THE LITHIUM-METAL-POLYMER ENERGY PACK FOR STATIONARY APPLICATIONS

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INTRODUCTION

The Lithium-Metal-Polymer (LMP) energy pack is an advanced energy storage system developed by AVESTOR for stationary and automotive applications. This paper describes the technology and its benefits in stationary applications.

LMP Energy packs have a high-energy performance, even under extreme environmental conditions. At 1/3 the volume of lead-acid batteries and 1/5 the weight, for equivalent energy capacity, LMP can reduce the floor space and cabinet or rack volume allocated for energy storage in most stationary applications.

The telecom applications are the first targeted by AVESTOR. LMP Energy Packs have been successfully developed and are ready for commercialization. They have been field tested since 1999 in twelve different sites in North America. Cells and modules have been under test in the laboratory for as long as ten years. From the lab test results, we extrapolate a practical life well in excess of 10 years, even under extreme environmental conditions.

The technology can be adapted to all stationary applications. This paper will explain how the LMP thin film construction and all solid cell can be optimized for high energy or for high power applications. The LMP energy packs can be manufactured in different sizes to meet different requirements.

Construction of the first manufacturing plant is underway and commercial deployment of LMP modules will start by September of 2002.

LMP ELECTRO-CHEMISTRY

The Lithium-Metal-Polymer electro-chemical cell concept has been the fruit of over 20 years of development, focussed on harnessing the high electro-chemical potential and light weight of lithium, without suffering the disadvantages of liquid electrolytes, the weight and cost penalties of carbon or graphite, or the hazards of exposed lithium metal. The LMP system breakthrough is the use of a special polymer as a solid electrolyte and dry electrolyte, which completely encapsulates and seals the lithium metal. The result is a totally solid state electro-chemical cell, having neither liquid nor gel components, in which near 100% of the mass is comprised of electrically active materials. The low molecular mass of lithium, as the metallic component of the cell, further increases the specific energy (energy/unit mass) of the cell.

The LMP cell is a laminate of four thin materials –

- a metallic lithium foil anode. - the ultra-thin lithium foil acts as both a lithium source and a current collector.
- a solid polymeric electrolyte – this lithium ion carrier is obtained by dissolving a lithium salt ($Li(CF_3SO_2)_2N$) in a solvating co-polymer.
- a metallic oxide cathode based on a reversible intercalation compound of vanadium oxide, blended with lithium salt and polymer to form a plastic composite
- and an aluminium foil current collector

The cell laminate structure is illustrated in Figure 1.

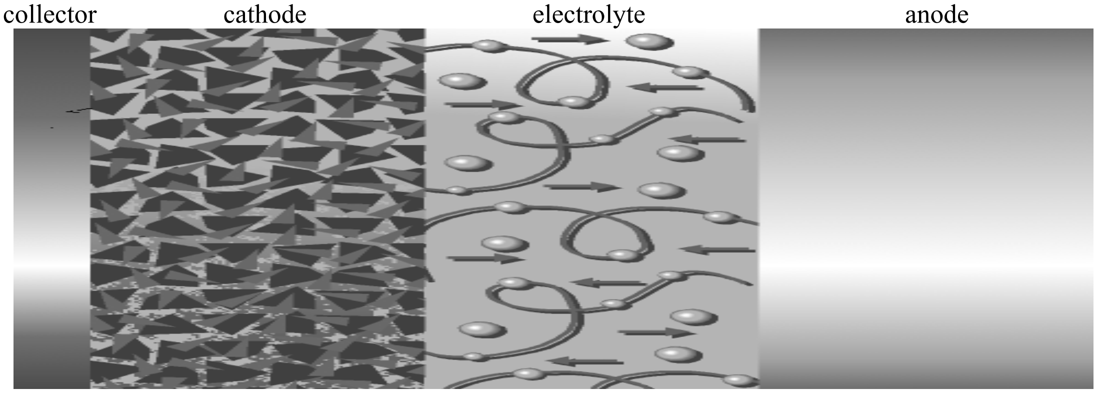

FIGURE 1: LMP CELL CONFIGURATION

The total thickness of the cell (4 active layers plus insulator) is under 100 microns (4 mils). In actual manufacture, 2 cells are laminated back to back around the aluminium collector and the insulation layer is the outside layer on both sides, over the lithium anodes, completely encapsulating the active layers of the cell.

