The 2001 NASA Aerospace Battery Workshop

J.C. Brewer, Compiler
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

Proceedings of a workshop sponsored by the NASA Aerospace Flight Battery Systems Program and held in Huntsville, Alabama, November 27–29, 2001

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Preface

This CD contains proceedings of the 34th annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center, November 27–29, 2001. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind.

The subjects covered included lithium-ion, nickel-hydrogen, and various advanced technologies and testing techniques.
Introduction

The NASA Aerospace Battery Workshop is an annual event hosted by the Marshall Space Flight Center. The workshop is sponsored by the NASA Aerospace Flight Battery Systems Program, which is managed out of NASA Glenn Research Center and receives support in the form of overall objectives, guidelines, and funding from Code R, NASA Headquarters.

The 2001 Workshop was held on three consecutive days and was divided into five sessions, some of which carried over from one day to the next. The first session was a General Session. The second session was a Nickel-Hydrogen Session. The third and fifth sessions covered the Lithium-Ion technology. The fourth session was a focused session on Lithium-Ion Charge Control.

On a personal note, I would like to take this opportunity to thank all of the many people that contributed to the organization and production of this workshop:

The NASA Aerospace Flight Battery Systems Program, for their financial support as well as their input during the initial planning stages of the workshop;

Huntsville Hilton, for doing an outstanding job in providing an ideal setting for this workshop and for the hospitality that was shown to all who attended;

Kumar Bugga, Jet Propulsion Laboratory, for organizing and conducting this year’s focused session; Joe Stockel, National Reconnaissance Office, and George Methlie, U.S. Government, for 11th-hour solicitation of presentations for a couple of sessions.

Marshall Space Flight Center employees, for their help in registering attendees, handling the audience microphones, and flipping transparencies during the workshop.

Finally, I want to thank all of you that attended and/or prepared and delivered presentations for this workshop. You were the key to the success of this workshop.

Jeff Brewer
NASA Marshall Space Flight Center
This Table of Contents does not reflect the order in which the presentations were made at the workshop. There were several last-minute additions and changes to the agenda that created, in some sessions, a mixture of subjects being presented. This CD, however, will take all inputs and group them together according to subject matter.

**General Session**

**Battery Safety Testing Introducing the EV-ARC**
Phill O’Kane and Martyn Ottaway, Thermal Hazard Technology

**Performance of Li-S Cells Under LEO Test Regime and at Low Temperatures (to –40 °C)**
Joon Kim, Yurii Mikhaylik, and Yordan Geronov, Moltech Corporation; and Rick Kettner, Spectrum Astro

**Development Status of Three Battery Systems for the X–38 Crew Return Vehicle**
Eric Darcy, NASA Johnson Space Center

**Performance of Small, Commercial, Primary, Cylindrical, Alkaline Cells**
Sonja N. Baldwin, Andrew J. Markow, David J. Surd, and C. Richard Walk, BAE Systems

**Battery System Studies in a Virtual-Prototyping Environment**
Zhenhua Jiang, Shengyi Liu, Roger A. Dougal, Lijun Gao, John W. Weidner, and Ralph E. White, University of South Carolina

**Nickel-Hydrogen Session**

**AEA Cell-Bypass-Switch Activation: An Update**
Denney Keys, Gopalakrishna M. Rao, and David Sullivan, NASA Goddard Space Flight Center; and Harry Wannemacher, QSS Group, Inc.

**EOS-AQUA Nickel-Hydrogen Cell Life Test Update**
R. F. Tobias, TRW

**Single Pressure Vessel Life Test Update**
Jeff Dermott, Eagle-Picher Technologies, LLC

**Methods Used to Prevent Capacity Fade in Nickel-Hydrogen Batteries**
Jack N. Brill and Matt Mahan, Eagle-Picher Technologies, LLC

**Packaging Design Concepts for Use in Small Satellite Applications**
William D. Cook, Eagle-Picher Technologies, LLC

**International Space Station Nickel-Hydrogen Battery Startup and Initial Performance**
Penni Dalton, NASA Glenn Research Center; and Fred Cohen, The Boeing Company; Presented by Gyan Hajela, The Boeing Company
Lithium-Ion Session I

SAFT Li-Ion Module Design
Dr. Y. Borthomieu and JP Semerie, SAFT Defense and Space Division Specialty Battery Group

Calendar and Cycle Life Prediction of 100Ah Lithium-Ion Cells for Space Applications
Takefumi Inoue, Takeshi Sasaki, Nobutaka Imamura, Hiroaki Yoshida, and Minoru Mizutani, Japan Storage Battery Co., Ltd.; and Masayoshi Goto, Mitsubishi Electric Corporation

Thermal Modeling of Prismatic Lithium-Ion Cells
Pinakin M. Shah, Mine Safety Appliances Company; and Michael T. Nispel, Consultant

SAFT Li-Ion Cells GEO and LEO Life Test Up-Date
H. Croft and R.J. Staniewicz, SAFT Advanced Battery System Division; Y. Borthomieu and J.P. Planchat, SAFT Defense and Space Division Specialty Battery Group

Evaluation of Cycle Life and Characterization of YTP 45 Ah Li-Ion Battery for EMU
Yi Deng, Judith Jeevarajan, and Raymond Rehm, Lockheed Martin Space Operations; Bobby Bragg, NASA Johnson Space Center; and Brad Strangways, Symmetry Resources, Inc.

Lithium Ion DD Cells Space Application Cycling Update
Haiyan Croft and Bob Staniewicz, SAFT America, Inc.

Simulated LEO Cycling of AEA-STRV Lithium-Ion Battery Modules 2001 Update
Philip Johnson and Chuck Lurie, TRW; and R. Spurrett, AEA Technology

PROBA, The First ESA Spacecraft Flying Lithium-Ion
M. Schautz, D. Olsson, and G. Dudley, ESTEC; and A. Holland, AEA Technology

Focused Session – Lithium-Ion Charge Control

Life Test Results With Adaptive Charge Control
Albert H. Zimmerman and Michael V. Quinzio, The Aerospace Corporation

A Dual Mode Lithium Ion Battery Charge Controller
Steve Girard and Greg Miller, Eagle-Picher Technologies, LLC

Impact of Charge Methodology Upon the Performance of Lithium Ion Cells
M.C. Smart, B.V. Ratnakumar, L. Whitcanack, K. Chin, and S. Surampudi, Jet Propulsion Laboratory

Performance of Li-Ion Cells Under Battery Voltage Charge Control
Hari Vaidyanathan, Consultant; and Gopalakrishna M. Rao, NASA Goddard Space Flight Center
Lithium-Ion Session II

DPA of 1.6 Ah Li-Ion Pouch Cells Using Coin Cells
Enoch Wang, U.S. Government

Performance and Safety Tests on Samsung 18650 Li-Ion Cells: Two Cell Designs
Yi Deng, Judith Jeevarajan, and Raymond Rehm, Lockheed Martin Space Operations; Bobby Bragg; NASA Johnson Space Center; and Wenlin Zhang, Schlumberger Perforating and Testing

Performance and Safety Testing of Cylindrical Moli Lithium-Ion Cells
Judith A. Jeevarajan, Yi Deng, and Ray Rehm, Lockheed Martin Space Operations; Walt Tracinski, Applied Power International; and Bobby J. Bragg, NASA Johnson Space Center

Pulse Performance of Small Lithium-Ion Cells
Eric C. Darcy, NASA Johnson Space Center; and Philip R. Cowles, COM DEV Battery Group

Low Temperature and High Rate Performance of Lithium-Ion Systems for Space Applications
R. Gitzendanner, F. Puglia, and C. Marsh, Lithion, Inc.

Study of the Effects of Overdischarge on SONY 18650HC Cells
G.J. Dudley, ESA-ESTEC; and R. Spurrett, AEA Technology
2001 NASA Aerospace Battery Workshop Attendance List

Mark J. Adamson
Lockheed Martin
Lockheed Martin Comm. and Power Center
M/S 264A
100 Campus Drive
Newtown, PA 18940
Ph. (215) 497-1706 FAX (215) 497-1616
E-mail mark.j.adamson@lmco.com

Stephen C. Ballard
GS Battery USA
7576 Trade Street
Suite B
San Diego, CA 92121
Ph. (858) 547-6430 x202 FAX (858) 547-6437
E-mail stephenb@gsbattery.com

Dilipkumar N. Bhula
United Space Alliance
600 Gemini
Houston, TX 77058
Ph. (281) 282-5601 FAX (281) 282-5810
E-mail dilip.bhula@usahq.unitedspacealliance.com

Bobby J. Bragg
NASA Johnson Space Center
MS EP5
NASA Rd. 1
Houston, TX 77058
Ph. (281) 483-9060 FAX (281) 483-3096
E-mail bbragg@ems.jsc.nasa.gov

John W. Baker
Mine Safety Appliances Company
38 Loveton Circle
Sparks, MD 21152
Ph. (410) 472-7716 FAX (410) 472-7800
E-mail

L. Krista Barker
The Boeing Company
3800 Lewiston Street
Suite 100
Aurora, CO 80011
Ph. (303) 677-3950 FAX
E-mail kristab@qwest.net

Yannick Borthomieu
SAFT Advanced Batteries
BP 1039
Rue G. Leclanche
88060 Poitiers Cedex 9
France
Ph. 33-5-4955-4014 FAX 33-5-4955-4780
E-mail yannick.borthomieu@saft.alcatel.fr

Jeffrey C. Brewer
NASA Marshall Space Flight Center
ED11
Marshall Space Flight Center, AL 35812
Ph. (256) 544-3345 FAX (256) 544-5841
E-mail jeff.brewer@msfc.nasa.gov

Ratnakumar Bugga
Jet Propulsion Laboratory
MS 277-207
4800 Oak Grove Dr.
Pasadena, CA 91109
Ph. (818) 354-0110 FAX (818) 383-6951
E-mail ratnakumar.v.bugga@jpl.nasa.gov
2001 NASA Aerospace Battery Workshop Attendance List

Dwaine Coates  
Boeing  
3100 West Lomita  
MC W/231/2019  
Torrance, CA 90509  
Ph. (310) 517-5138  FAX (310) 517-7676  
E-mail dwaine.k.coates@boeing.com

William D. Cook  
Eagle-Picher Technologies, LLC  
1216 W. C Street  
Joplin, MO 64801  
Ph. (417) 623-8000  FAX (417) 623-6661  
E-mail wcook@epi-tech.com

Philip R. Cowles  
COM DEV Space Group  
155 Sheldon Drive  
Cambridge Ontario  
N1R 7H6  
Canada  
Ph. (519) 622-2300 x 2417  FAX (519) 622-5843  
E-mail philip.cowles@comdev.ca

William L. Crabtree  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-5305  FAX (256) 544-5841  
E-mail larry.crabtree@msfc.nasa.gov

Haiyan Croft  
SAFT America  
107 Beaver Court  
Cockeysville, MD 21030  
Ph. (410) 771-3200  FAX (410) 771-0234  
E-mail haiyan.croft@saftamerica.com

Karen Cunningham  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-5618  FAX  
E-mail karen.cunningham@msfc.nasa.gov

Eric C. Darcy  
NASA Johnson Space Center  
MS EP5  
Houston, TX 77058  
Ph. (281) 483-9055  FAX (281) 483-3096  
E-mail edarcy@ems.jsc.nasa.gov

Jerry W. David  
Naval Surface Warfare Center  
Commander NAVSURFWARDCENTDIV  
Attn: Jerry David, Bldg 2949  
300 Highway 361  
Crane, IN 47522-5001  
Ph. (812) 854-4193  FAX (812) 854-3589  
E-mail david_j@crane.navy.mil

Frank Davies  
Hernandez Engineering  
NASA Johnson Space Center  
EP5  
Houston, TX 77058  
Ph. (281) 483-9033  FAX  
E-mail fdavies@ems.jsc.nasa.gov

Edward E. Deason  
MEVATEC  
Consultant  
3028 Augusta Trace  
Hampton Cove, AL 35763  
Ph. (256) 536-5919  FAX  
E-mail eedpe@aol.com
2001 NASA Aerospace Battery Workshop Attendance List

Yi Deng
Lockheed Martin Space Operations
NASA - JSC
2101 NASA Road 1
EP5
Houston, TX 77058-3799
Ph. (281) 244-0985  FAX (281) 483-3096
E-mail ydeng@ems.jsc.nasa.gov

Dr. Roger A. Dougal
University of South Carolina
Dept. of Electrical Engineering
301 S. Main Street
Columbia, SC 29208
Ph. (803) 777-7890  FAX (803) 777-5594
E-mail dougal@engr.sc.edu

Ted Edge
NASA Marshall Space Flight Center
ED11
Marshall Space Flight Center, AL 35812
Ph. (256) 544-3381  FAX (256) 544-5841
E-mail ted.edge@msfc.nasa.gov

Chris Garner
U.S. Naval Research Laboratory
4555 Overlook Ave. SW
Washington, DC 20375
Ph. (202) 767-9075  FAX (202) 767-4633
E-mail garner@ssdd.nrl.navy.mil

Donald K. Georgi
Batteries Digest Newsletter
1261 Townline Road
Maple Plain, MN 55359
Ph. (612) 479-6190  FAX (612) 479-3657
E-mail teksym@aol.com

Jeffrey C. Dermott
Eagle-Picher Technologies, LLC
3220 Industrial Road
Joplin, MO 64804
Ph. (417) 623-8333 x121  FAX (417) 623-0233
E-mail jdermott@epi-tech.com

Geoffrey J. Dudley
European Space Agency
POB 299
2200 AG Noordwijk
The Netherlands
Ph. 31 71 565 3834  FAX 31 71 565 4994
E-mail geoff.dudley@esa.int

Eric Folk
Sverdrup
ED11
Marshall Space Flight Center, AL 35812
Ph. (256) 544-0140  FAX (256) 544-5841
E-mail eric.folk@msfc.nasa.gov

Pete George
NASA Marshall Space Flight Center
ED11
Marshall Space Flight Center, AL 35812
Ph. (256) 544-3331  FAX (256) 544-5841
E-mail pete.george@msfc.nasa.gov

Shirley Georgi
Batteries Digest Newsletter
1261 Townline Road
Maple Plain, MN 55359
Ph. (612) 479-6190  FAX (612) 479-3657
E-mail teksym@aol.com
Steve Girard  
Eagle-Picher Technologies, LLC  
3220 Industrial Road  
Joplin, MO 64801  
Ph. (417) 623-8333 FAX (417) 623-0233  
E-mail sgirard@epi-tech.com

Gyan Hajela  
Boeing  
6633 Canoga Avenue  
MS: LB33  
Canoga Park, CA 91303  
Ph. (818) 586-3251 FAX (818) 586-2007  
E-mail gyan.hajela@west.boeing.com

Roger P. Hollandsworth  
Lockheed Martin Missiles and Space  
Advanced Technology Division  
3251 Hanover St.  
O/L9-21 B/204  
Palo Alto, CA 94304  
Ph. (650) 424-2556 FAX (650) 354-5795  
E-mail roger.hollandsworth@lmco.com

Dr. Judith A. Jeevarajan  
Lockheed Martin Space Operations  
2101, NASA Rd 1  
Mail Stop EP5  
Houston, TX 77058  
Ph. (281) 483-4528 FAX (281) 483-3096  
E-mail jjeevara@ems.jsc.nasa.gov

Takefumi Inoue  
Japan Storage Battery Co., Ltd.  
1 Inobabacho, Nishinoshio,  
Kissoin, Minami-ku  
Kyoto, Japan 601-8520  
Ph. 81-75-312-0043 FAX 81-75-316-3052  
E-mail takefumi_inoue@gs.nippondenchi.co.jp

Leigh L. Hummer  
AZ Technology, Inc.  
7047 Old Madison Pike  
Suite 300  
Huntsville, AL 35806  
Ph. (256) 837-9877 x125 FAX (256) 837-1155  
E-mail leigh@aztechnology.com

Rob L. Gitzendanner  
Lithion - Yardney Technical Products  
82 Mechanic St.  
Pawcatuck, CT 06379  
Ph. (860) 599-1100 x474 FAX (860) 599-5122  
E-mail rgitz@lithion.com

Albert Himy  
Navy / JJMA  
4300 King Street  
Suite 400  
Alexandria, VA 22302-1503  
Ph. (703) 933-6663 FAX (703) 933-6774  
E-mail ahimy@jjma.com

Leigh L. Hummer  
AZ Technology, Inc.  
7047 Old Madison Pike  
Suite 300  
Huntsville, AL 35806  
Ph. (256) 837-9877 x125 FAX (256) 837-1155  
E-mail leigh@aztechnology.com

Nathan D. Isaacs  
Mine Safety Appliances Company  
38 Loveton Circle  
Sparks, MD 21152  
Ph. (410) 472-7700 FAX (410) 472-7800  
E-mail nedizakmsa@aol.com

Jeffrey M. Johnson  
The Boeing Company  
PO Box 3707  
M/C 19-RL  
Seattle, WA 98124-2207  
Ph. (253) 657-2981 FAX (253) 773-5974  
E-mail jeffrey.m.johnson@boeing.com
2001 NASA Aerospace Battery Workshop Attendance List

Bob Kapustka  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-3302  FAX  
E-mail bob.kapustka@msfc.nasa.gov

Daniel E. Ketchum  
Orbital Science Corp.  
21839 Atlantic Blvd.  
Dulles, VA 20166-6801  
Ph. (703) 948-8112  FAX (703) 406-3412  
E-mail ketchum.daniel@orbital.com

Rick Kettner  
Spectrum Astro  
1440 N. Fiesta Blvd.  
Gilbert, AZ 85233  
Ph. (480) 892-8200  FAX (480) 892-2949  
E-mail rick.kettner@specastro.com

Dr. Joon Kim  
Moltech Corporation  
9062 S. Rita Rd.  
Tucson, AZ 85718  
Ph. (520) 799-7643  FAX (520) 799-7501  
E-mail joon.kim@moltech.com

Tim W. Kolankowski  
Wilson Greatbatch, Ltd.  
10000 Wehrle Dr.  
Clarence, NY 14031  
Ph. (716) 759-5479  FAX (716) 759-2562  
E-mail tkolankowski@greatbatch.com

Richard D. Kramer  
Teledyne Solutions, Inc.  
5000 Bradford Dr.  
Suite 200  
Huntsville, AL 35805  
Ph. (256) 726-3571  FAX (256) 726-3865  
E-mail doug.kramer@tdytsi.com

Paul W. Krehl  
Wilson Greatbatch, Ltd.  
10000 Wehrle Dr.  
Clarence, NY 14031  
Ph. (716) 759-5293  FAX (716) 759-5220  
E-mail pkrehl@greatbatch.com

Dr. Harlan L. Lewis  
NAVSEA Crane  
300 Highway 361  
Code 6095, B3287  
Crane, IN 47522-5001  
Ph. (812) 854-4104  FAX (812) 854-1212  
E-mail lewis_h@crane.navy.mil

David Lizius  
COM DEV Space Group  
155 Sheldon Drive  
Cambridge Ontario  
CANADA  
Ph. (519) 622-2300 x2844  FAX (519) 622-1691  
E-mail david.lizius@comdev.ca

Eric Lowery  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-0080  FAX (256) 544-5841  
E-mail eric.lowery@msfc.nasa.gov
2001 NASA Aerospace Battery Workshop Attendance List

Steve Luna  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-3402 FAX (256) 544-5841  
E-mail steve.luna@msfc.nasa.gov

Matt Mahan  
Eagle-Picher Technologies, LLC  
1216 West C Street  
Joplin, MO 64801  
Ph. (417) 623-8000 x543 FAX (417) 623-6661  
E-mail mmahan@epi-tech.com

Michelle A. Manzo  
NASA Glenn Research Center  
MS 309-1  
21000 Brookpark Rd.  
Cleveland, OH 44135  
Ph. (216) 433-5261 FAX (216) 433-6160  
E-mail michelle.manzo@grc.nasa.gov

Dr. Catherine Marsh  
U.S. Government  
1570 Dunterry Place  
McLean, VA 22101  
Ph. (703) 847-6428 FAX  
E-mail cmarshal@starpower.net

Jeff Martin  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256)544-4217 FAX  
E-mail jeff.martin@msfc.nasa.gov

Stephen L. Martins  
COM DEV  
155 Sheldon Dr.  
Cambridge, Ontario  
N1R 7H6  
Ph. (519) 622-2300 x2449 FAX (519) 622-1691  
E-mail stephen.martins@comdev.ca

Dean W. Maurer  
Loral Skynet  
POB 7018  
Bedminster, NJ 07921  
Ph. (908) 470-2310 FAX (908) 470-2457  
E-mail dwm@loralskynet.com

Roger L. May  
SAFT America  
107 Beaver Court  
Cockeysville, MD 21030  
Ph. (410) 771-3200 FAX (410) 771-0234  
E-mail roger.may@saftamerica.com

Barbara I. McKissock  
NASA Glenn Research Center  
MS 301-3  
21000 Brookpark Road  
Cleveland, OH 44135  
Ph. (216) 433-6102 FAX (216) 433-6133  
E-mail bmckissock@grc.nasa.gov

William J. McMahan  
U.S. Army AMCOM  
AMSAM-RD-MG-NC  
Redstone Arsenal, AL 35898  
Ph. (256) 876-7626 FAX (256) 842-9476  
E-mail bill.mcmahan@rdec.redstone.army.mil
2001 NASA Aerospace Battery Workshop Attendance List

George Methlie
2120 Natahoia Ct.
Falls Church, VA 22043
Ph. (703) 533-1499  FAX (703) 533-2472
E-mail pkaren@starpower.net

Martin Milden
2212 So. Beverwil Dr.
Los Angeles, CA 90034-1034
Ph. (310) 836-7794  FAX (310) 836-4494
E-mail mmilden@mediaone.net

Tim J. Nelson
Symmetry Resources, Inc.
POB 785
108 Cullman Rd.
Arab, AL 35016
Ph. (256) 586-8911  FAX (256) 586-9443
E-mail t_nelson@otelco.net

Michael T. Nispel
12 Pine Road
Malvern, PA 19355
Ph. (610) 725-9549  FAX (215) 619-7899
E-mail mnispel@msn.com

David O'Dell
NASA Marshall Space Flight Center
ED11
Marshall Space Flight Center, AL 35812
Ph. (256) 544-3416  FAX
E-mail david.odell@msfc.nasa.gov

Phill O'Kane
Thermal Hazard Technology
1 North House
Bond Avenue
Bletchley MK1 1SW
England
Ph. 44 1908 646800  FAX 44 1908 645209
E-mail phill.okane@science.org.uk

Dr. Ben Oni
Tuskegee University
Department of Electrical Engineering
Tuskegee, AL 36088
Ph. (334) 727-8990  FAX (334) 724-4806
E-mail oni@tusk.edu

Rex Oswald
Boeing
POB 2999
3100 W. Lomita
Torrance, CA 90509-2999
Ph. (310) 517-7651  FAX (310) 517-7676
E-mail walter.r.oswald@boeing.com

Gopal Rao
NASA Goddard Space Flight Center
Code 563
Greenbelt, MD 20771
Ph. (301) 286-6654  FAX (301) 286-1751
E-mail grao@pop700.gsfc.nasa.gov

Raymond B. Rehm
Lockheed Martin Space Operations
2101 NASA Rd 1
M/S EP5
Houston, TX 77058
Ph. (281) 483-9214  FAX (281) 483-3096
E-mail rrehm@ems.jsc.nasa.gov
2001 NASA Aerospace Battery Workshop Attendance List

Paul Replogle  
United Space Alliance  
8550 Astronaut Blvd.  
Cape Canaveral, FL 32920-4304  
Ph. (321) 867-7872  FAX (321) 867-9829  
E-mail reploglep@usasrb.ksc.nasa.gov

Ronald S. Repplinger  
Eagle-Picher Technologies, LLC  
1216 West C Street  
Joplin, MO 64801  
Ph. (417) 623-8000  FAX (417) 623-6661  
E-mail repplinger@epi-tech.com

Dr. Pinakin M. Shah  
Mine Safety Appliances Company  
38 Loveton Circle  
Sparks, MD 21152  
Ph. (410) 472-7720  FAX (410) 472-7800  
E-mail pinakins@aol.com

Robert Siegler  
Wilson Greatbatch, Ltd.  
10000 Wehrle Dr.  
Clarence, NY 14031  
Ph. (716) 759-5275  FAX (716) 759-5220  
E-mail rsiegler@greatbatch.com

Robert Spotnitz  
Battery Design Co.  
2277 DeLucchi Drive  
Pleasanton, CA 94588  
Ph. (925) 895-4080  FAX  
E-mail rspotnitz@batdesign.com

Rob Spurrett  
AEA Technology  
Culham Science Centre  
Abingdon Oxon  
OX14 3ED  
Oxfordshire England  
Ph. 44 1235 46 4367  FAX 44 1235 46 3285  
E-mail rob.spurrett@aeat.co.uk

Brian J. Stein  
Mine Safety Appliances Company  
38 Loveton Circle  
Sparks, MD 21152  
Ph. (410) 472-7713  FAX (410) 472-7800  
E-mail bjsteinmsa@aol.com

Joe Stockel  
National Reconnaissance Office  
14675 Lee Rd.  
Chantilly, VA 20151  
Ph. (703) 808-4088  FAX (703) 808-4931  
E-mail joestk@ucia.gov

Robert F. Tobias  
TRW  
MS R4/1074  
One Space Park  
Redondo Beach, CA 90278  
Ph. (310) 813-5784  FAX  
E-mail bob.tobias@trw.com

Cynthia Tolliver  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-8590  FAX  
E-mail cynthia.tolliver@msfc.nasa.gov
2001 NASA Aerospace Battery Workshop Attendance List

Greta Tracinski  
Applied Power International  
1236 N. Columbus Ave., #41  
Glendale, CA 91202-1672  
Ph. (818) 243-3127  
FAX  
E-mail gtracinski@earthlink.net

Walter A. Tracinski  
Applied Power International  
1236 N. Columbus Ave., #41  
Glendale, CA 91202-1672  
Ph. (818) 243-3127  
FAX  
E-mail watracinski@earthlink.net

Dr. Hari Vaidyanathan  
10905 Silent Wood Place  
Gaithersburg, MD 20878  
Ph.  
FAX  
E-mail hari_vaidyanathan@hotmail.com

Charles R. Walk  
BAE Systems  
The Battery Technology Center  
1601 Research Blvd.  
Rockville, MD 20850  
Ph. (301) 838-6220  
FAX (301) 838-6222  
E-mail charles.walk@baesystems.com

Enoch I. Wang  
U.S. Government  
4051 Summer Hollow Court  
Chantilly, VA 20151  
Ph. (703) 874-1726  
FAX  
E-mail enoch_wang@yahoo.com

Harry E. Wannemacher  
QSS Group, Inc.  
3502 Moylan Dr.  
Bowie, MD 20715  
Ph. (301) 286-7551  
FAX (301) 286-1739  
E-mail harrywannemacher@juno.com

Tom Whitt  
NASA Marshall Space Flight Center  
ED11  
Marshall Space Flight Center, AL 35812  
Ph. (256) 544-3313  
FAX (256) 544-5841  
E-mail tom.whitt@msfc.nasa.gov

Sharon L. Wilson  
Naval Surface Warfare Center, Crane Division  
Crane, IN 47522  
Ph. (812) 854-4220  
FAX (812) 854-3589  
E-mail wilson_s@crane.navy.mil

Albert H. Zimmerman  
The Aerospace Corporation  
MS M2/275  
POB 92957  
Los Angeles, CA 90009-2957  
Ph. (310) 336-7415  
FAX (310) 336-6801  
E-mail albert.h.zimmerman@aero.org
# The 2001 NASA Aerospace Battery Workshop

## Authors
J.C. Brewer, Compiler

## Performing Organization
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

## Sponsoring/monitoring Agency
National Aeronautics and Space Administration
Washington, DC 20546–0001

## Abstract
This document contains the proceedings of the 34th annual NASA Aerospace Battery Workshop, hosted by the Marshall Space Flight Center, November 27–29, 2001. The workshop was attended by scientists and engineers from various agencies of the U.S. Government, aerospace contractors, and battery manufacturers, as well as international participation in like kind.

The subjects covered included nickel-hydrogen, nickel-cadmium, lithium-ion, and silver-zinc technologies.
AEA Cell-Bypass-Switch Activation: An Update

2001 NASA Aerospace Battery Workshop

Denney Keys
Gopalakrishna M. Rao
David Sullivan
Harry Wannemacher*

NASA GODDARD SPACE FLIGHT CENTER
*QSS GROUP, INC
Objectives

• Verify the Performance of AEA Cell Bypass Protection Device (CBPD) under simulated EOS-Aqua/Aura flight hardware configuration

• Assess the Safety of the hardware under an inadvertent firing of CBPD switch, as well as the closing of CBPD switch under simulated high cell impedance

• Confirm that the mode of operation of CBPD switch is the formation of a continuous low impedance path (a homogeneous low melting point alloy)
BACKGROUND
EOS-Aqua Flight Hardware

• Battery Cell:
  – Eagle-Picher 160 Ah NiH$_2$ (RNH 160-3)
  – Size:  ~ 12cm Diameter
    ~ 32cm overall Height
  – Weight:  ~ 4.3kg

• Cell-Bypass-Switch:
  – AEA Technology
    Cell Bypass Protection Device (CBPD)
NOTE: Tested devices have 6 series diodes in charge path (not 4 as shown)
AEA Cell-Bypass-Switch Spec

TRW spec for Aqua

90 grams

Icharg ≤ 75A

R ~ 500 microOhms

CBPD - Specification

- 75 grams
- Icharg < 35A
- I discharge < 235A
- Triggering - see operation summary
- R ~ 200 microOhms
- I operation < 400A - dependent on leads and mounting
Previously performed tests using AEA Engineering Model and Flight CBPDs, and demonstrated nominal performance under flight hardware configuration in laboratory atmosphere.

There was no evidence of cell rupture or excessive heat production during or after CBPD switch activation under simulated high cell impedance (open-circuit cell failure mode).

When current was not limited (low-impedance short), none of four switches tested provided continuous electrical contact.

