AVESTOR™ LITHIUM-METAL-POLYMER BATTERIES PROVEN RELIABILITY BASED ON CUSTOMER FIELD TRIALS

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INTRODUCTION

Over 20 years of research and development in Lithium-Metal-Polymer (LMP) batteries has resulted in a revolutionary design for stationary batteries offering high energy density, reliability and long life under the most extreme environmental conditions. The AVESTOR™ LMP battery is well into its commercialization phase with the telecommunications sector being the first target application.

Field trials in telecommunications stationary applications began in 1999. With 105 AVESTOR LMP batteries in 29 field trial sites today, the battery has proven its ability to provide highly reliable service and excellent performance. To control and monitor these installations, AVESTOR has used its own monitoring solution to gather valuable real-time data. The field trial batteries have been supporting service loads in existing network installations and have been applied as direct replacements to conventional lead acid batteries. The trial sites have covered a variety of climatic zones, in many cases experiencing very high temperature conditions and the harshest of conditions for battery performance and life.

This paper describes the results of the AVESTOR LMP batteries in field trials, based on the data gathered. It describes performance characteristics from batteries, during real power outages events and forced discharges. It demonstrates how battery performance data and environmental parameters were monitored and analysed remotely from the AVESTOR plant in Boucherville. It describes specific results of laboratory testing and simulations for stationary applications and their correlation with the field trial results.

AVESTOR LITHIUM-METAL-POLYMER BATTERY ELECTROCHEMISTRY & CONSTRUCTION

The AVESTOR Lithium-Metal-Polymer cell harnesses the high electrochemical 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 Lithium-Metal-Polymer system breakthrough is the use of a special polymer as a solid, dry electrolyte, which completely encapsulates and seals the lithium metal. The result is a totally solid state electrochemical cell, having neither liquid nor gel components, in which near 100% of the mass is comprised of electrically active materials.

The Lithium-Metal-Polymer 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 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.

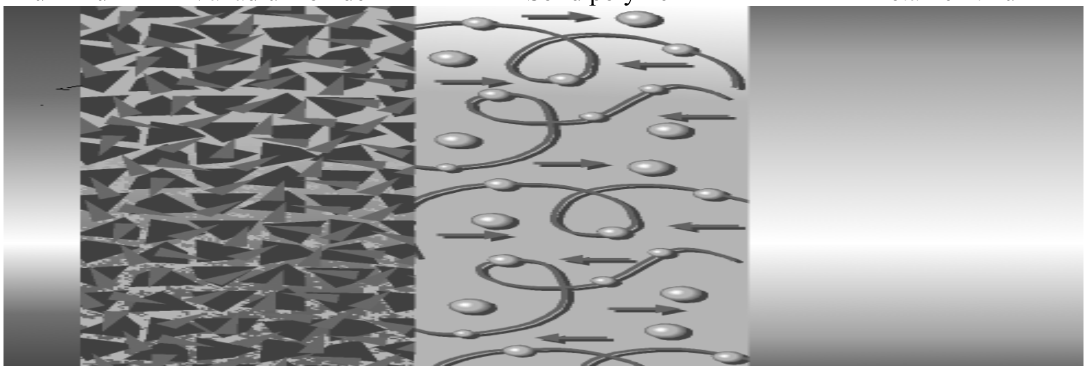

Figure 1: AVESTOR LITHIUM-METAL-POLYMER ELECTROCHEMICAL CELL

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

The Lithium-Metal-Polymer electrochemistry is optimized at temperatures of 40 to 60°C (104-140°F). Consequently, the battery is built with heating element layers interspersed in the cell stack to allow internal temperature control to be exercised by the battery itself. The battery's internal controls manage the cell temperature to 40°C (104°F) for normal operation and to 60°C (140°F) for longer discharges.

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 securely 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.