Immediately upon lamination of the component layers, the cell's electrochemical potential of 2.5 volts (nom.) is available for use, due to inherent mobility characteristics of the lithium ion. The electro-molecular processes during charge and discharge are as follows:

During discharge, oxidation, or stripping, of metallic lithium occurs at the anode. That is, a lithium ion and one electron are freed from the metallic lithium molecules. At the cathode, lithium ions are inserted into the host oxide (vanadium oxide) structure.

During charging, lithium ions are released for the host oxide and lithium is plated onto the anode, which is, the lithium ion and an electron reform onto the lithium metal foil. Unlike most other current battery technologies, the LMP system has no secondary reaction during the charging process, permitting very high coulombic and energy efficiencies.

A special characteristic of the LMP electro-chemical process is its tolerance to higher temperatures. The solid-state ionic mobility and chemical kinetics through the polymer electrolyte increase with temperature. Maintaining a cell temperature of 40-60°C (104-140°F) permits the achievement of the fast lithium ion transport for required power transfer from the cell. There is no system deterioration mechanism at any temperature that can be experienced in normal operation.

Under normal operating conditions, the system's self-discharge mechanism is only the very low, intrinsic electronic conductivity of the electrolyte polymer. The self-discharge demonstrated in over ten years of monitoring is less than 1% capacity discharge per year at ambient temperatures up to 60°C (140°F). This compares to values often 50 times greater for lead-acid cells.

LMP ENERGY PACK CONSTRUCTION

To build a practical LMP Energy Pack, manufacturing processes have been developed and implemented to extrude the vanadium oxide and lithium films and to laminate the layers to produce the electro-chemical cell, as described above. The electro-chemical cell laminate construction defines a fixed set of cell characteristics, such as, energy capacity per unit of surface, ratio of positive to negative electrode capacity, ratio of electrolyte to electrode capacity and current collector arrangement, which remains unchanged regardless of cell shape or scale-up level. The cell energy capacity is, then, simply a function of the total surface area of its laminate.

The cell format used is flat rectangular plaques of appropriate dimensions to suit the desired dimensional parameters of the energy pack, which are subsequently stacked and connected along their edges, in parallel or series, to produce the appropriate energy pack output voltage. The versatility of the construction permits appropriate configuration of the pack to best suit application requirements, and, significantly, permitting single packs to have the desired final potential for the applications (e.g., 24V or 48V, in telecom applications). This eliminates the need for external series connection of packs into "strings" and any necessity for cell balancing external to the Pack.

As noted above, the LMP electro-chemistry is optimized at temperatures of 40 to 60°C (104-140°F). Consequently, the energy pack is built with heating element layers interspersed in the cell stack to allow internal temperature control to be exercised by the pack itself. The pack's internal controls manage the cell temperature to 40°C (104°F) for normal operation and to 60°C (140°F) for discharges of longer than 30 minutes in duration.

Included in the construction is a spring load structure to maintain a uniform pressure over the stacked cells. This serves to increase the uniformity of the lithium plating process that occurs during charging and, thus, assure the higher coulombic efficiency of the cell.

The electrochemical cell assembly is enclosed in a hermetically sealed internal casing filled with an inert gas. This case is hermetically sealed to provide protection against any damage to the cell lamination, protection against humidity and containment in case the pack is submitted to high temperature from an external source. All electronic components are housed outside this internal casing, but within the external casing that provides thermal insulation, mechanical protection and connection and handling accessories.

A cutaway view of the entire construction is illustrated in Figure 2.