With simulated high cell impedance (open-circuit cell failure mode), continuous electrical contact was achieved. X-ray analysis confirmed the observation, but upon disassembly, there was no fusion between the two alloy halves.
Switch Disassembled
(CBPD F029 - Charge side)

- Note contact area where switch halves separated easily
• Failure to provide fused contact between the two alloy halves may be due to an oxide layer on the surface(s) of the solid or molten alloy

• Because in-orbit switch closure would occur in vacuum, additional tests were performed under vacuum to confirm proper switch operation
STUDIES IN VACUUM
Tests Performed in Vacuum

• Test#1:  Flight CBPD F029 (Unused discharge half)  
  (charge side was cut off for DPA)   
  Activated through discharge diodes   
  Switch-axis Horizontal (launch orientation)

• Test #2:  Flight CBPD F030  
  (previously tested and failed to provide continuous contact)  
  Activated through charge diodes  
  Switch-axis Horizontal (launch orientation)

• Test#3:  Engineering Model CBPD EM05  
  (completely untested)  
  Activated through charge diodes  
  Switch-axis Horizontal (launch orientation)
Test#1 Vacuum test setup  
(switch activated by installing turn-on jumper)

AEA CBPD  
(Discharge side)

EPI NiH₂ Cell

R ≈ 0.08 mΩ  
(4.3 inches of #2 awg wire + terminals)

R ≈ 0.17 mΩ  
(11 inches of #2 awg wire + terminals)

R ≈ 25 mΩ  
(chamber pass-thru)  
(added to limit current)

"Turn-on Jumper"

V

2001 NASA Aerospace Battery Workshop
Test #1 Data (CBPD F029)

Graph showing:
- Cell Voltage
- Switch Current
- Switch Voltage
- Switch Temp (+)
- Switch Temp (-)

Y-axis: Voltage (V)
X-axis: Elapsed Time (seconds)

Data points at:
- Elapsed Time: 0, 500, 1000, 1500, 2000, 2500
- Voltage: -0.2, 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4

Temperature range from -40 to 140 °C.
AEA Cell-Bypass Switch Activation: An Update

Test#2 & 3 Vacuum test setup
(switch activated by 10 amps through charge diodes)

![Diagram of test setup]

- **AEA Cell-Bypass Diode (CBPD)**
- **EPI NiH₂ Cell**
- **10A**
- **Turn-on Jumper**
- Resistance values:
  - $R \approx 0.08 \text{m}\Omega$ (4.3 inches of #2 awg wire + terminals)
  - $R \approx 0.17 \text{m}\Omega$ (11 inches of #2 awg wire + terminals)
  - $R \approx 25 \text{m}\Omega$ (added to limit current)

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Test #2 Data (CBPD F030)
AEA Cell-Bypass Switch Activation: An Update

Testing Continues

Will this @#$% test never end...
Test #3 Data (CBPD EM05)

- Cell Voltage
- Switch Current
- Switch Temp (+)
- Switch Temp (-)
- Switch Voltage

Elapsed Time (seconds)

0  500  1000  1500  2000  2500  3000  3500

Current (A) / Temperature (°C)
Fein Focus X-ray (CBPD EM05)
Fused alloy (CBPD EM05)

Microscopic

Side view

Top view

X-Ray
<table>
<thead>
<tr>
<th>Test #</th>
<th>CBPD #</th>
<th>Result</th>
</tr>
</thead>
</table>
| 1     | F029 (discharge) | - Switch fully closed after intermittent start  
- Retest after cool-down showed intermittent contact  
- Switch resistance during test and after cool-down = 1.5 milliohms |
|       | Charge side of this switch was previously activated, and removed for DPA |
| 2     | F030     | - Switch fully closed for this test under vacuum  
- Retest after cool-down showed stable contact  
- Switch resistance during test and after cool-down = 1.8 milliohms |
|       | Previously activated at atmosphere, and failed to provide continuous contact |
| 3     | EM05     | - Switch fully closed  
- Switch resistance during test and after cool-down = 0.16 milliohms  
- X-ray shows solid contact  
- Microscopic view shows fused alloy |
|       | Untested engineering model |
Conclusions

• The nominal performance of AEA CBPD under flight operating conditions (vacuum except zero-G, and high-impedance cell) has been demonstrated

• There is no evidence of cell rupture or excessive heat production during or after CBPD switch activation under simulated high cell impedance (open-circuit cell failure mode)

• The formation of a continuous low impedance path (a homogeneous low melting point alloy) has been confirmed
Acknowledgements

• Mr. Bill Moulford, AEA Technology
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• Mr. Bruno Munoz, GSFC
• Mr. Thomas Rozanski, GSFC
EOS-AQUA Nickel-Hydrogen Cell
Life Test Update

R. F. Tobias
TRW Space And Electronics Group
Redondo Beach, California

The 2001 NASA Aerospace Battery Workshop
The Huntsville Hilton
Huntsville, Alabama
November 27-29, 2001
Presentation outline

• EOS-AQUA Overview
• Electrical Power System
• Cell Design
• Experimental Setup
• Test Results
• Summary
• Objective- To provide cloud, precipitation, sea surface temperature, terrestrial and oceanic productivity and atmospheric temperature data for Global Modeling

• Launch on a Delta II MELV in March 2002

• Polar, sun synchronous, 705 km orbit with the 1:30 PM nodal crossing

• Spacecraft weight is approximately, 2,933 Kg

• Six year mission
• AIRS (Atmospheric Infrared Sounder) - Measures visible and infrared bands simultaneously over 2,300 spectral channels

• AMSR-E (Advanced Microwave Scanning Radiometer) - Measures the earth’s microwave radiation in 6 bands

• AMSU-A (Advanced Microwave Sounding Unit) - Measures earth’s microwave radiation over 20 channels

• HSB (Humidity Sounder for Brazil) - Measures microwaves over 4 channels

• CERES (Cloud and Earth’s Radiant Energy System) - Two units measure radiation at all wavelengths

• MODIS (Moderate-Resolution Imaging Spectroradiometer) - Measures visible and infrared radiation in 36 spectral bands
Overall Dimensions
(Stowed)
X= 255.9 in.
Y= 98.1 in.
Z= 105.9 in.

Overall Dimensions
(Deployed)
X= 316.7 in.
Y= 657.8 in.
Z= 164.4 in. (Bus)
Z= 190.1 in. (S/A)
Payload External Features
• EPS via software provides power management, load shedding control, and battery management
• Electrical power is provided by the solar array and flight battery modules on orbit and a flight battery or ground power during prelaunch preparations
• Spacecraft power is nominally 22.0 - 38.6 Vdc
• Circuit protection is provided by fusing, battery clamping overvoltage protection, bonding and grounding, and EMC controls
• Battery consists of 24 series-wired 160 Ah NiH2 cells contained in two-12 cell modules
  – Rate of charge is automatically controlled by charge determination and depth-of-discharge control software
Cell Design

- **Configuration**
  - Stack: Single
  - Electrode arrangement: Back-to-Back
  - Bussing: “Pineapple shape”
- **Internal coating**
  - Zirconium oxide wall wick with catalyzed wall stripes
- **Terminals**
  - Seals: Ziegler nylon compression
  - Placement: Rabbit ears
- **Negative Electrodes**
  - Number: 64
  - Substrate: Electro etched nickel foil
  - Pt Loading: 8 mg/cm²
Cell Design (con’t)

- **Positive Electrodes**
  - Number: 64
  - Plaque: Slurry
  - Thickness: 0.030 inch
  - Porosity: 80 %
  - Impregnation: Aqueous electrochemical
  - Active Material Loading: 1.65 g/cc void

- **Separator**
  - Type: Zircar
  - Layers: Two

- **Electrolyte**
  - Type: KOH
  - Concentration: 31 %
  - Precharge: Nickel
Cell / Sleeve Arrangement
Bottom View of Cell Pack
Cell Packs

TRW
Experimental Design

- Test consists of two 6-cell packs
- Configuration designed to simulate conductive thermal design of the spacecraft battery
- Cells mounted in aluminum sleeves and placed on a mounting platform which contains cooling coils to control temperature
- Entire assembly is located in an insulated chamber
Experimental Conditions

• Real Time LEO Condition
• Total orbit time: 94.6 minutes
• Depth-of-discharge: 25 % nominal
• Constant power discharge: 550 watts for 34.8 minutes
• Charge to a given RR:
  – Initial current Approximately 45 amps
  – Taper current To 32 amps
  – Trickle current 1.6 amps for 2 minutes minimum
# Cell Capacity Comparison

(Nameplate Capacity = 160 Ah)

<table>
<thead>
<tr>
<th>Temp</th>
<th>TRW ATP</th>
<th>Eagle-Picher ATP</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Deg C</td>
<td>162.6</td>
<td>146.9</td>
</tr>
<tr>
<td>10 Deg C</td>
<td>184.0</td>
<td>186.7</td>
</tr>
<tr>
<td>0 Deg C</td>
<td>202.8</td>
<td>186.9</td>
</tr>
</tbody>
</table>
EOS-Aqua Life Test
Current-Voltage-Temperature Profile

Time (Minutes)

Current (Amps)

Pack Voltage (Volts)

Sleeve Top Temp (Deg C)

Current
Pack Voltage
Sleeve Top Temp

0 20 40 60 80 100 120 140

-100 -80 -60 -40 -20 0 20 40 60 80 100

2 4 6 8 10

2 3 4 5 6 7 8 9 10
Test Anomalies

- Temperature control problems were the major cause of the test anomalies - old equipment which required constant vigilance
- Software and hardware problems during initial startup
- Electrical problems - Several times the power in the building was turned off for facilities repair
EOS-Aqua Life Test
Discharge Voltage vs. Cycle

Voltage (Pack)

End of Discharge

Midpoint

Cycle Number

0 5000 10000 15000 20000
EOS-Aqua Life Test
Recharge Ratio & Pack Voltage vs. Cycle
<table>
<thead>
<tr>
<th>Cycle</th>
<th>EOC Dispersion</th>
<th>EOD Dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>3 mv</td>
<td>3 mv</td>
</tr>
<tr>
<td>3000</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>6000</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>9000</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>10250</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>11450</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>14500</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>17850</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>
Summary

• As of 10/31/01 the cells have successfully completed over 17,900 LEO cycles at 25 % DOD
  – EODV is over 1.230 volts - well above the end of life requirement of 1.100 volts
• Pressure and end of discharge voltage decreased initially but stabilized after the RR was increased from 1.04 to 1.06.
• After approximately 10,000 cycles an increase in pressure with cycling has been observed
• End of charge voltage increasing slightly with cycles
• Voltage dispersion is minimal
Single Pressure Vessel Life Test Update

Jeff Dermott
Eagle-Picher Technologies, LLC
Joplin, Missouri
NiH$_2$ Life Testing at EPT was originally started to support early flight programs.

Test bed has been expanded over past 20 years to include new designs.

Single Pressure Vessel (SPV) represents a significant change battery design.

SPV life testing was required to prove reliability of the design.
SPV battery combines 22 cells into one vessel.

Two transducers used for pressure monitoring.

Typical 50AH SPV Characteristics

- Length = 24.7 inches
- Weight = 30.4 kg
- Diameter = 10.1 inches
- Specific Energy = 54.6 Wh/kg
- Energy Density = 59.3 Wh/L
SPV cells have stack design similar to IPV cells.

Major difference is the Electrolyte Containment System (ECS).

The ECS consist of 2 sealed plastic bags with gas vents.

SPV cells share H₂ gas.
Three batteries have been subjected to Life Testing.

Two of these are still on test at EPT. They are identified as RL-2(S162) and RL-3(S262).

Both of these batteries were built by EPT at the Range Line Facility and they represent the current SPV technology.
# SPV LIFE TEST SUMMARY

<table>
<thead>
<tr>
<th>Battery</th>
<th>RL-2(S162)</th>
<th>RL-3(S262)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nameplate Capacity</td>
<td>50 AH</td>
<td>60 AH</td>
</tr>
<tr>
<td>No. of Cells</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Test Temperature</td>
<td>-5°C</td>
<td>+5°C</td>
</tr>
<tr>
<td>Test Start Date</td>
<td>6/3/96</td>
<td>1/28/97</td>
</tr>
<tr>
<td>No. of Cycles</td>
<td>27,723</td>
<td>24,705</td>
</tr>
<tr>
<td>DOD</td>
<td>30%</td>
<td>25%</td>
</tr>
<tr>
<td>EODV</td>
<td>26.861V</td>
<td>27.717V</td>
</tr>
<tr>
<td>EOCV</td>
<td>34.558V</td>
<td>33.949V</td>
</tr>
<tr>
<td>Battery</td>
<td>RL-2(S162)</td>
<td>RL-3(S262)</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Cycle Duration</td>
<td>100 minutes</td>
<td>100 minutes</td>
</tr>
<tr>
<td>Nominal Charge Rate</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Nom. Discharge Rate</td>
<td>21 amps</td>
<td>21 amps</td>
</tr>
<tr>
<td>Max. Discharge Rate</td>
<td>42 amps</td>
<td>42 amps</td>
</tr>
<tr>
<td>Recharge Ratio</td>
<td>1.02</td>
<td>1.02</td>
</tr>
</tbody>
</table>

- Exact cycle conditions are proprietary.
- Each cycle contains two discharges.
- Charge is controlled based on pressure.
RL-2 TREND DATA

- Cycle Number
- Battery Voltage
- Battery Pressure (psig)

Legend:
- EODV
- EOCV
- EODP
- EOCP
Based on current EPT IPV life test data cells cycling at 25-30% DOD should survive at least 75,000 cycles.

Trend data indicates RL-2 EODV will be at 25.453V (1.157V/cell) when it reaches 75,000 cycles.

Trend data indicates RL-3 EODV will be at 27.188V (1.235V/cell) when it reaches 75,000 cycles.

Neither battery is showing any significant pressure trends at this time.
CONCLUSIONS

- Both batteries are showing stable performance under the current cycle regime.
- EODV trends indicate the batteries will meet performance levels of IPV’s at similar DOD.
Chris Guilfoyle: Eagle-Picher Technologies, LLC

Kevin Gray: Eagle-Picher Technologies, LLC
Methods Used To Prevent Capacity Fade In Nickel Hydrogen Batteries

Jack N. Brill and Matt Mahan
Eagle-Picher Technologies LLC
Background

- For some time it has been known that storage of cells with an internal hydrogen pressure can lead to capacity fade.

- Cells stored for periods of 8 years or more have shown normal performance when the nickel precharge is maintained.

- Other cells stored for less time have exhibited capacity loss.

- The loss in capacity is attributed to loss of precharge.
Precharge Loss

- The loss of cell precharge can occur for various reasons.
  - Extended trickle charge.
  - Repeated overcharge of cells during integration and testing.
  - Allowing cells to stand in a partial charge condition for extended periods followed by overcharge.
Capacity Loss

- The capacity loss typically is a result of a second voltage plateau developing.

- A portion of the capacity is unusable since the cell terminal voltage is less than 1.00 volt.

- Normally the total capacity of the cell is the same.
Capacity Loss (Cont’d)

- Typical cell discharge with a second voltage plateau.
• Typical battery discharge with a cell having a second voltage plateau.
Capacity Loss (Cont’d)

• Capacity losses may occur as a result of:

  ❖ Discharge and storage after extended open circuit period in a charged condition.

  ❖ Storage after discharge without a resistor drain.

  ❖ Open circuit storage of cells after precharge is lost.

  ❖ Warmer storage temperatures increase rate of capacity loss.

• If returned to inactive storage without the proper precautions or maintenance, loss of useable capacity can occur.
Methods

- Two methods are used to assess the precharge in nickel hydrogen cells.
  - Cells can be evaluated and stored independently.
  - Cells grouped within a battery need to be evaluated and stored alike due to the configuration.
Method 1- Individual Cells

• Allows individual verification of cell precharge.

• Decisions as to storage can be made collectively or as a single group.

• Method involves:
  ♦ Discharging the cells from full charge to 0.9 volt at a C/2 rate.
  ♦ Discharging the cells at a C/100 rate to a voltage of –1.20 volts.
  ♦ Charging the cells at a C/100 rate to a voltage of 0.7 volt.
Individual Cells (Cont’d)

- Typical C/2 capacity discharge
Individual Cells (Cont’d)

• Typical nickel precharge
Individual Cells (Cont’d)

- Typical hydrogen precharge
Individual Cells (Cont’d)

- Typical nickel precharge at low rate charge
Individual Cells (Cont’d)

- Typical hydrogen precharge at low rate charge

![Graph showing voltage over time with S/N 20 and S/N 23 lines, rate = C/100]
Cells Assembled in a Battery

- Batteries, when let down, often terminate discharge with the first or second cell leaving hydrogen pressure in the remaining cells.

- Batteries during integration and testing are often allowed to remain for extended periods at open circuit conditions in a charged or partial charged state.

- Storage under these conditions is conducive to development of a second voltage plateau.

- Capacity loss (fade) occurs due to the second voltage plateau.
Method 2 - Batteries

- Evaluates cells within a battery pack.

- A decision may be made that allows proper storage of batteries for the precharge found.

- Method involves:
  - Discharging the fully charged battery at a C/2 rate until the first cell reaches 0.500 volt.
  - Resistor draining each cell to 0.100 volt.
  - Discharging the battery at a C/20 rate for 5 minutes (reverses cells).
  - Placing the battery at open circuit and observing the voltage recovery.
Batteries (Cont’d)

- Typical nickel precharge voltage
Batteries (Cont’d)

- **Typical hydrogen precharge**

![Graph showing typical hydrogen precharge with time in minutes on the x-axis and terminal voltage in volts on the y-axis. The graph shows a decrease in voltage over time, with values ranging from -0.6 to 0 volts.](image-url)
Storage

• The precharge in the cell dictates the method of storage.

• Nickel (positive) precharge:
  ❖ Storage is best at low temperature.
  ❖ Cells should be fully discharged.
  ❖ Either open circuit or active storage can be used.

• Hydrogen (negative) precharge:
  ❖ An active storage plan must be implemented.
  ❖ Storage is best at low temperature.
  ❖ Cells must be at least partially charged.
  ❖ A low rate at constant potential should be placed across the cell to prevent self discharge.
Summary

• When storing cells or batteries, the precharge should be determined prior to storage.
  - Positive precharge – fully discharged, open circuit, cold.
  - Hydrogen precharge – active mode, constant potential, cold.

• Positive precharge is preferred to prevent capacity fade during ground storage or integration.
Packaging Design Concepts for Use in Small Satellite Applications

William D. Cook
Eagle-Picher Technologies LLC
Background

- Small Satellite Battery Usage Has Progressed From the Early 1990’s to Become a Dominant Factor in the Aerospace Industry
- To Date Sixty-Five Small Satellites Have Been Launched
- The Industry Has Demanded the Same Level of Reliable Performance from the Small Batteries As Needed with the Larger Battery Designs.
- Initial Design Concepts Were Small and Cheap.
Wide Variety of Battery Designs

- 4AH to 23AH
- Layout
  - Horizontal Design
  - Coffee Can Design
  - Banded Design
  - Split Design
- Options
  - Cell Bypass
  - Heaters
  - Temperature Monitors
  - Cell Monitoring
  - Strain Gage / Amplification
Battery Launches

Battery Launches

AH

QTY SHIPPED

0 4 6 7 10 12 16 20 23
6 AH Battery Design

10 CPV’s
6AH
Two SG
One Heater
Horiz Mount
Horizontal Mount Sleeve Design
Horizontal Mount Battery Designs
Vertical Mount (Coffee Can) Battery Design

11 CPV’S and 1 IPV
Two SG/Amp
Thermistor
Vertical Cell Design
Vertical Mounted Battery Designs
Unique Battery Mounting Designs

10 CPV’S
10 AH Design
Unique Battery Designs
Packaging Ratio %

Battery AH

Packaging Ratio
Energy Density Wh/In³

![Energy Density vs Battery Weight Graph]

- The x-axis represents Battery Weight ranging from 4 to 23.
- The y-axis represents Energy Density ranging from 0 to 0.7.
- The graph shows a peak at around Battery Weight 16, with a significant increase in energy density compared to other weights.
- There is a notable decrease in energy density after the peak.

The graph indicates that energy density is highest when the battery weight is around 16.
Battery Design / Selection

- Determine AH Capacity
- Establish an Envelope to Determine Basic Battery Layout
- Thermal Requirements to Determine Sleeve and Heater Design
- Strain Gage Requirements to Monitor Cell Capacity
- Thermistor Requirements to Monitor Temperature
- Heater Control (Internal or External Control)
- Max EOC and Min EOD to Determine Number of Cells
Summary

- Small NiH$_2$ Batteries Have Established Themselves in Satellites for the Aerospace Market
- Packaging Ratio Averages 1.34% of Cell Mass
- Specific Energy Averages 13.23Wh/lb
- Energy Density Averages .36 Wh/in$^3$
- Battery Designs Using Horizontal Mounting Exhibit Better Thermal Heat Transfer Than Those Using Vertical Mounting
International Space Station Nickel-Hydrogen Battery Start-Up and Initial Performance

2001 NASA Aerospace Battery Workshop

November 28, 2001

Presented by Gyan Hajela/The Boeing Company

Penni Dalton / NASA GRC
Fred Cohen / The Boeing Company
Battery Orbital Replacement Unit (ORU) was designed to meet the following requirements:

- 6.5-year design life
- 38,000 charge/discharge Low Earth Orbit cycles
- 81-Amp-hr nameplate capacity
  - Maximum reference Depth of discharge (DOD) less than 35%
- 4 kWh Nominal storage capacity
- Contingency orbit capability
  - One additional orbit at reduced power after a 35% DOD without recharge
  - Maximum of two times per year
- Operating Temperature
  - 5 +/-5 C Standard orbit
  - 5+5/-10 C Contingency orbit
- Non-operating Temperature
  - -25 to +30 C
- 5-year Mean Time Between Failure
- On-orbit replacement using ISS robotic interface
- One launch to orbit and one return to ground
ISS Battery Subassembly Orbital Replacement Unit

- 81 ampere-hour-4 kilowatt hour capacity
- 6.5 Year Life
- 38,000 orbit cycles
## Reference Orbit Design Parameters For Battery ORU

### CONTINUOUS POWER REQUIREMENTS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time (min)</th>
<th>Energy (Watt-hrs)</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td></td>
</tr>
<tr>
<td>Constant Power Charge</td>
<td>0.0</td>
<td>43.9</td>
<td>1995*</td>
</tr>
<tr>
<td>Taper Charge</td>
<td>43.9</td>
<td>57.0</td>
<td></td>
</tr>
<tr>
<td>Total Charge</td>
<td></td>
<td></td>
<td>1677*</td>
</tr>
<tr>
<td>Constant Power Discharge</td>
<td>57.0</td>
<td>92.0</td>
<td>1342</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2300</td>
</tr>
</tbody>
</table>

### PEAKING POWER REQUIREMENTS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time (min)</th>
<th>Energy (Watt-hrs)</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td></td>
</tr>
<tr>
<td>Constant Power Charge</td>
<td>0.0</td>
<td>7.5</td>
<td>1554*</td>
</tr>
<tr>
<td>Constant Power Charge</td>
<td>7.5</td>
<td>43.9</td>
<td>2072*</td>
</tr>
<tr>
<td>Taper Charge</td>
<td>43.9</td>
<td>57.0</td>
<td></td>
</tr>
<tr>
<td>Total Charge</td>
<td></td>
<td></td>
<td>1677*</td>
</tr>
<tr>
<td>Constant Power Discharge</td>
<td>57.0</td>
<td>84.5</td>
<td>967</td>
</tr>
<tr>
<td>Constant Power Discharge</td>
<td>84.5</td>
<td>92</td>
<td>375</td>
</tr>
<tr>
<td>Total Discharge</td>
<td></td>
<td></td>
<td>1342</td>
</tr>
</tbody>
</table>

### CONTINGENCY POWER REQUIREMENTS

<table>
<thead>
<tr>
<th>Condition</th>
<th>Time (min)</th>
<th>Energy (Watt-hrs)</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td></td>
</tr>
<tr>
<td>Constant Power Discharge</td>
<td>0.0</td>
<td>92.0</td>
<td>997*</td>
</tr>
<tr>
<td>*Designates a maximum value</td>
<td></td>
<td></td>
<td>650</td>
</tr>
</tbody>
</table>
ORU As-Built Design

- Assembled/acceptance tested by Space Systems Loral under contract to the Boeing Company
- Each ORU consists of:
  - 38 series connected Nickel-hydrogen individual pressure vessel cells
    - RNH-81-5 EPI
    - Back to back configuration
    - 31% potassium hydroxide electrolyte
  - Individual cell Kapton film heaters – primary and secondary
  - Individual cell Graphite thermal sleeves
  - Radiant fin heat exchanger (RFHX) baseplate
  - 120 Amp fuse
    - 2 60 Amp modules
  - Deadface load to “safe” ORU from 76 V to 1.9 V
  - Battery Signal Conditioning and Control Module
- Dimensions
  - 37 x 41 x 19 in³
- Weight
  - 372 pounds
- Operating Voltage
  - 38 to 61.3 V
Flight ORU with Cover Removed
ORU Baseplate Layout
Flight ORU with MLI Blanket
Battery ORU Integration

- Part of the Photovoltaic Module (PV) on the P6 (port) Integrated Equipment Assembly (IEA)
  - Launched ISS 4A, November 30, 2000
- ISS will have 4 PV modules at Assembly Complete
- Each PV module has
  - 12 ORUs/6 Batteries
    - 3.6 to 4.4 years from cell activation prior to flight
- Current ISS configuration has 2 power channels
  - 2B and 4B
Battery Control

- **Photovoltaic Control Unit**
  - Integrates charge return
  - Calculates battery State of Charge (SOC)
  - Provides charge current rate to battery charge/discharge unit

- **Battery Charge Discharge Unit (BCDU)**
  - Two Battery ORUs connected in series to one BCDU
  - During insolation, the BCDU
    - Conditions power from source bus to battery
    - Charges battery at calculated charge setpoints per charge algorithm
  - During eclipse, the BCDU
    - Extracts power from battery
    - Supplies conditioned power to source bus

- **Battery Signal Conditioning and Control Module (BSCCM)**
  - Conditioned battery signals to/from the LDI in BCDU
    - Cell heater function
    - Letdown function
  - Analog multiplexed voltage
    - Individual cell voltages
    - 4 strain gauge readings for pressure
    - 6 cell and 3 baseplate temperatures

- **Cooling provided through ISS Thermal Control System**
  - Radiant fin heat exchanger baseplate
  - Mounted to ISS structure using ACME screws
  - Mated to TCS
On-orbit Start-up

- All battery ORUs were launched in a discharged state
- Reduced power available during start-up
  - Use of Shuttle Auxiliary Power Control Unit
  - Charging and thermal conditioning only during insolation
- Thermal conditioning
  - Warm ORUs using internal heaters
  - Use average of 4 cell temperatures
  - 0 to 10 °C
- Charging
  - Low rate charge (~10 A) to 76 V per battery
  - 3 consecutive insolation charges at 30 A
  - Followed by taper charge in 4th isolation period
  - Total 103 Amp-hours charge to reach 100% SOC
  - Using this charge regime on ground, battery capacities ranged from 83.0 to 89.9 Amp-hours
Battery Charge Algorithm

- Battery Charge Algorithm is programmable
- Pre-set maximum charge rate to taper based on SOC
  - Reduce stress on batteries
  - Maximize available solar array power
  - Minimize heat generation
  - Taper charge start at 94% SOC – reduced charge efficiency
- Available charging current depends on:
  - ISS vehicle user loads
  - Extravehicular activity operations
  - ISS operational modes (sun-tracking versus locked arrays)
- BOL 100% SOC is set at 81 Ah
  - Algorithm calculates SOC using a pressure versus SOC relationship
    - Acceptance test data used to initialize
    - Strain gauge calibration
    - Moles H2
    - PSI per Amp-hour
On-orbit Operation

- Current maximum charge rate table:

<table>
<thead>
<tr>
<th>SOC%</th>
<th>20</th>
<th>94</th>
<th>96</th>
<th>98</th>
<th>100</th>
<th>101</th>
<th>&gt;105</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chg rate (Amps)</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>27</td>
<td>10</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

- Settable parameters can be changed by upload from ground station
  - Charge algorithm
    - SOC versus Recharge Ratio
      - Algorithm is using SOC 100% now
  - Charge rate
  - Strain gauge calibration curves
  - Pressure offsets
On-orbit Data

- Data is telemetered to ground
  - Available real time through console screens in Engineering Support Rooms and Mission Control Center
  - Available through archived Orbiter Data Reduction Complex
- Representative data - from Flight Day 320, (Nov. 2001)
- Approximately one year in orbit
- Channel 2B-2 battery (2 series connected ORUs)
- Spaces in data are due to data drop-outs/loss of signal
- Battery voltage (76 cells) 92 to 118 Vdc
- Maximum charge rate 50 Amps
  - Note that due to ISS EPS conventions, charging current is shown as negative
- SOC ~85 to ~103% (average DOD 15%)
- ORU temperature range ~-2 to +3.3 °C
  - Note heater cycling due to ISS operation at less than ORU power design loads
- Pressure ~500 to ~725 psi
- Cell voltages ~1.26 to ~1.5 Vdc
On-orbit Battery ORU Data
Battery 2B-2 Battery & Bus Voltages

Battery/Main Bus Voltages

Volts

Batt Volt
Source Volt
FI Volt
DCRBI Volt

22:48:00 00:00:00 01:12:00 02:24:00 03:36:00 04:48:00 06:00:00
On-orbit Battery Data
Battery 2B-2  Charge/Discharge Current

Charge/Discharge Current

ECLIPSE = DISCHARGE
INSOLATION= CHARGE

-60
-40
-20
0
20
40
60

Amps

22:48:00 00:00:00 01:12:00 02:24:00 03:36:00 04:48:00 06:00:00

Batt Curr
Source Curr
Fl Curr
DCRBI Curr

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P. Dalton / F. Cohen
On-orbit Battery ORU Data
Battery 2B-2 ORU Voltages

On-orbit Battery ORU Data
Battery 2B-2 ORU Voltages

Battery ORU Voltages

Volts
65
60
55
50
45
40
35
30
22:48:00 00:00:00 01:12:00 02:24:00 03:36:00 04:48:00 06:00:00

- BattA Volt
- BattB Volt
On-orbit Battery ORU Data
Battery 2B-2 Monitored Cell Temperatures (deg F)

Battery A Cell Temperatures (deg F)

Battery B Cell Temperature (deg F)
On-orbit Battery ORU Data
Battery 2B-2  Monitored Cell Pressure

Battery A Cell Pressures

Battery B Cell Pressures
Conclusions

- ISS electrical power system is successfully maintaining power for all on-board loads
- ISS Eclipse power currently supplied by six Ni-H2 batteries (12 ORUs)
  - Designed for 35% DOD
  - Operating at approximately 15-25% DOD
- Operating nominally
- Meet/exceed all ISS requirements
SAFT Li-Ion Cell