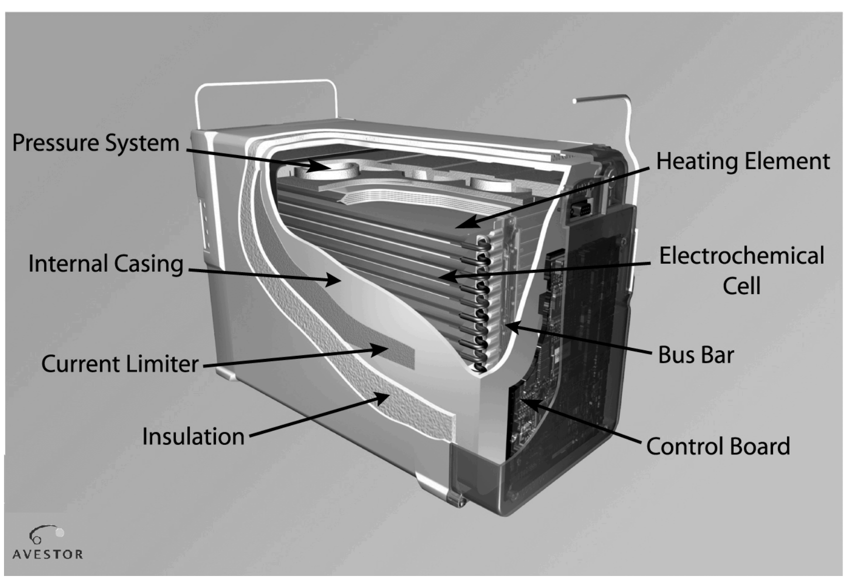

Figure 2: AVESTOR LITHIUM-METAL-POLYMER BATTERY CONSTRUCTION

Table 1: AVESTOR LITHIUM-METAL-POLYMER BATTERY CONFIGURATION EVOLUTION

Model	Maturity	Configuration	Purpose
NPS1	Laboratory	24V, 70Ah module	Lab evaluations & performance prediction
NPS2	Laboratory	24V, 70Ah module	Lab evaluations & performance prediction
NPS3	Prototype	24V, 80Ah module	Field trial
NPS4	Prototype	48V, 40Ah module	Field trial
NS55	Prototype	48V, 40Ah module	Manufacturing process development
SE48S70	Commercial	48V, 70Ah module	Commercial manufacture

Over recent years, the AVESTOR LMP battery module for telecom stationary applications has evolved through laboratory, prototype, and pre-production models to its commercial design. During this process, it has been optimized for performance and for manufacturability, based on data and experience from laboratory tests, field trials and process development. Table 1 provides a summary of this evolution in the product. Results and analysis in this paper span the history of this development and includes data from the various configuration vintages.

A STRUCTURED TEST PROGRAM

The AVESTOR LMP battery development program has always been managed with recognition of the responsibility to assure the long-term performance and reliability of the new electrochemical system. Following long years of primary R&D on the basic electrochemical cell and its materials that began in the 1980's, a 30,000 square foot prototype manufacturing facility and laboratory was built in 1995. This facility was capable of manufacturing the equivalent of about 400 batteries (1.2 MWh) per year to support an extended laboratory test program and a field trial program that would put the new battery design into real life application under a variety of environmental conditions.

Basic electrochemical cells, the building block of the battery, have been undergoing laboratory cycling and life testing since 1993. These tests have been used to confirm the characteristics of the cells under various conditions of temperature and current and different cycling protocols and float ratios over a period of several years. The data accumulated forms the basis and the benchmark for expectations of battery module performance in real application environments.

Field trial installations in outside plant cabinet environments began in 1999. The outside plant application is clearly recognised as the most hostile and challenging battery environment. Sites were selected to expose batteries to a wide range of climatic conditions: heat and humidity in the Southeast, dry heat in the Nevada desert, relatively stable moderate climates of the west coast, extremely variable climate in the north central states, the cold of Canada and, most recently, of Alaska. All sites have been fully instrumented and provided with remote monitoring equipment permitting detailed tracking of internal and external temperatures, humidity, battery and load voltages and currents. Data has been collected in real time by remote access. Performance during normal operation, power failure triggered discharges and forced discharges has been analysed against theoretical and lab test data expectations.

In addition, seven (7) third party laboratories, representing power equipment manufacturers and network operating companies, have conducted testing of performance and/or system integration. Independent agencies have successfully completed approval testing against product safety requirements to UL and NEBS level 3 standards.

The balance of this paper will elaborate on the results and conclusions of this test program.

Laboratory testing

Previous published papers have described at length the results of in-house laboratory testing over the past years. Key results are summarized here for insight into the functional characteristics of the Lithium-Metal-Polymer battery and as a benchmark against which to judge the field trial results which follow.