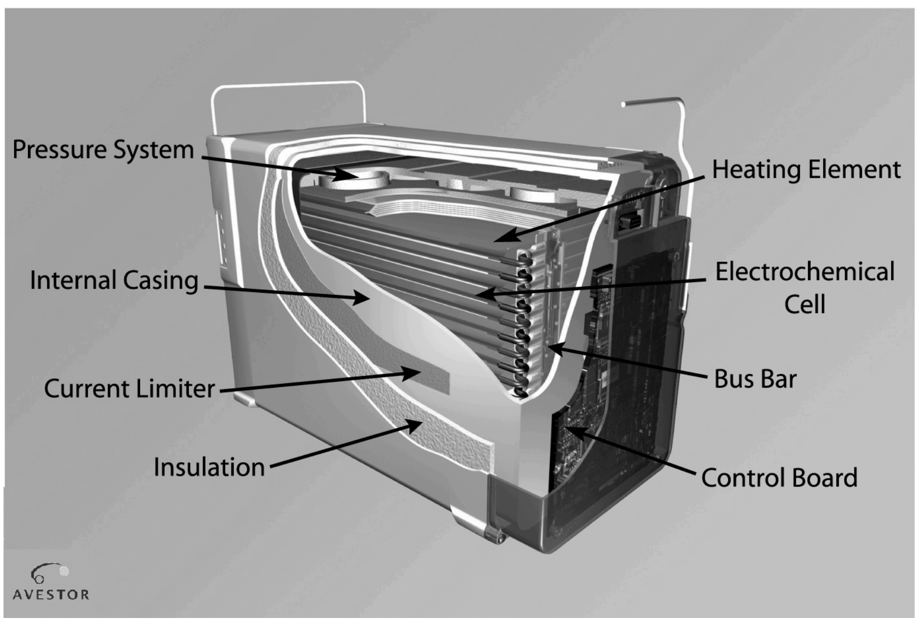

FIGURE 2: LMP ENERGY PACK CONSTRUCTION

DESIGN VERSITILITY FOR VARYING POWER/ENERGY APPLICATION REQUIREMENTS

The versatility of the basic cell laminate structure to be configured into different energy pack module dimensions has been discussed above. This presents opportunities to configure different module form and fit, to optimize the space allocated to energy storage in the specific application, and, thus, make available the highest fill of revenue generating equipment.

Equally, the laminate structure itself can be adjusted to suit the power/energy requirement of the application. In general, the higher the discharge rate desired, the thinner must be the cell films and the lower will be the energy capacity of the cell. Alternately, higher energy capacity can be achieved by increasing the laminate film thickness at the expense of discharge rate. The laminate dimensions used in the design for telecom application maximize pack capacity while providing a maximum continuous discharge rate of C/4 (i.e., full capacity discharge in four hours).

In mobile applications, this versatility has been used to tailor LMP energy pack characteristics for hybrid electric vehicles (HEV), which require high power and more modest energy storage capacity (peak power supplement criteria) and for all-electric vehicles (EV), which require higher energy storage capacity (extend vehicle range criteria).

LABORATORY TESTING OF LMP LIFE CHARACTERISTICS

Laboratory testing to validate the stability of the LMP electrochemistry over time and temperature and charge/discharge cycling have been ongoing for over ten years.

Accelerated life testing

Cells are cycled between 3.10 and 2.33 Volts and are subject to a cycling protocol that simulates what would be expected in a typical float (standby backup) application. Cells and modules have been cycled and maintained at temperatures varying between 40°C (104°F) and 105°C (221°F) and at floating ratio (percentage of time spent on float) varying from 85% to 99.4%. (Floating ratios in the range of 99.7% are typical in standby applications, such as telecom power backup.). Our analysis uses the standard criteria for end of life employed in evaluating lead-acid batteries, i.e., 20% capacity loss. It is important to note that, unlike the lead-acid batteries, which experience sudden and precipitous capacity loss after that point, LMP batteries are characterized by a gradual capacity fade with no sudden loss mechanism. In the case of LMP, therefore, using 20% capacity loss, as the definition of end of life is simply a convention – the energy pack can continue in service long after that point is reached.

