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Lessons: Electrovaya's Technology Roadmap & System Design Approach to Lithium Ion SuperPolymer® Battery Systems for Transportation

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Electrovaya has developed battery systems for a spectrum of BEVs and PHEVs and across most classes of vehicles including its Norwegian joint-venture. Electrovaya's systems are based upon its proprietary Lithium Ion SuperPolymer® technology. This paper explores: 1.Cathode technology pathway from Phosphate (110 Wh/kg) beginnings to current MN-Series (175 Wh/kg). R&D expectations include 230 Wh/kg commercialized within 18-months and target of 300Wh/kg within 5-years. 2.The thermal, mechanical, electrical and packaging design of the battery system and the resultant cell design; 3.Integrated intelligent battery management systems (iBMS™) for cell-level and system-level management, balancing and other safeguards.

Keywords: Lithium Ion Battery, Lithium IBattery Electric Vehicles, Plug-in Hybrid Electric Vehicles

1. Preamble

Electrovaya has over 150 patents worldwide. These patents cover its fundamental structural technology innovations, its system level designs including its intelligent battery management system for transportation, as well as some nanomaterial developments. Electrovaya has won several awards from NASA, Frost &Sullivan and others, while Deloitte has listed Electrovaya as one of the fastest growing companies in North America.

For a battery dominant electric vehicle to be technically and commercially viable, Electrovaya's believes the following characteristics are required or advantageous:

1.1 Required Characteristics for Success:

1. Capability to evolve (Platform Technology) : Historically battery technologies have been characterized by ongoing incremental improvements. Paradigm shifts (e.g. nickel metal batteries to lithium ion batteries) happen infrequently. A platform technology is necessary in order to maintain leadership and continually evolve.

2. Sufficient Range & Low weight (Energy Density): The driving range of an electric vehicle is determined by the capacity of the battery. Higher energy density implies a longer driving range for a given system size and weight. This has historically been the principal limiting factor of the electric vehicle industry.

3. Scale-up (Large-format Cells): Scale-up is perhaps the most fundamental of all engineering concepts and is necessary to ensure efficiency and reliability. This is a requirement for transportation, which by definition requires large battery systems and thus large-format solutions.

1.2 Additional strengths, which provide significant competitive advantages:

4. Power electronics (battery management system): Intelligent power electronics are required for electric vehicles and Electrovaya offers the option of its proprietary iBMS™, which is a fully integrated solution developed for system optimization, protection and communication.

5. Systems approach & expertise: At every stage of a battery system design (including cell, module, system and interface), Electrovaya considers the system integration needs for the optimisation and design of the thermal, mechanical, electrical and electronic properties of the system. This integrated system approach and expertise leads to a system designed for optimal integration and reliability.

6. Manufacturing expertise: Low capital cost manufacturing and the ability to quickly scale-up while meeting North American or European environmental standards will be critical in order to meet growth expectations.

2. Electric Vehicle Experience

2.1 Summary of Experience:

- Joint Venture with Miljobil Grenland/Tata Motors.
- Global Marketing Collaboration with ExxonMobil
- Heavy-duty & Medium-duty Vehicle Applications – Buses, Delivery Vans - Electrovaya is working on a pre-commercial program for zero-emission delivery vans. Partners include Arvin Meritor, Unicell, and Purolator (a division of Canada Post). This program is supported by the Sustainable Development Technology Canada.
- Light-duty Vehicle Applications
    - Tata Motors – launch 2009
    - PHEV - Electrovaya is working on a 100 mpg sports utility vehicle. Partners include FEV, Raser Technologies and Pacific Gas & Electric, a utility company
    - Phoenix Motorcars – a Californian based start-up electric vehicle company
    - Specialty Vehicles:
- Off-road vehicles – various partners
- Urban vehicles – Maya300, a neighborhood electric vehicle
- Autonomous vehicles – underwater vehicles for mapping deep waters
- Military/defense Vehicles

2.2. Joint Venture with Miljobil Grenland/Tata Motors

Electrovaya is a joint-venture partner on Europe's first BEV launching in September 2009. It has been working with Tata Motors on this project for some time. The vehicle has undergone extensive road testing for several years.

This vehicle will be in launched in September 2009. It will be the first zero-emission production vehicle in Europe powered by lithium ion batteries.

