, flat wound prismatic, cylindrical wound, etc.) does not have a dominant effect on the cost for a set cell chemistry system. Specifically the amounts of electrode materials and the number, capacity and electrode area of the cells, are the determining cost factors. Having said this in order to provide a specific design for the calculations, a prismatic cell in a stiff-pouch container has been selected by the Argonne model and therefore for all models in this report. For this design, calculations of the current collector and terminal resistances are easily done with a one-dimensional model because the terminals are almost the same width as the electrodes.

Figure A – 1 Prismatic Cell Design



We see in Figure A - 1 how our Optodot design of tabs extending nearly the full length of the electrode applies to the assumed cell configuration and our corresponding coating layout.

Baseline Manufacturing Plant

The model's single baseline plant is designed to produce 100,000 NCA-Gr baseline battery packs per year. The baseline battery pack produced by the plant has sixty, 40-Ah capacity cells, providing a total pack power of 50 kW and total energy of 8.7 kWh. The model designs a manufacturing plant with the sole purpose of producing the specific battery being modeled. In this study we have expanded substantially beyond this single battery pack and electrochemical couple so while this one benchmark is useful for a point estimate, it is not entirely relevant to our goals. Having said this, all the models in this study do assume an annual output of net 100,000 battery packs in all studied configurations.

A brief bullet point summary of the key characteristics of the Baseline Model would include:

- Model assumes water based anode slurry, NMP based cathode slurry
- 100,000 net battery packs per year are produced for each configuration

- The rate of 100,000 battery packs is achieved by operating three shifts at the equivalent of 300 days per year.
    - The exceptions are the Receiving and Shipping operated for two shifts per day.
- The coating lines are 1.5 meter wide continuous roll-to-roll coating processes carried out at a line speed of 10 m/min.

Positive Electrode Materials Studied

Three cathode materials were included in this study and Table A-1 identifies their assumed specific capacity. Graphite was the sole anode active material paired with these cathodes in the study.

Table A-1 Cathode Specific Capacities

Specific Capacity	NCA-G	LFP-G	LMO-G
mAhr/g	**160**	**150**	**100**

Electrode Thickness Restrictions in the Model

A limit of 100 microns has been chosen for the default maximum electrode thickness. This thickness represents a graphite electrode balanced to a positive loading equal to 3.5 mAhr/cm2 and is the largest thickness that ASI measurements have been validated at Argonne. However, a low volumetric capacity electrode, such as LMO, will result in a lower area-specific capacity as the limit will be determined by the positive electrode thickness.

Appendix B - Battery Pack Energy Selection, Vehicle Type, SOC & Useable Energy

There are three choices in approach to designate the energy requirement and the user of the model must enter one of the following three measures of energy: battery pack energy, cell capacity, or vehicle electric range. Defining one of these values will determine the value of the other two. An iterative procedure then solves for the user defined energy parameter (energy, capacity, or range) and remaining battery properties by varying the cell capacity and electrode thickness. The result is the dimensions, mass, volume, and materials requirements for the cells, modules, and battery pack.

In order to fully specify a battery design, the user of BatPaC must supply criteria for power, energy, and life. These criteria will depend on the application for which the battery will be used.

While the users may change some of the settings as they prefer, we list our suggestions in Table 3.1. The battery type is defined by the end-use application. Hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs) have increasing levels of electrical energy storage for use by the vehicle drivetrain. The model will use Table 3.1 or the user's explicit inputs to size the battery correctly for the chosen application.

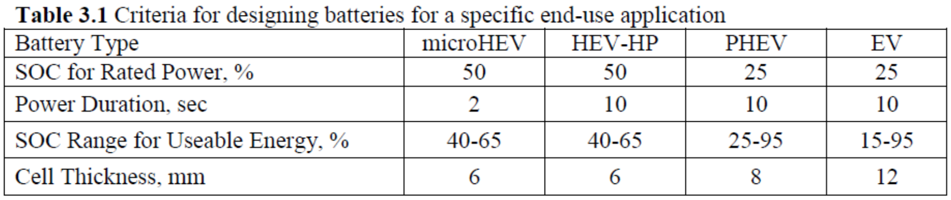


Table 3.1 Criteria for designing batteries for a specific end-use application

Battery Type	microHEV	HEV-HP	PHEV	EV
SOC for Rated Power, %	50	50	25	25
Power Duration, sec	2	10	10	10
SOC Range for Useable Energy, %	40-65	40-65	25-95	15-95
Cell Thickness, mm	6	6	8	12

The micro HEV is a micro or mild-hybrid that provides a moderate power level, ~25 kW, for two seconds. This design is best suited for cell chemistries capable of very high power-to-energy (P/E) ratios. The HEV-HP is a power-assist hybrid that provides the rated power for a full 10 second pulse. The power for both HEV applications is rated at 50 % state-of-charge (SOC). The energy available for discharge and charging is 25 % of the total energy to ensure long cycle life.

As the capacity of the HEV cells is typically small, a cell thickness of 6 mm is used. The PHEV utilizes a much larger portion of the total energy, 70 %. At the end of discharge, the PHEV battery is operated in a charge sustaining mode. Therefore, the power rating for the battery is determined at 25 % SOC. PHEV cells should be much larger than HEV cells and thus a cell thickness of 8 mm is assumed. Finally, EV batteries use 80 % of their total energy with their power rated near the end of discharge. EV cell thicknesses are set to 12 mm.

Appendix C - Optodot Separator and Cu Foil Cost Assumptions (delivered)

Component	$ Cost / Square Meter
Release Liner	0.1195
Boehmite	0.1243
PVdF	0.0293
NMP	0.0007
SG&A, Labor, Profit	0.1200
Total Cost	0.3938
Cu Foil & Tie Layer (2X Sides)	2.2000

1. CSP coated on Release Liner assumes 10 re-uses (one side coat).
    a. Cost assumed at 0.1195/sqm. This is conservative because the planned two side coat would use the same PET film and cost less per sm of CSP.
2. Boehmite
    a. Raw material assumed at $11.96/kg ($0.01196/g)
    b. 8 microns of CSP coating = 12 gsm
    c. Weight ratio of Boehmite to fluoropolymer of 78:22
        i. Boehmite is 9.36 gsm unyielded equates to unyielded cost of $0.1119/m^2
        ii. Coating yield of 95%, a 90% yield of mix chemicals is assumed
    d. Provides yielded cost of $0.1243/m^2
3. PVdF
    a. Using the Argonne cost of $10/kg, or $0.01/g, and a usage of 2.64 gsm
    b. Equates to a yielded cost of $0.0293/m^2
4. NMP
    a. Using the Argonne Model figures:
        i. Cost of $3.20/kg
        ii. Assumption of 99.5% recycling of the NMP
    b. Coating solids of 24%
    c. At 99.5% recovery, the yielded loss of NMP during the coating process is 0.22 gsm
    d. Therefore yielded cost of NMP is $0.0007/m^2
5. Total yielded materials cost is $0.2738/m^2
6. Labor cost assumption $0.04/m^2
7. Overhead cost assumption (G&A, R&D, depreciation, etc.) $0.04/m^2
8. Profit Margin set at $0.04/m^2
9. Separator coating: 1.5 meter width coating line running at 125 m/min line speed

Cu Foil & Tie Layer (2X Sides)

1. Graphene coating applied to standard cost $1.80 / sqm Cu Foil (Argonne model)
2. Cost per side assumed at $0.20 with net cost to pack manufacturer = $2.20/sqm