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FY 2000

**Progress Report for the Electric Vehicle
Battery Research and Development Program**

**Energy Efficiency and Renewable Energy
Office of Transportation Technologies
Office of Advanced Automotive Technologies
Energy Management Team**

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1. INTRODUCTION

Electric Vehicle Battery Research and Development Program

The Electric Vehicle Battery Research and Development Program has been a part of the Office of Advanced Automotive Technology since its inception. Advanced batteries have been an integral part of the Department of Energy's work on electric vehicles since the late 1970's. Advanced battery research and development have always been part of the high-risk activities sponsored by the Department in this area. The goal of the Battery Research and Development Program is to create battery technology that enables fully competitive electric vehicles. The current goal is to achieve this by the 2003 to 2005 time frame.

The Electric Vehicle Battery Research and Development Program has already had several major successes. It has successfully developed and introduced the nickel metal hydride advanced battery for electric vehicle use. Over 1000 nickel metal hydride battery electric vehicles have been put into service in the last few years. The program has also conducted the Advanced Battery Readiness Working Group for a decade. The Advanced Battery Readiness Working Group meets regularly to address regulatory issues concerning the shipping, in-vehicle safety, and recycling or reclamation of advanced batteries. This group has created or motivated the creation of new regulations that support the use of advanced battery technologies for hybrid and electric vehicles.

The Electric Vehicle Battery Research and Development Program also conducts extensive benchmarking activities of advanced batteries from abroad. Current work in benchmarking nickel metal hydride battery modules is being expanded to benchmark lithium ion systems (at the cell level).

Advanced batteries remain a key critical technology for the commercialization of electric vehicles. The development of advanced batteries is carried out by the United States Advanced Battery Consortium (USABC). USABC has nearly a decade of experience in managing advanced battery development programs with the Department of Energy for both electric and hybrid electric vehicles. It conducts the world's largest research and development efforts for advanced automotive batteries. It is generally recognized as the leading advanced battery development effort on a world-wide basis.

This report highlights the activities and progress achieved during FY 2000 under the Electric Vehicle Advanced Battery Program. This report consists of program summaries from the major development efforts in this program. The information presented here only reflects what appears in the public domain and does not include any "Protected Battery Information."

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2. ELECTRIC VEHICLE BATTERY RESEARCH AND DEVELOPMENT PROGRAM AND FY 2000 HIGHLIGHTS

A. Electric Vehicle Battery Research and Development Program

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The Electric Vehicle Battery Research and Development Program was established to develop advanced batteries capable of meeting the industry's long-term goals. The long-term goals were set to enable fully competitive electric vehicles in response to the Zero Emission Vehicle program began in California in 1990. Zero emission vehicles continue to be sought in California and the Northeast to mitigate severe criteria pollutant emissions from mobile sources.

The goal of the Electric Vehicle Battery Research and Development Program [1-3] is to support the development of a domestic advanced battery industry that will allow fully competitive electric vehicles by the 2003 to 2005 time frame. The technical objectives of the program are defined in Table 1.

The Electric Vehicle Battery Research and Development Program is organized as follows:

- The Department of Energy serves as the overall program manager.
- The United States Advanced Battery Consortium conducts cost shared development of advanced batteries with competitively selected developers. The Department of Energy is substantially involved in the management of the USABC and participates in its Management Committee, Technical Advisory Committee, and work groups.
- The USABC also closely follows the work performed by the Exploratory Battery Research and Development program and other elements of the work of the Energy Management Team. The USABC is also responsible for High Power Energy Storage Program in support of the Partnership for a New Generation of Vehicles.
- The USABC conducts the development of lithium ion and lithium polymer batteries.
- The Department of Energy also manages the Benchmark Testing of Advanced Electric Vehicle Batteries.

Table 1. U.S. Advanced Battery Consortium Goals for Electric Vehicle Batteries

Primary criteria	Long-term goals^a (2003 to 2005)
Power density ^b W/L	460
Specific power ^b W/kg (80% DOD/30 sec)	300
Energy density ^b Wh/L (C/3 discharge rate)	230
Specific energy ^b Wh/kg (C/3 discharge rate)	150
Life (years)	10
Cycle life ^b (cycles) (80% DOD)	1000 1,600 (@ 50% DOD) 2,670 (@ 30% DOD)
Power and capacity degradation ^b (% of rated spec)	20%
Ultimate price ^c (\$/kWh) (10,000 units @ 40 kWh)	<\$150 (desired to 75)
Operating environment	-30°C to 65°C
Recharge time ^b	< 6 hours
Continuous discharge in 1 hour (no failure)	75% (of rated energy capacity)
Secondary criteria	Long-term goals (2003 to 2005)
Efficiency ^b (C/3 discharge and C/6 charge) ^d	80%
Self-discharge ^b	<20% in 12 days
Maintenance	No maintenance. Service by qualified personnel only.
Thermal loss ^b	Covered by self-discharge
Abuse resistance ^b	Tolerant Minimized by on-board controls
Specified by contractor Packaging constraints Environmental impact Safety Recyclability Reliability Overcharge/over-discharge tolerance	
^a For interim commercialization (reflects USABC revisions of September 1996).	
^b Specifics on criteria can be found in <i>USABC Electric Vehicle Battery Test Procedures Manual, Rev. 2</i> , DOE/ID-10479, January 1996.	
^c Cost to the original equipment manufacturers.	
^d Roundtrip charge/discharge efficiency.	

Significant Accomplishments for FY 2000

In March 2000, the Department of Energy awarded USABC a Phase III cooperative agreement covering the period March 2000 to June 2003. This agreement is for \$62 million dollars, with a cost share of 35 percent from the Department of Energy and 65 percent from industry.

The USABC is committed to continue work on lithium ion and lithium “dry” polymer batteries. The USABC is also evaluating lithium “gel” polymer batteries and may consider other lithium based battery technologies in the future. The USABC is organizing to conduct a Phase III solicitation for new developers in early FY 2001.

The USABC continues to cooperate with the Lithium Battery Energy Storage Research Association of Japan (LIBES) under agreements signed in 1998 between the Department of Energy and the Japanese Ministry of International Trade and Industry. This cooperation is focused at methods for electric testing and tolerance to abuse testing of lithium batteries. Both sides also are exploring ways in which the battery users and developers can work more closely to understand the needs of the market and offer appropriate prototype technology for evaluation.