Figure 1: Tata Electric Vehicle

The 4-door, 4-passenger vehicle can travel 200 km on a single charge and accelerate to 60 mph in less than 10 seconds. The vehicle has undergone extensive testing over several years. Future plans include a fast charge capability.

3. Required Characteristics of EV Batteries

3.1 "SuperPolymer": a Nanostructured Platform Technology

Electrovaya's technology breakthrough is a fundamental and novel nanostructure. This breakthrough corresponds to a superior energy density. In other words, it enables more energy to be stored in a smaller space. As a result, applications are smaller, lighter and more powerful.

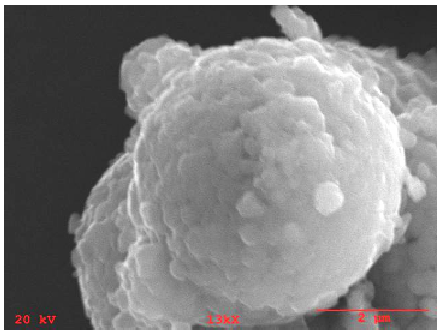

Figure 1: SuperPolymer® Nanostructure

This proprietary breakthrough is a fundamental structural difference and industry innovation. As a foundation, it allows Electrovaya to incorporate component innovations. Thus Electrovaya's technology provides a "platform" from which to continually evolve.

As a result, Electrovaya offers a roster of chemistry solutions. Its roster will continuously evolve with improvements in component materials. In this way, Electrovaya's core advantages are maintained as its battery performance metrics continue to improve. This protects its technology from being a "transitional" solution.

3.2 Current chemistry options:

Manganese Cathode (recommended) – Electrovaya's MN-Series is a lithiated manganese doped material that offers excellent energy density (185 Wh/kg) and adequate safety (comparable to phosphate).

Phosphate Cathode –This material has good safety characteristics and reduced energy density. Electrovaya has offered this chemistry for nearly 5-years in partnership with Phostech Lithium and University of Texas.

Anode: Electrovaya recommends the current industry standard: graphite/carbon anode. It has investigated the titanate chemistry. However, because the energy density of titanate cells is similar to nickel metal hydride batteries Electrovaya does not find it suitable for most electric transportation applications.

3.3 Energy Density Roadmap

Energy density is widely considered the most important metric of a battery technology. It determines the size and weight of the battery system. Higher energy density translates into smaller, lighter battery systems or applications with longer run-times or ranges.

Electrovaya's technology is primarily characterized by superior energy density. Its nanostructured Lithium Ion SuperPolymer® platform technology provides a faster, more efficient transport of lithium. This equates to its ability to pack more energy into smaller and lighter spaces. Electrovaya's proprietary SuperPolymer® technology is a "platform technology" that allows it to evolve with component chemistry evolutions.

For BEV and PHEV application, Electrovaya recommends its MN-Series (up to 200 Wh/kg). This offers significantly greater energy density than its Phosphate-Series. Electrovaya's development plan is to achieve its next-generation MN-Series with 225 Wh/kg within 12-months and further generation of 275Wh/kg 18-months thereafter.

As a result of its intrinsic energy density advantage, Electrovaya is able to optimize its technology for balanced energy-power density with little apparent trade-off. Its balanced optimization offers superior energy density with excellent power density. This balance has been developed for plug-in hybrid and full battery electric vehicle applications. Thus, offering an good balance of

energy that is exceptionally well suited to PHEVs and BEVs.

3.3 Large Format, Prismatic Cells

Electrovaya only manufactures flat, prismatic cells. These "pouched" cells allow for large cell sizes to be manufactured. The thermal attributes are excellent. The packaging efficiency could be no better. Prismatic cells also feature intrinsic safety features of "bulging cells" if there is pressure built up due to impurities (this avoids the shrapnel, explosion effect of cylindrical cells).

Advantages of large-format, prismatic cells:

- Prismatic cells are much safer than spiral wound cells due to their packaging. Under stress a prismatic pouched cell will "puff"; much like a microwaveable bag of popcorn will pop when heated. In comparison, a cylindrical wound cell is contained in a metal "can". As a result, Electrovaya's standard cells cannot explode, because there is no mechanism that could cause compression of gases inside the cell.
- Excellent thermal properties and optimized thermal management.
- Large format cells offer significant scale-up advantages.
- Very good reliability. Electrovaya's technology has been tested for low temperature performance, vibration, reliability and 10-year calendar life in various applications.