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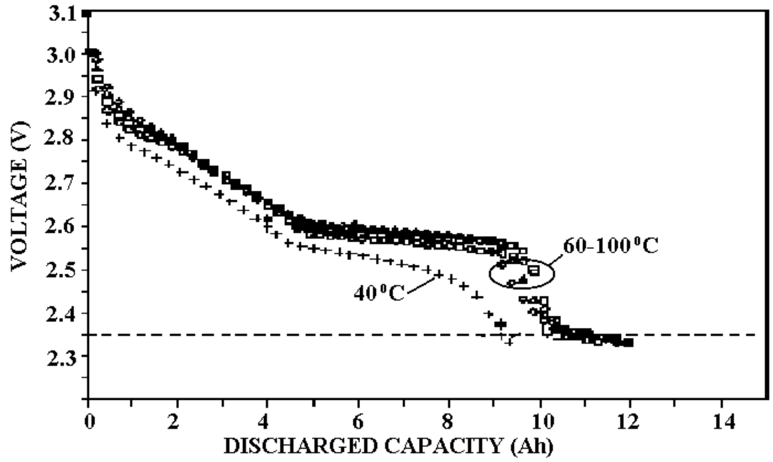


Figure 3: CELL DISCHARGE CURVES

The basis for the Lithium-Metal-Polymer electrochemical cell performance characteristics is its linear, reversible voltage versus state of discharge curve. Laboratory measurements of individual 2.7V cell voltage profiles, at different temperatures, are indicated in Figure 3.[1] The battery module temperature control has been designed to raise cell temperature from 40 to 60^0C after the cell voltage discharges to 2.75 volts, to shift to the more efficient discharge curve operating conditions.

To construct a practical battery module, an appropriate number of basic electrochemical cells are stacked together and connected in series with appropriate module temperature and current control. For the 24V NPS2 module, the resulting discharge characteristics are shown in Figure 4.[2] Here, we see the module initially floating at 31V at a steady state temperature about 40^0C. On removal of external power the module voltage follows the expected discharge curve down. After approximately 30 minutes, the temperature set point control moves to 60^0C and the internal module temperature is controlled in the range of 58 to 62^0C, by cycling the internal heaters off and on. Only a partial discharge is displayed in this chart.

On reconnection of external power, the modules will go into a slow charge mode, controlled by the module current limiter. As seen in Figure 5,[3] for the 24V module, a steady current of 7.5A is drawn over a 12 hour period, recharging the cell voltages. At approximate 30 minute intervals, the heaters cycle on to maintain internal temperature, interrupting charging, as indicated by the drop in voltage level during the 5 minute heating cycle. At the end of the charging period, current draw drops to the float level.