At high floating ratios and with the LMP cells at their normal internal operating temperature of 40°C (104°F), the Arrhenius analysis indicates a projected life in the range of 25 years. The life expectancy for LMP, projected by this accelerated testing, is reduced by less than 25% for every 10°C (50°F) over 40°C (104°F). This compares to 50% per 10°C (50°F), in the same temperature range for lead-acid batteries. At operating temperatures in the range of 40°C (104°F) to 80°C (176°F) the predominant aging mechanism is a slow decay of the vanadium oxide/polymer cathode capacity to provide insertion sites for the lithium ions, which progresses as a function of the number of deep discharges experienced. Above 80°C (176°F), the aging mechanism is related to the slow internal resistance increase to ionic mobility of the electrolyte.

Module discharge cycling tests at normal operating temperature

Several modules have been tested at their normal operating temperature (40-60°C) (104-140°F) and a cycling profile that submits them to the following pattern, at regular intervals:

- a series of shallow discharges
- one 25% discharge
- a series of shallow discharges
- one deep 100% discharge
- a series of shallow discharges
- a long float period (six months)

The temperature is truly representative of the practical environment, as the LMP Energy Pack's internal temperature control system maintains its temperature at this level in actual operation. The six-month floating cycle is slightly more severe than the typical telecom application of 99.7% float. Figure 3 indicates the resulting projection of time to reach 20% capacity loss. Approximately 28 years of duty is projected before capacity erodes to 80% of the nominal level.

Self-discharge tests

Laboratory cells have been monitored for over 10 years at a shelf temperature ranging from room ambient temperatures to 60°C (140°F). Results indicate capacity retention in excess of 90% after 10 years.