♦ AGENDA

☐ VES140 Cell Design

☐ Module design

☐ Conclusion
VES 140 S Cell design

VES 140 S

1116 +/- 25 g
**Cell Performances**

**VES 140 S cell:**

- Max Weight = 1142g
- Dimensions: Diameter 54, length 250 mm
- Min Guaranteed BOL Energy > 139 Wh @ 4.10 V

- Space Qualified by various customers

- VES140 C will be qualified mid of next year
Cell Performances

♦ VES 140 S cell:

- 3 years of storage at ambient T: prediction at 15 years < 5%

- Cycling law $N=1.5\times10^6\times e^{-0.0846\times DOD}$
  - 27 equivalent GEO years at 80% DOD (< 3% fading)
  - 20,000 LEO cycles at 20% DOD (<12% Fading)

♦ Will fly onboard Stentor
Cell Module Principles

Cell

Positive terminal on can
Negative terminal on post

Structure of 12 cells
Structure of 9 cells
Structure of 6 cells

3 to 12 // Cells = Cell Module

x modules = 1 Battery

Cell Modules are installed in a supporting structure.
Li-Ion VES : Battery Modularity

Cell

Module

Connection

Cells

Electronics

Battery

Structure

File : O/DDE/ST/power/s2701-01.ppt
The VES 140 battery (STENTOR)

- 2 batteries of 80 Ah (11 cell packages in series per battery)
- Each cell module consists in 2 units cells in parallel
- The battery includes a balancing system which is managed by the board central computer using accurate cell voltage measurements
- The charge and tapering at end of charge are ensured by the PSR and the EPS software
- Each cell module includes a by-pass system
- EQM battery for the French technological satellite STENTOR (French space agency program)

Launch date: March 2002
Battery Schematic

Cell Modules series connected + balancing relays and resistors
(to by-pass C/400 current on the highest charged cells)
This specific module design has been used for thermal and mechanical studies
Application: 6 Cells Stentor module
Cell Module Design

- Module aluminum housing
- Cell to housing thermal junction
- Cell to housing electrical insulation

- First electrical insulation
- Second electrical insulation
## Module Mechanical Performances

### SINE

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 to 19 Hz</td>
<td>± 10 mm</td>
</tr>
<tr>
<td>19 to 70 Hz</td>
<td>13.5 g</td>
</tr>
<tr>
<td>70 to 100 Hz</td>
<td>8 g</td>
</tr>
</tbody>
</table>

**Sine vibrations level OX and OY**

### RANDOM

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 100 Hz</td>
<td>+6dB/Oct</td>
</tr>
<tr>
<td>100 to 2000 Hz</td>
<td>0.05 g²/Hz</td>
</tr>
</tbody>
</table>

**Global 9.8 gRms**

**Random vibration level OX and OY.**
**Duration 3 minutes per axis**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 to 100 Hz</td>
<td>+6dB/Oct</td>
</tr>
<tr>
<td>100 to 350 Hz</td>
<td>0.2 g²/Hz</td>
</tr>
<tr>
<td>350 to 2000 Hz</td>
<td>0.05 g²/Hz</td>
</tr>
</tbody>
</table>

**Global 11.8 gRms**

**Random vibration level OZ.**
**Duration 3 minutes per axis**
Intra-Cell gradient is very low (about 1°C worst Case)

- Voltage between: 3.25 Volts and 4.0 Volts
- Dissipation during discharge: 5 Watts and 1.19 Watts (Average = 2.06 Watts)

110 Wh are Discharged

2001 NASA Aerospace Battery Workshop: November 26-29, 2001
Modularity of the concept issued from Stentor

4 Cells Module  5 Cells Module  6 Cells Module

MODULE DESIGN FOR NEW PLATFORMS
Modularity of this concept

7 Cells Module  
8 Cells Module  
9 Cells Module
Modularity of this concept

10 Cells Module  
11 Cells Module  
12 Cells Module
Cell Wiring
3P Module

- Heaters and balancing shunts
- Sleeves
- Glass fiber sheet
- By-Pass
3P Module

Negative terminals cabling

Positive terminals cabling

Kapton insulated alveolus
3P Module

- Serial power connection “bus-bar”
- Bypass switch
- TM / TC connections with the Lion electronics

File: O/DDE/ST/power/s2701-01.ppt

2001 NASA Aerospace Battery Workshop: November 26-29, 2001
12P Module Base-Plate
12P Module Base-plate
12P Module
Cell By-Pass

2001 NASA Aerospace Battery Workshop: November 26-29, 2001
Cell Module By-Pass

Cell Modules are protected by non dissipative by-pass: Single pole double throw actuator:

- NEA 8020 100A    STENTOR bypass : Qualified
- NEA 8030 200A    Prototype level
- NEA 8043 430A    Development on going for 12 cells in parallel

In case of cell module overcharge, by-pass cell module.
**NEA 430 A - Bypass characteristics**

♦ Single pole double throw:

- T1-T3 path is established by fuse blowing.
- Steady state carrying current is 430A.

Fuse characteristics:

- 1.2 ± 0.2 Ohms
- 0.35 A No fire
- 1 A Fire
NEA module bypass

♦ NEA Bypass (100A) already qualified on STENTOR
♦ Change on current carrying capability from 100A to 430A for 12 parallel cells
♦ Heritage from Stentor:
  □ Same Actuation system
  □ Same Materials (except Delrin casing changed to higher temperature resistant material)
  □ Same processes
  □ Same Test Procedures
Module Range Weight

<table>
<thead>
<tr>
<th>Configuration</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Weight (Kg)</td>
<td>4,35</td>
<td>5,7</td>
<td>6,9</td>
<td>8,1</td>
<td>9,3</td>
<td>10,5</td>
<td>11,8</td>
<td>13</td>
<td>14,2</td>
<td>15</td>
</tr>
<tr>
<td>Cell/Battery Structure Coef</td>
<td>1,281</td>
<td>1,259</td>
<td>1,219</td>
<td>1,193</td>
<td>1,174</td>
<td>1,159</td>
<td>1,158</td>
<td>1,148</td>
<td>1,140</td>
<td>1,140</td>
</tr>
<tr>
<td>Module Energy Density (Wh/kg)</td>
<td>95,9</td>
<td>97,5</td>
<td>100,7</td>
<td>103,0</td>
<td>104,6</td>
<td>105,9</td>
<td>106,0</td>
<td>106,9</td>
<td>107,7</td>
<td>108</td>
</tr>
</tbody>
</table>

Specific energy at battery level > 100 Wk/kg
Failure Modes

♦ Cell Short :

☐ Soft Short only considered :
  • if short current lower than the balancing current :
    – continuous activation of the balancing
    – compensation of the short by the balancing
  • if short current higher than balancing current :
    – decrease of the energy of the cell package
    – reversal during discharge : soft shorting of cells
    – battery operating with one cell package less
Failure Modes (cont ’d)

♦ Cell open :
  □ Loss of 1 cell per cell package :
    • increase of the max DOD
    • increase of the max current
    • higher current discharge in the package
    • reversal at max DOD
    • Soft short of cell package
    • battery designed to adapt the loss of one cell package
Failure Rates

♦ Soft Short Circuit : 0.8 FIT

♦ Open Circuit : 0.8 FIT

♦ Drift : calculation to be done in function of battery design margin (DOD)
SAFT is qualifying a module range:

- From 3 to 12 P
- Up to 30 kW (with 100 V battery: 24 S)
- Specific energy >105 Wh/kg

Base-lined on 3 programs, including 2 GEO Satcoms
First FM Delivery Date: June 02
Calendar and Cycle Life Prediction of 100Ah Lithium-Ion Cells for Space Applications

Takefumi Inoue, Takeshi Sasaki, Nobutaka Imamura, Hiroaki Yoshida, and Minoru Mizutani
Large-scale Lithium-ion Battery Plant, Battery Manufacturing Center
Japan Storage Battery Co., Ltd.
and
Masayoshi Goto
Commercial Satellite Department, Kamakura Works
Mitsubishi Electric Corporation

Abstract

Calendar and cycle life characteristics of 100Ah lithium-ion cells were evaluated under the test conditions with wide range of temperature, depth of discharge, and state of charge. From this test results, based on the plausible deterioration models, our prediction shows that our lithium-ion cell has capability sufficient to achieve the GEO and LEO mission life requirements. We also present the relations between the cell internal resistance and the capacity loss to estimate the end of discharge voltage during the missions.

1. Introduction

Small-sized lithium-ion batteries have been already widely commercialized for cellular phones, handy VCR and other portable electronics equipments. Space applications such as the next generation satellites and other space usage also requires high energy density lithium-ion battery. However, its requirements are far larger in capacity, higher in reliability, and longer in life in vacuum condition comparing to the conventional small-sized commercial batteries.

Japan Storage Battery Co., Ltd. (JSB) has developed large capacity lithium-ion cells through cooperation with Mitsubishi Electric Corporation (MELCO). The cell with rated capacity of 100Ah has completely gastight structure achieved with ceramic hermetic seal [1] and has been qualified for space applications by MELCO [2].

In 1999 [1], we have already presented long life capability of our lithium-ion cells for space applications achieving 3,000 cycles on 25 %DOD cycle test and 12 months storage without no deterioration, and we had predicted over 30,000 cycle life at 25 %DOD at 15 °C based on the evaluation test data.

In this paper, we report further test results of calendar life and cycle life of our lithium-ion cells and refined life prediction for practical GEO and LEO satellite mission including estimation of capacity retention and internal resistance value under various conditions.

2. Cell structure and specifications

Fig.1 shows the 100Ah elliptic cylindrical cell appearance developed by JSB. The electrode assembly is constructed by spirally winding the positive and negative electrodes together with micro porous separators, which is contained in the elliptic cylindrically-shaped casing. The cell features are shown in Table1.
Table 1 Specifications of 100Ah lithium-ion cell

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Elliptic cylindrical</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>208 H, 130 W, 50 T</td>
</tr>
<tr>
<td>Mass</td>
<td>2.79kg</td>
</tr>
<tr>
<td>Casing material</td>
<td>Aluminum alloy</td>
</tr>
<tr>
<td>Positive material</td>
<td>Lithium cobaltate (LiCoO$_2$)</td>
</tr>
<tr>
<td>Negative material</td>
<td>Carbon materials</td>
</tr>
<tr>
<td>Separator</td>
<td>Microporous plastic film</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Lithium salt dissolved in mixture of alkyl carbonate solvents</td>
</tr>
<tr>
<td>Rated capacity</td>
<td>100Ah</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>3.6V</td>
</tr>
<tr>
<td>Specific energy</td>
<td>130Wh/kg (Rated value at BOL)</td>
</tr>
</tbody>
</table>

The nominal voltage of 3.6V is equivalent to that of three serial-connected cells of conventional nickel-cadmium (NiCd) and nickel-hydrogen (NiH$_2$) cells. The specific energy value of 130Wh/kg is twice of that of conventional NiH$_2$ cells.

The elliptic cylindrical cell design has the following advantages for space applications:

1) Good heat dissipation,
2) Efficient packing configuration,
3) Efficient production (low cost).

The good heat dissipation is obtained through close contact to wide flat surface on both sides of the cell. The empty space is remarkably reduced from battery assembly compared with cylindrical cells. Moreover, the cell construction of its electrode assembly is appropriate for mass production because of winding of only single positive and negative electrodes with separators comparing to the multi-electrode stacking construction.

3. Test conditions

3-1 Calendar life test

Calendar life tests were performed at various conditions to evaluate the effect of temperature and state of charge (SOC) during storage. A matrix of four temperatures (60, 35, 15, and 0 °C) and seven SOCs (100, 80, 60, 30, 5, 1, and 0 %) was used. Number of cells for each test condition is shown in Table 2.
Table 2  Calendar life test matrix  (36 cells overall)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>SOC / float charging voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>100% / 3.98V</td>
</tr>
<tr>
<td>60</td>
<td>1 cell</td>
</tr>
<tr>
<td>35</td>
<td>1 cell</td>
</tr>
<tr>
<td>15</td>
<td>1 cell</td>
</tr>
<tr>
<td>0</td>
<td>1 cell</td>
</tr>
</tbody>
</table>

*For confirmation of dispersion.

Capacity check condition:

Charge: Constant current of 20 A followed by constant voltage of 3.98 V for 8 hours overall at 15 °C.

Discharge: Constant current of 20A to cut-off voltage of 2.75 V at 15 °C.

3-2  Cycle life test

Cycle life tests were performed at various conditions to evaluate the effect of temperature and depth of discharge (DOD) during cycling. A matrix of four temperatures (60, 35, 15, and 0 °C) and five DODs (80, 50, 25, 10, and 3 %) were used. Number of cells for each test and detailed test condition are shown in Table 3 and Table 4, respectively.

Table 3  Charge and discharge cycle life test matrix (33 cells overall)

<table>
<thead>
<tr>
<th>Temperature / °C</th>
<th>DOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 %</td>
</tr>
<tr>
<td>60</td>
<td>1 cell</td>
</tr>
<tr>
<td>35</td>
<td>2 cells</td>
</tr>
<tr>
<td>15</td>
<td>2 cells</td>
</tr>
<tr>
<td>0</td>
<td>1 cell</td>
</tr>
</tbody>
</table>

*For confirmation of dispersion.

Table 4  Conditions for cycle life tests

<table>
<thead>
<tr>
<th>DOD / %</th>
<th>Charge condition</th>
<th>Discharge condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Constant current value / Constant voltage value / Over all duration</td>
<td>Constant current value / Duration / Cut-off voltage if reached</td>
</tr>
<tr>
<td>80</td>
<td>50A / 3.98V / 3.6h</td>
<td>50A / 1.6h / 2.75V</td>
</tr>
<tr>
<td>50</td>
<td>50A / 3.98V / 3.0h</td>
<td>50A / 1.0h / 2.75V</td>
</tr>
<tr>
<td>25</td>
<td>50A / 3.98V / 0.55h</td>
<td>50A / 0.5h / 2.75V</td>
</tr>
<tr>
<td>10</td>
<td>50A / 3.98V / 0.22h</td>
<td>50A / 0.2h / 2.75V</td>
</tr>
<tr>
<td>3</td>
<td>50A / 3.98V / 0.066h</td>
<td>50A / 0.06h / 2.75V</td>
</tr>
</tbody>
</table>

Capacity check condition:

Charge: Constant current of 20 A followed by constant voltage of 3.98 V for 8 hours overall at 15 °C.

Discharge: Constant current of 20A to cut-off voltage of 2.75 V at 15 °C.

4.  Results and discussion

4-1  Calendar life test

Fig.2 shows changes in capacity retention of the 100Ah cells on the calendar life test at 100 % SOC (float charging voltage of 3.98V). Capacity loss at 60 °C and 35 °C is large, especially at the beginning of the test comparing to the quite small loss at 15 °C and 0 °C. The capacity loss values
during last 6 months remain approximately at only 1 % and 0.5 % at 15 °C and 0 °C, respectively.

![Graph showing capacity retention over time at different temperatures](image)

**Fig.2** Change in capacity retention on calendar life test. (Floating charge at 3.98V corresponding to 100% SOC storage)

From this test results, estimation was carried out for calendar capacity loss during stand-by period such as solstice season at GEO application. We also recommend low temperature stand-by and storage.

**4-2 Cycle life test**

Fig.3 shows changes in capacity retention of the 100Ah cells on 50 %DOD cycle life test. The graph shows that the capacity loss is the smallest at 15 °C.

![Graph showing cycle number vs. capacity retention at different temperatures](image)

**Fig. 3** Observed capacity loss on 50% DOD cycle life test
The measured capacity loss in this cycle life tests includes calendar capacity loss also, because the cells have been kept at charged conditions during each cycle life test period. Therefore, true cycle capacity loss to be used for life prediction must be calculated from subtracting the calendar capacity loss from the observed capacity loss.

\[
\text{[ True cycle capacity loss ]} = \text{[ Observed capacity loss on cycle test ]} - \text{[ Calendar capacity loss ]}
\]

True cycle capacity loss is shown in Fig.4 calculated from calendar capacity loss, cycle test duration, average SOC, and the temperature. As shown in this graph, the true cycle capacity loss has almost no dependence on the temperature except at 0°C likely to be caused by some other mechanism.

From this investigation, we clarified the relation between the amount of true cycle capacity loss and number of cycles.

![Fig. 4 Compensated cycle capacity loss on the cycle life test (50%DOD).](image)

**4-3 Internal resistance analysis**

Cell Impedance and internal resistance at 15 °C were measured for all cells after calendar and cycle life tests and it was found that the cell internal resistance lineally increases with capacity loss percentage. The proportional coefficient was almost constant throughout all ranges of the test temperature, SOC and DOD for both calendar and cycle life tests. Fig.5 shows various time range internal resistance for degraded cells in various extent after the life tests.
The solid lines and two circles are actually measured data. The broken lines are predicted ones from those measured values. All the internal resistance and impedance measurements were carried out after cell temperature was stabilized at 15 °C for every life test temperatures. Impedance values of aged cell are predictable using of Fig.5 and estimated capacity loss value.

### 4-4 Practical prediction for actual satellite usage condition

From our investigation described above, cell capacity loss is predictable for actual satellite mission under various conditions in terms of cycling DOD, cycling duration, storage SOC, and the temperature calculating the amount of calendar capacity loss and cycle capacity loss independently.

#### 4-4-1 GEO satellite mission

**4-4-1-1 Conditions**

The condition is shown below.

*<Eclipse season>*
- Average cycle DOD: 56% (70% Max.)
- Cycle number: 45 cycles/season x 2season/year x 15years = 1,350 cycles
- Duration: 45 days/season x 2season/year x 15years = 1,350 days
- Average temperature: 10 °C

*<Solstice season>*
- Average storage SOC: 50%
- Average storage temperature: 0 °C
- Duration: 275 days/year x 15years = 4,125 days
4-4-1-2 Estimation results

Fig. 6 shows the estimated capacity retention during typical GEO satellite mission. The capacity is estimated to be retained at 77% at the end of the 18 years mission even charging voltage being maintained at 3.98 V. If the cell is charged at 4.1 V after the mission, the capacity retention will be further improved to 93%. From Fig. 5, cell internal resistance for continuous discharge at C/2 rate is estimated to be 2.6 m-ohm at the end of this mission.

![Graph showing predicted capacity retention during typical GEO satellite mission.]

Fig. 6. Predicted capacity retention during typical GEO satellite mission.

4-4-2 LEO satellite mission

4-4-2-1 Conditions

The condition is shown below.

<On orbit>
Average cycle DOD: 20% (30% Max.)
Cycle number: 40,000 cycles
Duration: 8 years = 2,920 days
Average temperature: 15 °C

<Ground storage>
Average storage SOC: 10%
Average storage temperature: 0 °C
Duration: 3 years = 1,095 days
4-4-2-2 Estimation results

Fig.7 shows the estimated capacity retention during typical LEO satellite mission. The capacity is estimated to be retained at 61% at the end of the 11 years mission even charging voltage being maintained at 3.98 V. If the cell is charged at 4.1V after the mission, the capacity retention will be further improved to 77%. From Fig.5, cell internal resistance for continuous discharge at C/2 rate is estimated to be 2.9 m-ohm at the end of this mission.

![Fig.7 Predicted capacity retention during typical LEO satellite mission.](image)

5. Conclusions

Our 100Ah lithium-ion cells with elliptic cylindrical shape have been tested, focusing on the calendar and cycle life performance and internal resistance required for their use in LEO and GEO satellite missions. It was confirmed that the cell life is predictable under any conditions for these applications using obtained test data and it has capability sufficient to achieve the required life of both satellite missions.

References


Thermal Modeling of Prismatic Lithium-Ion Cells

Pinakin M. Shah
Mine Safety Appliances Company, Sparks, MD

Michael T. Nispel
12 Pine Road, Malvern, PA
Objectives and Cell Details

- To Estimate the Transient Thermal Profiles of an Aerospace, Prismatic, 50 Ah, Lithium-Ion Cell During Repeated Low Earth Orbit (LEO) Charge / Discharge Duty Cycles.
- Perform Parametric Studies to Determine the Effects of Various Changes in Design; e.g., Materials, Dimensions, Boundary Conditions, Cell Age, etc.
- Low Earth Orbit (LEO) Satellite Battery, 90 Minute Duty Cycle @ 40% DOD -- 54 Minute Charge; 36 Minute Discharge
- Nameplate Capacity -- 50 Ah
- Dimensions -- 7” H x 3.2” W x 2.1” D
Methods of Solution

- Finite Element Methods (FEM) Selected
- Heat Generation Rate
  - Entropic and Ohmic Contributions
- Modeling
  - Commercial Program
    - StarTopaz Module of Stardyne
  - Transient Inputs / Outputs
  - Parametric Studies
Model Basics

- 3-Dimensional Model
- 1/2 Cell Modeled Along Axis of Symmetry
- 1/4 Cell Model With Second Plane of Symmetry Precluded Because of Differences in Material Properties of Current Collectors and Terminal Posts
- ~6500 Total Nodes
Physical Model Components and Materials

- TOTAL NUMBER OF NODES ~6500

- Hardware Parts -- Case, Cover, Bottom (316L SS and Al)
- Terminal Seal Posts – Aluminum and Copper
- Terminal Seal Insulators – Tefzel®
- Positive Collectors, Comb, Pad – Aluminum
- Negative Collectors, Comb, Pad – Copper
- Insulators (Cell Inside Liners and Spacers) -- Tefzel®
- Electrolyte/Separator – Part of The Gap Between Stack & Case
- Electrolyte – Part of the Gap Between Stack & Case
- Electrode Stack – Lumped Mass With Average Properties
- Outside Insulation – Glass Fiber Filled Phenolic; 1 cm Thick
Model Components

- External Insulation
- Tefzel® Terminal Post Insulators
- Helium Head Space
- Cu Busbar Comb/Pad/Post
- Separator Overhang
- Electrode Stack
- Case & Cover (SS)
- Tefzel® Insulators
- Gap -- Electrolyte and / or Helium
- Al Busbar Post/Comb/Pad
- Helium Head Space
# Thermophysical Properties

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>MATERIAL</th>
<th>Specific Heat, $C_p$ (cal/g-°K)</th>
<th>Thermal Conductivity, $k$ (W/m-°K)</th>
<th>Density (g/mL)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case, Cover</td>
<td>316L SS</td>
<td>0.120</td>
<td>16.20</td>
<td>8.0</td>
<td>1</td>
</tr>
<tr>
<td>Positive Busbar</td>
<td>Aluminum</td>
<td>0.215</td>
<td>237.00</td>
<td>2.7</td>
<td>1,2</td>
</tr>
<tr>
<td>Negative Busbar</td>
<td>Copper</td>
<td>0.092</td>
<td>398.00</td>
<td>8.9</td>
<td>1,2</td>
</tr>
<tr>
<td>Positive Electrode (including Electrolyte)</td>
<td>Li$_x$CoO$_2$, C, PVDF, and Electrolyte</td>
<td>0.218</td>
<td>2.18</td>
<td>2.9</td>
<td>2,5</td>
</tr>
<tr>
<td>Negative Electrode (including Electrolyte)</td>
<td>C, PVDF, and Electrolyte</td>
<td>0.218</td>
<td>1.40</td>
<td>1.4</td>
<td>2,5</td>
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<tr>
<td>Separator</td>
<td>PP/PE</td>
<td>0.494</td>
<td>0.83</td>
<td>1.1</td>
<td>2</td>
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<tr>
<td>Electrolyte</td>
<td>1M LiPF6 in PC+EC+EMC+DEC</td>
<td></td>
<td></td>
<td>1.2</td>
<td>4</td>
</tr>
<tr>
<td>Insulators (Internal)</td>
<td>Tefzel®</td>
<td>0.250</td>
<td>0.24</td>
<td>1.7</td>
<td>3</td>
</tr>
<tr>
<td>External Insulation</td>
<td>Phenolic with Glass</td>
<td>0.230</td>
<td>0.26</td>
<td>1.8</td>
<td>3</td>
</tr>
</tbody>
</table>

**REFERENCES:**

4. Mine Safety Appliances Data
The Stack Consists of ~140 Pairs of Positive and Negative Electrodes and Is Modeled As a Single Mass

The High Thermal Conductivity, Metallic Current Collectors Are All Oriented in the Same Plane

This Plane of Orientation Is Accounted for by Modeling the Stack With Orthotropic Properties

Thermal Conductivity Has Different Values in the Directions Normal and Parallel to the Electrodes

The Stack Is Separated Into 3 Major Components:
- Current Collectors -- Aluminum(+) and Copper (−)
- Active Materials -- Positive and Negative (with Electrolyte)
- Separator (with Electrolyte)
Orthotropic Resistances to Heat Flow

Direction(s) of Heat Flow
PARALLEL to Plate Surface

Positive Electrode

Direction of Heat Flow
NORMAL to Plate Surface

Direction(s) of Heat Flow
PARALLEL to Plate Surface

Negative Electrode

Separator
**Orthotropic Properties**

- Composite Thermal Conductivity Calculations
  - Normal Direction -- Fourier’s Law of Conduction Through a Layered Wall
  - Parallel Direction -- Parallel Resistances

<table>
<thead>
<tr>
<th></th>
<th>Lumped parameter model (cal/s-cm-°C)</th>
<th>Orthotropic model (cal/s-cm-°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>normal to plate surface</td>
<td>0.00425</td>
<td>0.00348</td>
</tr>
<tr>
<td>parallel to plate surface</td>
<td></td>
<td>0.0752</td>
</tr>
</tbody>
</table>

- $k = 18\%$ Lower in Normal Direction
- $k = 1770\%$ Higher in Parallel Direction
Heat Generation Rate

- Heat Generation Consists of Three Major Components:
  - Entropic Contribution Within the Stack by Electrochemical Reactions,
  - Ohmic Contribution Due to Resistance to Current Flow Within the Stack, and
  - Ohmic Contribution Due to Resistance to Current Flow Through the Metallic Busbar Components and Welded Joints.
Heat Generation Calculations

- Rate Equation for Total Heat Generation

\[ Q_T = q_T t = -0.239 \cdot I \cdot t [(E^\circ - E_L) - T(dE^\circ/dT)_p] \]

- Open Circuit Voltage, \( E^\circ \), Determined As a Function of DOD by Testing Sony 17670 Cells

- Load Voltage, \( E_L \), Projected From Pouch Cell Performance Data for Beginning, Middle, and End of Life Conditions

- \( (dE^\circ/dT)_p = -4.14 \times 10^{-4} \) V/°K From Published Literature*

OCV vs. State of Discharge

Sony 17670 Cells: Successive 18 Minute Discharges @ C/1.5 Rate (20% DOD) With 4 Hours Rest in Between
Projected Voltage Profiles (Beginning, Middle, and End of Life Conditions)

- **Charge**
  - Begin
  - Mid
  - End

- **Discharge**
  - Begin
  - Mid
  - End

**Legend**
- Blue – Current
- Other – Potential

**Graph Details**
- **Cell Potential (Volts)**
- **Current (Amperes)**
- **Time (minutes)**
**Total Heat Generation Rates**

![Graph showing heat generation rates over time for different battery conditions.](image)

- **Discharge**
- **Charge**

- **Heat Evolved** → Positive
- **Heat Absorbed** → Negative

**Legend:**
- Blue line: Sony 17670 Cell
- Red line: Beginning of Life
- Green line: End of Life

**Axes:**
- **Y-axis:** Heat Generation Rate (cal/sec)
- **X-axis:** Time (minutes)
Ohmic And Entropic Contributions
Model Input Conditions

- Heat Generation in Tabs, Combs, Pads, and Posts

<table>
<thead>
<tr>
<th></th>
<th>Discharge</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Heat, kcal</td>
<td>-6.735</td>
<td>0.942</td>
</tr>
<tr>
<td>Copper Busbar, kcal</td>
<td>-0.015</td>
<td>-0.014</td>
</tr>
<tr>
<td>Aluminum Busbar, kcal</td>
<td>-0.024</td>
<td>-0.023</td>
</tr>
</tbody>
</table>


- Other Input Conditions:
  - Zero Contact Resistance Between All Components
  - Multiple, Consecutive Duty Cycles With No Rest in Between
Boundary Conditions

INITIAL CONDITIONS: ALL NODES @ 298 °K

- Isothermal @ 25 °C
- Isothermal @ 25 °C
- Isothermal @ 25 °C
- Isothermal @ 25 °C
- Adiabatic (Due to Axis of Symmetry)
- Radiation Heat Loss
End of Discharge Temperatures

Max. Temperature, °K

Min. Temperature, °K

Cycle Number
General Results

- Maximum Temperature Rise of ~6°C, Depending on Particular Conditions of a Run

- Significant Parameters
  - Rise in Cell Impedance Due to Cycling
  - Hardware Material: 316L SS vs. Aluminum
  - Boundary Condition at the Ends of Terminal Posts
  - Location of Tabs / Connection of Terminals to Stack

- Less Significant Parameters
  - Electrolyte Level
  - Headspace Gas
**Electrolyte Level Variations**

- Electrode Stack Always Fully Saturated
- Side Gaps in Cell
  - Fully Filled With Electrolyte, or
  - Half Filled With Electrolyte
    - Other Half With Nothing or Helium

Top gap: 100% Saturation = Liquid Electrolyte  
50% Saturation = Nothing or Helium Gas

Bottom Gap: Free Liquid Electrolyte
Boundary Conditions -- Headspace

- Empty Space
  - Adiabatic -- No Heat Transfer From All Surfaces in Contact With the Headspace

- Helium Gas
  - Conductive Heat Transfer Through Gas Medium
Thermal Profile Comparisons -- ‘New’ vs. ‘Cycled’ Cell
End of Discharge Results

Max. Temp
302.13K
306.19K

Min. Temp
297.46K
296.93K

New Cell

Cycled Cell
Temperature Profile Comparisons in Busbars

END OF DISCHARGE

New Cell

Cycled Cell
Stainless Steel Versus Aluminum Hardware

- Material for Case and Cover Changed From 316L SS to Al

<table>
<thead>
<tr>
<th></th>
<th>Stainless Steel</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/mL</td>
<td>8.03</td>
<td>2.70</td>
</tr>
<tr>
<td>$C_p$, cal/g-°K</td>
<td>0.12</td>
<td>0.215</td>
</tr>
<tr>
<td>$k$, W/m-°K</td>
<td>16.2</td>
<td>236.8</td>
</tr>
<tr>
<td>Emmisivity</td>
<td>0.54*</td>
<td>0.05*</td>
</tr>
</tbody>
</table>

Effects of Hardware Material Change

316L SS          Aluminum

END OF DISCHARGE (Cycle 5)
Modification of Current Collector Tab Location

Change in Tab Location

Electrolyte-Filled Gap

Electrolyte/Separator Gap
**Terminal Post Boundary Condition -- Adiabatic vs. Isothermal**

**ISOTHERMAL at 25°C -**
This Condition Simulates a High Rate of Heat Loss Through the Attached Cable.

**ADIABATIC - This Simulates a Condition of No Heat Transfer Through the Cable Because of the Adjacent Cells**

---

**END OF DISCHARGE**
CONCLUSIONS:

- This Study Has Been Successful in Providing a Time and Cost Effective Tool for Estimating Thermal Profile of a Lithium-Ion Cell.