The Benchmark Testing of Advanced Electric Vehicle Batteries Program is continuing to test electric vehicle nickel metal hydride modules and is beginning to evaluate electric vehicle lithium ion and lithium polymer cells being received from overseas developers.

Program Participants

The participants in this program are:

- United States Advanced Battery Consortium
- AVESTOR (subsidiary of Hydro-Quebec)
- SAFT (France)
- Argonne National Laboratory

References

- [1] Sutula, R. A., Heitner, K. L., Rogers, S. A., Duong, T. Q., Kirk, R. S., Kumar, B., and Schonefeld, C., “Electric and Hybrid Vehicle Energy Storage R&D Programs of the U.S. Department of Energy,” the 16th International Electric Vehicle Symposium, Beijing, China, October 1999.
- [2] Sutula, R. A., Heitner, K. L., Rogers, S. A., Duong, T. Q., Kirk, R. S., Kumar, B., and Schonefeld, C., “Advanced Automotive Technologies Energy Storage R&D Programs at the U.S. Department of Energy: Recent Achievements and Current Status,” paper No. 2000-01-1604, the 2000 Future Car Congress, Arlington, VA, April 2000.
- [3] Sutula, R. A., Heitner, K. L., Rogers, S. A., Duong, T. Q., Kirk, R. S., Battaglia, V., Henriksen, G., McLarnon, F., Kumar, B., and Schonefeld, C., “Recent Accomplishments of the Electric and Hybrid Vehicle Energy Storage R&D Programs at the U.S. Department of Energy: A Status Report,” the 17th International Electric Vehicle Symposium, Montreal, Canada, October 2000.

3. LITHIUM ION BATTERY DEVELOPMENT

A. SAFT Lithium Ion Energy Storage Technology

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Objectives

- Develop a lithium ion battery system for electric vehicle that can meet the required high performance levels for energy and power, has a long life, a low cost, and is tolerant of abuse.

Approach

- Adopt a cylindrical form factor instead of the earlier prismatic design.
- Internally connect cells in various fixed, series and parallel configurations to obtain a voltage design flexibility.
- Engineer technology based on existing and emerging battery materials available from international suppliers.

Accomplishments

- Developed a lithium ion cell technology base, which begins to provide the transportation industry with a high performance battery for electric vehicles.
- Integration into the Ford KA and Renault 106 electric vehicles.

Future Directions

- Continue development of the cell technology and begin to create module and pack level technology.

Since they were first introduced in the early 1990's, lithium ion batteries have enjoyed an unprecedented growth and success in the consumer marketplace. Combining performance with affordability, they have become the product of choice for portable computers and cellular phones. Building on the same energy and life cycle attributes, but adding new higher power and larger cell capability, lithium ion technology is now poised to play a similar role in the transportation sector.

SAFT has developed a family of battery products which address energy storage

applications where light weight, long life, and excellent power capabilities are needed. Significant progress in the packaging and control of high energy, yet compact, batteries has been accomplished for a variety of vehicle applications.

The current SAFT Lithium Ion electric vehicle cell technology has evolved from programs initiated in 1993 in Europe. Today several vehicles are being road tested in Europe using SAFT lithium ion batteries. As part of this evolution, SAFT has developed an integrated modular concept to provide design flexibility and packaging efficiency. With abuse tolerance being

a primary objective of the program, the batteries currently being tested have demonstrated an energy density of 100 Wh/kg at the battery level, with a target of achieving 120 Wh/kg by the summer of 2000.

Figure 1 shows the family of High Energy (HE) and High Power (HP) lithium ion cells and EV module package.



Figure 1. Lithium ion family of cells and EV module

High Energy Lithium Ion Batteries

SAFT’s initial development of lithium ion EV batteries focused on prismatic designs. After initial evaluation, it was determined that a cylindrical form factor offered certain performance and manufacturing advantages, specifically with respect to quality control, automated assembly and reproducibility on an industrial scale. Table 1 shows the lithium ion cell performance data.

Having decided on a cylindrical cell design, SAFT next tackled the issue of physical packaging within the automotive envelope. To meet the different energy and voltage requirements of individual automakers, an innovative solution was employed, utilizing a common six (6) cell module. It had the capability that the same module could be provided with three different voltages and capacities by internally connecting the cells in different fixed, series and parallel connections. Thus the standard High Energy module can be supplied in 21, 10.5 or 7 volt configurations, providing design flexibility without compromising industrial manufacturing efficiency. The module

dimensions and the ability to reconfigure the module for its three design voltages are illustrated in Figure 2.

Table 1. Lithium ion high energy cell performance [1]

Electrical Characteristics	
Nominal voltage (V)	3.6
Capacity at C/3 rate (Ah)	44
Specific energy (Wh/kg)	138
Energy density (Wh/dm ³)	304
Specific power (W/kg)	>300
Power density (W/dm ³)	642
Mechanical characteristics	
Diameter (mm)	54
Height (mm)	220
Weight (g)	1.07
Volume (dm ³)	0.5
Operating conditions	
Operating temperature range (°C) as given by the thermal management system	-10/+45
Transport or storage temperature range (°C)	-40/+65
Voltage limits	
In charge (V)	4
In discharge (V)	2.7

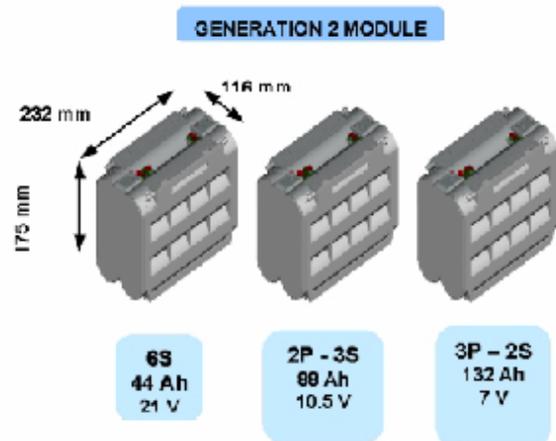


Figure 2. High energy module design flexibility

SAFT's design places individual cell monitoring and control at the module level, effectively utilizing a hierarchical approach for cell, module, and battery control. Each module is designed to monitor and control the charge and discharge of the individual cells contained within it as well as to communicate information to the next higher level battery and vehicle control systems. The module is liquid cooled for providing effective thermal management for both warm and cold weather operation as well enabling fast charging strategies. The modules are further combined into an integrated battery pack that incorporates the modules, the thermal management system, and the centralized electronic controls. A conceptual battery package design is illustrated in Figure 3. The design provides a self-contained unit that provides the needed energy, with all the controls and management functions integrated into a single package. Effectively, this becomes an energy black box that is then installed in a vehicle. Specific battery designs are considered proprietary, and not shown here.