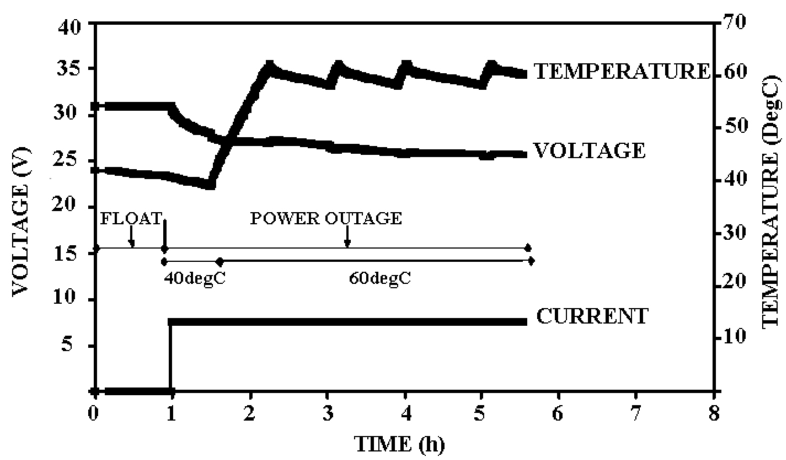


Figure 4: TYPICAL MODULE DISCHARGE BEHAVIOUR

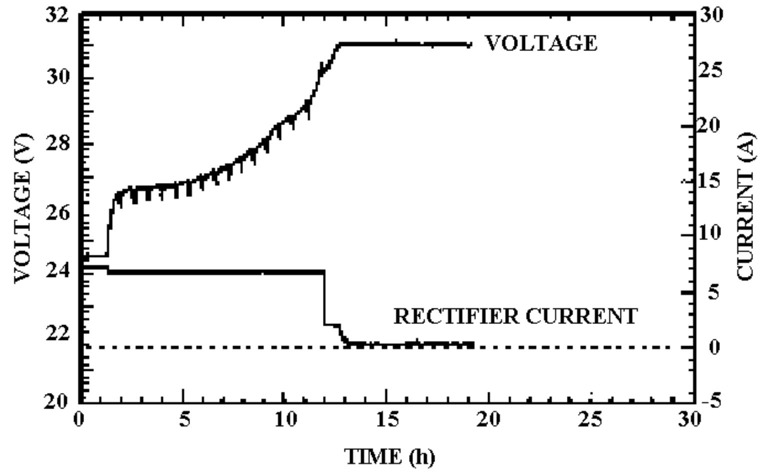


Figure 5: MODULE CHARGE CHARACTERISTICS

Projections of battery life are made by subjecting cells or modules to cycling protocols that simulate operational environments and measuring capacity loss over time, 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%. The analysis uses the standard criteria for end of life employed in evaluating lead-acid batteries, i.e., 20% capacity loss. This definition of end of life is simply a convention – AVESTOR LMP batteries are characterized by a gradual capacity fade with no sudden loss mechanism and can continue in service long after the 80% point is reached. Figure 6 demonstrates that tests performed in the AVESTOR laboratory lead to predictions that, at 99.4% float operation, the battery will maintain over 80% of its rated capacity for 25 years, or, at 98.1% floating, for over14 years. Floating rates actually recorded during AVESTOR field trials demonstrate that North American telecom applications actually float at rates of approximately 99.6%, which would lead to even higher LMP expected operating life.

Independent laboratory accelerated life testing performed on 24V NPS3 modules by Southern California Edison, using a cycling protocol of their own design intended to simulate North American power grid performance, is illustrated in Figure 7[4]

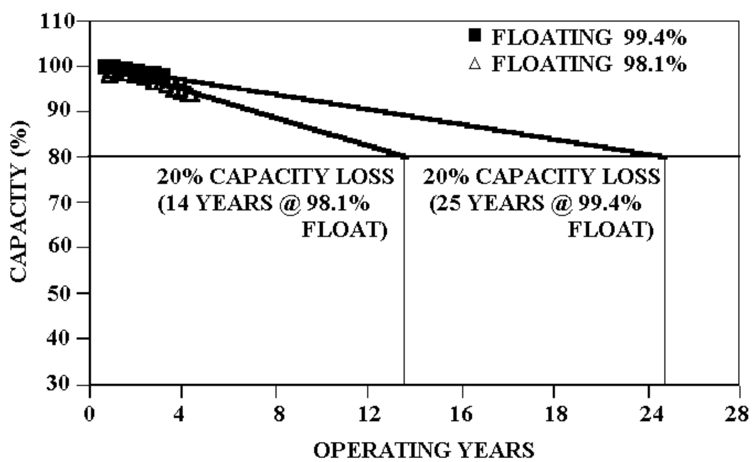


Figure 6: AGING TEST RESULTS (24V MODULE @ 60^{0}C)

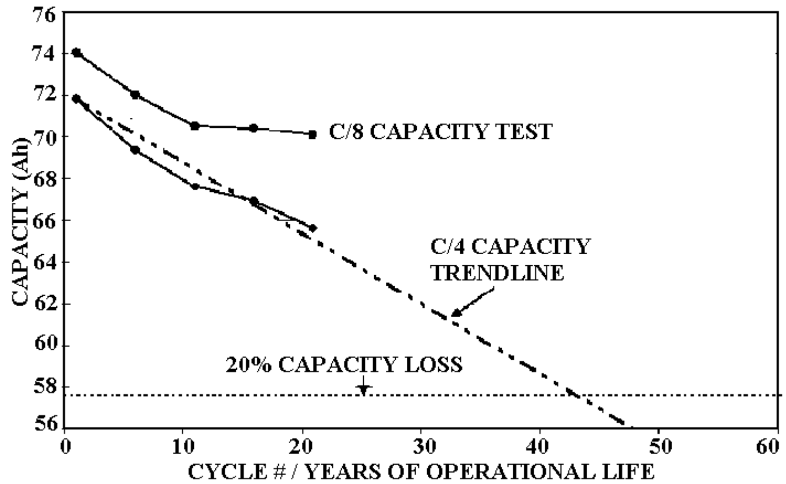


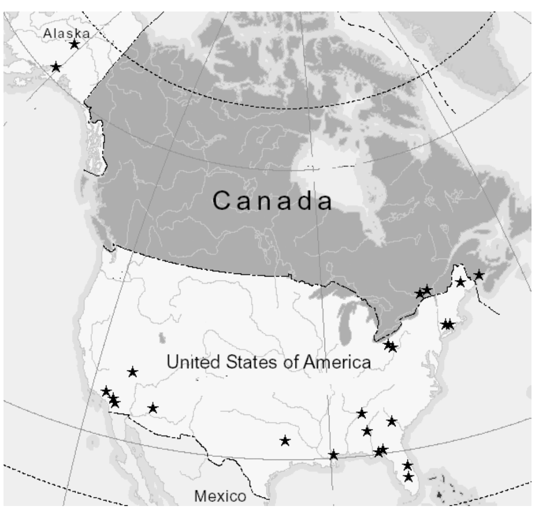
Figure 7: BATTERY CAPACITY AND END OF LIFE ESTIMATION (SCE)