- A Number of Parametric Studies Are Possible to Optimize Component Designs and to Determine the Effects of Material Properties, Cell Aging, and Boundary Conditions on the Thermal Performance of a Cell.

- FEM Analyses Can Enhance Safety Studies by Projecting Operating Limitations Without Costly Experimentation.
SAFT Li-Ion Cells GEO and LEO Life Test Up-Date

* Advanced Battery System Division
Cockeysville, MD

** Specialty Battery Group
Defense and Space Division
Poitiers, France
AGENDA

♦ Cell Designs and Qualification Status

♦ Life Test and Calendar Results

♦ Conclusions
Cell electrochemistry

- Positive: Metallic oxide containing Lithium ions
  Ni based mixed oxide (cost and performance versus Cobalt oxide)

- Negative: Mix of Graphite.
  (Flat curve, no metallic lithium, no dendrite formation)

- Electrolyte: LiPF6 salt + organic solvent mixture
  (alkyl carbonates: PC, EC, DMC) + proprietary additive: VC

- Separator: PP/PE/PP
VES 140 and HE44 Cell

VES 140

HE44
# VES 140 and HE44 Cell

<table>
<thead>
<tr>
<th></th>
<th>VES140</th>
<th>HE44</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Status</strong></td>
<td>Qualified</td>
<td>In test</td>
</tr>
<tr>
<td><strong>Production Method</strong></td>
<td>Industrial Line</td>
<td>Automated Line</td>
</tr>
<tr>
<td><strong>Number of cells manufactured</strong></td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td><strong>Electrochemistry</strong></td>
<td>Generation 4</td>
<td>Generation 4</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td>A</td>
<td>A+ 6% on positive</td>
</tr>
<tr>
<td><strong>Porosity</strong></td>
<td>B</td>
<td>B- 5% on negative</td>
</tr>
<tr>
<td><strong>Case Material</strong></td>
<td>Aluminum</td>
<td>Aluminum</td>
</tr>
<tr>
<td><strong>Terminals</strong></td>
<td>Same side (axial)</td>
<td>Same side (non axial)</td>
</tr>
<tr>
<td><strong>Length (mm)</strong></td>
<td>250</td>
<td>244.3</td>
</tr>
<tr>
<td><strong>Diameter (mm)</strong></td>
<td>54</td>
<td>54</td>
</tr>
<tr>
<td><strong>Max Weight (g)</strong></td>
<td>1.142</td>
<td>1.132</td>
</tr>
<tr>
<td><strong>Capacity (Ah)</strong></td>
<td>38.6</td>
<td>44</td>
</tr>
<tr>
<td><strong>Energy (Wh)</strong></td>
<td>139</td>
<td>154</td>
</tr>
</tbody>
</table>
Test in progress

223 CELLS IN TEST

64 CELLS IN CALENDAR TEST

169 CELLS IN CYCLING TEST

84 CELLS IN LEO TEST

85 CELLS IN GEO TEST
## SUMMARY OF LEO LIFE TEST RESULTS

<table>
<thead>
<tr>
<th>Cell Reference</th>
<th>Cell Version</th>
<th>Test</th>
<th>DOD</th>
<th>Nb Cells Tested</th>
<th>Nb cycle Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO1</td>
<td>VES 140 O</td>
<td>Accelerated</td>
<td>10%</td>
<td>3 Cells</td>
<td>13 100</td>
</tr>
<tr>
<td>LEO2</td>
<td>VES 140 O</td>
<td>Accelerated</td>
<td>20%</td>
<td>3 Cells</td>
<td>12 270</td>
</tr>
<tr>
<td>LEO3</td>
<td>VES 140 O</td>
<td>Real Time</td>
<td>30%</td>
<td>6 S Module</td>
<td>6 100</td>
</tr>
<tr>
<td>LEO4</td>
<td>VES 140 O</td>
<td>Accelerated : Variable DOD</td>
<td>10 to 30 %</td>
<td>3 S Module</td>
<td>20 280</td>
</tr>
<tr>
<td>LEO5</td>
<td>VES 140 O</td>
<td>Real Time</td>
<td>30%</td>
<td>3 S Module</td>
<td>9 040</td>
</tr>
<tr>
<td>LEO6</td>
<td>VES 140 O</td>
<td>Real Time</td>
<td>40%</td>
<td>3 S Module</td>
<td>4 500</td>
</tr>
</tbody>
</table>
LEO Cycling 30 % (LEO3 test)

- Test on 6 cells Module
- Real time LEO cycling 30% DOD : 3.80V
- Energy checks +Peak Power evaluation : every 100 cycles
- Test started in August 1999
- Temperature 20 °C
- 7,000 cycles performed
LEO Cycling 30 % DOD (LEO3 test)
SAFT

LEO Cycling 30 % DOD (LEO3 test)

Energy loss at 25 000 cycles : 20 %
## SUMMARY OF GEO LIFE TEST RESULTS

<table>
<thead>
<tr>
<th>Test Reference</th>
<th>Cell Version</th>
<th>Test</th>
<th>DOD</th>
<th>Nb Cells Tested</th>
<th>Nb Seasons Performed</th>
<th>Fading Measured</th>
<th>Fading @15 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO1</td>
<td>Prototype 2</td>
<td>Semi accelerated 2c/day +PPS</td>
<td>40%</td>
<td>6 S Module</td>
<td>34</td>
<td>8,0%</td>
<td>7,1%</td>
</tr>
<tr>
<td>GEO2</td>
<td>Prototype 2</td>
<td>Accelerated : ( I_c = 12 ) amps</td>
<td>80%</td>
<td>2S2P Module</td>
<td>30</td>
<td>10,9%</td>
<td>10,9%</td>
</tr>
<tr>
<td>GEO3</td>
<td>Prototype 2</td>
<td>Semi Accelerated +PPS : ( I_c = 4 ) Amps</td>
<td>60%</td>
<td>6 S Module</td>
<td>20</td>
<td>6,1%</td>
<td>9%</td>
</tr>
<tr>
<td>GEO4</td>
<td>Prototype 2</td>
<td>Real Time+PPS : ( I_c = 4 ) amps</td>
<td>60%</td>
<td>6 S Module</td>
<td>5</td>
<td>2,0%</td>
<td>12%</td>
</tr>
<tr>
<td>GEO5</td>
<td>HE44</td>
<td>Accelerated : Constant DOD, ( I_c = 15 ) Amps</td>
<td>60%</td>
<td>10 cells</td>
<td>66 (2259 cycl)</td>
<td>14,8%</td>
<td>3,6%</td>
</tr>
<tr>
<td>GEO6</td>
<td>VES140 0</td>
<td>Accelerated : ( I_c ) from 12 to 6 amps</td>
<td>80%</td>
<td>3S2P Module</td>
<td>56</td>
<td>4%</td>
<td>2,1%</td>
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<tr>
<td>GEO7</td>
<td>VES140 0</td>
<td>Semi accelerated : ( I_c = 6 ) amps</td>
<td>85%</td>
<td>3S2P Module</td>
<td>30</td>
<td>3,5%</td>
<td>3,5%</td>
</tr>
<tr>
<td>GEO8</td>
<td>VES140 0</td>
<td>Accelerated : Constant DOD, ( I_c = 15 ) Amps</td>
<td>70%</td>
<td>2 cells</td>
<td>62 (2259 cycl)</td>
<td>16,0%</td>
<td>2,9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60%</td>
<td>2 cells at 4V</td>
<td>61 (2206 cycl)</td>
<td>11,8%</td>
<td>2,0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60%</td>
<td>2 cells at 3.9 V</td>
<td>61 (2210 cycl)</td>
<td>10,0%</td>
<td></td>
</tr>
<tr>
<td>GEO9</td>
<td>VES140 0</td>
<td>Semi Accelerated : ( I_c = 4 ) Amps</td>
<td>90%</td>
<td>3S Module</td>
<td>16</td>
<td>0,8%</td>
<td>1,5%</td>
</tr>
<tr>
<td>GEO10</td>
<td>VES140 0</td>
<td>Real Time + PPS : ( I_c = 4 ) amps</td>
<td>70%</td>
<td>3S Module</td>
<td>8</td>
<td>0,5%</td>
<td>1,9%</td>
</tr>
</tbody>
</table>

Less than 3 % fading for 15 years GEO mission @ 80 % DOD
GEO 5 : Life tests performed on HE44 cells

- 10 HE44:
- 60% DOD Accelerated GEO cycling: Constant DOD
- Ambient Temperature
- Charge current: 15 Amps
- 2,400 constant 60% DOD cycles = (66 seasons)
- Energy variation @15 years: 3.5%
GEO 5 : 60 % DOD Life tests on HE44 cells
GEO 5 : 60 % DOD Life tests on HE44 cell

![Graph depicting energy (Wh) vs. cycles No. for GEO 5 battery tests.](image-url)
GEO 6: Life tests performed on VES 140 cells achieved 28 years lifetime @ 80% DoD

- 1 battery of 6 cells (3s2p)
- EOCV: 4.05 V during the first 10 seasons, 4.07 V during the next twenty then 4.1 V from 31st to 56th
- 80 to 82% DOD (ratio of Energy @4.1 V) and 20 °C
- Charge current: C/3 during the first 15 seasons, C/4 afterwards from season 15 to 40 and C/6 afterwards
- Accelerated conditions: 1 week = 1 season at BOL up to 14 days = 1 season
- Electric propulsion cycles neglected
- Cell balancing every six simulated months
- 56 seasons already performed (28 years)
- Capacity check after each season:
  
  **2.2% Energy loss at season 30th (15 years)**
GEO6: 56 seasons (80% DoD Lifetest)

BOL Energy 267 Wh

End Of Discharge Voltage

30 Seasons
Available energy
263 Wh

50 Seasons
Available energy
253 Wh

Eclipse Number

File: O/DDE/ST/power/s2738-01-01
GEO6: EODV (80% DoD Lifetes)

EODV at Eclipse 23

- EOC increase from 4.05 to 4.07 V
- Test interruption for 1 week
- EOC increase from 4.07 to 4.1 V
- Decrease of Ic from 12 to 9 Amps
- DOD Increase
- Decrease of Ic from 9 to 6 Amps

File: O/DDE/ST/power/s2738-01-01

2001 NASA Aerospace Battery Workshop: November 26-29, 2001
GEO8 : 60 and 70% Constant DOD GEO VES 140 Accelerated Cycling

♦ Test configuration :
  - 2 VES140 @ 70 % DOD 4 V
  - 2 VES140 @ 60 % DOD 4 V and 2 VES140 @ 60 % DOD 3.9 V

♦ Accelerated GEO cycling : Constant DOD, 20 °C

♦ Charge current : 15 Amps

♦ 2200 constant DOD cycles = 60 seasons performed

♦ Energy variation @ 15 years :
  - 2.9 % @ 70 % DOD 4V
  - 2 % @ 60 % DOD 4V
  - 2.3 % @ 60 % DOD 3.9 V
GEO8 : 60 and 70% Constant DOD GEO
VES 140 Accelerated Cycling - EODV
GEO8: 60 and 70% Constant DOD GEO VES 140 Accelerated Cycling - Energy

![Graph showing energy vs cycle number for GEO8 batteries with 60% and 70% DOD.]

- L396 70% 4V
- L405 70% 4V
- L400 60% 4V
- L402 60% 4V
- L399 60% 3.9V
- L401 60% 3.9V

Cycle No.
GEO9 : 90% DOD GEO VES 140

- Module configuration (3S VES140)
- Accelerated GEO cycling 90% DOD, 20 °C
- Charge current : 4 Amps
- EOCV = 4.0 V
- Season profile
- Test started in December 2000
- 15 seasons performed
- Energy variation : 0.8 %
GEO9 : 90% DOD GEO Accelerated Cycling

FT G4 Li-Ion, Mod 23, 90% DoD; Bay 102; Bat 6

Date:
20/11/00 09/01/01 28/02/01 19/04/01 08/06/01 28/07/01 16/09/01 05/11/01
GEO9 : 90% DOD GEO Accelerated Cycling

SAFTG4 Li-Ion, Mod 23, 90% DoD; Bay 102; Bat 6

0.8% Fading after 15 seasons @ 90% DOD
Mathematical law based on experimental values:

\[ N = 8.9 \times 10^5 \exp(-0.0547 \times \text{DOD}) \]

For 80% DOD:
- 2250 cycles performed with 4% loss

Margin factor = 8
11250 cycles to failure
LIFE TIME PREDICTION FOR VES 140

![Graph showing life time prediction for VES 140 with Nb CYCLES on the y-axis and DOD % on the x-axis. The graph includes data points for extrapolation and experimental results, marked by triangles.](image-url)

File: O/DDE/ST/power/s2738-01-01

2001 NASA Aerospace Battery Workshop: November 26-29, 2001
Calendar effects

Cell capacity decrease due to lithium loss:
- Corrosion of lithium is due to a parasitic reaction occurring between the lithium inserted in the carbon and the electrolyte.

Main driving Parameters:
- The conductance of the passivation interface layer (Solid Electrolyte Interface)
- The initial construction of the SEI
- The temperature
Calendar effect

Thanks to Li excess, calendar effect is limited over the life.
Calendar test plan

♦ Storage Temperature
  ● From 0°C to 60°C

♦ EOCV
  ● From 3.70 V to 4.10 V

♦ Conditions
  ● OCV and floating
Cell stored @30 °C EOCV=4V float conditions
Capacity @25 °C 14 Amps

Date

L72
L99
Cells stored @30 °C EOCV=4V float conditions
Capacity @60 °C 14 Amps
Cell stored @ 30 °C EOCV=4V float condition

Internal resistance after 1 s and 5 mn
Calendar effect laws

- Lithium loss Chemical reactions:
  \[ t = A(T) \times x^2 + B(T) \times x \]
  \[ x = 0.2 \times t^{0.59} \text{ at } 20 \text{ °C} \]
  \[ x = \%\text{Li loss}, t = \text{duration in day}, T = \text{temperature °K} \]

- If \( x < 12\% \) no capacity loss
  If \( x > 12\% \) Capacity loss = \( x - 12\% \)

- A and B coefficients determined with experiments
Capacity decrease due to calendar effect and versus temperature

Capacity Loss due to Calendar Effect vs Temperature

- Capacity ratio at $T$ °C
- Time (Year)

Graph showing the capacity ratio at different temperatures over time.
Life and calendar tests have shown:

- Limited effect of the EOCV
- Impacts of high charge (>12 Amps) current on fading effects:
  - Reversible energy loss due to current density
  - Partial localized Li plating (at end of charge)
- Advantages of the Li excess (Ni based) for calendar
Conclusion (2)

♦ LEO life tests demonstrate 8 years missions @ 20-25 % DOD

♦ 56 GEO seasons @ 80 % DOD have been performed:
  less than 3 % fading for 15 years

♦ Expected calendar effect is less than 7 % for 18 years at 20 °C

Total energy decrease for 15 years in GEO: 10 %
Evaluation of Cycle Life and Characterization of YTP 45 Ah Li-Ion Battery for EMU

Yi Deng, Judith Jeevarajan, Raymond Rehm
Lockheed Martin Space Operations
Bobby Bragg
NASA Johnson Space Center
Brad Strangways
Symmetry Resources, Inc.
Outline

• Introduction
• Configuration of cell and battery of Yardney Technical Products (YTP)
• Principle of work in Li-ion cell/battery
• Cycle life test
• Characterization tests at various temperatures
• Thermal testing on battery before and after 500 cycles
• Conclusion
Introduction

Li-ion batteries, with longer cycle life and higher energy density features, are now more and more attractive and applied in multiple fields. YTP 45 Ah Li-ion battery has been evaluated here and may be employed in EMU in the future. Evaluations were on:

• Cycle life test – 500 cycles total
  Completed 40 cycles in simulated shuttle use mode
  Completed 460 cycles in an accelerated use mode
  Recorded differential voltage of individual cell in battery

• Characterization test
  Discharge capacity measurement in environment temperature of –10, 25, 50 degree C before and after 500 cycles

• Thermal testing
  Charge and discharge at 50 degree C and –10 degree C before and after 500 cycles
Configuration of Battery

Cell capacity: 45 Ah
Cell nominal voltage: 3.6 V
Cell dimensions: 3.45” x 4.47” x 1.77”
Cell weight: 1.108 Kg
Energy density: 366.3 Wh/L
Specific energy: 147.5 Wh/Kg

The battery module with 5 cells in series
Battery capacity: 45 Ah
EMU requirement voltage: 16.0 – 21.8V
Battery voltage: 16.0 – 20.5V
Principle of Reaction in YTP Li-ion Cell/Battery

**Positive Electrode**

\[ \text{Li}_{1-x}\text{Ni}_{1-y}\text{Co}_y\text{O}_2 + x\text{Li}^+ + x\text{e}^- \]

\[ \text{LiNi}_{1-y}\text{Co}_y\text{O}_2 \]

**Negative Electrode**

\[ x\text{Li}^+ + \text{Specialty C} \]

\[ \text{CLi}_x \]

**Discharge**

\[ \text{LiNi}_{1-y}\text{Co}_y\text{O}_2 + C \]

**Charge**

\[ \text{Li}_{1-x}\text{Ni}_{1-y}\text{Co}_y\text{O}_2 + x\text{Li}^+ + xe^- \]

Electrolyte: 0.92M LiPF$_6$ in EC:EMC
Experimental:

• Maccor Series 2000 was employed to perform cycling test on EMU Li-ion battery

• Tenney environmental chamber was used for thermal testing on battery
Cycle Life Test

Comprehensive cycling:

• CC charge protocol was employed in all 500 cycle life tests with no taper charge.

• Shuttle Airlock charger real time charge at initial 40 cycles with 1.55A charge and 3.8A partial discharge (26.6Ah, 59% DOD) and full discharge at every 20th cycle to 16.0V.
  
  First 9 cycles – 1.55A charge to 21.0V or 4.2V/cell max.
  From 10 through 40 cycles– 1.55A charge to 20.5V or 4.1V/cell max.

• Accelerated charge/discharge for subsequent 460 cycles with successive constant current of 11.0A, 5.0A, 2.0A, and 1.0 A charge to 20.5V for battery (4.1V/cell) and 11.0A partial discharge (26.6 Ah, 59% DOD) and full discharges at 3.8A to 16.0V at every 20th cycle.
Trends of Discharge Capacity and Energy in the Initial 500 Cycle Life Testing

YTP 45A-h, 5-cell Li-Ion EMU Battery Cycling Tests
Real Time and Accelerate Cycling at Room Temp.
Discharge Capacity and Energy versus Cycle Trends
3.8A to 16V (3.0V) battery (cell) voltage on 20 cyc interval; All other cycles to 26.6A-h

The charge termination voltage was reduced to 20.5V (4.10V) battery (cell) voltage for cycles after cycle 9. The charge termination voltages for cycles 1 through 9 were 21.0V (4.20V).

Partial Discharges at 3.8A for cycles 1 through 40; at 11.0A for all subsequent partial discharge cycles.
YTP 45A-h, 5-cell Li-Ion EMU Battery Cycling Tests
Real Time and Accelerated Cycling at Room Temp.
End-of-Discharge Battery Voltage versus Cycle Trend
3.8A to 16V (3.0V) battery (cell) voltage on 20 cycle interval; All other cycles to 26.6A-h

The charge termination voltage was reduced to 20.5V (4.10V) battery (cell) voltage for cycles 10 through 500. The charge termination voltages for cycles 1 through 9 were 21.0V (4.20V).

Partial Discharges at 3.8A for cycles 1 through 40; at 11.0A for all subsequent partial discharge cycles.
The Differential of Voltage of Individual Cells in Battery at End-of-Charge (EOC) and End-of-Discharge (EOD) in the Initial 500 Cycles

YTP 45A-h, 5-cell Li-Ion EMU Battery Cycling Tests
Real Time and Accelerated Cycling at Room Temp.
End-of-Discharge and End-of-Charge Cell Voltage Differentials
3.8A to 16V (3.0V) battery (cell) voltage on 20 cycle interval; All other cycles to 26.6A-h

The charge termination voltage was reduced to 20.5V (4.10V) battery (cell) voltage for cycles 10 through 500. The charge termination voltages for cycles 1 through 9 were 21.0V (4.20V).

Partial Discharges at 3.8A for cycles 1 through 40; at 11.0A for all subsequent partial discharge cycles.

EOC plot

EOD plot
OCV Performance

The battery was fully charged and kept at open circuit for six months after completed previous 500 cycle tests. The OCVs of individual cells in battery were measured before balancing condition supplied. The OCV of all individual cells in battery is almost same with voltage at 4.1V.
Characterization Tests of Battery at Various Temperatures Before 500 Cycles

Charge battery at 4.5 A to 21.0V; Discharge battery at 10.0A to 14.5V
Discharge Characteristics for the EMU Li-ion Battery Before and After 500 Cycles

Charge battery at 4.5A to 21.0V (20.5V) at initial (final); Discharge battery at 10.0 A to 14.5V (15.0V) at initial (final)
### Test Data of Battery Discharge Capacities and Energies at Various Temperatures Before 500 Cycles
(cut off voltage at 21.0V during battery charge and cut off voltage at 14.5V during battery discharge)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Capacity of discharge (Ah)</th>
<th>Energy of discharge (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>48.09</td>
<td>880.7</td>
</tr>
<tr>
<td>25</td>
<td>44.96</td>
<td>818.7</td>
</tr>
<tr>
<td>-10</td>
<td>31.31</td>
<td>538.4</td>
</tr>
</tbody>
</table>

### Test Data of Battery Discharge Capacities and Energies at Various Temperatures After 500 Cycles
(cut off voltage at 20.5V during battery charge and cut off voltage at 15.0V during battery discharge)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Capacity of discharge (Ah)</th>
<th>Energy of discharge (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>36.56</td>
<td>659.2</td>
</tr>
<tr>
<td>25</td>
<td>33.50</td>
<td>598.7</td>
</tr>
<tr>
<td>-10</td>
<td>20.12</td>
<td>332.2</td>
</tr>
</tbody>
</table>
YTP 45A-h, 5-cell Li-Ion EMU Battery Cycling Tests
Characterization Testing, Cycle 2; 50 deg. C
Battery Voltage and Center Cell Case Temperature Profiles
Charge 4.50A to 21.0V (4.35V) battery (cell) voltage, Discharge 10.0A to 14.5V (2.25V)

Thermal Property of Center Cell Case in Battery When Charge/Discharge at Cell Extreme Temperature
Testing at 50 °C Environmental Temp. Before 500 Cycles

Internal chamber temp. risen to 50.4 deg. C.
Reduced chamber temp. setpoint by 0.6 deg. C
YTP 45A-h, 5-cell Li-ion EMU Battery Cycling Tests
Final Characterization Testing 45/50 deg C chg/dsch
Battery Voltage and Center Cell Case Temperature Profiles
Charge 4.50A to 20.5V (4.1V) battery (cell) voltage, Discharge 10.0A to 15V (3.0V)

Thermal Property of Center Cell Case in Battery When Charge/Discharge at 45/50 °C Environmental Temp. After 500 Cycles
Comparison of Center Cell Temperature at 50/45 °C Before and After 500 Cycles

50°C charge and 50°C discharge at initial test. 45°C charge and 50 °C discharge at final test.
Thermal Property of Center Cell Case in Battery When Charge/Discharge at -10 °C Environmental Temp. Before 500 Cycles
Thermal Property of Center Cell Case in Battery When Charge/Discharge at -10 °C Environmental Temp. After 500 Cycles

YTP 45A-h, 5-cell Li-Ion EMU Battery Cycling Tests
Final Characterization Testing, -10 deg. C
Battery Voltage and Center Cell Case Temperature Profiles
Charge 4.50A to 20.5V (4.1V) battery (cell) voltage, Discharge 10.0A to 15.0V (3.0V)
Comparison of Center Cell Case Temperature at -10 °C Before and After 500 Cycles

![Graph comparing initial and final temperatures over time](image-url)
Conclusion

- Battery showed less than 9% drop of initial discharge capacity and energy within 500 cycles with 475 cycles 59% DOD plus 25 cycles 100% DOD.
- The EOD voltage ranged for 16.0-18.0V which fits the requirement for operation of the EMU.
- In 500 non-stop cycles, the results of maximum differential voltage of individual cells in the battery displayed:
  
  less than 0.13V at EOC and showed decrease trend after 350th cycle;
  
  less than 0.33 V at EOD and showed increase trend.
- Capacity variation resulting from temperature extremes is only minimally affected by the 500 cycles.
- External temperature of battery case displayed increase tendency after 500 cycle tests, due to increased internal impedance.
Acknowledgment

We acknowledge Yardney Technical Products, Inc. for supplying the EMU Li-ion cells as a Phase II deliverable.
LITHIUM ION DD CELLS
SPACE APPLICATION CYCLING UPDATE

HAIYAN CROFT
BOB STANIEWICZ
SAFT America Inc.
Advanced Battery Systems Division
Cockeysville, MD

The 2001 NASA Aerospace Battery Workshop
Huntsville, Alabama
November 27-29, 2001
DD Cell
OVERVIEW

- DD CELLS
  - CHEMISTRY
  - HOW ACCELERATED TESTING IS PERFORMED
  - LEO TESTING
  - GEO TESTING
  - 100% DOD at RT
  - 100% DOD at –20°C
- CONCLUSION
CHEMISTRY

- POSITIVE MATERIAL: $\text{LiNi}_{1-x-y}\text{Co}_x\text{M}_y\text{O}_2$
- NEGATIVE IS ADMIXTURE OF TWO GRAPHITES WITH NON-PVDF BINDER

- CAPACITY: 9.5 AH
- ENERGY DENSITY: 140 WH/KG
● STAINLESS STEEL HARDWARE

● CELL DIMENSION: CYLINDRICAL
  ● CELL OD: 32 MM OR 1.32 IN
  ● CELL HEIGHT: 122MM OR 4.8 IN

● MULTIPLE TABS ON ELECTRODES

● CELL WEIGHT: 250 GRAMS
**LEO AND GEO CYCLING DEMONSTRATING PERFORMANCES FOR PLANETARY AND INTERPLANETARY APPLICATIONS**

<table>
<thead>
<tr>
<th>DEPTH OF DISCHARGE</th>
<th>CYCLES ACHIEVED TO DATE</th>
<th>EOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>20,000</td>
<td>40K CYCLES</td>
</tr>
<tr>
<td>60%</td>
<td>2800</td>
<td>1350</td>
</tr>
<tr>
<td>100% @ -20C</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>
WE JUDGED WHAT MIGHT BE REASONABLE, ACCELERATED TRADE-OFFS OF TIME AND CURRENT TO ACCOMPLISH CYCLE DEMONSTRATION

GEO – ACCELERATION IS STRAIGHTFORWARD:
WE ADOPTED 1.2 HOURS FOR DISCHARGE
4.8 HOURS FOR CHARGE

THE DISCHARGE IS AT A CONSTANT DOD RATHER THAN A TRUE SEASON WITH THE WELL-KNOW PARABOLIC ECLIPSE DURATION

LEO – ACCELERATION REQUIRES A CAREFUL BALANCE OF SHORTEN TIME AND CURRENT INCREASE

<table>
<thead>
<tr>
<th>CYCLES/DAY</th>
<th>CURRENT (A)</th>
<th>TIME (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30% DOD</td>
<td>28.7</td>
<td>DIS 10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CHG 5.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35</td>
</tr>
</tbody>
</table>
ACCELERATED TIMES AND CURRENT

SLOW DOWN 1.5 CYCLES TO TYPICAL ORBIT TIME OF 105 MIN

DIAGNOSTICS:
1. FULL SOC CAPACITY
2. RESIDUAL CAPACITY AT E.O.C.V.
3. IMPEDANCE

SLOWING DOWN TO REAL TIME ORBIT RATES OF 105 MIN. EVERY 50 CYCLES IS ESSENTIAL SO THAT E.O.D.V. REFLECTS TRUE ORBIT CONDITIONS
DD cells LEO test - 30% DOD EODV @ 25C

11 DD cells with 9 Ah nominal capacity

Average V Loss/ Cycle
1.6E-06 V / Cycle

49 Accelerated Cycles: Charge @ 5.25A to 3.8V for 35 min
   Dscharge @ 10A for 15.12Min

Real Time Cycle: Charge @ 3.15A to 3.75V for 65 min
   Dscharge @ 5.25A for 28.8Min
DD Cells LEO 30% DOD @ 25°C Discharge Capacity

11 DD cells with 9 Ah nominal capacity
Diagnostics were performed every 500 cycles
Curves shown are the Capacity @4.0V and 3.75V during diagnostics

Capacities @ 4.0V
Average Ah Loss 4.8E-05 Ah / Cycle

Capacities @ 3.75V
Average Ah Loss 4.5E-05 Ah / Cycle

10,000 15,000 20,000 25,000 30,000
11,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
0 5,000 10,000 15,000 20,000 25,000 30,000
Cycle No.
Discharge Capacity (Ah)
DD Cells Internal Resistance

- 11 DD cells with 9 Ah nominal capacity
- Diagnostics were performed every 500 cycles
- Curves shown are the Total Resistances @3.75V during diagnostics
11 DD cells with 9 Ah nominal capacity
Diagnostics were performed every 500 cycles
Curves shown are the Energy @4.0V and 3.75V during diagnostics

Average Wh Loss
1.48E-04 Wh / Cycle
25°C 30% DOD LEO Cycling, Prediction For 40,000 Cycles

- **EODV**: 3.46V
- **DV**: 64 mV
- **EODV**: 3.396
- **Capacity**: 8.5Ah @4.0V
- **DAh**: 1.92Ah
- **6.58Ah@4.0V**
- **Energy**: 30Wh
- **DWh**: 5.9Ah
- **24Wh**

- **EOL Conditions** are 9Wh out, still a reserve of 5Wh charged or a reserve of 55% over demand
ACCELERATED GEO TESTING

50 TIMES

ACCELERATED GEO AT CONSTANT DOD

EVERY 50 CYCLES

DIAGNOSTICS
1. FULL SOC CAPACITY
2. RESIDUAL CAPACITY AT E.O.C.V.
3. IMPEDANCE
DD Cells GEO 60% DOD @ 25C   Discharge Capacity

Capacity @ 4.0V
Average Ah Loss 3.19E-04 Ah / Cycle

Capacity @ 3.85V
Average Ah Loss 2.9E-04 Ah / Cycle

8 DD cells with 9.2 Ah nominal capacity
Diagnostics were performed every 50 cycles
Curves shown are the capacity @4.0V during diagnostics

Accelerated Cycles:
Discharge @ 4.5A for 1.2 Hr or 5.4Ah
Charge for 4.8 Hr with 3.85V limit
DD Cells GEO 60% DOD @ 25C

**Internal Resistance**

- 8 DD cells with 9 Ah nominal capacity
- Diagnostics were performed every 50 cycles
- Curves shown are the Internal Resistances @3.75V during diagnostics

**Average mOhm /Cycle Increase**
- 3.E-04 mOhm / Cycle
- 1.2E-03 mOhm / Cycle

**Instantaneous Resistance**

<table>
<thead>
<tr>
<th>Cycle No.</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

**5 Minute Resistance**

<table>
<thead>
<tr>
<th>Cycle No.</th>
<th>0</th>
<th>500</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Diagnostics were performed every 50 cycles.