FIGURE 3: Capacity loss - test results and projection at 99.4% float duty cycle

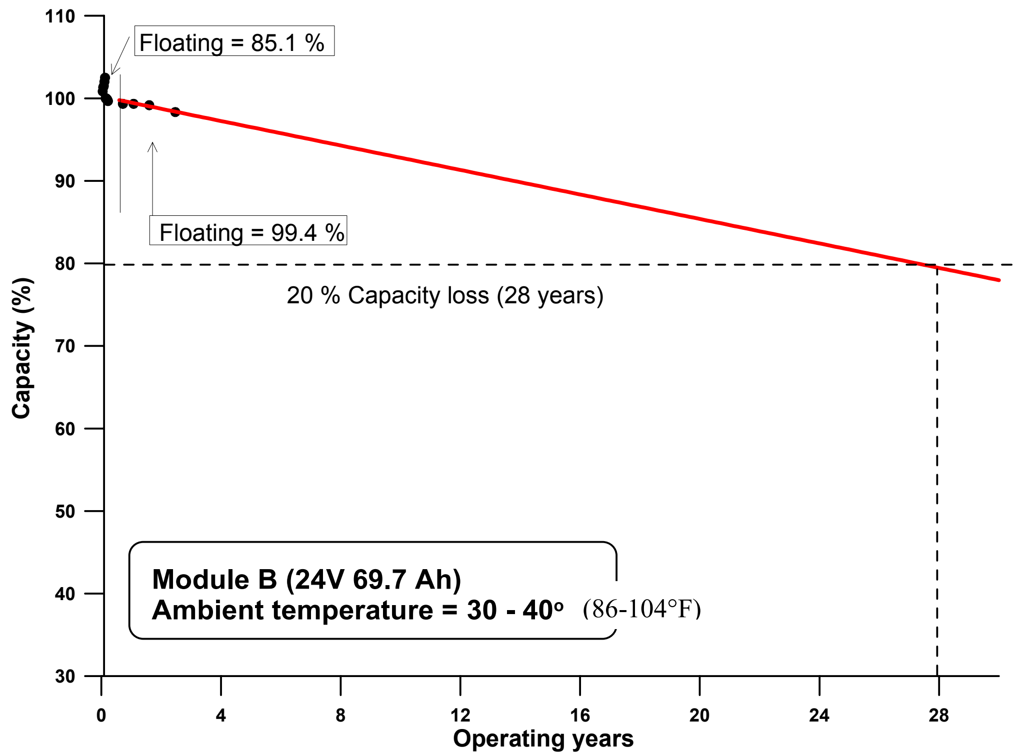

FIGURE 4: LMP Energy Pack Field Trial Sites

Average Minimum Temperature (°F)

Zone 1 -- Bellow -50°
Zone 2 -- -40° to -50°
Zone 3 -- - 30° to -40°
Zone 4 -- -20° to -30°
Zone 5 -- -10° to -20°
Zone 6 -- 0° to -10°
Zone 7 -- 10° to 0°
Zone 8 – 20° to 10°
Zone 9 -- 30° to 20°
Zone 10 -- 40° to 30°
Zone 11 – Greater than 40°

TELECOM APPLICATION FIELD TRIALS

Field trials of over fifty LMP Energy Packs have been ongoing at more than twelve outside plant sites, supporting actual service loads for as long as over two years. The results of these experiences have been reported extensively at the International Telecommunications Energy Conferences (INTELEC)[1,2]. These sites are located in various climatic zones, but have predominantly been installed in areas that regularly experience high temperature conditions, to prove in the reliability of the technology under worst case operating conditions. (Sites are indicated on the climatic map in Figure 4.) The packs have been operating in ambient temperatures that vary between –6° and 51°C (21.2° and 124°F). Installations have been monitored on a continuous basis. None are indicating any capacity loss to date. The LMP Energy Pack electro-chemistry is performing in full accordance with theoretical and laboratory test expectations.

TECHNOLOGY COMPARISONS – LITHIUM-METAL-POLYMER vs. LEAD-ACID vs. NICKEL-CADMIUM

Table 1 summarizes key characteristics of the Lithium-Metal-Polymer Energy Pack technology as compared to two other common stationary battery systems. It is the implications of these characteristics for the system's use in practical, stationary applications that are of importance in assessing the value of the technology. These are also indicated in the Table.

Through the field trials and energy assessments performed on the Lithium-Metal-Polymer Energy Pack for telecommunications applications, we have uncovered a number of interesting opportunities for total system integration benefits. These are attainable by reconsidering deployment practices and energy system design and optimizing them to take advantage of the LMP technology's unique features. A sampling of typical considerations are indicated below:

Solid Electrolyte – the complete absence of any liquid component in the energy pack eliminates special transportation and handling measures and precautions, eliminates requirements for mats, trays or other spill containment devices, eliminates typical liquid level verification and filling procedures

Anode/cathode materials – the materials in the LMP Energy Pack are fully encapsulated and present no environmental hazard in the completed product form. They offer high recycling value - the residual value of the recycled raw materials fully covers the cost of the recycling process.

- all copper connection terminals eliminate terminal cleaning and re-torquing procedures

No secondary electro-chemical reaction - no gases or other secondary products are produced by the primary metal plating reaction internal to the LMP cell. With no gas release, no venting is required for the module, or for the cabinet or shelter in which it is installed. The absence of any corrosion effects leads to a stable and predictable aging process.

Slow, linear degradation mechanism – the predictable and measurable variations over the battery life has significant impact on deployment strategies. The slow rate of capacity loss, compared to other technologies, should be considered in capacity provisioning and eliminate the consideration of the 80% capacity point as being determinant for capacity rating and end-of-life determination.

- state of charge and state of health algorithms are simplified. Self-monitoring by the Energy Pack's internal controls eliminate the need to provision and integrate specialized external battery monitoring equipment

Intrinsic over/under voltage buffer – the Energy Pack characteristics protect it from permanent damage in the case of extreme discharge. There is no need to provide any external low voltage disconnect equipment to protect the battery investment, avoiding cost and complexity and avoiding the introduction of a single point of failure into the power backup system.