Performance

A summary of the performance for the HE Lithium Ion chemistry at the module and battery system level are contained in Tables 2 and 3, respectively.

Abuse Tolerance

For any EV battery system to be utilized in a commercial vehicle, it must not only provide acceptable performance at affordable pricing, but must also exhibit acceptable tolerance to abuse conditions. The SAFT HE lithium ion batteries have been tested for abuse tolerance during their development.

Future Development

As an ongoing program, the objectives are to simultaneously improve performance while concurrently driving down the cost of manufacturing. SAFT's Lithium ion Pilot facility in Bordeaux France began operation in 1999. As to future performance, Table 4 shows the targets for the HE Lithium Ion battery system both for the immediate future and long term. Tables 5 and 6 contain the cell initial characterization data and calendar life results from the Pilot facility.

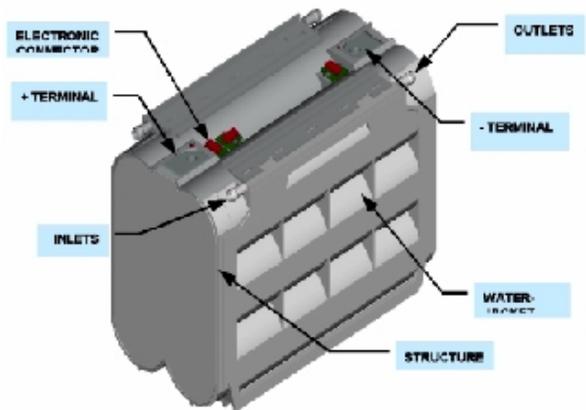


Figure 3. High energy module

Table 2. Current Performance – Module Level Electrochemistries [1]

Specific energy (Wh/kg)	138 (ECE 15) 120 (D/2)
Volumetric energy (Wh/dm ³) (ECE 15)	304
Specific power (W/kg) (80% DOD)	1,000 cycles performed
Safety (EUCAR procedure)	Flames Fumes

Table 3. High Energy Battery System Performance [1]

Volumetric energy (Wh/dm ³) (ECE 15)	119
Specific power (W/kg) (80% DOD)	200
Cycle life (80% DOD)	200 cycles performed
Safety	Not yet tested

Table 4. Lithium Ion High Energy Battery Performance Objectives [1]

	July 1999	September 1999	Ultimate Goal
Specific energy (Wh/kg) (D/2)	100	120	140
Specific power (W/kg) (80% DOD)	200	230	270
Cycle life (80% DOD)	600	800	1,000
Safety (EUCAR procedure)	No flames	No flames No fumes	No flames No fumes

Table 5. Lithium Ion Cell Initial Characterization Data [2]

Capacity and Energy	
Capacity (@C/3, 4.0V) (Ah)	39
Energy (@C/3, 4.0V) (Wh)	137
Energy Density (Wh/l)	274
Specific Energy (Wh/kg)	130
Power (30s pulse @80% DoD)	
Cell resistance (mΩ)	4
Voltage limit power (W/kg)	~590
Current limit power (W/kg)	~400
Self Discharge (%/month)	
@ -10°C	≤ 5%
@ 20°C	≤ 10%
@ 40°C	≤ 15%
Abuse Tolerance	
No fire (only smoke) observed at penetration test up to 3.95V EOCV (~120 Wh/kg)	
Operating Temperature Range	
Normal operation	[+5°C, +45°C]
With reduced current	[-10°C, +60°C]

Table 6. Lithium Ion Calendar Life Results at 20 °C [2]

State of charge: 25%	
Storage duration (Month)	17.5
Power Loss (actual power @80% DoD) (%)	1.4
Estimated calendar life for a 20% power loss (year)	13
State of charge: 50%	
Storage duration (Month)	10.7
Power Loss (actual power @80% DoD) (%)	-2.5
Estimated calendar life for a 20% power loss (year)	8.2
State of charge: 100%	
Storage duration (Month)	10.7
Power Loss (actual power @80% DoD) (%)	-3.3
Estimated calendar life for a 20% power loss (year)	5.4
State of charge: 100%	
Storage duration (Month)	3
Power Loss (actual power @80% DoD) (%)	-1
Estimated calendar life for a 20% power loss (year)	5.2

References

- [1] Sack, T. T., Saft, M. C., Chagnon, G., Oweis, S., Romero, A., Zuhowski, M., Faugeras, T., Sarre, G., Morhet, P., and d’Ussel, L., “Lithium Ion Energy and Power Storage Technology,” paper No. 2000-01-1589, the 2000 Future Car Congress, Arlington, VA, April 2000.
- [2] Blanchard, P., Cesbron, D., Rigobert, G., and Sarre, G., “Performance of SAFT Li-ion Batteries for Electric Vehicles,” the 17th International Electric Vehicle Symposium, Montreal, Canada, October 2000.

4. LITHIUM POLYMER BATTERY DEVELOPMENT

A. AVESTOR Lithium Metal Polymer Battery Development

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Objectives

- Develop a Lithium Metal Polymer Battery (LMPB) system to achieve the power and energy targets specified as USABC commercialization goals.

Approach

- Generate high surface area battery system by laminating thin, long layers of current collector, electrode, and electrolyte material operating about 80°C.

Accomplishments

- Assembly of the first 8 kWh LPB pack completed. Now being lab tested.
- Tests at the cell level show good results for EV and HEV applications.
- Integration into the Ford Think City electric vehicle.