The protocol was designed based on actual annual outage statistics from a major US utility and from a major US telecom operating company. After cycling the battery for an equivalent of 21 years of real-life battery operation, the battery capacity loss was only 5% for discharge rates of C/8 and 9%, for C/4. The linear extrapolation of the C/4 battery capacity degradation over its cycle life indicates the battery would reach 20% capacity reduction at over 40 years of operation.

Field Trials

Field trials have been ongoing since 1999 in sites that have been selected to cover the environmental extremes of North America. The locations of the 29 sites are illustrated on the map in Figure 8, along with an indication of the variety of equipment cabinets in which the batteries have been installed. (Some of the locations indicated have multiple trial sites.)

Ambient temperatures experienced in the battery compartment of the cabinets are continually monitored by the field trial monitoring equipment and confirm the high operating temperature to which battery systems are routinely subject. In Figure 9, the range of temperature experienced by the batteries during each week of the monitoring period is indicated, for some specific sites. It is observed that in the Florida, Arizona and California sites the mean weekly battery compartment



Application	Locations	Cabinet Type
Telco	MA	Lucent 80D-BP
Telco	FL, NV, AZ, GA	Lucent 80E-BP
Telco	CT	Lucent 82D-BP
Telco	AL, CA, QC, NB	Nortel DMS-1U
Telco	QC	Nortel Bulk cabinet
Telco	TX	Siemens – 914EX
Telco	CA, OH	Alcatel Litespan 2000
Telco	OH	Alcatel 2030
Wireless	AL	ADS
Signalling	MS, FL	Alpha PN-3
CATV	FL	Alpha PN-3
CATV	AK	Lectro
Telco	CA	Advanced Fiber Communications (AFC) UMC-1000

Figure 8: FIELD TRIAL SITES

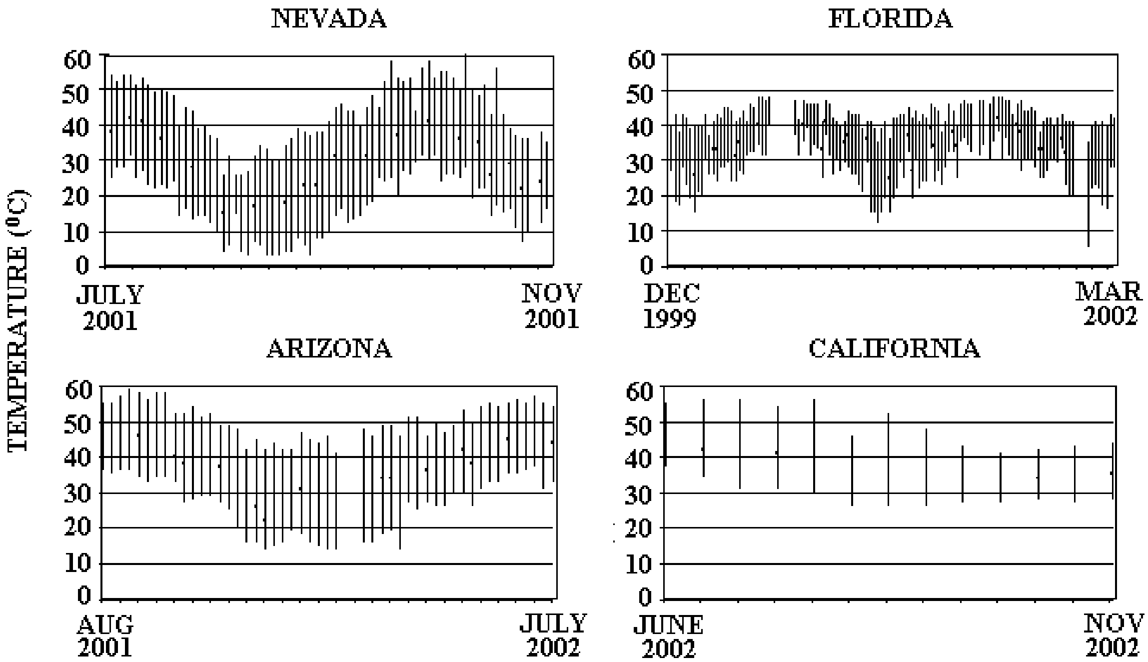


Figure 9: FIELD TRIAL SITE CABINET WEEKLY TEMPERATURE

temperatures were never below 30^0C and temperatures over 40^0C were a frequent occurrence in all sites.