Curves shown are the capacity @4.0V during diagnostics.

Accelerated Cycles:
- Discharge @ 4.5A for 1.2 Hr or 5.4Ah
- Charge for 4.8 Hr with 3.85V limit

Average Wh Loss:
- 1.23E-03 Wh / Cycle
- 1.2E-03 Wh / Cycle

8 DD cells with 9 Ah nominal capacity

DD GEO 60% DOD @ 25C Energy

Cycle No.

Energy (Wh)
25°C 60% DOD GEO Cycling

- By EOL 1350 cycles, 5.4% Energy Loss
- 2800 cycles, 11.5% Energy Loss
LIMITED NO. OF CELLS ON OCV TEST

- Cells stored on open circuit at 50% SOC at ambient temperature which is reasonable since a cycling cell is on average at 50% SOC

- Capacity measurement conducted at ambient temperature

- Diagnostic tests performed for impedance and capacity

- After 2.5 years storage data shows almost no capacity loss or impedance growth yet, thus we are unable to quantitatively state a loss factor on this group of cells, but it will be very low.
DD 100% Depth of Discharge CYCLING @ -20°C

Charge @ C/10 to 4.1/4.0V with C/50 limit @ -20C
Discharge @ C/5 to 3.0V @ -20C (Cell 153 to 2.7V)

DD5-19,20 1M LiPF6 EC:DEC:DMC:EMC (1:1:1:2)
DD5-148,153 1M LiPF6 EC:DEC:DMC:EMC (1:1:1:3)
100% DOD

-20°C 100% DOD Cycling

- @ 4.0V Charge Limit Capacity loss is less than 4.1V Charge Limit
- @4.0V Charge Limit  
  17% loss at 1430 cycles
CONCLUSION

- 30% DOD LEO Cycling,
  Predicted 19% Energy loss by 40,000 cycles

- By EOL 1350 cycles, 5.4% Energy Loss
  2800 cycles, 11.5% Energy Loss

- 100% DOD at -25°C, 17% loss at 1430 cycles for 4.0V charge limit
Simulated LEO Cycling of AEA-STRV Lithium-Ion Battery Modules
2001 Update

Philip Johnson and Chuck Lurie
TRW Space and Electronics Group
Redondo Beach, California 90278

R. Spurrett
AEA Technology plc
Abingdon, Oxon., England

The 2001 NASA Aerospace Battery Workshop
Huntsville Hilton
Huntsville, Alabama
November 27 - 29, 2001
Scope

- Lithium-ion battery modules, similar to the modules flown on the STRV spacecraft, have been on test for almost three years.

- The modules, designed and assembled by AEA Technology plc, each contain twelve Sony 26650 cells.

- Characterization testing and LEO cycling through 7700 25% DOD cycles were reported at this workshop last year.

- This presentation summarizes the results of the simulated LEO cycling to date.
Test Articles

- STRV modules consist of two 6-cell strings of Sony 26650 cells.

- Test modules were reconfigured
  - one 6-cell string
  - two 2-cell strings
  - two individual cells

- Each cell is equipped with a thermocouple at its midpoint.
Test Plan
Simulated Leo Cycling

• Depth of Discharge: 25% (basis 2.7 Ah nameplate capacity)
• Orbit: 100 minutes with 36 minute eclipse periods
• Charge regime: 0.5C to CVL; taper until eclipse discharge
• Charge management: Pack level, e.g.,
  – 6-cell average voltage for the 6-cell packs
  – 2-cell average voltage for the 2-cell packs
  – individual cell control for the single cells
• Discharge: 0.42C (36 minutes)
• Two modules were tested; one at 25°C and one at 15°C
Test Setup

- COMPUTER PC
- THERMAL CONTROL CHAMBERS
- THERMAL CONTROL PLATES
- HP 3852
- DVM
- MUX
- RELAY CARD
- COMPUTER FAIL DETECTOR
- TEST CONTROLLER DATA LOGGER
- TEST CHANNEL ARCHITECTURE
- PROGRAMMABLE POWER SUPPLY
- PROGRAMMABLE ELECTRONIC LOAD
- 2 - 10X
- CELL TEST CHANNEL
- SENSING / DATA LOGGING
Simulated LEO Cycling Results

- 25°C End of Discharge Voltage trend charts
  - 6-cell pack
    - Became 5-cell pack at 9000 cycles
    - Discussion of unplanned event
  - 2-cell pack (typical of two)
  - single cells (both cells on one plot)

- 15°C End of Discharge Voltage trend charts
  - 6-cell pack
  - 2-cell pack (typical of two)
  - single cells (both cells on one plot)

- 6/5-cell pack dispersion analysis
  - EODV Trending
  - Rate of Change of EODV
  - EOCV Trending
25% DOD LEO Cycling at 25 Deg C
6/5-Cell Pack

- Min EODV
- Avg EODV
- Max EODV
- Min CVL
- Avg CVL
- Max CVL

Capacity charged
Capacity discharged

6-cell pack
5-cell pack

Residual capacity
0.076 Ah
0.29 Ah

Voltage (volts)
Capacity (ampere hours)

Cycles
Cell No. 4 Anomaly

- Cell 4 was at the lowest SOC of the 6 cells in the $25^\circ$C pack
  - 0.023 volts lower than the pack average at 25% DOD EOD
  - The test was started and run with about the same imbalance

- During test set configuration, following capacity discharge and CVL adjustment, the pack load went full-on driving cell 4 into reverse and terminating the test.

- The test was restarted manually, one time
  - e.g., the reversal event occurred twice.
Cell No. 4 Anomaly  

- Anomaly Data  
  - The events were short and only grab samples are available  
  - Duration, each event: 5 - 15 seconds  
  - Voltage, Current  
    - First: \( V = -7.8 \) volts, \( I > 10 \) amperes  
    - Second: \( V < -10 \) volts, \( I = 4.8 \) amperes  
    - Temperature excursions were negligible  

- The test was shut down  
  - The problem diagnosed and corrected  
  - No physical damage was observed and the test was resumed with Cell 4 in place  

- Performance was degraded and Cell 4 was removed from the test after \(~1700\) additional cycles
Cell No. 4 Performance Change
End of Discharge Voltage Following Anomaly

Average Cell Voltage, Nos 1, 2, 3, 5, 6
Average + 3s
Average - 3s
Cell No. 4 Voltage

CVL = 3.8 Volts
CVL = 3.9 Volts
Open Circuit
Cell No. 4 Performance Change
End of Discharge Voltage Following Anomaly -- Detail

- Average Cell Voltage, Nos 1, 2, 3, 5, 6
- Average + 3s
- Average - 3s
- Cell No. 4 Voltage

CVL = 3.8 Volts
CVL = 3.9 Volts
25% DOD LEO Cycling at 25 Deg C
2-Cell Pack

Capacity charged: 0.088 Ah
Capacity discharged: 0.29 Ah
Residual capacity: 0.09 Ah
25% DOD LEO Cycling at 25 Deg C
Single Cells

Voltage (volts)

Capacity charged, AEA83P2

Capacity charged, AEA83P5

Capacity discharged, AEA83P2

Capacity discharged, AEA83P5

Residual capacity: 0.086 Ah

0.29 Ah
25% DOD LEO Cycling at 15 Deg C
6-Cell Pack

Voltage (volts)

Capacity (amperes hours)

Cycles

Min EODV  Avg EODV  Max EODV
Min CVL  Avg CVL  Max CVL
Capacity charged  Capacity discharged

Residual capacity  0.16 Ah  0.43 Ah

0.16 Ah  0.43 Ah
25% DOD LEO Cycling at 15 Deg C
2-Cell Pack

Voltage (volts)

Capacity charged

Capacity discharged

Residual capacity 0.17 Ah 0.43 Ah

Capacity (ampere hours)

Cycles

0 2000 4000 6000 8000 10000 12000 14000

AEA84P3 Cell 1 EODV

AEA84P3 Cell 2 EODV

AEA84P3 Cell 1 CVL

AEA84P3 Cell 2 CVL
25% DOD LEO Cycling at 15 Deg C
Single Cells

Residual capacity
0.18 Ah
0.45 Ah

Capacity charged, AEA83P5
Capacity discharged, AEA83P5
Capacity charged, AEA83P2
Capacity discharged, AEA83P2

Voltage (volts)
Capacity (ampere hours)
EODV Dispersion Trending

AEA STRV 6-Cell Packs at 15°C and 25°C

-0.050 -0.025 0.000 0.025 0.050 0.075 0.100 0.125

0 2000 4000 6000 8000 10000 12000 14000

Cycles

0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75

EODV CV (%)

-0.025 0.000 0.025 0.050 0.075 0.100 0.125

25C pack is 6 cells 25C pack is 5 cells

6/5-Cell Pack AEA83P1, Range, 25C (volts)
6-Cell Pack AEA84P1, Range, 15C (volts)
6/5-Cell Pack AEA83P1, Coefficient of Variation at 25C (%)
6-Cell Pack AEA84P1, Coefficient of Variation at 15C (%)

6/5-Cell Pack AEA83P1, Range, 25C (volts)
6-Cell Pack AEA84P1, Range, 15C (volts)
6/5-Cell Pack AEA83P1, Coefficient of Variation at 25C (%)
6-Cell Pack AEA84P1, Coefficient of Variation at 15C (%)
EOCV Dispersion Trending

AEA STRV 6-Cell Packs at 15ºC and 25ºC

- 6-Cell Pack AEA83P1, Range at 25 Deg C (volts)
- 6-Cell Pack AEA84P1, Range at 15 Deg C (volts)
- 6-Cell Pack AEA83P1, Coefficient of Variation at 25 Deg C (%)
- 6-Cell Pack AEA84P1, Coefficient of Variation at 15 Deg C (%)

EOCV Range (volts)

EOCV CV (%)

Cycles
Summary

• Simulated 25% DOD LEO cycling of AEA STRV battery modules is continuing at 15°C and 25°C
  – The STRV “two 6-cell strings” configuration was modified to provide 6-cell strings, 2-cell strings and individual cells.
  – Charge control is at the pack level.
• > 13000 cycles have been completed.
• A significant cell reversal anomaly occurred and has been described.
• EOD and EOC voltage dispersion (in the absence of cell level balancing) is stable and similar for all packs.
• The test is continuing.
PROBA, The First ESA Spacecraft Flying Lithium-Ion

M. Schautz, D. Olsson & G. Dudley
European Space Technology Centre (ESTEC)
A. Holland (AEA Technology)

Contents:
Proba overview
Battery design
In-orbit performance
PROBA Objectives

- **PRoject for On Board Autonomy:**
  - Onboard resource management, housekeeping
  - Scheduling and execution of scientific observations
  - Scientific data collection, storage, processing & distribution
  - Data communication management
  - Performance evaluation, failure detection
  - Failure detection, reconfigurations, software exchanges

- **Payload:**
  - Compact High Resolution Imaging Spectrometer (CHRIS)
  - Space radiation Environment Monitoring (SREM)
  - Debris in orbit evaluator (DEBIE)

- **Technology Demonstration:**
  - GPS receiver for navigation and attitude determination
  - High resolution camera (HRC) and wide angle camera (WAC)
  - Autonomous star tracker
  - High performance computer
  - Lithium ion battery (BAT)
Spacecraft Overview

- **Mass:** 95 kg
- **Dimensions:** 600 x 600 x 800 mm
- **2 yr mission**
- **Polar (97.8 deg), 600 km orbit**
- **3-axis stabilised**
  - Attitude detection by star tracker + GPS-based attitude sensor + 3-axis magnetometer
  - Control by magneto-torquer + reaction wheels
- **Radiation-hard version of SPARC V7 processor (10 MIPS)**
- **No propulsion (2 deg/yr drift from sun-synchronism acceptable)**
- **No heaters (passive T/C)**

NASA Aerospace Battery Workshop 27-29 Nov. 2001
• Regulated 28V bus with $S^3R$ control (heritage from STRV)
• Body-mounted GaAs SA (90W peak)
• Triple redundant majority-voting PCU

• Dual redundant BCRs and BDRs
• Single 9 Ah Lithium-Ion Battery
• Each PDU output has current-limiter. SO also have PCU-controlled switch

NASA Aerospace Battery Workshop 27-29 Nov. 2001
Battery Choice for PROBA

- Originally specified Ni-Cd battery, using spare ESTEC stock of 7 Ah cells to be packaged into battery similar to Meteosat-1.
- 21y old freezer-stored Ni-Cd cells were found still to have nominal performance!
- But marginal capacity with respect to needs and high mass (6.4 kg compared to 1.9 kg for Li-Ion)
- Small Li-ion battery concept from AEA Technology already qualified.
- Less critical pre-launch and integration handling constraints.
- Opportunity to fly Li-ion quickly.
- Added as a technology demonstration but confidence sufficient to rely entirely on single lithium ion battery.
Lithium ion battery development

- Use of commercial off-the-shelf (COTS) SONY hard-carbon cells for space introduced by AEA Technology for STRV 1d (launched Nov. 99) in the frame of a UK national programme sponsored by the BNSC.

- Battery concept developed qualified for small-medium applications by AEA Technology under UK-funded ESA GSTP contract in 1997-1998. This included comprehensive lot acceptance testing philosophy required to overcome reduced configuration control associated with COTS components

- Ground life-testing at ESTEC very promising (ongoing tests have now reached >16000 30% DoD LEO cycles)

- Confirmation obtained that cells remain balanced in state of charge without need for adjustment by electronics

- EM + PFM batteries for Proba provided under rider to above contract starting Jan. 2000

- Battery PFM qualification completed Nov 2000
Cell Stringing Approach

“Conventional” stringing

High capacity cells

1.5 Ah cells

Cell bypass

AEA/SONY PROBA 6s6p battery. Any cell failure leads (eventually) to loss of 1 (redundant) series string. No cell bypass necessary.
Battery Construction

36 Sony 18650 HC cells glued into insulating GRP plates. Spot-welded nickel cell interconnects. Ni-plated copper bus bar

Exploded view
PROBA Battery

- Mass: 1.87 kg
- Specific energy: 104 Wh/kg
- GRP cell-holding plates supported in aluminium structure.
- Cell interconnects protected by Kapton sheets.
- Single-point failure tolerant design.
- Shown mounted on interface plate (Verhaert) providing thermal decoupling from spacecraft
Proba Schedule

- 10 M€ program funded from ESA General Study Technology Program (GSTP)
- Kicked off February 1998
- Prime contractor: Verhaert Design and Development (Belgium)
- SDR June 1998
- FAR July 2001
- Launched from Shriharikota (India) on PSLV Oct 22 2001
- Currently in checkout / calibration phase
- One ground station (Redu Belgium)
Launched together with Bird (German minisatellite) as piggyback payload to Indian experimental remote sensing satellite.
Early in-flight battery performance

Charge terminates when battery voltage including harness voltage drop reaches programmable limit (taper charge not operational). DoD expected to increase from 8% to 15% in operational phase.

NASA Aerospace Battery Workshop 27-29 Nov. 2001
Early in-flight battery performance (2)

Battery currently cold because of limited payload use during check-out phase (no heaters)
Conclusions

Battery performance is nominal

Lithium-ion batteries are baselined for most future European programmes including Stentor, Rosetta (+Roland lander), Mars Express (+Beagle lander), Smart-1, Cryosat, GOCE, Netlander ...etc.

First European Spacecraft to rely entirely on lithium ion battery is now in orbit.
Life Test Results with Adaptive Charge Control

Albert H. Zimmerman* and Michael V. Quinzio
Electronics and Photonics Laboratory
The Aerospace Corporation
El Segundo, California USA 90245

Abstract

Adaptive charge control has been developed to enable a power system to automatically sense the recharge needs of each cell in its complement of batteries, and to provide only the recharge that that cell requires. This enables the charge control system to handle any imbalances in performance behavior between the cells, to minimize the stress on each cell, and to automatically adjust recharge behavior according to the cell’s changing needs over life. Results will be presented from thermal vacuum life tests on Li-ion cells, from a life-test running Li-ion cells in the same pack as nickel cadmium and nickel metal hydride cells, and from a nickel hydrogen life test. Adaptive charge control has demonstrated the capability to optimally operate cells having widely different behavior in the same battery pack.

Introduction

An Adaptive Charge Control (ACC) technique has been developed at The Aerospace Corporation\(^1\) that is capable of determining and maintaining the correct amount of recharge needed by battery cells as they are charged and discharged over their lifetime. As a battery cell is operated in a power system, the ACC determines the amount of recharge required by each cell to keep that cell at a required operating voltage level. As each battery cell ages or otherwise changes its performance, the ACC automatically adjusts the recharge to both maintain performance while eliminating any unneeded overcharge. The basis for this charge control method is the following general conclusion that we have come to - that any unneeded overcharge on a battery cell produces a significant stress that contributes to wear out and that can be avoided.

The basis for the ACC system is the use of a recharge fraction specific to each individual cell in a battery. When the prescribed recharge fraction is reached for a cell, all recharge current is shunted around that cell but remains available to recharge other cells that may need more recharge. The needed recharge fraction for each cell is based on where the minimum discharge voltage and peak recharge voltage levels are relative to an operational voltage band consistent with cell performance and the minimum voltage level needed from each cell for the power system. The ACC allows this voltage band to expand if needed to accommodate changes in cell performance over life. Within the ACC paradigm, cell failure occurs when a cell cannot deliver the required capacity above the minimum system level voltage and when the cell cannot be recharged without exceeding maximum safe levels for recharge voltage and recharge fraction. Thus, not only will the ACC respond to changes in cell performance due to aging, but it will also
automatically adjust for any variations in temperature, charge current, or current measurement accuracy that may affect battery performance.

Here we describe three different battery life tests that demonstrate the features and capabilities of the ACC system, as well as providing a useful database for the performance of a range of battery cells operating in a minimum stress cycling mode. The first of these tests demonstrates the use of the ACC system in a thermal vacuum test of a mockup nanosatellite power system. This system operates a 2-cell lithium-ion battery having a capacity of 0.8 Ah, and operating with a predicted diurnal nanosatellite temperature swing at 20% DOD. The second test is designed to demonstrate the ability of the ACC system to correctly adapt to the disparate charge needs of cells having widely different performance behavior, but still operating successfully in a single battery pack. This test puts two 7 Ah lithium-ion cells, two 7 Ah NiCd cells, and two 7 Ah NiMH cells in a single battery pack and operates them in series at 5 deg C and 20% DOD. The ACC system is expected to adapt to the needs of each of these cells and operate it in an optimal way over its cycle life. This test also provides the first head-to-head comparison between lithium-ion, NiCd, and NiMH cells when operated under identical charge control and environmental conditions. The final test applies the ACC system to five 60 AH advanced nickel hydrogen cells operated at –5 deg C and 60% DOD. Here the ACC system is used to minimize the overcharge stresses that have contributed to early failure in numerous other 60% DOD life tests of nickel hydrogen cells.

**Nanosatellite Power System Mockup Test**

This test uses two commercial lithium-ion cells having a 0.8 Ah capacity. The cells are sealed with thermally conductive RTV into a layer within the middle of a spherical nanosatellite mass simulator made of pure silicon. The cells were instrumented for both voltage and temperature measurements. The mockup was placed in a thermal vacuum chamber and operated in a 90-minute orbit; 30 minutes in eclipse and 60 minutes in the sun. During the entire orbit the bottom of the spherical mockup was cooled using a cooling plate that was held at 13-14 deg C. During the sunlit part of each orbit the temperature was raised with a heater on the top of the spherical mockup. Typically, the battery cell temperature varied about 8 deg C, between about 16 and 24 deg C, during each orbit. Discharge during each eclipse period was at 320 ma, providing a 20% DOD. Figure 1 shows the battery cells in an aluminum holder before being sealed into the spherical silicon mockup.

Figure 2 shows the end of discharge and end of charge voltage performance of these cells during the course of this life test. Cell recharge is done at 320 ma until a 0.75 recharge fraction is reached, then recharge is continued at a rate chosen by the ACC system to allow all cells to reach their prescribed recharge fraction about 1-2 minutes before the end of the sunlit period. Since each cell goes to zero current when the prescribed recharge fraction is attained, the end of charge voltage shown in Figure 1 is for a charged cell at zero current. Peak cell recharge voltages are presently 4.01 to 4.03 volts at the 320-ma recharge rate. The life test is planned to go until cell failure is reached. Failure for a cell is defined as occurring when the peak charge voltage goes above 4.1 volts while in the same cycle the end of discharge voltage drops below 3.0 volts.
Figure 1. Bottom Hemisphere of Nanosatellite Mockup Showing lithium-ion Cells.

Figure 2. End-of-Charge and End-of-discharge voltages for lithium-ion cells in nanosatellite mockup life test.
An indicated earlier, the recharge fraction is the principal means of maintaining the state of charge of each cell, while avoiding unnecessary overcharge. For lithium-ion battery cells, which have very low self-discharge rates, a recharge fraction near 1.00 is anticipated as the desirable charge control point. As indicated in Figure 3, the ACC system does in fact establish an average recharge fraction level within measurement error of 1.0 for each cell. The oscillatory behavior of the recharge fraction for the first approximately 6500 cycles of the test was because the charge control algorithm did not have the recharge fraction damping-mode activated. This mode basically prevents any change in the prescribed recharge fraction of a cell if the cell peak recharge and minimum discharge voltages are already drifting in the desired direction. As demonstrated around cycle 7000, this feature stabilizes the recharge fraction so that it does not overshoot the needed level. Much of the noise seen in the recharge fraction arises from the thermal fluctuations seen by these cells, as well as cycle-to-cycle fluctuations in performance.

It should be noted that a fixed recharge fraction could not be used for controlling these cells. The actual recharge fraction needed is most likely closer to 1.00 than can be accurately measured. Thus, the choice of any fixed recharge fraction will eventually result in either undercharge or some small amount of long-term overcharge. Either of these situations is undesirable for lithium-ion battery cells.

The end of life for these cells occurs when the voltage during one cycle swings from 4.1 volts during recharge, to 3.0 volts during discharge, which is a 1.1-volt swing. Figure 4 shows the delta between the peak recharge voltage and the minimum discharge voltage. This delta is slowly increasing as the cells are cycled. Extrapolation to 1.1 volts gives an indication of the expected cycle life for these cells, about 25,000 to 30,000 cycles.

![Figure 3. Recharge fractions for lithium-ion cells in nanosatellite mockup life test.](image-url)
ACC Demonstration in Mixed Cell Pack

The ACC system is theoretically capable of responding to any cell type or chemistry to find the most appropriate recharge conditions for that cell. To evaluate this capability in a battery pack that contains mismatched cells, a pack was built that contained two 7 Ah lithium-ion cells, two 7 Ah NiCd cells, and two 7 Ah NiMH cells. Each of these cell types should require significantly differing charge management for optimum life. In addition, the cells were obtained from commercial sources, and no attempts were made to match cell performance characteristics. This test pack was put in a life test at 5 deg C using a 20% DOD cycle with 30 minutes for discharge and 60 minutes for recharge. The recharge current returned 75% of the recharge in 30 minutes, then dropped back to a lower recharge rate appropriate to attain the highest cell recharge fraction 1-2 minutes before the end of the recharge period. After each cell reached its prescribed recharge fraction, all current was shunted around that cell, effectively putting it at zero current.

Figures 5-7 indicate the end of discharge and peak recharge voltages for the NiCd, NiMH, and Li-ion cells respectively in this test pack for the 2400 cycles presently completed. It should be noted in Figs. 5 and 6 that the NiCd and NiMH cells are not closely matched to each other. All cells have stabilized at 1850 cycles.
Figure 5. End-of-discharge and peak recharge voltages for the two NiCd cells in the mixed cell test.

Figure 6. End-of-discharge and peak recharge voltages for the two NiMH cells in the mixed cell test.
The ACC system has in fact adapted to the recharge requirements of each of these three cell types quite well. Figure 8 shows for each cell type the recharge fractions that the ACC system found to be needed for optimized charge maintenance. As anticipated, for the lithium-ion cells the recharge fraction is within measurement accuracy of 1.000. It is interesting that the recharge fraction for the two lithium-ion cells has dropped slightly as they are cycled. Whether this is due to changes in the cells or to a drift in the charge control electronics cannot be established at present, however the ACC system has in fact found that this slight shift is required to maintain optimum charge control. The NiCd and NiMH cells have settled on a recharge fraction of about 100.5%, which is significantly lower than is traditionally used in life tests of these cell types. Clearly for these nickel electrode based cells, the ACC system has adopted a minimum stress recharge protocol that has eliminated all unneeded overcharge.

Trending of the data from this pack as the cells degrade is best done by following the difference between the minimum discharge voltage and the peak recharge voltage for each cell. This plot is shown in Fig. 9. Each cell has stabilized with a slight upwards slope in this plot. The cell failure levels in Fig. 9 are about 0.52 volts for the NiCd and NiMH cells, and 1.1 volts for the Li-ion cells. If the slopes seen in Fig. 9 are extrapolated to these failure conditions, the Li-ion cells should give about 65,000 cycles, the NiCd cells 34,000 cycles, and the NiMH cells 24,000 cycles.

![Figure 7. End-of-discharge and peak recharge voltages for the two lithium-ion cells in the mixed cell test.](image-url)
Figure 8. Recharge fractions for the six cells in the mixed cell test.

Figure 9. Difference between peak recharge and minimum discharge voltages for lithium-ion cells in the mixed cell test.
Advanced Nickel Hydrogen Cell Test

A recently completed project has provided a correlation between life test performance for nickel hydrogen battery cells and cell design variables, test environment, and charge control protocols. These results indicated that maximum NIH₂ lifetime performance could be obtained by using 26% KOH, cold operation (-5 deg C), and minimizing overcharge. In addition, the use of a dual anode stack arrangement decreases the superficial current density on the nickel electrodes and the ionic diffusion path lengths by a factor of two. A single layer of zircar separator in the dual anode stack provides just as much electrolyte volume in the stack as does the double layer zircar separator in a back-to-back stack design. However, the ionic conduction path through the single layer of zircar is 50% as long. The use of separate leads from each nickel electrode further reduces cell impedance. An axial terminal design provides matched resistances between the stack units over the entire length of the stack. The cells are mounted with a thermal conduction flange at their center, thus minimizing thermal gradients through the stack length.

Five 60 Ah cells of this design were put into a stressful life test involving 60% DOD and 16 cycles per day. The test temperature was set such that the average cell temperature (top of stack) was -5 deg average at the end of recharge. Each cycle involved discharge for 30 minutes, followed by recharge for 60 minutes using the ACC system in its auto taper mode. In this mode, which is most appropriate for high DOD cycling where charge must be returned quickly, recharge is started at a peak rate (C rate in this test). When the voltage of any cell rises to within 1 mv of a specified peak voltage target, the current is cut back (10% in this test). This process continues until any further reduction in current would prevent the required recharge fraction from being attained for any cell. When this occurs, the current is simply set at the level needed to return the needed recharge fraction, and the voltage is allowed to rise with no further changes in current. If the voltage goes above the target peak charge voltage level, the recharge fraction may be decreased if the cell also remains above the target minimum discharge voltage, or the peak recharge voltage target may be increased if the cell has gone below the target minimum discharge voltage. This mode essentially provides a software current taper based on the voltage behavior of the individual cells in the test pack.

The cells were started cycling after recharge to about 80% state-of-charge. The ACC system was set such that the target minimum discharge voltage was 1.10 volts for each cell and the peak recharge voltage target was 1.50 volts. This corresponds to cycling between about 5% and 65% state of charge. This cycling range was chosen to provide the Ah throughput while minimizing overcharge of the cells. For the first several hundred cycles, the ACC system allowed the cells to slowly run down to the desired state-of-charge range. This is indicated in Figures 10 and 11, which show the end-of-charge voltage and the recharge fraction over the first 1000 cycles. After about 260 cycles the cells had dropped down to the desired state-of-charge range, and have proceeded to stabilize. While we have insufficient stable data to extrapolate meaningfully to the end of life, the difference between the minimum discharge voltage and the peak recharge voltage may be plotted to trend cell changes over life. This plot is shown in Figure 12, where a voltage difference of about 0.58 corresponds to cell end of life. At these temperatures and cycling conditions, these cells need only about 100.3% recharge ratio for stable performance.
Figure 10. End of discharge voltages for NiH$_2$ cells test in advanced dual-anode test.

Figure 11. Recharge fractions for NiH$_2$ cells test in advanced dual-anode test.
Conclusions

The ACC system for automatically maintaining the optimum recharge protocol in a power system has been demonstrated to effectively manage a wide variety of battery cells, and to handle wide variability between cells in the system. The ability of the charge control system to maintain a truly minimum stress condition is illustrated by the exceptionally low recharge fractions that the ACC system has selected as appropriate for nickel hydrogen, nickel cadmium, and nickel metal-hydride cells. For lithium ion cells the ACC system has rapidly zeroed in on a recharge fraction within measurement error of 1.000, as desired for cells that have no tolerance for overcharge.

These tests will continue to the point where the cells fail, which if present trends continue should be well beyond 50,000 cycles for the lithium-ion cells. The lithium-ion cells are presently out-performing the NiCd cells, which are performing better than the NIMH cells. The nickel hydrogen cells cycling at 60% DOD have a target of 60,000 cycles in this test, but will continue to the point where all cells have failed.
Acknowledgements

The Aerospace Corporation is gratefully acknowledged for supporting this work as part of the Aerospace IR&D Program.