Temperature tolerance – the Energy Pack eliminates requirement for external heating or cooling, removing the battery system as a design consideration for climate control equipment provisioning and temperature control set points in the cabinet or shelter.

Weight and volume reduction – the lower weight and volume of the LMP Energy Pack for equivalent capacities permits reduction in cabinet or shelter size, reduction of structural reinforcement for cabinets metalwork and/or building floors, reduction in transportation and handling costs

Integral 48V energy modules – the elimination of series connections of cells to achieve desired output voltages permits increased flexibility in module placement, simplifies cabling harnesses and reduces the number of cables and connections. Current module configurations provide 48V directly to meet the usual requirements of telecom equipment. The versatility of the LMP cell structure permits the design of energy pack models to accommodate other module voltage levels appropriate to the specific application (e.g., 24V, 36V, 42V, 125V, 250V).

CONCLUSION

The promise of an energy pack based on the high electro-chemical potential and light weight of lithium metal has been known for many years. This paper has demonstrated that this promise has been substantiated by the Lithium-Metal-Polymer Energy Pack, which has now undergone full product development, laboratory and field testing and has been deployed in some of the toughest environments in real-life applications. Manufacturing and assembly processes have been developed and proven and full scale, commercial production capability will be on line to meet industry needs, with first shipments currently scheduled for September 2002. The product is real, and delivers substantial technical and economic advantages in use. Several of its features and characteristics beg the designer and user community to review the existing paradigm of energy systems and rethink deployment, system integration and procedural standards to take full advantage of the capabilities of this technology.

TABLE 1: Comparison of Technology Characteristics

	Lithium-Metal-Polymer (LMP)	**Valve-Regulated Lead-Acid (VRLA)**	**Nickel Cadmium (NiCd)**	**Implications for application**
Electrolyte	Solid polymer	Liquid or gel (H_2SO_4)	Liquid (KOH & H_2O)	Acid handling, spill containment, evaporation of liquid electrolyte
Anode/cathode materials	Lithium metal/ vanadium oxide encapsulated in polymer	Lead (Pb)	Cadmium (Cd)	Environmental & disposal issues
Basic electro-chemistry	Metallic plating	Chemical reaction	Chemical reaction	System stability
Secondary charging reactions	None	Hydrogen formation	Hydrogen formation	Venting requirements, flame arresting provisions
Aging mechanism	Change to cathode molecular bond structure Linear & predictable degradation	Accelerated positive plate corrosion, negative plate sulfation & electrolyte "dry-out" Catastrophic decline after 20% degradation	Separator oxidation & electrolyte "dry out"	Regular maintenance requirements; complex life prediction & monitoring requirements Service outage risks
Life degradation over 40°C	<25% per 10°C (50°F)	~50% per 10°C (50°F)	25% per 10°C (50°F)	Outside plant cabinet, high temperature zone performance
Capacity degradation @<0°C	2-4%/ 10°C (50°F)	9-25%/ 10°C (50°F)	4-8% / 10°C (50°F)	Outside plant cabinet, cold temperature performance
Extreme ambient temperature risks: - high temperature - low temperature	 No risk No risk	 Thermal runaway Freezing, container cracking	 Thermal runaway Freezing, container cracking	Risk level for applications without climate control
Energy density	157 Wh/l	56 - 87 Wh/l	22 - 65 Wh/l	Space optimization
Specific energy	120 Wh/kg	21 - 30 Wh/kg	15 - 40 Wh/kg	Handling & floor loading
Float current @ normal operating temperature	<1 mA /100Ah @ 40°C (104°F)	~50mA/100Ah @ 20°C (68°F)	~25mA @ 20°C (68°F)	
Shelf life	10 years	0.5 years	NA	Inventory storage issues

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