Future Directions

- Optimization of cell design and further development of a robust electrochemical cell technology.
-

The Lithium Metal Polymer Battery (LMPB) is an advanced battery technology under development for both EV and HEV applications. Considerable efforts have been made in the last six years in the development of a viable advanced battery for EVs. The United States Advanced Battery Consortium (USABC) has been at the forefront of this battery development. Present performance of EV cells and modules, when scaled up to the pack level with design concept now under development, can nearly achieve the power and energy targets defined as USABC commercialization goals. The life characteristics are being evaluated for statistically significant cohort groups.

AVESTOR has been developing the LMPB for twenty years for electric vehicles and stationary applications. Since 1993, the LMPB has been under development for EV applications under a series of USABC cost-shared contracts totaling \$96 millions (US) to date.

Battery Construction

A lithium metal polymer cell is made by laminating together five thin materials including an insulator, a lithium foil anode, a solid conductive polymer electrolyte, a metal oxide cathode and a current collector. The total thickness of this all-solid laminate is less than 100 microns (0.004 inches) and it is wound into a prismatic

shape to form an electrochemical cell (EC), shown in Figure 1. The technology relies on generating high surfaces areas to build the high energy and power capacities required of advanced technology batteries. A full-sized EV battery contains kilometers of this laminate. Each layer in the battery is produced in a continuous web process, suitable for high-speed cost effective manufacturing. Long battery laminates are assembled into discrete electrochemical cells (ECs). Electrical contact is made across the entire edge of the cell laminate, rather than just at the beginning and at the end of the laminate. This is accomplished by offsetting the positive current collector foil to one side and the negative lithium foil to the other side. Metal spraying is then used to provide continuous current collection along the entire length of the laminate. This technique allows highly efficient electrical and thermal contacts to the EC.

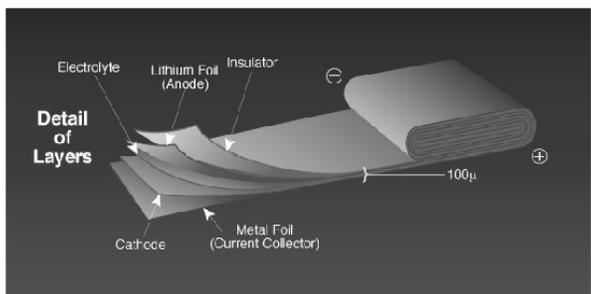


Figure 1. Lithium metal polymer cell laminate [1]

Since changes in the dimension of a cell, or in the total amount of wound material do not affect the fundamental current uniformity or thermal control, the LMPB technology is extremely adaptable to varied constructions for particular applications or customers. Cells of different heights, lengths, and thicknesses are fabricated using the same manufacturing equipment. This flexibility allows LMPB product configurations to be uniquely adapted to different vehicles with little changes in the process and production cost. Unit ECs are packaged into a stack of flat cells to create a module. Because of the solid state nature of the lithium metal polymer battery, the cells can be wired into parallel and/or series arrangements within a single container to build the desired module capacity and voltage. The packaging also provides the mechanical, electrical, and thermal

controls required for operation. Each module (Figure 2) is a fully functioning battery system, including intelligent control and monitoring electronics that interface with the battery pack controller. Modules are assembled inside a battery pack tailored for a specific vehicle. The pack includes an enclosure, which provides mechanical support and thermal insulation along with control hardware and vehicle interfaces.

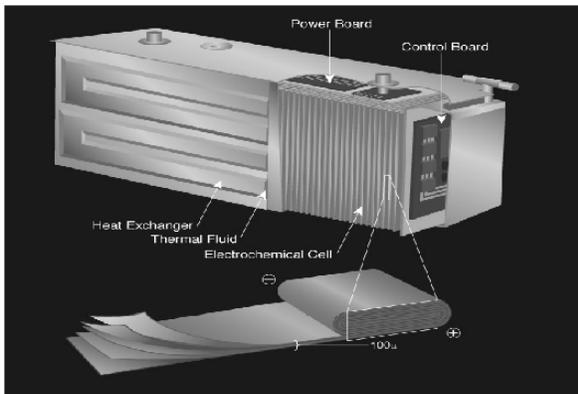


Figure 2. LMPB module design [1]

LMPB For EV Application

Battery Prototype Performance

Preliminary performances of EV cells, modules and packs tested under the USABC cycling protocols reveal that the LMPB technology already meets key essential performance characteristics for a competitive EV, including a high power for acceleration and a sustained high speed as well as a high capacity for the long range. The projected characteristics of the module under development are shown in Table 1.

Currently, life cycle tests are being performed on a group of 30 cells. The LMPB research team is continuously working on improving the technology with a cycle life target of 1,000 cycles at the pack level. 8 kWh battery packs have been built and tested. Discharge characteristics of a 82V, 96 Ah pack under a 240 W/kg DST profile are shown in Figure 3. Peak power capability of this pack versus depth of discharge is shown in Figure 4. The peak power of 16.5 kW represents about 95% of the peak power capability of the four

series-connected modules due to the resistance of the pack interconnections and terminals.

Integration into the Ford Think City

The LMPB technology was recently integrated into the Ford Think City energy storage system, the first such vehicle expected to utilize a LMPB. Meeting these objectives required a certain electrochemical configuration, along with the module and pack design, battery management and thermal management systems. This technology has been integrated into other vehicles [3].

Conclusion

The LMPB has been under development for EV applications for seven years, under USABC contracts. Assembly of the first 8 kWh LMPB pack has been completed and it is being used for laboratory testing. The LMPB has proven its flexibility in meeting the performance requirements of both EV and HEV batteries and has the design flexibility to meet varying automotive requirements within each class of vehicles.

Table 1. Characteristics of EV cells and modules under development [2]

	Cell	Module
Specific Energy, Wh/kg, @ C/3)	205	155
Energy Density (Wh/l, @ C/3)	333	220
Specific Power (W/kg, @ 80 % DoD)	420	315
Power Density (W/l, @ C/3)	700	506

References

[1] St-Pierre, C., Rouillard, R., Belanger, A., Kapfer, B., Simoneau, M., Choquette, Y., Gastonguay, L., Heiti, R., and Behun, C., "Lithium Polymer Battery for Electric Vehicle and Hybrid Electric Vehicle Applications," the 16th International Electric Vehicle Symposium, Beijing, China, October 1999.