References

A DUAL MODE LITHIUM ION BATTERY CHARGE CONTROLLER

NASA Aerospace Battery Workshop
November 27-29, 2001
Overview

- Design concept was initially developed to support launch and orbital activity for a reusable space vehicle.
- Charging to be performed pre-launch and in orbit while docked.
- Design consists of two elements: An on-board system and an external system.
Two Common Approaches for Lithium Ion Chargers

- Battery Level Chargers
  - Advantages: Simpler and cheaper
  - Disadvantages: Lacks cell balancing

- Cell Level Chargers
  - Advantages: Cell balancing for improved life and performance
  - Disadvantages: More complex, higher cost and thermal issues
Dual Mode Lithium Ion Charger

Uses a combination of the two approaches:

- Bulk charge with control and termination based on the cell and/or battery level
- Cell balancing charge with control and termination based on cell level
Proposed Charge Steps

- Bulk charge at C/5 or greater until predetermined cell and/or battery voltage level
- Bulk charge at C/10 or greater until predetermined cell and/or battery voltage level
- Cell balancing charge at C/100 or greater with current control and termination at cell level
Charger System Description

- Two subsystems
  - Battery Management System (BMS)
    - On-board the battery
    - Provides charge control at cell level
  - External Current Source (ECS)
    - External Current Source/Sink
    - Provides bulk charge/discharge current to battery/BMS
BMS Requirements

- Input Power: From ECS
- Environment:
  - Operating: Pre-flight
  - Non-operating: Flight
- Communication: Serial data link to ECS
- Protection: Battery and individual cell monitoring
ECS Requirements

- Input Power: 120VAC, 60Hz
- Operating Environment: Ground, sheltered
- Communication:
  - Serial data link to BMS
  - Operator interface
- Protection: Battery monitoring and BMS serial data link
- Added Function: User selected battery via hardware or software tag
Projected BMS Hardware

- Embedded controller with A/D, digital I/O and SPI
- Mechanical relay for bulk current enable/disable
- Isolated constant current sources for each cell
- Voltage sense and conditioning
- Enclosure and filtering for environmental and EMC protection
- Connectors for charger to battery integration
Projected ECS Hardware

- Embedded controller with D/A, digital I/O, SPI and user interface
- Current source and Load bank
- System power supply
- Fan/heatsink cooling system
- System enclosure for environmental and EMC protection
- Connectors for charger to umbilical integration
Summary

- Concept attempts to achieve “best of both worlds”
- Cell balancing at lower current removes large heat source from the battery system
- External subsystem reduces on-board mass and provides convenient user interface
- Embedded controllers provide for greater flexibility
Impact of Charge Methodology Upon the Performance of Lithium Ion Cells

M. C. Smart, B. V. Ratnakumar, L. Whitcanack, K. Chin and S. Surampudi

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

NASA Battery Workshop
Huntsville, Alabama
Nov. 27, 2001
Outline

- Introduction
- Charge Characteristics of Lithium Ion Prototype Cells
  - Charge Rate Characteristics at Different Temperatures
  - Effect of Charge Methodology Upon Cycle Life Performance
  - Effect of Charge Voltage Upon Cell Performance
    - Impact upon Low Temperature Performance
    - Impact of Charge Voltage at High Temperature
- Charge Characteristics of Three-Electrode Cells
  - Charge Characteristics at Low Temperature
- Charge Characteristics of Lithium-Ion 8-Cell Battery
- Conclusions
- Acknowledgements
Lithium-Ion Cells for NASA and DoD Applications: Program Objectives

- Assess viability of using lithium-ion technology for future NASA and Air Force applications.

- Demonstrate applicability of using lithium-ion technology for future Mars Lander and Rover applications.
Lithium-Ion Cells for NASA and DoD Applications:
Summary of General Characterization Tests On-Going at JPL

- Cycle life performance at room temperature (25°C)
- Cycle life performance at low temperature (-20°C)
- Discharge rate characterization (at 40, 25, 0, and -20°C)
- Charge rate characterization (at 40, 25, 0, and -20°C)
- Capacity retention characterization tests
- Storage characterization tests (cruise conditions)
- Pulse capability tests (Entry Descent and Landing)
- VT charge characterization tests
- Electrical characterization by a.c. impedance
- LEO and GEO characterization tests
- Thermal characterization (microcalorimetry)
Charge Characteristics of Prototype Lithium Ion Cells

• Charge acceptance at various rates and temperatures
  • Various chemistries, cell designs and sizes studied
  • Range of charge rates investigated (C/20 to C rate)
  • Range of temperatures investigated (-40°C to +40°C)

• Effect of Charge Methodology Upon Cycle Life Performance
  • Effect of charge voltage
  • Effect of taper current cut-off
  • Effect of storage on the bus (float charging)

• Effect of charge voltage upon cell performance
  • V/T characterization
• Depending upon the chemistry employed (i.e., cathode and anode type) the voltage profile on charge and discharge can be distinctively different.
Lithium-Ion Cells for Mars Surveyor 2001 Lander
Room Temperature Charge Characteristics

25 Ahr MSP01 Design Lithium-Ion Cell

- Cell charged to 4.1 V
- Constant potential charge to C/50
- Temperature = 23°C

Charge Capacity (Ah)

Time (Hours)

2.5 A Charge current (C/10)
7.5 A Charge current (C/3.3)
12.5 A Charge current (C/2)
5.0 A Charge current (C/5)
Lithium-Ion Cells for Mars Surveyor 2001 Lander
Low Temperature Charge Characteristics (-20°C)

25 Ahr MSP01 Design Lithium-Ion Cell

Cell charged to 4.1 V
Constant potential charge to C/50

Temperature = -20°C

- 2.5 A Charge current (C/10)
- 5.0 A Charge current (C/5)
- 7.5 A Charge current (C/3.3)
- 12.5 A Charge current (C/2)
Lithium-Ion Cells for NASA and DoD Applications: Charge Capacity as a Function of Temperature

Prototype 25 Ahr Lithium-Ion Cell

Charge Capacity (Ah)

5.0 A Charge Current (C/5) to 4.1 V

Cell charged to 4.1 V
Constant potential charge to C/50

* C/5 Charge Current

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Large Capacity Lithium-Ion Cells for Mars Lander Applications
Charge Characteristics as a Function of Temperature

- At lower temperatures, significantly more capacity is obtained while the cell is in the taper mode (constant potential charging).

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With a fresh cell, the impact of the taper current cut-off value does not have a dramatic impact upon charge capacity (given that it is <C/30 and the constant current charge is of moderate rate (<C/5)).
Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Taper Current on Charge Characteristics

- At low temperatures (-20°C), approximately 6% more capacity is obtained with an extended “taper mode” vs. C/50 cut-off.

Diagram:
- Temperature = -20°C
- Charge Capacity (Ahr) and Cell voltage (V)
- 20.561 Ahr
  C/50 Current Cut-Off
- 21.850 Ahr
- 2.5 Amp Charge to 4.1 V
- Constant Potential Charge:
  (a) C/5 Current Cut-Off
  (b) C/125 or 24 Hours
Later in cell life, significantly more time is spent in the taper mode (constant potential charging) while being charged.

Due to increased impedance, the overall charge time can increase (even though capacity has declined with cycling).

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Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Cycle Life on Charge Characteristics

- Later in cell life, the impact of the selected taper current cut-off value upon charge capacity is more dramatic (due to increased cell impedance and poorer lithium intercalation/de-intercalation kinetics)
Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Taper Current on Charge Characteristics

- Extended taper charging appears to limit cycle life characteristics (similar to floating at high V).
- Capacity decline most likely due to enhanced impedance build-up and increased electrolyte oxidation.
Lithium-Ion Cells for NASA and DoD Applications: Storage Characteristics of a 25 Ahr Cell - Results of 11 Month Storage Test

Cell Stored on the Buss at 10°C (70% SOC)

Yardney 25 Ah MSP01 Lithium-Ion Cell
Cell Stored at 70% State-of-Charge
Temperature = 10°C

Cell Y018

3.875 V
Lithium-Ion Cells for NASA and DoD Applications:
Storage Characteristics of a 25 Ahr Cell- Results of 11 Month Storage Test
Cell Stored on the Buss at 10°C (70% SOC)

- Float charging (storage on the bus) results in minimal cell performance degradation if a moderately low voltage (low SOC) is selected.
Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Charge Voltage on Charge Characteristics

- Selected charge voltage has a more dramatic impact upon charge capacity at lower temperatures.
- Although charging to higher voltages yields higher capacity, it may also be accompanied by undesirable effects (i.e., electrolyte oxidation and/or lithium plating)
Large Capacity Lithium-Ion Cells for Future Mars Applications
Effect of Charge Voltage on Cycle Life Characteristics

- **4.20 V Charge Voltage**
  - 5.0 Amp Charge current (C/5)
  - C/50 Taper Current Cut-Off
  - Temp = 23°C
  - Capacity fade rate = 0.029 %/cycle
  - 83.9% of Initial capacity after 500 cycles

- **4.10 V Charge Voltage**
  - 5.0 Amp Charge current (C/5)
  - C/50 Taper Current Cut-Off
  - Capacity fade rate = 0.022 %/cycle

Discharge Capacity (Amp-Hour)

Cycle Number
An increase in cell impedance and a decrease in low temperature performance capability was observed upon cycling between two temperature extremes.

It was ascertained that the charge voltage at high temperature can influence trend.
Lithium-Ion Cells for NASA and DoD Applications:
Rover Cell Design - Variable Temperature Cycling

Discharge Capacity

- Using lower charge voltages at high temperatures was observed to preserve the low temperature performance capability and extend life characteristics.
Lithium-Ion Cells for Mars Lander Applications
Mission Simulation Cycling (Temperature Range = -20 to +40°C)

- Under typical Mars surface operation conditions, the cell (battery) charging process can occur over a range of temperatures.

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Lithium-Ion Cells for Mars Lander Applications

Mission Simulation Cycling

- If the cell/battery charging begins when the temperature is the coldest (-20°C), representing a worst case scenario, high charging currents (> C/5) cannot be sustained.
- However, due to the constant potential current taper mode, full charge is accomplished.

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Charge Characteristics of Experimental Lithium Ion Cells (Three Electrode Cells)

• Cell Design/Chemistry
  • MCMB anodes and LiNiCoO$_2$ cathodes
  • Cells equipped with Li metal reference electrodes
  • Number of different electrolyte studied (esp. low temp)
  • 300-400 mAh size cells
  • Jelly roll design (cylindrical)

• Charge acceptance at various rates and temperatures
  • Effect of charge voltage
  • Effect of charge current and taper current cut-off
  • Effect of electrolyte (and corresponding SEI layers formed) upon charge characteristics
  • Identification of conditions which lead to lithium plating
Formation Characteristics of a MCMB-LiNiCoO$_2$ Cell
Fabricated with JPL Quaternary Carbonate Low Temperature Electrolyte

- Three-electrode cell design enables one to determine individual electrode potentials in addition to the cell voltage.
Formation Characteristics of MCMB-LiNiCoO$_2$ Cells
Fabricated with JPL Quaternary Carbonate Low Temperature Electrolyte

Anode Potential During Charge

- Upon charge, the anode electrode potential is typically between 0.025-0.250 V at 23°C.
- During cell formation, initial charge goes to forming protective SEI layer.
• At low temperatures, the anode potential can become negative with respect to Li⁺/Li.
As shown, the point at which the anode potential becomes the most negative (~ -70mV vs. Li+/Li) is when the charge voltage and current are highest.
Effect of Charge Rate Upon Electrode Polarization Behavior of Li-Ion Cells: Charge Characteristics at Low Temperature

-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15

Anode Potential (V vs. Li⁺/Li)

• As shown, the anode potential becomes more negative when higher charge currents are used at low temperature

Temperature = -20°C

1.0 M LiPF₆ EC+DEC+DMC+EMC (1:1:1:3)
Anode Electrode

A ▲ 50 mA Charge Current to 4.1 V
B ● 70 mA Charge Current to 4.1 V
C ▲ 135 mA Charge Current to 4.1 V

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• Although the anode potential became negative, no lithium plating was observed with this cell in the subsequent discharge profiles.
• This might be due to the fact that the potentials were not sufficiently negative and/or any lithium plated on the electrode surface had time to intercalate during the taper mode.
In some cases, the anode can be excessively polarized in contrast to the cathode resulting in the possibility of lithium plating occurring.

In this example, the anode potential never becomes positive during entire charge.
Effect of High Temperature Exposure on MCMB-LiNiCoO$_2$ Cells

Effect of Electrolyte Upon High Temperature Resilience

- **Room Temperature Charge**
- **Charge at -20°C (70 mA)**
- **Charge at -20°C (135 mA)**

**Electrolyte:**
- 1.0 M LiPF$_6$ EC+DMC+EMC (5:3:2)

Temperature = -20°C

Evidences of Lithium Plating
Tafel Polarization Measurements of MCMB and LiNiCoO$_2$ Electrodes
Effect of Electrolyte upon Polarization at Different Temperatures

- Tafel polarization measurements allow further insight into the kinetics of lithium intercalation/de-intercalation on MCMB anodes and LiNiCoO$_2$ cathodes in these electrolytes.

- These measurements were made at scan rates slow enough (0.5 mV/s) to provide near-steady state conditions and yet with minimal changes in the state of charge of the electrode or its surface conditions.

- The cells were tested in near full state of charge and biased over a 150 mV range.

- Both anode and cathode polarization characteristics were measured at various different temperatures (23, 0, -20 and –40°C).

In most cases, the cathode displays poorer kinetics and is performance limiting.

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Linear Micropolarization Measurements

* At low overpotentials ($<$RT/αnF) the electrochemical rate equation can be linearized resulting in a linear current-potential relation.

* The curves were obtained under potentiodynamic conditions at scan rates of 0.02 mV/sec.

* The polarization resistance, or the exchange current density, can be calculated from the slopes of the linear plots.

* The electrodes were tested in near full state of charge and biased over a 10 mV range.

* The resulting polarization resistance value is indicative of the facility of both the lithium intercalation and de-intercalation processes in the material (encompassing Li+ diffusion through the SEI layer as well as bulk diffusion in the carbon electrode).

▷ Polarization resistance is observed to be higher for the cathode with most systems.
▷ Good tool to investigate kinetics at different temperatures as a function of electrolyte type
Tafel Polarization Measurements of MCMB and LiNiCoO$_2$ Electrodes
Effect of Electrolyte upon Polarization at Different Temperatures

- In the case where no lithium plating was observed (good low temp electrolyte), the cathode was observed to have poorer kinetics at low temperature.
- Whereas, in the case where lithium plating was observed (poor low temp electrolyte) the anode displayed poorer kinetics and increased polarization.

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Charge Characteristics of Prototype Lithium Ion Batteries

• **MSP01 Yardney 8-Cell Lander ATLO battery testing**
  • Lander battery is being tested according to a Mars mission simulation profile
  • Test plan reflects needs and requirements of ‘09 Smart Lander
  • Test plan includes initial characterization, cruise period, EDL profile, and surface operation profile.

• **Charge Control**
  • 25 Ahr 8-cell battery (24-34.4 V)
  • Battery voltage controlled charging
  • Constant current and constant potential charging
  • Individual cell monitoring
  • Battery protection limits
    • Individual cell voltage exceeded (> 4.2 V)
    • Temperature limits exceeded (> 50°C for any input)
    • Charge/discharge capacity limit (>35 Ahr)
    • Step time (> 10 hours)
  • Battery cell balancing methodology (TBD)
    (i.e., resistively discharging cells to specified voltage)
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Lithium Ion Technology Demonstration for 07 Smart Lander Application
2001 MSP01 Lander Battery Testing

**Discharge Capacity (Ahr)**
- Effect of cell balancing upon performance evaluated
- 25% more capacity delivered after cell balancing
- Much tighter grouping of cells observed (small cell voltage dispersion)

**Cell Voltage Dispersion (ΔV)**

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 31.20 V (3.9V per cell)
Discharge Current = 5 A (C/5 Rate)
Discharge Cut-off = 24.0 V (3.0 V per cell)
Cell Voltage Cut-Off = 2.5 V and 4.15 V

- **Yardney MSP01 8-Cell Lander Battery**
  - Discharge Capacity
    - 31.2 V (Prior to cell balancing): 20.593 Ahr
    - 31.2 V (After cell balancing): 25.652 Ahr
    - 32.00 V (After cell balancing): 29.085 Ahr

  - **Cell Voltage Dispersion**
    - 31.2 V Charge (Prior to cell balancing): 4.081 V High, 3.994 V Low
    - 31.2 V Charge (After cell balancing): 4.081 V High, 3.994 V Low
    - 32.00 V Charge (After cell balancing): 4.150 V High, 3.795 V Low
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at Different Temperatures

32 V Charge - Discharge Capacity (AHr) at Various Temperatures

<table>
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<th>Temperature (°C)</th>
<th>Discharge Capacity (AHr)</th>
<th>Cell Voltage Dispersion (ΔV)</th>
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- Battery capacity at different temperatures determined
- Capacity determined after cell balancing
- Greater cell voltage dispersion observed at lower temperature

Discharge Capacity (AHr)  
Cell Voltage Dispersion (ΔV)
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at 20°C
32.8 V Charge (After Cell Balancing-Second Time)

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 32.80 V (4.0 V per cell)
Discharge Current = 5 A (C/5 Rate)
Discharge Cut-off = 24.0 V (3.0 V per cell)
Cell Voltage Cut-Off = 2.5 V and 4.15 V

Temperature = 23°C

After Cell Balancing

~ 31.4 AHr when first cell reaches 4.1 V (91% of total)
34.36 AHR Total Charge
Lithium Ion Technology Demonstration for 07 Smart Lander Application

2001 MSP01 Lander Battery Testing-Cruise Period Test

- Cells balanced prior to storage test
- Cell dispersion potential issue depending upon charge methodology

Yardney MSP01 8-Cell Lander Battery

Temperature = 10°C

Bus voltage = 30.40 V (70% SOC)

\[ \Delta V = 0.054 \text{ V} \] (10th Hour)

\[ \Delta V = 0.066 \text{ V} \] (338th Hour)

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Summary and Conclusions

- The charge characteristics of a number of aerospace quality lithium-ion cells has been investigated.
- The effect of charge voltage upon performance has been determined, especially at lower temperatures, and has been observed to result in higher capacities.
- The effect of charge taper current cut-off methodology upon performance has been determined with the following observations being made: (1) lower taper current values at low temperature can result in significantly more capacity, (2) the impact of taper current value selection becomes more significant later in cell life, and (3) extended taper charging can limit life characteristics.
- The possibility of lithium plating occurring at low temperatures (and/or with high charge voltages) has been investigated in experimental three electrode cells. It was observed that high charge voltages, high charge currents and undesirable electrode kinetics can lead to conditions where lithium plating on the anode can occur.
- The charge characteristics of an 8-cell lithium ion battery has been investigated (without individual cell charging) with emphasis upon determining the extent of cell voltage dispersion.
Acknowledgments

The work described here was funded by the Code S Battery Program, Mars Exploration Program and the Mars 2003 MER Program and carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).
Lithium-Ion Cells for Mars Surveyor 2001 Lander
Charge Characteristics as a Function of Temperature

25 Ahr MSP01 Design Lithium-Ion Cell

Charge Capacity (Ah)

Time (Hours)

* C/2 Charge Current
Large Capacity Lithium-Ion Cells for Future Mars Applications

Effect of Taper Current on Charge Characteristics

- With a fresh cell, approximately 10% of the total capacity is obtained in the “taper mode” of the charge.

4.10 V Charge Voltage
5.0 Amp Charge current (C/5)
0.001 Amp Taper Cut-Off (C/25,000)
Temp = 23°C
Effect of High Temperature Storage Upon the Performance of Li-Ion Cells:
Cell Stored for 10 Days at 60°C (Full SOC)

- The three-electrode cells are also helpful in trying to understand the impact of high temperature storage upon the polarization effects of the individual electrodes.
Performance of Li-Ion Cells Under Battery Voltage Charge Control

Hari Vaidyanathan, Consultant
Gaithersburg, Maryland
And
Gopalakrishna M. Rao, NASA-Goddard Space Flight Center
Greenbelt, Maryland

2001 NASA Aerospace Battery Workshop
Huntsville, Alabama
November 27-29, 2001
Objective

Determination of Cycling Performance as a Battery Pack under LEO regime
- Number of cycles
- Charge voltage
- Temperature
- Reconditioning Effect
Cells Under Study

• **Prismatic Cells**
  - Yardney Technical Products, Inc. (YTP), 20 Ah, mixed-oxide (Co and Ni) positive, graphitic carbon negative, LiPF$_6$ salt mixed with organic Carbonate solvents
  - Mine Safety Appliances Company (MSA), 10 Ah, Co oxide positive, graphitic carbon negative, LiPF$_6$ salt mixed with organic Carbonate solvents

• **Cylindrical Cells**
  - SAFT, 12 Ah, mixed-oxide (Co and Ni) positive, graphitic carbon negative, LiPF$_6$ salt mixed with organic Carbonate solvents
LEO Cycling: Conditions

- Continuous cycling in a regime consisting of 30 min. discharge and 60 min. charge at the rate of 16 cycles/day
- Temperature = -20°C to 20°C
- Depth of discharge = 40%
- Voltage clamped at a Battery/Pack voltage at C/2 charge rate with current taper
- Recharge ratio = 1-1.01
TEMPERATURE VARIATION DURING CYCLING

![Temperature Variation Graph]

- TEMPERATURE (°C)
- CYCLE NUMBER

Lines representing different conditions:
- YTP
- SAFT
- MSA
Table 1 – History YTP

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Note: Values for cycles 4576-4613 are average values. The specific value for cycle 4613 is included since the charge voltage changed.
Table 2 - History SAFT

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<td>3441</td>
<td>25.1</td>
<td>34.7</td>
<td>4.30</td>
</tr>
</tbody>
</table>

* 7 cells
END OF DISCHARGE VOLTAGES:
YTP 20 Ah

- 20°C
- -10°C

Cycle Number

Pack

Avg. Cell

0 2000 4000 6000 8000

0 20 40

0 20 40 60 80

0 10 20 30

0 10 20 30 40
END OF DISCHARGE VOLTAGES:

SAFT 12 Ah

- Pack
- Avg. Cell

Cycle Number

- 20°C
- -10°C
- 0°C

PACK, V
AVG. CELL V
END OF DISCHARGE VOLTAGES:
MSA 10 Ah

-10°C 0°C

MALFUNCTION

Pack

Avg. Cell

Cycle Number
END OF DISCHARGE VOLTAGES:
YTP Cells at -10°C

Voltage (V)

Cycle Number

- S/N200
- S/N181
- S/N196
- S/N195
- S/N188
- S/N194
- S/N184
- S/N192
Test Status

- One cell in the SAFT pack is showing 2.954V after 6226 cycles with low end of charge voltage of 4.09V.
- One cell in the YTP pack is showing low end of discharge (2.84V) and high end of charge voltage (4.5V) after 6714 cycles.
- One cell in the MSA pack is showing low voltage (2.905 decreasing to 2.77V) during discharge after 3441 cycles. The voltage is high during charge 4.47 increasing to 4.48V.
- Tests stopped and the health of cells under evaluation.
Reconditioning

- The low voltage cell increased to 3.6V from 2.77 V in the SAFT pack and pack voltage increased by 430 mV when reconditioned by discharging at C/20.
- The low voltage cell increased to 2.77V from 2.5 V in the MSA pack and the pack voltage increased by 800 mV when reconditioned.
- YTP pack did not show any significant effect.
Conclusions

- Li-ion cells manufactured by YTP, SAFT and MSA have completed 6714, 6226 and 3441 cycles, respectively.
- An increase in charge voltage limit was required in all cases to maintain the discharge voltage.
- SAFT and MSA cells were capable of cycling at -10°C and 0°C with an increase in the charge voltage limit, whereas Yardney cells could not be cycled.
- Reconditioning improved the discharge voltage of SAFT and MSA cells; it is important to note that the effect has been temporary as in Nickel-Hydrogen and Nickel-Cadmium batteries.
- Demonstrated that the charge operation with VT clamp at battery rather than at cell level is feasible.
- Continuation of testing depends on the health of the cells and on the funding situation.
DPA of 1.6 Ahr Li-ion Pouch Cells Using Coin Cells

NASA Space Power Workshop
Enoch Wang
US Government
11/27/01
Objective

- To identify the limiting electrode(s)
  - To shed understanding on failure mechanism
Why Coin cells?

- It gives more direct and definitive results in determining failed electrode(s)
- It gives both qualitative and quantitative info on electrodes degradation
Experimental

Overview

- Bring cells to “complete” state of discharge.
- Open pouch cells in glovebox.
- Observe condition of electrodes and other components.
- Build button cells (Li metal half-cells) using portions of anodes & cathodes from each pouch cell.
- Cycle button cells at low rate (C/10) and high rate (LEO rates).
- Determine limiting electrode (anode or cathode).
Experimental (cont’d)

- **Cycling conditions**
  - Low rates to determine intrinsic capacity
    - C/10 Charge and Discharge for LiCoO2
    - C/10 Charge and C/10 Discharge + trickle for MCMB
Cycling conditions (cont’d)

LEO rates to determine rate capability loss

- 40% DOD
- Cathode
  - 36 min Discharge (loading) @2/3C to 2.8V
  - 54 min Charge (unloading) @ C to 4.2V
- Anode
  - 36 min Charge (unloading) @ 2/3C to 2.5V
  - 54 min Discharge (loading) w/ trickle @ C to 20 mV
## Pouch Cells Background

<table>
<thead>
<tr>
<th>Pouch Cells</th>
<th>Positive</th>
<th>Negative</th>
<th># cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM6-D6</td>
<td>LiCoO2 from vendor A</td>
<td>0.5% SP MCMB2528</td>
<td>~9000</td>
</tr>
<tr>
<td>LM7-G3</td>
<td>LiCoO2 from vendor B</td>
<td>2% SP* MCMB2528</td>
<td>~4900</td>
</tr>
<tr>
<td>LM7-G5</td>
<td>LiCoO2 from vendor B</td>
<td>2% SP* MCMB2528</td>
<td>~4600</td>
</tr>
<tr>
<td>LM7-M2</td>
<td>LiCoO2 from vendor A</td>
<td>2% SP* MCMB2528</td>
<td>~4500</td>
</tr>
</tbody>
</table>

*bad batch of negative electrodes*
LM6-D06 Cycle Life
LM7-G03 Cycle Life

[Graph showing the End of Discharge Potential (Volts) and Efficiency (%) over cycles.]
LM7-G5 cycle life

Aerospace Lithium Ion Battery Technology

$\text{Li}_x\text{C}_6/\text{Li}_x\text{CoO}_2$ LEO LM7-G05, Stabilization

C: 4.1 V cv w/ 332 mA (C/5, 0.4 mA/cm²) max to 20 mA; D: 332 A cc to 3.0 V

End of Discharge Potential (Volts)

Efficiency (%)

Cycle

EODP

Coulombic Efficiency
LM7-M2 cycle life

Aerospace Lithium Ion Battery Technology

Li$_x$C$_6$/Li$_x$CoO$_2$ LEO LM7-M02, Stabilization

C: 4.1 V cv w/ 332 mA (C/5, 0.4 mA/cm$^2$) max to 20 mA; D: 332 A cc to 3.0 V

End of Discharge Potential (Volts) vs. Cycle

Efficiency (%) vs. Cycle
**LM6-D06 Pouch**

**Observations**
- Mossy Li deposits around perimeter of separator bag.
- Mossy Li deposits on pouch surface.
- Heavy deposits of mossy Li around cathode tab.
- Most of Li missing from reference electrode.
Results (contd.)
LM6-D06 Anode

Observations
- Discoloration around perimeter of electrode
- No visible Li deposits on electrode surface
- Mossy Li deposits around perimeter of separator bag

Edge #1
- 0.192 – 0.196 mm, 4k – 6k Ω

Edge #2
- 0.192 – 0.202 mm, 4k – 13k Ω

Edge #3
- 0.195 – 0.212 mm, 40k – 60k Ω

Edge #4
- 0.194 – 0.208 mm, 1k – 5k Ω

Fresh Material
- Thickness: 0.157 – 0.160 mm
- Resistance: 5 – 10 Ω
Results (contd.)
LM6-D06 Cathode

Observations
- Cathode appeared “fresh”.
- No visible Li deposits on electrode surface
- Mossy Li deposits around perimeter of separator bag

**Cycled Cathode**
- Thickness: 0.160 – 0.165 mm
- Resistance: 120 - 190 Ω

**Fresh Cathode**
- Thickness: 0.151 – 0.154 mm
- Resistance: 70 – 90 Ω
Results (contd.)
LM7-G03 Anode

**Observations**
- Blotched areas
  - smooth hard texture
  - raised deposits
  - 20k - 40k Ω
  - reacted with H₂O

<table>
<thead>
<tr>
<th>Edge</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>1k – 4k Ω</td>
</tr>
<tr>
<td>#2</td>
<td>2k – 40k Ω</td>
</tr>
<tr>
<td>#3</td>
<td>1k – 3k Ω</td>
</tr>
<tr>
<td>#4</td>
<td>0.4 – 2k Ω</td>
</tr>
</tbody>
</table>

**Fresh Material**
Resistance: 5 – 10 Ω
Results (contd.)
LM7-G03 Cathode

Observations

- Areas with dark discoloration (300 - 400 Ω)
- Side A (170 - 200 Ω)
- Side B (80 - 100 Ω)
LM6-D06 Cathode

Large polarization but NO loss of cyclable Li

![Graph](image_url)

**LM6-D06 Cathode**

**Pre-Discharge/Charge Cycle (C/10)**

- Volts: 2.80, 3.00, 3.20, 3.40, 3.60, 4.00, 4.20
- mAh/g of Li\textsubscript{2}CoO\textsubscript{2}: 0, 25, 50, 75, 100, 125, 150

**Graph Details:**

- Pre-Dchg: 163 mV
- Chg: 245 mV

No loss of cyclable Li observed.
Negligible Li left in anode
Fresh anode @ C/10

3rd Cycle Charge Button Cells (C/10)
Fresh anode @ LEO rate

1st LEO Cycle Charge  Button Cells

Voltage vs. mAh/g MCMB

Charge Time
Discharge Time
Coin Cell Results
LM6-D6 Anode

No degradation in intrinsic capacity

1st Cycle LM6-D6 Anode Button Cell
(C/10)