At each site, forced discharge tests were performed on a regularly scheduled basis at intervals as agreed upon and scheduled with the site owner. A forced discharge was provoked by disconnecting the site primary power source and allowing the batteries to carry the system load for a period of time roughly equal to that expected to utilize the full capacity of the battery reserve. Continuous remote monitoring was provided on all sites and data on all discharges, whether event triggered or forced, were analysed in detail.

The total field trial plan to date has provided a database covering 72 forced discharges tests. Discounting those cases where systems loads and/or time restrictions prevented achieving significant discharge data, the tests covered a range of loads equivalent to C/4 to C/22 conditions and discharges that lasted from 2.8 to 21.5 hours. During the field trials, data that was collected included load voltages and currents, individual cell voltages within the module and internal and external temperatures. In all cases operational performance was consistent with design expectations.

An example of the cell voltage data collected from a typical forced discharge is shown in Figure 10 for a site equipped with two NPS4 modules. This forced discharge lasted 7 hours 53 minutes at a discharge rate of approximately C/7.8. The module performance may be compared with the laboratory measurements at the cell level presented above in Figures 3, 4 and 5. We can see that the module performance conforms to expectations. The effect of the heater cycles on the voltage during charging is not visible due to the compressed time scale of the chart. The right hand chart in Figure 10 displays the performance of the individual series-connected cells within the module, each operating in a balanced fashion and tracking voltage simultaneously. At the end of the charge, the equalization control takes over to balance each cell individually, visible as the successive voltage peaks observed in the chart.

During the course of the field trials, the battery installations were called upon to provide backup power during a total of 57 failures of the primary power source for periods ranging from under 1 minute to 7 hours. No case of service interruption to

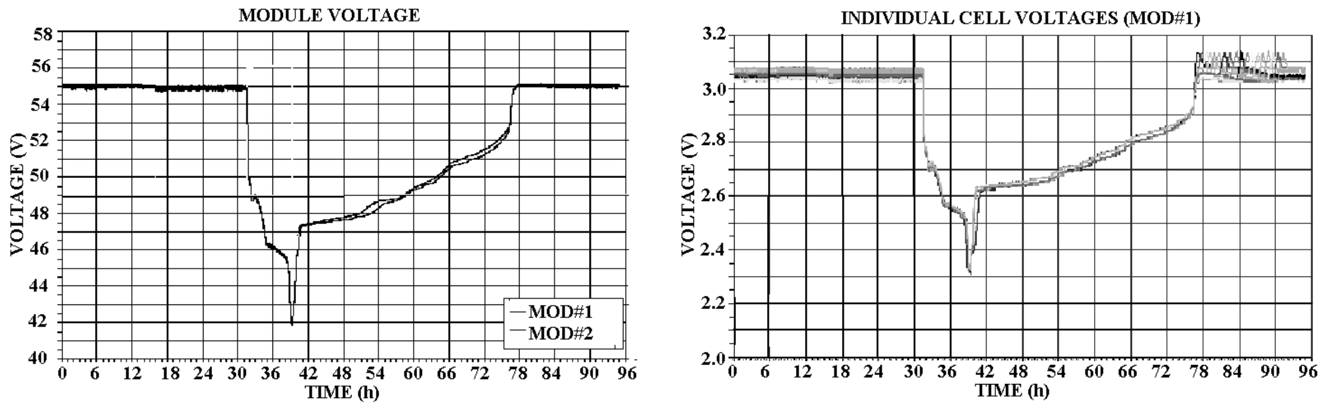


Figure 10: FIELD TRIAL CELL VOLTAGE MEASUREMENTS

customers was recorded. Figure 11 indicates the distribution of event-triggered discharge durations accumulated over the total field trial experience.

Records of system performance were monitored for all event-triggered battery discharges. Figure 12 presents a set of discharge curves from an event driven discharge (left side chart), compared to a curve from a forced discharge at the same site of similar depth of discharge (right side chart). The voltages of all eight NPS3 24V battery modules are shown. In this case the load present on the system was lower during the power failure driven discharge than during the forced discharge. The duration required to reach approximately the same degree of discharge was consequently longer. The recharge time is similar, except for differences due to the depth of discharge reached before recharge, as, in both cases, the charging system had enough excess capacity to charge the battery system at its maximum rate. It may be concluded that the battery system performance to support the load during real power failure situations was in conformance to expectations and that forced discharge tests have been adequate simulations of real power loss events.