[2] St-Pierre, C., Rouillard, R., Belanger, A., Kapfer, B., Simoneau, M., Choquette, Y., Gastonguay, "Lithium Polymer Battery for Evs and HEVs," paper No. 2000-01-1587, the

2000 Future Car Congress, Arlington, VA, April 2000.

[3] Rouillard, R., Richard, M., Pomerleau, D., St. Germain, P., St-Pierre, C., Gastonguay, L., Choquette, Y., Davis, D. H., and Huse, J. B., "Development of Lithium Polymer Battery for the GM Precept," the 17th International Electric Vehicle Symposium, Montreal, Canada, October 2000.

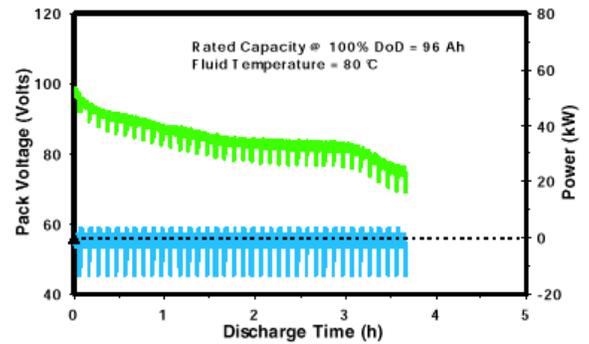


Figure 3. Discharge Characteristics of 7.9 kWh Pack DST Profile (80% DoD) [2]

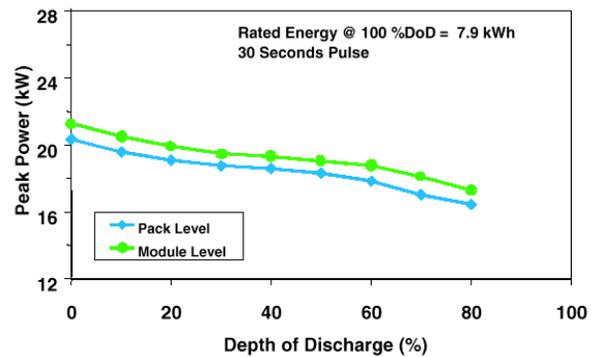


Figure 4. Peak Power Capability of 7.9 kWh pack [2]

5. BENCHMARK TESTING OF ADVANCED ELECTRIC VEHICLE BATTERIES

A. Benchmark Testing Program

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Objectives

- Benchmark developers' technologies as a way of using limited resources for the greatest benefit, allowing DOE to gauge the maturity of certain battery technologies and/or to identify their barriers and guiding DOE to allocate appropriately its research funds to address identified barriers or to support other advanced battery technologies.

Approach

- Conduct effort independently and hold results in confidence between DOE and the developer/supplier.
- Select representative nickel metal hydride and lithium ion battery technologies, intended for electric vehicle (EV) and hybrid-electric vehicle (HEV) applications.
- Perform tests based either on the USABC Battery Test Procedures Manual for EV batteries or on the PNGV Battery Test Procedures Manual (HEV).

Accomplishments

- Batteries representing technologies from foreign developers/suppliers were acquired and tested during fiscal years 1999 and 2000.

Future Directions

- Continue testing with additional foreign battery technologies focusing on lithium-based batteries.

One of the objectives of DOE's battery testing program is the direct comparison of foreign battery technologies with those developed domestically. To accomplish this objective, batteries representing technologies from foreign developers/vendors were acquired and tested during fiscal years 1999 and 2000. These batteries are from Panasonic/Matsushita (Japan), and Shin-Kobe (Japan). In addition, the SAFT 'F' series

NiMH modules were received from USABC. They represent two nickel metal hydride technologies and one lithium ion technology, respectively. These batteries are intended for electric vehicle (EV) and hybrid-electric vehicle (HEV) applications. The tests performed on the batteries are based on either the USABC Battery Test Procedures Manual for EV batteries [1] or on the PNGV Battery Test Procedures Manual (HEV)

[2]. The tests were conducted in the Electrochemical Analysis and Diagnostics Laboratory (EADL) at Argonne National Laboratory.

EV Applications

Panasonic/Matsushita EV95 Modules

The testing of six EV95 12-V, 95-Ah Ni/MH modules (see Figure 1) began in November and December of 1998. Briefly, the test plan consisted of core performance testing,¹ thermal performance in the temperature range of -10 to +50°C, and 50 and 80% DST life cycling at 25 and 40°C. During the testing, reference performance tests (RPTs) were used to gauge changes in battery performance. The RPTs consisted of 100% C/3 discharge, 100% DOD DST discharge and peak power measurements. The RPTs were performed every 50 cycles (~1 per month) during life cycling. The module designations and a list of the tests performed on them are given in Table 1.



Figure 1. Front view of the Ni/MH module.

Testing will be completed during the first quarter of FY 2001, resulting in sufficient data to make accurate life projections.

SAFT Ni/MH ‘F’ Modules

Twenty-nine ‘F’ modules arrived from SAFT (France) in May 1999. They were assembled into minipacks according to series number; see Table 2 for number of modules in a given minipack and USABC identifier.

Table 1. Module Designations and Tests Performed

Module Designation	Tests Performed
NH-12/95-9/98-PAN-M1	Core Performance and Thermal Performance
NH-12/95-9/98-PAN-M2	Core Performance and 50% DST Life at 40°C
NH-12/95-9/98-PAN-M3	Core Performance and 80% DST Life at 25°C
NH-12/95-9/98-PAN-M4	Core Performance and 80% DST Life at 40°C
NH-12/95-9/98-PAN-M5	Core Performance and 80% DST Life at 25°C
NH-12/95-9/98-PAN-M6	Core Performance and 80% DST Life at 40°C

Table 2. Identifiers and Series for SAFT ‘F’ Minipacks

Identifier	No. of Modules
NH-24/107-5/99-SFT-P5	2
NH-96/107-5/99-SFT-P1	7
NH-60/114-5/99-SFT-P2	5
NH-72/110-5/99-SFT-P3	6
NH-108/113-5/99-SFT-P4	9

The test plan includes core performance testing, 48-h stand test and 80% DOD DST cycling. The DST power level is 120 W/kg. After some discussions, it was decided to keep P4 cycling, while the other minipacks were dismantled. The test of P4 is still in progress. RPTs will be performed to gauge changes in minipack performance with time. The RPTs consisted of 100% C/3 discharge, 100% DOD DST discharge and peak power measurements. The RPTs were performed every 50 cycles (~1 per month) during life cycling. (Detailed data is protected battery information.)