Charge
Discharge

Charge Time 10.5 h
Discharge Time 10 h

mAh/g
No degradation in LEO rate

Charge Time 10h
Charge Time 36 h
Discharge Time 54h
Discharge Time 13.6 h

1st LEO Cycle LM6-D6 Anode Button Cell

Charge
Discharge

mAh/g
Fresh cathodes at C/10
Fresh cathodes at LEO

3rd Cycle Cathode Control Button Cell

(LEO)

Volts

Charge Time 49 min

Discharge Time 36 min

mAh/g of Li$_2$CoO$_2$
Significant degradation in intrinsic capacity

1st Cycle LM6-D6 Cathode Button Cell (C/10)

Charge Time 6.25 h
Discharge Time 6.18 h
Coin Cell Results
LM6-D6 Cathode

Significant degradation in LEO rates

1st LEO Cycle  LM6-D6 Cathode Button Cell

<table>
<thead>
<tr>
<th>Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20</td>
</tr>
<tr>
<td>4.00</td>
</tr>
<tr>
<td>3.80</td>
</tr>
<tr>
<td>3.60</td>
</tr>
<tr>
<td>3.40</td>
</tr>
<tr>
<td>3.20</td>
</tr>
<tr>
<td>3.00</td>
</tr>
<tr>
<td>2.80</td>
</tr>
</tbody>
</table>

mAh/g of Li$_2$CoO$_2$

Charge Discharge
LM6-D06 LEO cycles in full cells

Full cell V curves indicative of predominant cathode polarization
Coin Cell Results
LM7-M2 Anode

No loss in intrinsic capacity

3rd Cycle MCMB Button Cell (C/10)
LM7M2 Nippon Anode

"x" in MCMB

Volts

mAh/g of MCMB

3 Dchg
3 Chg
Some loss in LEO rate capability

1st LEO Cycle LM7-M2 Anode Button Cell
Coin Cell Results
LM7-M2 Cathode

Degradation in intrinsic capacity

1st Cycle LM7-M2 Cathode Button Cell
(C/10)

Charge Time 8.55 h
Discharge Time 9.32 h
Coin Cell Results
LM7-M2 Cathode

Complete loss of LEO rate capability

1st LEO Cycle LM7-M2 Cathode Button Cell
Full Cell Results
LM7M-2, LEO Cycle 3880

Full cell V curves indicative of predominant cathode polarization
Coin Cell Results
LM7-G5 Anode

No loss in intrinsic capacity

Typical Cycle LM7-G5 Anode Button Cell
(C/10)

Discharge Time 14.62 h
Charge Time 10.5 h
Discharge
Charge

Charge Time 10.5 h
Discharge Time 14.62 h
Coin Cell Results
LM7-G5 Anode

Degradation in LEO rate capability

1st LEO Cycle LM7-G5 Button Cell
Coin Cell Results
LM7-G5 Cathode

No loss in intrinsic capacity

2nd Cycle LM7-G5 Cathode Button Cell (C/10)
Coin Cell Results
LM7-G5 Cathode

No degradation in LEO rate capability

1\textsuperscript{st} LEO Cycle LM7-G5 Button Cell

Charge Time 53 min
Discharge Time 36 min

Charge
Discharge

Volts
mAh/g of Li\textsubscript{x}CoO\textsubscript{2}
Full Cell Results
LM7G-5, LEO Cycle 4600

Full cell V curves indicative of predominant anode polarization
Coin Cell Results
LM7-G3 Anode

No loss in intrinsic capacity

1st Cycle LM7-G3 Anode Button Cells (C/10)
Coin Cell Results
LM7-G3 Anode

Some degradation in LEO rate capability

1st LEO Cycle LM7-G3 Anode Button Cell

Charge Time: 36 min
Discharge Time: 54 min
Coin Cell Results
LM7-G3 Cathode

Some loss in intrinsic capacity

1st Cycle LM7-G3 Cathode  Button Cell
(C/10)

Volts

mAh/g of Li$_2$CoO$_2$
Coin Cell Results
LM7-G3 Cathode

Degradation in LEO rate capability

1st LEO Cycle LM7-G3 Cathode Button Cell

Charge Time 50 min
Discharge Time 36 Min
Results (contd.)
LM7-G03 LEO cycles

Full cell V curves indicative of cathode & anode polarizations
## DPA Cells Summary

<table>
<thead>
<tr>
<th>Pouch Cells</th>
<th>Coin half Cells</th>
<th>Intrinsic Capacity (mAh/g)</th>
<th>LEO Capacity (mAh/g)</th>
<th>Li Loss (x) on Cycling Li$_x$CoO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM6-D6</td>
<td>Cathode</td>
<td>85 (U) / 84 (L)</td>
<td>0 (U) / 14(L)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>315 (L) / 299 (U)</td>
<td>169 (L) / 122 (U)</td>
<td></td>
</tr>
<tr>
<td>LM7-M2</td>
<td>Cathode</td>
<td>121 (U) / 121 (L)</td>
<td>0 (U) / 0(L)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>316 (L) / 312 (U)</td>
<td>105 (L) / 108 (U)</td>
<td></td>
</tr>
<tr>
<td>LM7-G3</td>
<td>Cathode</td>
<td>128 (U) / 126 (L)</td>
<td>&lt;78 (U) / 54(L)</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>299 (L) / 314 (U)</td>
<td>128 (L) / 113 (U)</td>
<td></td>
</tr>
<tr>
<td>LM7-G5</td>
<td>Cathode</td>
<td>143 (U) / 143 (L)</td>
<td>110 (U) / 54(L)</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Anode</td>
<td>337 (L) / 317 (U)</td>
<td>101 (L) / 113 (U)</td>
<td></td>
</tr>
<tr>
<td>Fresh</td>
<td>Cathode</td>
<td>140 (U) / 140 (L)</td>
<td>127 (U) / 54(L)</td>
<td>0.01</td>
</tr>
<tr>
<td>Electrodes</td>
<td>Anode</td>
<td>330 (L) / 323 (U)</td>
<td>164 (L) / 120 (U)</td>
<td></td>
</tr>
</tbody>
</table>
## Li-ions accounting

<table>
<thead>
<tr>
<th>LiCoO2 eltd.</th>
<th>MCMB eltd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>LiCoO$_2$</td>
</tr>
<tr>
<td>Charge</td>
<td>Li$_{0.5}$CoO$_2$</td>
</tr>
<tr>
<td>Disch.</td>
<td>Li$_{0.9}$CoO$_2$</td>
</tr>
<tr>
<td>charge</td>
<td>Li$_{0.5}$CoO$_2$</td>
</tr>
<tr>
<td>Disch.</td>
<td>Li$_{0.7}$CoO$_2$</td>
</tr>
</tbody>
</table>

---

**Capacity loss could be due to:**
1) Loss of cyclable Li
2) Electrode(s) polarization
Preliminary Failure Mechanisms

LM6-D6 and LM7-M2
- Cathode severely polarized due to possible structural degradation
  - XRD of post-mortem LiCoO2 electrodes showed broadened peaks

LM7-G5
- Anode polarized due to possible SEI destruction/repassivation
  - Loss of cyclable lithium

LM7-G3
- Both electrodes were polarized, with possible structural degradation of the cathode
Performance and Safety Tests on Samsung 18650 Li-ion Cells:
Two Cell Designs

Yi Deng, Judith Jeevarajan, Raymond Rehm
Lockheed Martin Space Operations

Bobby Bragg
NASA Johnson Space Center

Wenlin Zhang
Schlumberger Perforating and Testing
In order to meet the applications for space shuttle in future, two types of Samsung cells, with capacity 1800mAh and 2000mAh, have been investigated. The studies focused on:

• Performance tests
  Completed 250 cycles at various combinations of charge/discharge C rates
  Discharge capacity measurements at various temperatures

• Safety tests
  Overcharge and overdischarge
  Heat abuse
  Short circuit: Internal and external short
  Vibration, vacuum, drop tests
## Information of cells

<table>
<thead>
<tr>
<th>Model #</th>
<th>Capacity</th>
<th>Dimension</th>
<th>Weight</th>
<th>Energy density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Diameter</td>
<td>Height</td>
<td></td>
</tr>
<tr>
<td>ICR18650-18</td>
<td>1800mAh</td>
<td>18.0+0.3mm</td>
<td>64.9+0.3mm</td>
<td>42g</td>
</tr>
<tr>
<td>ICR18650-20</td>
<td>2000mAh</td>
<td>18.0+0.3mm</td>
<td>64.9+0.3mm</td>
<td>43g</td>
</tr>
</tbody>
</table>
Performance tests
Plot of CC/Cv charge for 1.8 Ah Samsung Li-ion cells at two different rates at RT
Plot of discharge of Samsung 1.8 Ah Li-ion cells at different C rate at RT.
Cycle life tests for 1.8 Ah Li-ion cells at various C rate combinations of charge/discharge

- Charge to 4.2V, discharge to 3.0V

- 1C/1C
- 1C/0.5C
- 1C/0.25C
- 0.5C/1C
- 0.5C/0.5C
- 0.5C/0.25C
Characterization of capacities of 1.8 Ah cells at various temperatures

Charge at C/2 at RT, discharge at C/2 to 2.7V.
# Discharge capacity at different temperatures

<table>
<thead>
<tr>
<th>Test temperature (°C)</th>
<th>Capacity of discharge (Ah)</th>
<th>Capacity of discharge (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.8 Ah cells</strong></td>
<td></td>
<td><strong>2.0 Ah cells</strong></td>
</tr>
<tr>
<td>40</td>
<td>1.71</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>95.6%</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95.8%</td>
</tr>
<tr>
<td>25</td>
<td>1.79</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>1.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100%</td>
</tr>
<tr>
<td>10</td>
<td>1.62</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>90.6%</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92.1%</td>
</tr>
<tr>
<td>-10</td>
<td>1.41</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>78.8%</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70.5%</td>
</tr>
</tbody>
</table>
Summary for performance tests

- In 250 cycles, the capacity drops with 100% DOD were 11%-12% both for 1.8Ah and 2.0Ah cells regardless combination of C rate at range from 1C to C/4.
- The optimum discharge capacity and energy were achieved at 25 °C
Safety tests
Over-discharge of Samsung 2.0 Ah li-ion cell at 1C rate into reversal

Results: Loss cell function but no physical damage.
Over discharge 1.8 Ah cell to 0.0V

Results: two weeks later after removal
150% more original capacity, cell loss of function but no physical damage.

1C rate discharge to 0.0V and held at open circuit for two weeks
Constant voltage overcharge of 2.0Ah cell to 5.0V

No physical damage, no leakage.

CID activated
High temperature exposure and heat-to-vent
(2.0Ah cell)

**V**
- Fully charged cell at 4.2V
- Expose to 65 °C for 3 hrs
- Weigh cell and inspect
- Back in oven and heat to 200 °C from RT

**T**
- Results: Venting and leads to explosion at 150°C
High temperature exposure and heat-to-vent (1.8Ah cell)

Fully charged cell at 4.2V
Expose to 65 °C for 3 hrs
Weigh cell and inspect
Back in oven and heat to 200 °C from RT

Results: venting and leads to explosion at 100 °C
Heat abuse test
Short circuit: Internal Short

Results: venting but no rupturing, no fire, no explosion
Internal short circuit test
Short circuit: External Short

2.0Ah cell with 0.05Ω load

Results: PTC activated immediately, and no physical damage.
### Summary for safety tests

<table>
<thead>
<tr>
<th>Safety test</th>
<th>1.8Ah cell test results</th>
<th>2.0 Ah cell test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1C rate overcharge to 4.5V</td>
<td>passed</td>
<td>passed</td>
</tr>
<tr>
<td>1C overcharge to 5.0V</td>
<td>No fire, no explosion</td>
<td>No fire, no explosion</td>
</tr>
<tr>
<td>High rate (3C) discharge to 2.7V</td>
<td>passed</td>
<td>passed</td>
</tr>
<tr>
<td>1C overdischarge to 0V and reverse 150% of 1C capacity</td>
<td>No fire, no explosion</td>
<td>No fire, no explosion</td>
</tr>
<tr>
<td>65°C heating test</td>
<td>passed</td>
<td>passed</td>
</tr>
<tr>
<td>Exposure at temperature higher than 65°C to 200°C</td>
<td>Explosion at 100°C</td>
<td>Explosion at 150°C</td>
</tr>
<tr>
<td>Vacuum test (0.1 psia for 6 hrs)</td>
<td>passed</td>
<td>passed</td>
</tr>
<tr>
<td>Drop test (6ft randomly drop)</td>
<td>passed</td>
<td>passed</td>
</tr>
<tr>
<td>Vibration test (*see appendix)</td>
<td>passed</td>
<td>passed</td>
</tr>
<tr>
<td>Short circuit: internal short</td>
<td>No fire, no explosion</td>
<td>No fire, no explosion</td>
</tr>
<tr>
<td>External short</td>
<td>No fire, no explosion</td>
<td>No fire, no explosion</td>
</tr>
</tbody>
</table>
Appendix

Vibration tests in X, Y, and Z axes for 15 min. respectively at following vibration condition:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-80 HZ</td>
<td>+3 dB/octave</td>
</tr>
<tr>
<td>80-350 Hz</td>
<td>0.1g²/Hz</td>
</tr>
<tr>
<td>350-2000 Hz</td>
<td>-3 dB/octave</td>
</tr>
</tbody>
</table>
Acknowledgment

Thanks Samsung for supplying the li-ion cell samples.
PERFORMANCE AND SAFETY TESTING OF CYLINDRICAL MOLI LITHIUM-ION CELLS

NASA Battery Workshop
November 2001

Judith A. Jeevarajan, Yi Deng, Ray Rehm

Lockheed Martin/NASA-JSC

Walt Tracinski,

Applied Power International

Bobby J. Bragg

NASA-JSC
# Moli 18650 Li-ion Cell Characteristics

<table>
<thead>
<tr>
<th>Avg. Weight</th>
<th>Avg. Diameter</th>
<th>Avg. Length</th>
<th>OCV</th>
<th>CCV</th>
<th>Discharge Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.786 g</td>
<td>18.059 mm</td>
<td>64.973 mm</td>
<td>3.726 V</td>
<td>3.445 V</td>
<td>1.593 Ah (1.65 Ah)</td>
</tr>
</tbody>
</table>

**Protective Features:**
- PTC-Positive Temperature Coefficient
- CID-Current Interrupt Device
- Shut-down Separator
- Vent
Discharge Capacity for Moli 18650 Li-ion Cell at 25 degrees C
(Charge and Discharge at 1 C Rate)

<table>
<thead>
<tr>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
</tr>
<tr>
<td>4.1</td>
</tr>
<tr>
<td>3.9</td>
</tr>
<tr>
<td>3.7</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.3</td>
</tr>
<tr>
<td>3.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capacity (Ah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
</tr>
<tr>
<td>2.9</td>
</tr>
<tr>
<td>3.1</td>
</tr>
<tr>
<td>3.3</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.7</td>
</tr>
<tr>
<td>3.9</td>
</tr>
</tbody>
</table>

1 (1.59 Ah)
(1.58 Ah) 10
Discharge Cycles of Moli 18650 Li-ion Cell at –10 degrees C
(Charge and Discharge at 1 C Rate)
Performance of Moli 18650 Li-ion Cell During Discharge at 10 degrees C
(Charge and Discharge at 1 C Rate)
Performance of Moli 18650 Li-ion Cell at 45 degrees C
(Charge and Discharge at 1 C Rate)
Cycle Life Test on Moli 18650 Li-ion Cell
(Temperature = 25 degrees C)

Difference in Capacity between Cycle 1 and Cycle 500 is 12 %

Charge: 1 C Rate
Discharge: 1 C Rate
Cycle Life Test of Moli 18650 Li-ion Cell
Discharge Capacities at 1C Charge and C/2 Discharge
(Temperature = 25 degrees C)

Difference in Discharge Capacity Between Cycle 1 and Cycle 500 is 19 %
Cycle Life Test for Moli 18650 Li-ion Cell
(Temperature = 25 degrees C)

Difference in Discharge Capacity between the Cycle 1 and Cycle 500 is 28%
### Characteristics of the Moli 18650 Li-ion Cell at Different Rates of Charge and Discharge at Room Temperature

<table>
<thead>
<tr>
<th>Cycle Number</th>
<th>Charge Rate</th>
<th>Discharge Rate</th>
<th>Capacity</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 500</td>
<td>1C</td>
<td>1C</td>
<td>1.613 Ah</td>
<td>12 %</td>
</tr>
<tr>
<td></td>
<td>1C</td>
<td>1C</td>
<td>1.413 Ah</td>
<td></td>
</tr>
<tr>
<td>1 500</td>
<td>1C</td>
<td>0.5 C</td>
<td>1.622 Ah</td>
<td>19 %</td>
</tr>
<tr>
<td></td>
<td>1C</td>
<td>0.5 C</td>
<td>1.319 Ah</td>
<td></td>
</tr>
<tr>
<td>1 500</td>
<td>1C</td>
<td>0.25 C</td>
<td>1.626 Ah</td>
<td>28 %</td>
</tr>
<tr>
<td></td>
<td>1C</td>
<td>0.25 C</td>
<td>1.179 Ah</td>
<td></td>
</tr>
<tr>
<td>1 500</td>
<td>0.5 C</td>
<td>1C</td>
<td>1.582 Ah</td>
<td>13.5 %</td>
</tr>
<tr>
<td></td>
<td>0.5 C</td>
<td>1C</td>
<td>1.368 Ah</td>
<td></td>
</tr>
<tr>
<td>1 500</td>
<td>0.5 C</td>
<td>0.5 C</td>
<td>1.593 Ah</td>
<td>11 %</td>
</tr>
<tr>
<td></td>
<td>0.5 C</td>
<td>0.5 C</td>
<td>1.423 Ah</td>
<td></td>
</tr>
<tr>
<td>1 500</td>
<td>0.5 C</td>
<td>0.25 C</td>
<td>1.599 Ah</td>
<td>9 %</td>
</tr>
<tr>
<td></td>
<td>0.5 C</td>
<td>0.25 C</td>
<td>1.452 Ah</td>
<td></td>
</tr>
</tbody>
</table>
Effective Internal Resistance Characteristics for the Moli 18650 Li-ion Cell

Room Temperature (25 degrees C)

Effective Internal Resistance (ohm)

% State-of-Charge
Fast Charge of Moli Li-ion 18650 Cell using a 3 C Current to 4.2 V

Voltage (V)

Current (A)

Time (minutes)
Overcharge of Moli 18650 Li-ion Cell to 5.0 V at 1 C Rate

Voltage (V) and Current (A)

Temperature (degrees C)
Overcharge Test of Moli 18650 Li-ion Cell to 12 V for 50 Minutes at 1C Rate
Discharge Cycle after Fast Discharge of Moli 18650 Li-ion Cell Using a 3 C Rate

Voltage (V) and Current (A) vs. Time (min)

Temperature (degrees C) vs. Time (min)

Test Protocol:
Charge at 1 C Rate;
Discharge at 3C Rate (gave 0.6 Ah);
Charge and Discharge at 1 C rate
Overdischarge into Reversal of Moli 18650 Li-ion Cell

Graph showing Voltage (V) and Current (A) over time (min). The graph also shows Temperature (deg. C) over time (min).
External Short Circuit Test of Moli 18650 Li-ion Cells with 50 mOhms

![Graph showing Voltage (V) and Current (A) over Time (min) with Temperature (degrees C)]
Heat-to-Vent Test of Moli 18650 Li-ion Cell

Cell that exhibited the worst case results
Simulated Internal Short Test of Moli 18650 Li-ion Cell

• Results dependent on nature of crush.
• Light crush did not cause any significant venting.
• Heavy crush caused significant venting with smoke and a small fire (no explosions).
Moli 18650 Li-ion Cell Tested Using an EAPU Profile

- Voltage (V)
- Current (A)

Time (min)
Vibration Test for the Moli 18650 Lithium-Ion Cell

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-80 Hz</td>
<td>+3 dB/octave</td>
</tr>
<tr>
<td>80-350 Hz</td>
<td>0.1 g²/Hz</td>
</tr>
<tr>
<td>350-2000 Hz</td>
<td>-3 dB/octave</td>
</tr>
</tbody>
</table>

• The Moli cells were subjected to the above vibration levels for 15 minutes in each of the independent x, y and z axes.

• Less than 5% changes in capacities recorded before and after the vibration was observed.
CONCLUSIONS

• The Moli lithium-ion cells were tested under normal and abuse conditions.
• The cells exhibit only 50% of their original capacity at about –10 degrees C.
• The optimum charge discharge rate with the least percentage loss in capacity is C/2 charge and C/4 discharge.
• The cells did not explode or go into a thermal runaway during venting at very high temperatures.
• The cells exhibited good tolerance under the vibration conditions tested.
• The cells could potentially be used in the build up of large batteries that have high current pulse (up to 3C) applications.
ACKNOWLEDGMENT

Walt Tracinski – Applied Power International
Gerald Steward- NASA-JSC
Anita Thomas- Lockheed Martin/NASA-JSC
Pulse performance of Small Lithium Ion Cells

Eric C. Darcy
NASA-JSC Battery Group
Houston
edarcy@ems.jsc.nasa.gov

Philip R. Cowles
COM DEV Battery Group
Cambridge Ontario
philip.cowles@comdev.ca

Abstract
Five types of small commercial cells were subject to capacity and resistance measurements under pulsed conditions and under a worst case application conditions. Results indicate that an 82S-102P array of 18650 cells will exceed the power/energy requirements for a proposed Space Shuttle EAPU battery system.
EAPU Subsystem Summary

- Currently a hydrazine-fueled turbine-driven unit drives the Shuttle hydraulics. There are three redundant systems.
- Drives: thrust vectoring, propellant valves, body flaps, landing gear, nosewheel steering ...
- Required during launch and de-orbit.
- NASA is looking at alternative battery solutions.
  - Safety
  - Reliability
  - Cost
APUs Are Critical To Flight Control

41 Orbiter Flight Control and Auxiliary Actuators

Catastrophic failure can occur during ascent or entry unless 2 of the 3 APUs are functioning perfectly.
Latest Worst Case Mission Profile

Accumulated Energy, kWh

Power, kW

Runtime, minutes

Simplified EAPU Battery Power Profile
2 Functional EAPU case during re-entry

Highest Peak, 130 kW, 3s
Simplified Mission Profile Used

Charge and 2-week wait on the pad

Launch discharge

3-Week rest

(18.18 kW)

De-orbit discharge

(125 kW)
Cell Parameters Tested

- Self-discharge
- Mission performance (using the simplified profile)
- Capacity (to 4.4V)
- Series resistance in pulse conditions

Prior to this, a preliminary sizing analysis indicated that the EAPU power/energy requirements could be met with at minimum a 82S x 102 P array of Sony 18650 HC lithium ion cells. This allowed the battery requirements to be scaled to single-cell level.
### Battery - Cell Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Battery</th>
<th>Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-series</td>
<td>82</td>
<td>1</td>
</tr>
<tr>
<td>P-Parallel</td>
<td>102</td>
<td>1</td>
</tr>
<tr>
<td>No. of cells</td>
<td>8364</td>
<td>1</td>
</tr>
<tr>
<td>Voltage range</td>
<td>205 - 360.8</td>
<td>2.5 - 4.4</td>
</tr>
<tr>
<td>Mass*</td>
<td>393 kg</td>
<td>0.0409 kg</td>
</tr>
<tr>
<td>Average discharge power</td>
<td>18.18 kW</td>
<td>2.17 W</td>
</tr>
<tr>
<td>Pulse power</td>
<td>125 kW</td>
<td>14.95 W</td>
</tr>
<tr>
<td>Min spec. voltage</td>
<td>230 V</td>
<td>2.805 V</td>
</tr>
</tbody>
</table>

*with a 1.16 parasitic mass factor assumed*
Test Set-Up

- Based on an existing test rig at COM DEV.
- Agilent (HP) equipment, ‘VEE’ test software.

Note: charge was done with a single-output 6631B power supply
Test Equipment

This test rack contains two power supplies 120 and 4A and 8V 10A, electronic load and the VXI rack which houses two precision digital voltmeters, a 64 channel switch multiplexer and four 32 channel switch cards. There is spare capacity for two more cards if expansion were required.

Kilovac relays are used to provide high current-switching capability.

Not shown are dumb loads and associated switches, and a PC with the Agilent ‘VEE’ software.

Two uninterruptible power supplies are used which have maintained operation up to 30 minutes. One long outage produced a graceful shutdown with all cell/battery connections open circuit.

The aim of the test rack was to provide a versatile, quickly reconfigurable facility for development work.
Test Cells and Test Plan

- Sony Hard Carbon, 1500 mAh, which has been our ‘standard’
- Sony Graphite 1500 mAh
- MCI 1600 mAh
- MCI 1800 mAh
- Panasonic 1800 mAh
- Tests were:
  - Initial screening with C/10 discharge
  - Charge to 4.4V with 10 mA taper charge
  - Pre-launch wait, 20°C for 2 weeks (measure self-discharge)
  - Launch phase. 20 minutes.
  - In-orbit wait, 3 weeks at 35°C (measure self-discharge)
  - De-orbit, 79 minutes, 3-second pulse at minute 73
  - Capacity and series resistance
Screening was done on a standard formation tester with a charge and discharge at C/10 rate.

While the cells deliver about their stated nameplate capacity, there are differences in end of discharge resistance which show up in later tests.

Following this test the cells were charged to 4.2V.
Prior to the Mission test, each cell was incrementally charged from 4.2 to 4.4V, 10 mA taper cut-off. Allowing chemical diffusion to finish (about 3-4 days) the cell voltages were measured about once a day.

Self-discharge is measured simply in microvolts per hour.

This gave a good indication of the self-discharge loss and the differences between cell types.

Shown also is the actual curve for the Sony HC cells.

‘Elapsed’ is the time from end of charge.

<table>
<thead>
<tr>
<th>Self-discharges by type</th>
<th>MicroV/h</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SonyHC</td>
<td>-28.6</td>
<td>1.0</td>
</tr>
<tr>
<td>SonyGR</td>
<td>-30.8</td>
<td>1.1</td>
</tr>
<tr>
<td>MCI 1600</td>
<td>-80.2</td>
<td>2.8</td>
</tr>
<tr>
<td>MCI 1800</td>
<td>-68.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Pana 1800</td>
<td>-140.7</td>
<td>4.9</td>
</tr>
</tbody>
</table>
Launch tested each cell in turn by imposing a 20 minute constant-power discharge of 2.17 Watt at 20°C.

Following this the in-orbit maximum mission length of 21 days was imposed, at 35°C.

<table>
<thead>
<tr>
<th>After launch</th>
<th>Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>SonyHC</td>
<td>4.2859</td>
</tr>
<tr>
<td>SonyGR</td>
<td>4.2802</td>
</tr>
<tr>
<td>MCI 1600</td>
<td>4.1991</td>
</tr>
<tr>
<td>MCI 1800</td>
<td>4.2212</td>
</tr>
<tr>
<td>Pana 1800</td>
<td>3.7893</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell</th>
<th>In-Orbit SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SonyHC</td>
<td>-45.1</td>
</tr>
<tr>
<td>SonyGR</td>
<td>-39.2</td>
</tr>
<tr>
<td>MCI 1600</td>
<td>-41.8</td>
</tr>
<tr>
<td>MCI 1800</td>
<td>-60.7</td>
</tr>
<tr>
<td>Pana 1800</td>
<td>-47.6</td>
</tr>
</tbody>
</table>
Descent

The 79 Minute de-orbit showing cell current (SonyHC)

Details of the 3-second pulse.
The table summarises the main cell parameters, weights them and provides an overall score.

- Rs is the average series resistance of the batches of four
- Wh is the energy capacity
- S_Dis is the pre-launch self-discharge
- De-orbit EMF is the voltage, or remaining charge, upon landing

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Rs, weight=2</th>
<th>Wh, Weight=1</th>
<th>S_Dis, weight=0.5</th>
<th>De-orbit EMF, weight=0.5</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>SonyHC</td>
<td>1</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>4.50</td>
</tr>
<tr>
<td>SonyGR</td>
<td>1.16</td>
<td>0.97</td>
<td>1.08</td>
<td>1.00</td>
<td>4.82</td>
</tr>
<tr>
<td>MCI1600</td>
<td>1.59</td>
<td>1.03</td>
<td>2.80</td>
<td>1.02</td>
<td>6.62</td>
</tr>
<tr>
<td>MCI1800</td>
<td>1.90</td>
<td>1.08</td>
<td>2.40</td>
<td>1.02</td>
<td>7.10</td>
</tr>
<tr>
<td>Pana1800</td>
<td>1.29</td>
<td>1.22</td>
<td>4.92</td>
<td>1.02</td>
<td>7.27</td>
</tr>
</tbody>
</table>

(low is best)
Pulse and Capacity Tests

- Separate tests were conducted to measure capacity under mean orbit discharge rates (about C/2.5).
- During discharge, pulses were imposed to measure resistance.
- Tests done at 0°C, 20°C and 35°C.
The Three Pulses

The sets of pulses were imposed every six minutes, all cells showed a slightly decreasing Rs from pulse to pulse, due to thermal dissipation.

\[ Rs = \frac{\Delta V}{\Delta I} \]
Typical Performance of Sony HC Cell

Voltage, Re vs Ah, DOD for Sony HC #12
Base I = 0.554A, at three temperatures
Re measured with 7A, 3s pulses every 6 min

Depth-of-Discharge, %
Conclusions

- All cells would support the mission.
- It is the performance during pulse conditions that drives the battery size.
- The Sony hard carbon has the best overall score and would permit the smallest battery to meet the mission requirements.
- The Sony HC cell has been extensively validated and qualified for space use. They have flown on:
  - Shuttle missions
  - STRV
  - Proba
- They are extremely safe.
Low Temperature and High Rate Performance of Lithium-ion Systems for Space Applications

R. Gitzendanner, F. Puglia, C. Marsh
Lithion, Inc.
Pawcatuck, CT USA
Research Goals

- As part of the Inter-Agency Lithium-ion Development Program, Lithion has undertaken an empirical analysis of the rate limiting steps in Lithium-ion cells.