Up to the end of February 2003, 1500 module-months of field trial experience have been clocked. During the course of field trials, no battery failure nor any sign of degradation related to the electrochemical system has been recorded. Early field trials permitted debugging of the battery module electrical control system - certain weaknesses in the implementation of cell equalisation and temperature control were determined by performance monitoring on NPS3 installations. These led to design improvements implemented in NPS4 and later models. In almost 1000 module-months of field trial experience since these

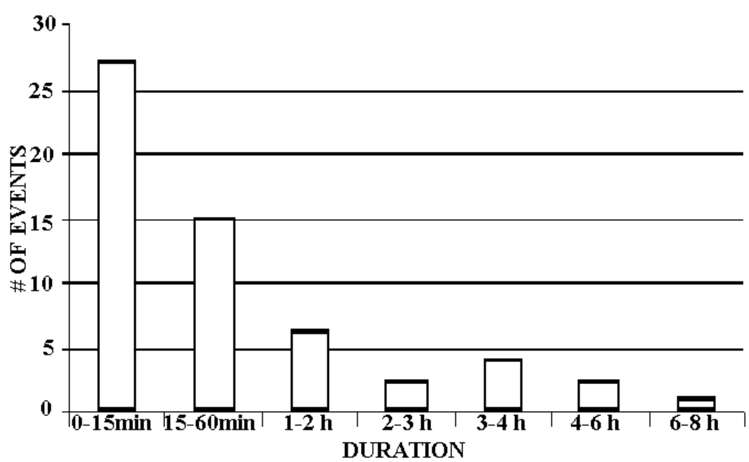


Figure 11: DISCHARGE EVENT DURATION

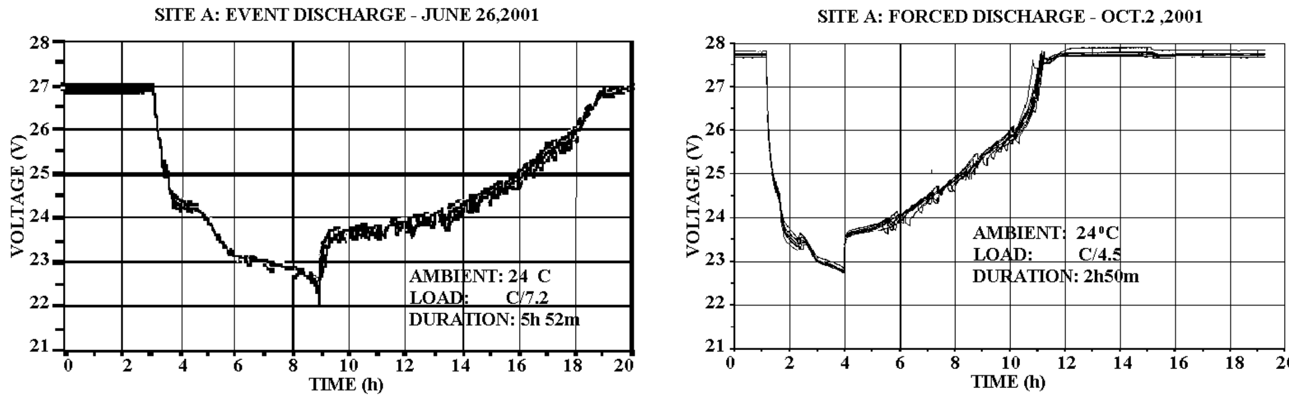


Figure 12: TYPICAL EVENT DRIVEN DISCHARGE

changes, there has not been a single failure of any nature, electrochemical or electronic, in any of the AVESTOR LMP field trial modules.

All forced discharge data has been compared to expectations of battery module storage capacity. Battery capacity delivered to the load is a complex function of ambient temperature, discharge current and duration of discharge. Simplified to indicate the impact of one variable at a time, Figure 13 demonstrates the relevant relationships
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- Temperature - As ambient temperature around the battery module decreases below 60^0C (140^0F), the battery module must expend a limited part of its reserve capacity to maintain its internal temperature at the optimum level, reducing the energy available for delivery to the load. The capacity vs. temperature chart indicates the impact of this factor on the NPS4 module capacity at a discharge rate of C/8.