Shin-Kobe Lithium-Ion EV Cells

Five cells were received on June 6, 2000. These cells are rated at 3.75 V and 90 Ah and are based on lithium-ion technology with manganese dioxide cathodes [3]. The test plan for these cells includes core characterization, 48-h stand test, thermal performance at 40°C (2 cells), 80%DOD DST life cycling (3 cells) and calendar life at 40°C (same cells used for thermal performance). These cells have started their life tests. RPTs will

¹ Reference [1], pp. 8-16.

be performed to gauge changes in cell performance with time. The RPTs consisted of 100% C/3 discharge, 100% DOD DST discharge and peak power measurements. The RPTs were performed every 50 cycles (~1 per month) during life cycling.

HEV Applications

Panasonic/Matsushita Test Pack

The test pack is based on Ni/MH technology and is rated at 144 V and 6.5 Ah [4]. The test plan includes state-of-charge curve measurement, C/1 capacity measurements, low- and medium-level hybrid pulse-power characterization (HPPC-L and HPPC-M)², 1 week stand test at 60% state of charge, thermal performance at 10 and 40°C, and cycle life using the normal heat engine profile³. The pack is currently performing the cycle life test with RPTs every 5,000 cycles. These RPTs consist of C/1 capacity measurement and an HPPC-M every 15,000 cycles.

Shin-Kobe HEV Cells

These cells are rated at 3.75 V and 3.6 Ah and are based on lithium-ion technology with manganese dioxide cathodes technology. The test plan includes state-of-charge curve measurement, C/1 capacity measurements, low- and medium-level hybrid pulse-power characterization (HPPC-L and HPPC-M), 1 week stand test at 60% state of charge, thermal performance at 10 and 40°C, and cycle life using the normal heat engine profile. Two cells will be characterized in terms of thermal performance at 40°C. The same cells will then undergo accelerated calendar life testing at 40°C. Three cells are currently performing the cycle life test with RPTs every 5,000 cycles. These RPTs consist of C/1 capacity measurement and an HPPC-M every 15,000 cycles.

The specific data from these tests is the subject of non-disclosure agreements with Argonne National Laboratory. Public data sheets about these batteries [3-5] are generally available from the developer.

References

- [1] USABC Battery Test Procedures Manual, Rev. 2, January 1996, DOE/ID-10479.
- [2] PNGV Battery Test Procedures Manual, Rev. 2, August 1999, DOE/ID-10597.
- [3] Lithium-ion cell data specification sheet, Shin-Kobe Electric Machinery Co., Ltd., Tokyo, Japan.
- [4] Panasonic/Matsushita Test Pack data specification sheet, Matsushita Electric Industrial Co., Ltd., Tokyo, Japan.
- [5] Press Release: Mn type Li-Ion Battery for HEV, Shin-Kobe Electric Machinery Co., Ltd., Tokyo, Japan http://www.shinkobedenki.co.jp/e/release/release00322_e.htm, published 03/00.

² Reference [2], pp.13-17.

³ Reference [2], pp.10-11.

6. INTERAGENCY WORKSHOPS ON ADVANCED BATTERY TECHNOLOGIES

A. Solid State Lithium Battery Workshop

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Objectives

- Assemble experts from industry, national laboratories, and academia to:
 - Review current research on solid state electrolytes and their interfaces in advanced batteries for EV and HEV applications emphasizing both applied and basic studies.
 - Increase knowledge of the electrochemical interfaces that occur within electrodes and at the electrode/electrolyte interfaces
 - Initiate interactions and information exchange between individuals concerned with research and those concerned with battery development.
 - Gather recommendations for improving collaboration and communication between academics and industry.

Approach

- Review current research on solid state electrolytes and their interfaces, with an emphasis on both applied and basic studies. The research includes:
 - theoretical studies of solid polymer electrolytes (SPEs),
 - lithium ion transport in SPEs, and
 - simulations of the electrolyte-cathode interface.
- Discuss experimental results on ion transport phenomena in SPEs (NMR and X-ray) and mechanical stresses on electrodes, among other topics.
- Identify problem areas and barriers to future progress in this field.
- Prepare summary of the recommendations and suggestions.

Accomplishments

- Twenty-one papers and presentations on various areas of interest generated and published.

Future Directions

- A workshop on interfaces, phenomena, and nanostructures in lithium batteries being organized December 11-13, 2000.

An Advanced Lithium Solid State Batteries Workshop was held July 13-15, 1999 in Towson,

MD. The purpose of the workshop was to assemble experts from industry, national

laboratories, and academia to review current research on solid state electrolytes and their interfaces in advanced batteries for EV and HEV applications. It emphasized both applied and basic studies, in order to increase the knowledge of the electrochemical interfaces that occur within electrodes and at the electrode/electrolyte interfaces. It included issues on improved stability of interfaces, improved conductivity, and higher transference numbers. It attempted to initiate interactions and information exchange between individuals concerned with research and those concerned with battery development; and to gather recommendations for improving collaboration and communication between academics and industry. The workshop addressed research and technology topics of electrolyte materials, interfaces, transport properties, modeling, and characterization.

Workshop Technical Synopsis

Overview

Ken Heitner, DOE, presented an overview of the technical goals established for high energy and high power batteries and polymer electrolytes [1].

Plenary Session

During the Plenary Session, Dr. Gauthier [1] described Hydro-Quebec’s (now AVESTOR’s) recent progress in developing, marketing, and eventually selling a warm, dry solid polymer electrolyte lithium battery. Performance characteristics for HQ’s modules in both EV and HEV configurations are shown in Table 1.

Session I. Modeling

This session consisted of two presentations on the modeling of polymer electrolytes in advanced batteries for EV and HEV applications. The first presentation by Dr. Newman [2] was concerned with modeling the internal pressure changes in a battery during both high power (30 second) and high energy (3 hour) discharge, where $V_{final}/V_{init} = 0.7$. Figure 1 shows that the model battery, optimized for both power and energy, utilizes very little of the available active material.