Challenges of Cylindrical Cells:
Spiral wound cylindrical batteries are poor choices for large systems and have been repeatedly tried with often challenging results in large systems. Common problems include:

- Thermal issues: heat removal is poor and so hot spots internally can cause poor performance and significant thermal problems;
- Packaging: the cell is contained in a metal canister, which when under pressure can explode. The metal canister can then become metal shrapnel;
- Scale-up limitations: These small cells entail:
- 22% volumetric loss in energy density
- Multiple interconnects and many points of failure
- Highly complex integration
- Complex electronic management

4. Beneficial Characterisitcs of EV Batteries

4.1 Integrated Battery Management

Electrovaya began developing a good power electronics team in 2003 when it realized the lack of well-understood, well-executed battery management systems. Now, after over 5 years of power electronics development, Electrovaya has developed and has been fielding commercial integrated, intelligent battery management system (iBMS™). The electronics team, with the integrated support of the battery team and the electrical/mechanical systems team, has developed the power electronics.

Electrovaya offers its proprietary integrated intelligent battery management system (iBMS™) to its clients as an option. The iBMS™ is an integrated solution with the following functions:

- Monitoring constantly all cells in the battery system
- Optimization of the battery system to extend life, reliability and performance
- Cell balancing and equalization
- Calculation of state of charge and state of health
- Communication including information for the driver display and alarms
- Protection of the battery system against overcharge/discharge, temperature and more
- Multi-level safety features

The iBMS™ consists of both distributed and system control intelligence integrated in the battery system design. It is available in several voltage configurations that can be scaled to almost any system design and is available as a fully integrated solution.

4.2 Systems approach & expertise

Electrovaya has a "holistic" design philosophy. It approaches the design of its battery systems for electric drive application with the whole system in mind.

Every element (mechanical, thermal, electrochemical, electrical, electronic) is optimized at every stage (chemistry choice, cell design, module design, system design, electronics design). The optimization parameters demand scale-up, performance, safety and cost competitiveness.

This integrated approach to design decisions prevents decisions from being made in department "silos". Instead mechanical, electrical, electronic, or cell design choices are made in an integrated decision making process. In this way, the tradeoffs of competing design decisions are evaluated together. For instance, mechanical designs and system voltage choices must be considered with equal consideration to the electrical wiring implications.

This decision making process lends itself exceptionally well to working with Automotive Partners. Electrovaya has the flexibility of providing direct support in varying capacities (cell, module, electrical, electronic, mechanical, system) to an OEM manufacturer and/or its integration partner. Together Electrovaya with its partners can evaluate and optimize the system features. In this manner, Electrovaya's battery expertise can be fully leveraged with its partners to ensure optimal system design features and priorities. This holistic design philosophy is key to the system robustness and cost effectiveness.

4.3 Local Manufacturing

Electrovaya has perhaps the largest manufacturing plant in North America for large format lithium ion batteries. Production is currently based in Mississauga, Ontario with a second production facility available in New York State. A European production base (joint-venture with Tata Motors) will soon be online.

The complete team of mechanical and thermal engineering, electrode and cell manufacturing, software and hardware team for the battery management system, testing and electrical engineering are all in one location. This increases efficiency and reliability, lowers cost and enables us to provide complete support in all areas.

Figure: Electrovaya Plant in Canada

5. Authors

Dr. Sankar Das Gupta is an internationally recognized scientist in electrochemistry with more than 25 years experience in materials engineering and battery science. He is a co-founder of Electrovaya. Dr. Das Gupta received his doctorate from of Imperial College, London and is also a graduate of Presidency College, Calcutta. He serves as Adjunct Professor in the Department of Materials Science in the School of Engineering at the University of Toronto.

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G. DasGupta has degrees from Oxford University University of Toronto. She is Vice-Chair of Electric Mobility Canada, a steering committee chair for a Canadian Govt. Roadmap of Electric Vehicles and a co-founder of the Plug-in Hybrid Development Consortium.

Dr. R. DasGupta studied at Imperial College, MIT and Cambridge Universities. He has over 6 years experience in lithium ion batteries.