- Discharge rate – The current module designs have been optimized for North American telecom applications, typically provisioned for eight hour reserve. Slower discharge rates will improve the available capacity, faster discharge rates will reduce available capacity, as indicated in the capacity vs. discharge rate curve of the NPS4 module, measured at an internal temperature of 60^0C, and shown relative to the rated battery capacity at C/8.

- Discharge duration – A compound effect of long discharge rate and low ambient temperature can come into play during a long, slow discharge. During the extended discharge interval the battery goes through a greater number of heating cycles, and, hence, expends a proportionally greater part of its reserve capacity to maintain its internal temperature, relative to that delivered to the load.

Applying the appropriate adjustments to forced discharge test results, within the limitations of the variable conditions that are inherent in a real installation subject to real load and temperature variations, no perceptible reduction in capacity has been observed in any of the 105 modules on trial. This is consistent with laboratory accelerated aging tests that predict less than 2% capacity loss in typical telecom (99.4%) float service for the modules, which have been in service for up to 3.5 years.

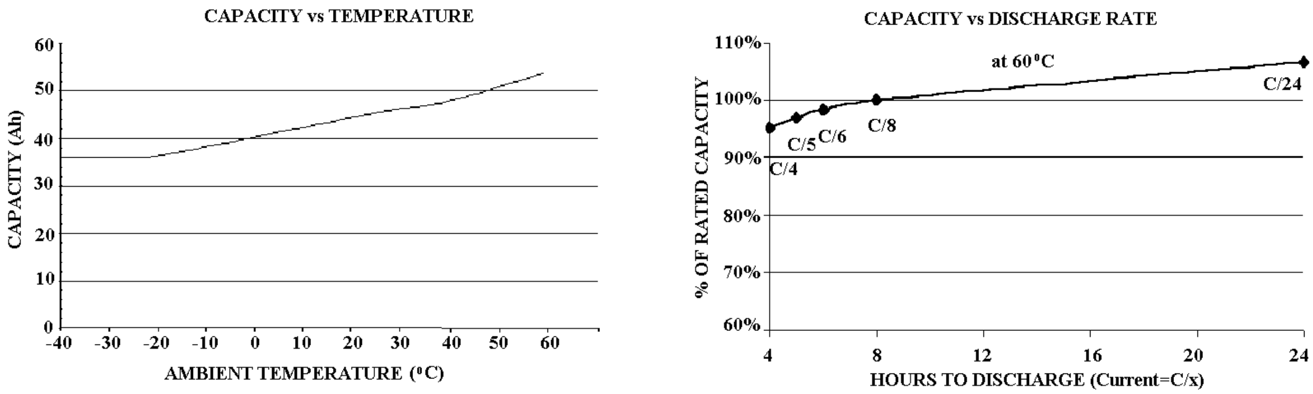

Figure 13: FACTORS AFFECTING CAPACITY DETERMINATION

CONCLUSION

AVESTOR LMP batteries have been the subject of a structured and extensive evaluation and testing program in the laboratory and in field trial installations. Real time data has been collected and analysed on over 1500 module-months of field experience to date. The environments in which these batteries have been installed are among the harshest existing in the outside plant for both extreme heat and extreme cold.

This program has allowed early detection and correction of a few electronic design issues in the first prototype model (NPS3). There has been no problem detected in any field trial with the electrochemical cell design and no electronic control malfunction or failure in any module vintage after NPS3. The field trial batteries have successfully provided backup power during all forced or external power failure events, without any loss of service to customers.

All electrochemical and control functions have performed in conformance to expectations and have confirmed theoretical and laboratory test data. No perceptible capacity loss has been detected in field trial units. Data will continue to be collected from field trial sites and, beginning this year, from commercial installations.

With a proven reliability for its first telecom battery, AVESTOR is now developing LMP batteries for other stationary applications in the telecom industry and for other applications in power utilities, nuclear plants, etc. It is also continuing its development of LMP batteries for the automotive industry.

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[1] D. Geoffroy, *et al*, “Lithium Polymer Battery in Warm Environment“, Proceedings of INTELEC 2000, September 2000
[2] J. Rouillard, *et al*, “Testing of Lithium Polymer Batteries in Outside Plant Cabinet for Telecommunication System“, Proceedings of INTELEC ‘99, June 1999
[3] C. Letourneau, *et al*, “Progress in Lithium Polymer Development for Telecommunication System”, Proceedings of INTELEC ’98, October 1998
[4] N. Pinsky, *et al*, “Stationary Applications of Advanced Batteries“, Southern California Edison Report, May 2002