The second presentation by Dr. Halley [3] showed results of molecular dynamics (MD) simulations used to study ion pairing in lithium perchlorate in polyethylene oxide (PEO).

Table 1. Performance characteristics of AVESTOR’s modules [1]

Parameter	Value	
	EV Config	HEV Config
Energy	155 Wh/kg 220 Wh/l	50 Wh/kg
Power	315 W/kg 450 W/l	1,100 W/kg, 10s pulse, 80%DoD
Cycle Life	600 @ 80% DoD	

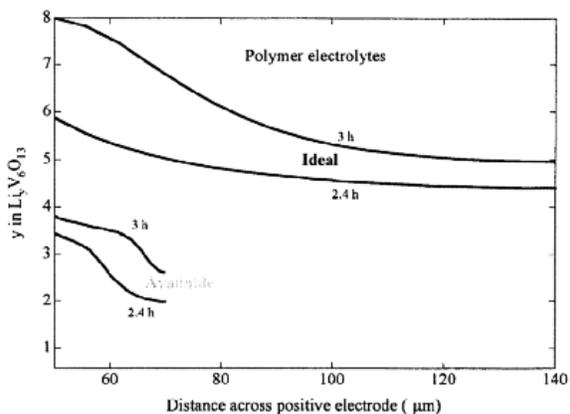


Figure 1. Active material utilization across the positive electrode for the best-available and ideal polymer electrolytes after 2.4 and 3 hours of discharge at the optimum current density.

Session II. Battery Systems/Electrolytes

The specific topics covered in this session included the performance limitations of polymer electrolytes, the performance of a new composite fumed silica/polymer electrolyte, and a discussion of the role of spontaneous density fluctuations in solid polymer electrolytes.

The first presenter in this session, Dr. Kerr [4] discussed the group’s work to develop structure-function relationships to be used to predict performance limitations and failure modes both in the bulk of the electrolyte and at the electrolyte/electrode interfaces.

The presentation by Dr. Khan [5] dealt with the development of a composite electrolyte displaying robust mechanical and conductive properties. This composite polymer electrolyte (CPE) is formed by using an inert filler, surface modified fumed silica (SiO₂), in low-molecular

weight polyethylene glycols to form gel-like electrolytes with room temperature conductivities on the order of 10^{-3} S/cm. Some features of these electrolyte systems are shown in Figure 2.

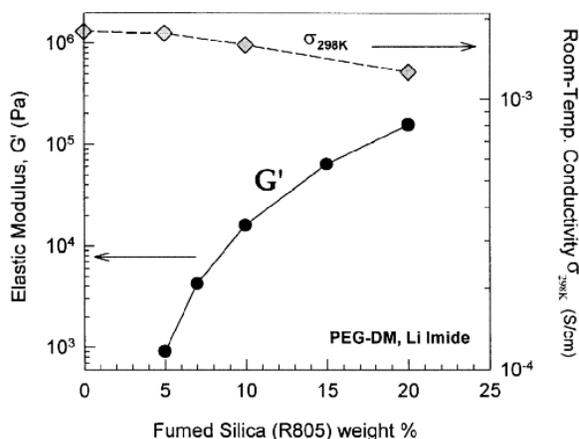


Figure 2. Effect of fumed silica content on the elastic modulus and room-temperature ionic conductivity of the composite polymer electrolyte.

Dr. Yang [6] discussed new materials being investigated to solve the two key problems of low conductivity and low lithium ion transference with polymer electrolytes by the use of anion complexing agents.

Dr. Selser [7] dealt with theoretical and experimental attempts to understand the relationship between collective motion and charge transport in solid polymer electrolytes, in particular the PEO/LiClO₄ system.

The final presentation in this session, by Dr. Dudney [8], discussed the use of Li Phosphorous Oxynitride (LIPON) as a protective layer in low energy and low power batteries.

Session III. Interfaces/SEI Characterization

The papers presented in this session of the workshop covered a range of topics, including reactivity of carbon anodes, general lithium battery interface studies, molecular dynamics simulations of battery interfaces, and mechanical stress investigations.

Dr. Nazri [1] dealt with the general issue of reactivity of carbonaceous anodes in lithium

batteries. Nazri's group has found that the use of highly crystalline graphite reduces the amount of gas generated during the first cycles. It also found that there are two classes of gaseous species generated, with distinct characteristics, and that the film forming on graphite electrodes as a result of lithium reaction with surface impurities is different in composition than the film formed due to the electrolyte decomposition. Dr. McLarnon [9] described the characterization of the solid electrolyte interface (SEI) structures in lithium polymer batteries. The results were obtained by using a new in situ optical-electrochemical cell developed at LBNL, which is based on internal-reflection-mode-Ellipsometry. Dr. Garofalini used molecular dynamics simulations [10] to study glass/cathode interface behavior. The effect of orientation on phase transportation, Li migration, and interface relation were determined. Dr. DeJonghe [1] dealt with mechanical stresses in electrodes, describing a cell configuration in which the gel/polymer electrolyte was isolated from a lithium metal anode by means of an intentionally applied surface film.

Dr. Hackney [1] discussed the use of high-resolution techniques (TEM, EELS) for the study of chemical instabilities in battery systems. These techniques, with a spatial resolution of 0.15-0.2 nm, allow the viewing of both Crystalline and amorphous regions of the electrolyte. Dr. Goldner [11] described a new physical vapor deposition process, called Ion Beam Directed Assembly (IBDA). In this process, ion beams are used together with one or more atomic/molecular beams to vacuum deposit thin films from which thin film batteries of desired composition and microstructure are formed.

The final speaker, Dr. Aurbach [12], presented a review of interactions between non-aqueous electrolyte solutions and lithium, lithiated carbons, and lithiated transition metal oxides used as cathode materials in Li batteries.

Session IV. Lithium-Ion Transport

Dr. Doeff [13] described experimental work being done to understand the transport properties of binary salt/polymer electrolytes. Dr. Denboer [14] described results of capacity secondary lithium batteries. In particular, nuclear magnetic resonance (NMR) was used to study the local

environment and dynamics of mobile Li in cathodes, anodes, and electrolytes. The final presentation in this session, by Dr. Klingler [15], described a novel electrochemical nuclear magnetic resonance method used to measure atomic concentrations as a function of distance and time from the solid electrolyte interface.

Technical Recommendations

Anode

- Improve fundamental understanding, including the issues of anode interface, Li₂O surface layer growth and passivating effects, and ion conduction across the interface, as well as fundamental calculations and modeling development coupled with experimental work.
- Continue investigation of composite anode/modified carbon materials and intermetallic compounds.
- Continue investigation of corrosion issues and adhesion research.

Electrolyte

- Continue research on
 - Composite electrolytes.
 - Gelled polymers.
 - Additives on polymer backbone.

Cathode

- Develop basic understanding of cathode SEI.
- Focus research on lower voltage cathode materials.

Programmatic Recommendations

- Participants noted a significant potential for international cooperation, in view of the large supply of talent abroad, and wished to emphasize the importance of collaborating with foreign researchers.
- The researchers noted a need to understand the key problems of developers. In particular, a means should be devised for developers to share their critical research needs with the laboratories without compromising the

need to protect proprietary information. Many researchers, both in predominantly fundamental research and in more directed areas, expressed a need for a technical issues list on which to base their investigations. In addition, the ability to factor in manufacturing and distribution costs is critical and likely requires the active involvement of both battery manufacturers and material suppliers.

- Participants noted a need for uniform samples from industrial base, to address uncertain composition, history, and manufacturing methods associated with materials.

References

- [1] Deppe, J., Heitner, K., Duong, T. Q., Maupin, P. H., and Landgrebe, A., "Advanced Lithium Solid State Battery Developments," paper No. 2000-01-1588, the 2000 Future Car Congress, Arlington, VA, April 2000.
- [2] Thomas, K. E., Sloop, S. E., Kerr, J. B., and Newman, J., "Comparison of lithium-polymer cell performance with unity and nonunity transference numbers," *Journal of Power Sources* 89 (2000) 132-136.
- [3] Halley, J. W., and Duan, Y., "Simulation of battery components and interfaces on the atomic scale: examples of what we can learn," *Journal of Power Sources* 89 (2000) 139-142.
- [4] Buriez, O., Han, Y. B., Hou, J., Kerr, J. B., Qiao, J., Sloop, S. E., Tian, M., and Wang, S., "Performance limitations of polymer electrolytes based on ethylene oxide polymers," *Journal of Power Sources* 89 (2000) 149-155.
- [5] Walls, H. J., Zhou, J., Yerian, J. A., Fedkiw, P. S., Khan, S. A., Stowe, M. K., and Baker, G. L., "Fumed silica-based composite polymer electrolytes: synthesis, rheology, and electrochemistry," *Journal of Power Sources* 89 (2000) 156-162.
- [6] McBreen, J., Lee, H. S., Yang, X. Q., and Sun, S., "New approaches to the design of polymer and liquid electrolytes for lithium

- batteries,” *Journal of Power Sources* 89 (2000) 163-167.
- [7] Walter, R., Walkenhorst, R., Smith, M., Selser, J. C., Piet, G., and Bogoslovov, R., “The role of polymer melt viscoelastic network behavior in lithium ion transport for PEO melt/LiClO₄ SPEs: the “wet gel” model,” *Journal of Power Sources* 89 (2000) 168-175.
- [8] Dudney, N. J., “Addition of a thin film inorganic solid electrolyte (Lipon) as a protective film in lithium batteries with a liquid electrolyte,” *Journal of Power Sources* 89 (2000) 176-179.
- [9] Kong, F., and McLarnon, F., “Spectroscopic ellipsometry of lithium/polymer electrolyte interfaces,” *Journal of Power Sources* 89 (2000) 180-189.
- [10] Garofalini, S. H., and Shadwell, P., “Molecular dynamics simulations of cathode/glass interface behavior: effect of orientation on phase transformation, Li migration, and interface relaxation,” *Journal of Power Sources* 89 (2000) 190-200.
- [11] Vereda, F., Clay, N., Gerouki, A., Goldner, R. B., Haas, T., and Zerigian, P., “A study of electronic shorting in IBDA-deposited Lipon films,” *Journal of Power Sources* 89 (2000) 201-205.
- [12] Aurbach, D., “Review of selected electrode-solution interactions which determine the performance of Li and Li ion batteries,” *Journal of Power Sources* 89 (2000) 206-218.
- [13] Doeff, M. M., Edman, L., Sloop, S. E., Kerr, J., and De Jonghe, L. C., “Transport properties of binary salt polymer electrolytes,” *Journal of Power Sources* 89 (2000) 227-231.
- [14] Wang, Y., Sakamoto, J., Kostov, S., Mansour, A. N., DenBoer, M. L., Greenbaum, S. G., Huang, C. K., and Surampudi, S., “Structural aspects of electrochemically lithiated SnO: nuclear magnetic resonance and X-ray absorption studies,” *Journal of Power Sources* 89 (2000) 232-236.
- [15] Gerald II, R. E., Klingler, R. J., Sandi, G., Johnson, C. S., Scanlon, L. G., and Rathke, J. W., “Li NMR study of intercalated lithium in curved carbon lattices,” *Journal of Power Sources* 89 (2000) 237-243.

APPENDIX: ABBREVIATIONS, ACRONYMS, AND INITIALISMS

ANL	Argonne National Laboratory
CPE	Composite polymer electrolyte
DOE	Department of Energy
EADL	Electrochemical Analysis and Diagnostics Laboratory (at ANL)
EC	electrochemical cell
EV	Electric Vehicle
FY	Fiscal Year
HP	High Power
HPPC	hybrid pulse-power characterization
HQ	Hydro-Quebec
LIBES	Lithium Battery Energy Storage Research Association of Japan
LIPON	Li Phosphorous Oxynitride
LMPB	Lithium Metal Polymer Battery
LPB	Lithium polymer battery
MD	molecular dynamics
NiMH	Nickel metal hydride
OAAT	Office of Advanced Automotive Technologies
OTT	Office of Transportation Technologies
PEO	polyethylene oxide
PNGV	Partnership for a New Generation of Vehicle
R&D	Research and Development
RPT	reference performance tests
SPE	solid polymer electrolytes
USABC	United States Advanced Battery Consortium
ZEV	Zero emission vehicles