- Goal is to improve High Rate performance:
  - Continuous Discharge
    - Goal: >50% capacity @ 20C and 25°C (to 3.0V cutoff)
    - Goal: >50% capacity @ 5C and -20°C (to 2.5V cutoff)
  - Pulse Discharge (< 1 second)
    - Goal: > 100C at 25°C (above 2.0V)
    - Goal: > 10C at -20°C (above 2.0V)
Targeted Applications

- **High Rate Pulse Power required for many applications**
  - Communications (Satellite, Radio, Terrestrial…)
  - Engine Start, Motor Drives, Actuators (Aircraft, Vehicular)
  - Military Lasers
  - Pulsed Radar…

- **High Rate Constant Current demands also necessary for many applications**

- **Typically battery design has been sized to meet highest rate requirement (oversized on capacity)**
  - Increase rate capability ⇒ Decrease battery size
Rate Capability of a Commercial 22650 Cell

High Rate Continuous Discharge

Cell Voltage (Volts)

Cell Discharge Capacity (Ah)

- C/5
- C/2.5
- 1C
- 2C

50% at 2C
High Rate Capability of Current 30Ah Cell

30Ah Cell
Continuous Current Discharge
All Cells Charged to 4.1V @ 5A
25°C

Cell Voltage (V)

Capacity (Ah)

Discharge Rate
- Blue: 25A
- Red: 50A
- Green: 125A
- Purple: 175A
- Black: 250A

12%
61%
89%
99%
Experimental Approach

The empirical approach is undertaken in 6 separate experiments:

1) Electrode Weight Loading, Anode Particle Size, & Ratio of Anode to Cathode (Complete)
2) Anode Conductive Diluents (Complete)
3) Separator Thickness and Porosity, & Binder Type (Modeling)
4) Electrolyte Salt and Solvent, & Cathode Material (In Process)
5) Mechanical Cell Construction Improvements (In Planning)
6) Validation/Verification Experiments
Experiment #1 Plan

- **Electrode Weight Loading, Anode Particle Size, & Ratio of Anode to Cathode**
  - Three Electrode Weight Loadings -- Full Factorial
    - Medium Loading (baseline chemistry)
    - Low Loading (~ 2/3 of baseline)
    - Very Low Loading (~ 1/3 of baseline)
  - Two Anode Particle Sizes -- Full Factorial
    - 10µm diameter nominal particle size
    - 6µm diameter nominal particle size
  - Three C/A Ratios -- Partial Factorial
    - Baseline
    - ~ 2/3 of Baseline
    - ~ 1/2 of Baseline
Experimental Testbed

- 10 Experimental Lots, 3 cells per Lot (typical)
- All Lots assembled and tested at same time
- All Lots used same prismatic cell hardware
  - Cell volume maintained so Capacity varied as a function of Weight Loading and C/A Ratio
    - Baseline Lots had nominal 7Ah capacity
  - Cell NOT designed for High Rate
    - Terminals only 0.090” diameter Mo GTMS (limits continuous discharge to ~ 20C)
    - Verification cells planned to use improved terminal design
Effect of Weight Loading on Capacity

Discharge Capacity (Ah) vs. Electrode Weight Loading

- Medium (Lot 1)
- Low (Lot 2)
- Very Low (Lot 3)

±1.96*Std. Dev.
±1.00*Std. Dev.
Mean
Effects on Efficiency

33% Less polarization between “best” and “worst” lots.
High Rate Constant Current Discharge

- 5 A (1C)
- 10 A (2C)
- 20 A (4C)
- 50 A (10C)
- 75 A (15C)
- 100 A (20C)

Cell Voltage (V) vs. Capacity (Ah)

- 96%
- 94%
- 85%
- 80%
- 66%
Comparison of Lot 1 versus Lot 6
-40°C, C/10 Discharge (25°C Charge)

Lot 1: 10 μ, Medium
Lot 6: 6 μ, Very Low

75% of polarization still present 2.8x APSA, 2.1x ESA

Cell Voltage (Volts)

Fraction of Individual Cell Capacity
Comparison of Lot 1 versus Lot 6
-40°C, C/10 Discharge (25°C Charge)

<table>
<thead>
<tr>
<th>Cell Capacity (Ah)</th>
<th>Lot 1 Voltage</th>
<th>Lot 6 Voltage</th>
<th>Typical C/10 at 25°C Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>2.60</td>
<td>3.05</td>
<td>3.05</td>
<td>3.05</td>
</tr>
<tr>
<td>2.70</td>
<td>3.10</td>
<td>3.10</td>
<td>3.10</td>
</tr>
<tr>
<td>2.80</td>
<td>3.15</td>
<td>3.15</td>
<td>3.15</td>
</tr>
<tr>
<td>2.90</td>
<td>3.20</td>
<td>3.20</td>
<td>3.20</td>
</tr>
<tr>
<td>3.00</td>
<td>3.25</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>3.10</td>
<td>3.30</td>
<td>3.30</td>
<td>3.30</td>
</tr>
<tr>
<td>3.20</td>
<td>3.35</td>
<td>3.35</td>
<td>3.35</td>
</tr>
<tr>
<td>3.30</td>
<td>3.40</td>
<td>3.40</td>
<td>3.40</td>
</tr>
<tr>
<td>3.40</td>
<td>3.45</td>
<td>3.45</td>
<td>3.45</td>
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<tr>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
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<tr>
<td>3.60</td>
<td>3.55</td>
<td>3.55</td>
<td>3.55</td>
</tr>
<tr>
<td>3.70</td>
<td>3.60</td>
<td>3.60</td>
<td>3.60</td>
</tr>
<tr>
<td>3.80</td>
<td>3.65</td>
<td>3.65</td>
<td>3.65</td>
</tr>
<tr>
<td>3.90</td>
<td>3.70</td>
<td>3.70</td>
<td>3.70</td>
</tr>
<tr>
<td>4.00</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>4.10</td>
<td>3.80</td>
<td>3.80</td>
<td>3.80</td>
</tr>
</tbody>
</table>
Effect on Charging at -40°C

### Graph:

- **X-axis (Fraction of Individual Cell’s Total Capacity)**
- **Y-axis (Cell Voltage (Volts))**

- **Lot 1 -40°C**
- **Lot 6 -40°C**
- **Lot 1 25°C**
- **Lot 6 25°C**

Key features:
- **10%** and **50%** lines
- Temperature markers: **-40°C** and **25°C**

The graph compares the effect of charging at different temperatures and cell lots on the cell voltage.
20A (4C) Discharge at -20°C

Discharge Capacity (Ah)

Cell Voltage (V)

Lot 1, 10m, Med Loading
Lot 4, 6m, Med Loading
Lot 3, 10m, V. Low Loading
Lot 6, 6m, V. Low Loading
Lot 6 High Rate Pulses (0.1s at 25°C): 10A → 350A
2C → 75C
25°C High Rate Specific Power

Cell Pulse Discharge Power Per Liter and Per Kilogram

- W/l (actual)
- W/kg (actual)
- W/l (MSP01 Hardware-calculated)
- W/kg (MSP01 Hardware-calculated)

Discharge Rate (C)

Watts per liter or kg

0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
High Rate Pulse Profile

Typical High Rate Airplane Battery Pulse Profile
(at 43.8% of Actual Requirement)

Test Time

Current (Amps)

1 second pulses
High Rate Pulse @ –20°C

Charge at -10°C and 12hr soak at -20°C prior to discharge

- Small Anode Particle Size, Medium Weight Loading
- Small Anode Particle Size, Low Weight Loading
- Small Anode Particle Size, Very Low Weight Loading

Cell Voltage (Volts)

Test Time (relative)

13.0°C  15.3°C  19.2°C
Summary

Lithion has investigated the first (of several) rate limiting steps in Lithium Ion performance

- Increased continuous discharge capability from ~5C to >20C
  - 63% of initial capacity available above 3.0 Volts!
- Demonstrated pulse capability as high as 75C at voltages above 2.0 Volts
  - Power density of 3200 W/kg and 7200 W/l has been demonstrated!
  - Approaching 3700 W/kg and 9,000 W/l (in a 33Ah cell size)
- Demonstrated discharge rates as high as 4C at –20°C (>70% capacity) and 2C at –30°C (>60% capacity)

These improvements in rate capability make Lithium Ion cells viable for many high rate, high power applications
Military Lasers, Radar Pulses, Electric Drive Systems (motors), Radio Communications, Actuators, etc

...and this is the first of the 6 experiments...
“Real-World” Application

Cell Discharged at 33 Amps

Discharge at Room Temperature
Discharge at -40°C

82% of RT Capacity to 3.0V at -40°C, 33A Rate
Update of LEO and GEO cycling
LEO Cycling at Lithion

40% DoD, 0.8C D/C, 0.5C; 25°C

End of Discharge Voltage vs Cycle number

Temperature °C

Cycle number

- X315 LEO to 3.9V
- X318 LEO to 3.9V
- X325 LEO to 3.7V
- X327 LEO to 3.7V
- Typical Cell Temp.
GEO Cycling at Lithion

60% DoD Cycles; Discharge at C/2; Charge at C/8 to set voltage
Accelerate by shortening non-Eclipse period to 14 days

End Voltage (V)

0 50 100 150 200
Cycle Number

Red: Cells are charged to 3.9V
Blue: Cells are charged to 4.1V

14 day solstice period
Cells taken off. Reconditioned
14 day solstice period
Other Ongoing Tests

- 5 Batteries developed for the MSP01 Mars Lander Program
  - Further Mars Mission Simulation Testing
  - Full Sky Astrometric Mapping Explorer (FAME)-NRL
    - Slightly elliptical GEO-type mission
    - Scheduled for launch in 2005
  - NASA Glen
    - LEO cycling at low temperatures
  - Wright Patterson Air Force Base
    - LEO cycling at Room Temperature (continuation of pack-level tests)
  - Lockheed Martin Astronautics
    - LEO cycling at reduced charge voltages
Acknowledgements

- This effort is funded by the Air Force Research Labs at Wright Patterson Airforce Base, contract number F33615-98-C-2898
- Guidance and assistance from Steve Vukson (COTR on the program, (937) 255-7770) is greatly appreciated.
- Co-Workers and other staff at Yardney Technical Products
Study of the effects of overdischarge on SONY 18650HC cells

G. J. Dudley (ESA-ESTEC)
R. Spurrett (AEA Technology)
The Concern

- Previously used secondary space battery cells can tolerate discharged to an open-circuit voltage of zero.

- Lithium-ion cells have minimum allowed open-circuit voltages of typically around 2.4 V, below which manufacturers warn of irreversible damage.

- This means that if the bus of a spacecraft with li-ion batteries collapses due to a fault condition, the spacecraft might not be recoverable.

- Several ESA scientific and earth-observation spacecraft are planning to use batteries of SONY 18650HC cells.

- The tests described here were an initial attempt to find out how long could a bus collapse last before the battery was unusable and the mission lost?
RSS Aerospace Battery Workshop 27-29 Nov. 2001

Predicted battery drain as function of bus voltage

Opposite: The predicted battery drain current as a function of bus voltage for a particular spacecraft with a 28 V regulated bus, scaled to a single string of 6 series cells.

Below the minimum operating battery voltage (in this case 18 V), the battery drain will be determined by residual currents through non-linear semiconductor components of the BDRs, switches etc.
Possible effects of over-discharge

- Apart from gross failures such as open or short-circuit cells, factors that are likely to be degraded as a result of overdischarge are:
  - Battery capacity
  - Battery resistance
  - Battery self-discharge rate
  - Spread of cell self-discharge rates

- The last one is important because this battery type relies on cells remaining ‘naturally’ balanced in state of charge.
Test Plan

- 6 SONY 18650HC cells were selected by AEA Technology according to standard flight-battery procedures and connected in series.

- Test sequence:
  - BOL capacity/self-discharge/internal resistance check
  - Discharge at C/10 to 2.5V
  - Overdischarge according to realistic scenario, removing individual cells at intervals and continuing with remaining cells.
  - Repeat capacity/self-discharge/internal resistance check
  - Stress cycling (to give indication of remaining cycle life)
  - Cycling overdischarged cells together in series to check on state of charge balance.
Initial capacity & self-discharge measurement

- Cell resistance estimated from charge--> discharge transients
- Self-discharge estimated from difference between last discharge capacity and previous charge capacity over 6-hour open-circuit period.

NASA Aerospace Battery Workshop 27-29 Nov. 2001
First overdischarge

Because of rapid rise in cell internal resistance, the test reached the lowest current step sooner than expected and then went into open-circuit.

NASA Aerospace Battery Workshop 27-29 Nov. 2001
Second overdischarge

Overdischarge resumed at constant current of 0.8 mA. Cell 6 then left shorted for 3.5 months.
# Test result summary

<table>
<thead>
<tr>
<th>Cell</th>
<th>Before</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ah overdischarged</td>
<td>0</td>
<td>0.132</td>
<td>0.263</td>
<td>0.154</td>
<td>0.179</td>
<td>0.263</td>
<td>0.263</td>
</tr>
<tr>
<td>OCV after overdischarge</td>
<td>2.88</td>
<td>2.651</td>
<td>0.002</td>
<td>2.50</td>
<td>2.44</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Cap 1&lt;sup&gt;st&lt;/sup&gt; charge</td>
<td>1.581</td>
<td>1.5966</td>
<td>1.6180</td>
<td>0.701</td>
<td>0.816¼</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cap 1&lt;sup&gt;st&lt;/sup&gt; dch</td>
<td>1.4450 (1.4717*)</td>
<td>1.4732</td>
<td>1.4759</td>
<td>1.4860</td>
<td>0.369</td>
<td>0.318</td>
<td></td>
</tr>
<tr>
<td>Cap 2&lt;sup&gt;nd&lt;/sup&gt; dch</td>
<td>1.4387</td>
<td>1.4553</td>
<td>1.4617</td>
<td>1.4639</td>
<td>0.439</td>
<td>0.335</td>
<td></td>
</tr>
<tr>
<td>Self-discharge current (mA)</td>
<td>1.0</td>
<td>3.2</td>
<td>2.4</td>
<td>2.3</td>
<td>[3.8]</td>
<td>[9.3]</td>
<td></td>
</tr>
<tr>
<td>Self-discharge current (mA)</td>
<td>1.0</td>
<td>3.2</td>
<td>2.4</td>
<td>2.3</td>
<td>[3.8]</td>
<td>[9.3]</td>
<td></td>
</tr>
<tr>
<td>Reoc (mohm)</td>
<td>115</td>
<td>115</td>
<td>122</td>
<td>117</td>
<td>678</td>
<td>927</td>
<td></td>
</tr>
</tbody>
</table>

* Average of 24 cells from same lot during AEA Technology lot acceptance testing.

After leaving cell shorted for 3.5 months.

Figures in square brackets are unreliable.
Stress - cycling results

- Cell 4 is practically the same as BOL cells from the same lot
- Cell 5 low capacity recovers considerably, capacity fall is then parallel to BOL cells
- Cell 6 very low capacity obviously is not going to recover
### Repeat tests after stress cycling

<table>
<thead>
<tr>
<th></th>
<th>BOL Cells</th>
<th>Cell 4</th>
<th>Cell 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress cycle 5 cap</td>
<td>1.3904*</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Stress cycle 200 cap</td>
<td>1.2774*</td>
<td>1.059</td>
<td></td>
</tr>
<tr>
<td>Cap 1&lt;sup&gt;st&lt;/sup&gt; dch</td>
<td>1.3471*</td>
<td>1.3546</td>
<td>1.2607</td>
</tr>
<tr>
<td>Cap 2&lt;sup&gt;nd&lt;/sup&gt; charge</td>
<td>--</td>
<td>1.3417</td>
<td>1.2585</td>
</tr>
<tr>
<td>Cap 2&lt;sup&gt;nd&lt;/sup&gt; dch</td>
<td>--</td>
<td>1.3537</td>
<td>1.2566</td>
</tr>
<tr>
<td>Self-discharge current (mA)</td>
<td>--</td>
<td>-2.0**</td>
<td>0.32</td>
</tr>
<tr>
<td>Reoc (mohm)</td>
<td>--</td>
<td>145</td>
<td>234</td>
</tr>
<tr>
<td>Voc eod</td>
<td>--</td>
<td>2.89</td>
<td>2.912</td>
</tr>
<tr>
<td>Repeat measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cap 1&lt;sup&gt;st&lt;/sup&gt; dch</td>
<td>1.3728</td>
<td>1.2717</td>
<td></td>
</tr>
<tr>
<td>Cap 2&lt;sup&gt;nd&lt;/sup&gt; charge</td>
<td>1.3708</td>
<td>1.2824</td>
<td></td>
</tr>
<tr>
<td>Cap 2&lt;sup&gt;nd&lt;/sup&gt; dch</td>
<td>1.3699</td>
<td>1.2701</td>
<td></td>
</tr>
<tr>
<td>Self-discharge current (mA)</td>
<td>0.15</td>
<td>2.05</td>
<td></td>
</tr>
</tbody>
</table>

Because of the observed capacity recovery during stress cycling, cells 4 and 5 were re-tested with the results shown opposite.

Self-discharge currents are again unreliable because of the unstable capacity.

A further test gave higher, but still unreliable figures.
Cycling cells 1, 3, 4 & 5 in series

- The dispersion in cell end of charge voltage decreases!
- End of discharge voltages reflect cell internal resistance
- Cells submitted to varying amounts of overcharge can still be cycled as a battery string!
Cells 1 & 3 conclusions

(<= 0.154 Ah overdischarge (relative to state of charge of a cell discharged at C/10 to 2.5 V) )

- Although cell 3 voltage on discharge fell to below 1V, open-circuit voltage was > 2.5V

- No evidence of degradation compared to BOL cells
Cell 4 conclusions
(0.179 Ah overdischarge (relative to state of charge of a cell discharged at C/10 to 2.5 V))

- Unchanged capacity, internal resistance and stress cycling results show negligible signs of degradation compared to fresh cells. The observations that:
  - a: the open circuit voltage recovered to 2.44 after stopping the overdischarge and
  - b: the capacity measured during the first charge following overdischarge exceeded subsequent charge capacity by 0.173 Ah, (the same as the overdischarge within experimental uncertainty)

suggest that no irreversible electrochemical processes have occurred.
Cell 5 conclusions
(0.263 Ah overdischarge (relative to state of charge of a cell discharged at C/10 to 2.5 V))

- Internal resistance increased 6-fold resulting in large apparent loss of capacity.
- During stress cycling the internal resistance reduced to about double the normal value after 60 cycles and thereafter remained at this level.
- The 0.2 Ah deficit in capacity at the end of stress cycles can be accounted for entirely by the higher ‘iR’ drop associated with the elevated internal resistance.
- Downward trend in capacity after 60 stress cycles parallels closely the behaviour of fresh cells, suggesting that the cell’s cycle life has not been compromised.
- The difference in capacity between the first charge following the overdischarge and the subsequent charge is again close to the overdischarged ampere-hours, suggesting that the majority of the overdischarged capacity is recoverable.
- This is remarkable in view of the fact that the cell was slightly reversed towards the end of overdischarge and the open circuit voltage was only 2 mV above zero.

Cell 6 conclusions
(0.263 Ah overdischarge + 3.5 month short-circuit)

- Capacity did not exceed 0.3 Ah during cycling. Cell unusable
Result summary

- Cells overdischarged by not more than 0.179 Ah (relative to the state of charge of a cell discharged at C/10 with to 2.5 V) are not significantly damaged.

- Cells overdischarged by 0.263 Ah suffer a very large increase in internal resistance, but this recovers to about twice the normal value during cycling. Cycle life and self-discharge current is apparently not affected.

- Overdischarge up to 0.263 Ah does not affect self-discharge rate.

- Cells left shorted for 3.5 months still have capacity but are unusable
Conclusions

- **Cells are not damaged provided the open circuit voltage (OCV) does not fall below 2.4 V.**

- **Large internal resistance increase at low states of charge means that:**
  - Lower voltages under load are acceptable
  - It is hard to overdischarge cells in a short time period

- **Cells are damaged if OCV < 2.4 V:**
  - Danger to battery is low discharge currents for prolonged periods
Addendum: Practical Implications

For a specific spacecraft power system the battery overdischarge Ah margin depends mainly upon the discharge current at the moment the bus undervoltage limit is reached.

The example opposite has an undervoltage limit of 3.33 V/cell but a value of 2.5 V/cell would decrease the margin by less than 0.02 C.

For a particular spacecraft mission it then is in principle possible to estimate how soon batteries would be destroyed following a collapse of the bus.

Approximate Ah margin as function of discharge current with BDR cut-off set at 3.33 V/cell
Acknowledgements

- Horst Fiebrich and Ferdinando Tonicello of ESTEC provided inputs on the likely current seen by the battery at low bus voltages.
- Carl Thwaite of AEA Technology is thanked for the LAT screening data and advice on test procedures.
Calculated self-discharge high because capacity was not stable

Final open-circuit EMF higher than BOL cells because of increased internal resistance

NASA Aerospace Battery Workshop 27-29 Nov. 2001
Cell 6 after overdischarge

Cell can still be cycled, albeit at low capacity (0.2 Ah)
Battery Safety Testing
Introducing the EV-ARC

Phill O’Kane & Martyn Ottaway
Thermal Hazard Technology

1 North House, Bond Avenue, Bletchley MK1 1SW, England.
www.thermalhazardtechnology.com
Accelerating Rate Calorimetry

- Devised by Dow Chemical in 1970’s
- Simulate worst case “runaway reaction”
- Widely used in Chemical and Battery Industry
- Applicable for most domestic batteries
- EV-ARC developed for larger batteries
THE QUESTIONS...

Is there a thermal hazard?
At what temperature does it begin?
How many processes; a simple or complex mechanism?
Is there an effect of impurity or additive?
How fast does it occur? The kinetics.
How big an event is it? The Thermodynamics.
What temperature will all control be lost?
What time is there before explosion?
How much pressure develops?
What is the rate of pressure rise?

i.e. IS MY PROCESS SAFE??!!!
How and why batteries give out heat due to Discharge or Chemical Reaction

...and therefore how to develop batteries and new chemistries that are more safe.

How batteries might have batch differences

...and therefore how to monitor production process to keep batch variation down
thermal hazard technology
thermal hazard technology
Development of Battery Safety and Test Options
Summary

With a Battery Safety Option the Accelerating Rate Calorimeter may be employed to study

- batteries (at various charge levels)
- battery components
- batteries when shorted
- batteries when overcharged or overdischarged
- batteries when charged, discharged cycled

To obtain….. safety, lifecycle or electrochemical efficiency data
Using the ARC with Batteries
Prismatic, Polymer, Coin, AA, 3/4A 18650 etc
Self-Heating Rate as a Function of Temperature

- Exotherm 1 at 148 - 163 degC
  (Max rate 3 degC/min)
- Exotherm 2 at 175 - 360 degC
  (Max rate 10 degC/min)
Self-Heating Rate as a Function of Temperature

- Onset near 90°C
- One exotherm until explosive decomposition near 200°C
Design and Development of the EV-Accelerating Rate Calorimeter
Experimental Set-up

- Adiabatic Tests
- Isothermal Tests

Batteries are not allowed to runaway!
thermal hazard technology
Electrothermal Dynamics
- Discharging
- Charging
- Cycling
Voltage and Current as a Function of Time

-- Graph details --

Voltage (V) range: 3.25 to 4.00
Current (mA) range: -400 to 200
Time (min) range: 150 to 275

Graph lines:
- Red: Voltage
- Green: Current

Graph notes:
- Data points and line segments indicate changes in voltage and current over time.
Temperature Rate and Current as a Function of Temperature
Temperature and Voltage as a Function of Time

Self heat rate = 6°C/hr

Sample (Alas) 437 g
Test cell mass 35 g

Temperature
Voltage

Time (min)
Temperature and Voltage as a Function of Time

- Temperature (°C)
- Voltage (V)

Sample Mass: 423 g
Test cell Mass: 33 g

Time (min):
125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 400, 425
Electrothermal Abuse
- Over-voltage
- Shorting
- Heating
20V / 5A Over-voltage Applied Continuously on Single 26650 Li-ion Battery (4.1V)
Temperature Rate and Pressure Rate as a Function of Temperature

Self heat rate of 30 °C/min
Temperature as a Function of Time

EuroARC file: D000406

Temperature (°C)

Time (min)

![Battery Image]
Summary

Extended Volume Accelerating Rate Calorimeter
EVARC

- small scale and large scale batteries
- battery packs (voltages to 20V)
- electric vehicle (EV) batteries
- electrothermal dynamics (ETD)
- electrothermal abuse (ETA)

Electrothermal Performance and Safety Characterisation
of Batteries
Performance of Li-S™ Cells Under LEO Test Regime and at Low Temperatures (to –40°C)

November 27, 2001

Spectrum Astro / Moltech Corporation
Product Attributes

**Rechargeable Li-S Cells**

Lightweight (lithium & sulfur) : Higher specific energy density than Li-ion

Rate capability exceeds Li-Ion

Environmentally benign

Low Material Costs

**Technology Can be applied to:**

Primary Batteries

Super capacitors
Theoretical Energy Density Comparison

Cathode Active Materials

Graph showing a comparison of theoretical energy densities for sulfur [Li-S] and Li-Ion/Polymer materials. The sulfur [Li-S] material has a value of 2600 Wh/kg, while the Li-Ion/Polymer material has a value of 510 Wh/kg.
Li-S and Li-ion Cell Performance Comparison

<table>
<thead>
<tr>
<th>C Rate</th>
<th>Wh/kg</th>
<th>Wh/l</th>
<th>Cycle Life</th>
<th>Self Discharge (% Month)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Li-S Potential</td>
<td>Li-Ion</td>
<td>Moltech 2002</td>
<td>Moltech 2003</td>
</tr>
<tr>
<td>15</td>
<td>500</td>
<td>375</td>
<td>250</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>250</td>
<td>125</td>
<td>750</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>5</td>
<td>600</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1000</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Legend:
- Li-S Potential
- Li-Ion
- Moltech 2002
- Moltech 2003
- Moltech Now
Cycle Life Evolution of Moltech Prototype Li-S Cells

C/3.5 Charge and C/2 Discharge (100% DoD)
Voltage vs Ah At Various Discharge Rates
Alpha-6 Improved Design

4.2 A, 750 W/kg
Cell Utilizing New Electrolyte Additive
Ragone Plots At Various Temperatures
Voltage vs Discharge capacity at different temperatures

Discharge 0.075 A
C/10

+25 °C
-40 °C
-30 °C
-20 °C
Voltage vs Discharge capacity at different temperatures

Discharge 0.15 A
C/5

- 40 °C
- 30 °C
- 20 °C
+ 25 °C
Voltage vs Discharge capacity at different temperatures

Discharge 3.5 A
5C

Voltage vs Discharge capacity, Ah

+25 °C
-20 °C
-30 °C
-40 °C
Over Discharge to 0V at 400mA/h
Continuous Cycling with Over Discharge to 0V
30 times Over Charge at 400mA/h
Li-S Cell Cycle Testing

Test Description

• 10 Sample Cells Were Placed in Cycle Testing
• Cells Had Been Previously Stored at Room Temp for 10 Months
• Cycle Consisted of 90 Minute Period; 60 Minute Charge, 30 Minute Discharge
  • Roughly 25% DOD

• Individual Cell Voltages, Currents, and Temperatures Were Captured Throughout the Cycling
Li-S Cell Cycle Testing (Cont’d)

Cells Individually Instrumented With Voltage, Current, and Temperature Monitors

Cells Then Placed Into Protective Enclosure For Cycling
Cell Stabilization
The Cells Were Initially Stabilized Using the Following Process

- Charge @ 250 mA for 3.5 hours (210 min.) (875mAh)
- Discharge @ 350 mA until cell reaches 1.8V
- Measure and record capacity from this discharge
- Repeat steps until 800 mA-h capacity is reached
Li-S Cell Cycle Testing (Cont’d)

• Cell Cycling Characteristics - Voltage

![Graph showing cell cycling characteristics with voltage values and timestamps](image-url)
Li-S Cell Cycle Testing (Cont’d)

• Cell Cycling Characteristics
Li-S Cell Cycle Testing (Cont’d)

• Cell Cycling Characteristics - Cell Temperatures

![Cell Temperatures Graph](image-url)
Li-S Cell Cycle Testing (Cont’d)

- Cells Successfully Completed 94 Cycles With No Noticeable Change in Voltage Characteristic
- Cycling Terminated Due to Test Equipment Issues
Li-S Future Testing

Next Step

• Plan is To Commence Cycle Testing of Latest Generation of Cells at Moderate (25 - 50%) Depth-of-Discharge
## Li-Polymer vs. Lithium-Sulfur

<table>
<thead>
<tr>
<th>Items</th>
<th>Li-polymer</th>
<th>Lithium-Sulfur</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α-δ Sample</td>
<td>Product in 2003</td>
</tr>
<tr>
<td>Operation Voltage</td>
<td>3.6V</td>
<td>2.1V</td>
</tr>
<tr>
<td>Cycle Life to 80% at 100% DoD Discharge</td>
<td>&gt;400</td>
<td>&gt;300</td>
</tr>
<tr>
<td>Specific Energy (Wh/kg)</td>
<td>120 -180</td>
<td>180</td>
</tr>
<tr>
<td>Volumetric Energy (Wh/l)</td>
<td>250 -350</td>
<td>170</td>
</tr>
<tr>
<td>Cell Capacity (mAh)</td>
<td>450 -900</td>
<td>800</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-10°C to 65°C</td>
<td>-40°C to 65°C</td>
</tr>
<tr>
<td></td>
<td>60% of RT at -40°C</td>
<td>Same or Better</td>
</tr>
<tr>
<td>Power (W/kg)</td>
<td>-</td>
<td>750W/kg or higher</td>
</tr>
<tr>
<td>Discharge Rate Capability</td>
<td>2C</td>
<td>&gt;6C</td>
</tr>
<tr>
<td>Charge Rate</td>
<td>2hr at R.T.</td>
<td>3hr at R.T.</td>
</tr>
<tr>
<td>Size and shape</td>
<td>Prismatic</td>
<td>Prismatic or cylindrical</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Alpha Cell Development Plan

<table>
<thead>
<tr>
<th>Alpha</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>Metal foil cells (MFC)</td>
</tr>
<tr>
<td>4</td>
<td>MFC with low impedance</td>
</tr>
<tr>
<td>5</td>
<td>Spray metal tabs at cathode and anode</td>
</tr>
<tr>
<td>6</td>
<td>PET substrate for cathode</td>
</tr>
<tr>
<td>7</td>
<td>Coated Separator on cathode</td>
</tr>
<tr>
<td>8</td>
<td>Thin film plastic cell</td>
</tr>
</tbody>
</table>
Product Roadmap

- **α-4**
  - 160 Wh/kg
  - 180 Wh/l
  - Cycles to
  - 120, 80%
  - December 2001

- **α-6**
  - 180 Wh/kg
  - 170 Wh/l
  - Cycles to
  - 300, 80%
  - December 2003

- **α-8**
  - 300 Wh/kg
  - 400 wh/l
  - Cycles to
  - >500, 80%
  - December 2003

To 1999
Anode Stabilization Layer Concept

SCHEMATIC OF MULTI-LAYER ASL CONCEPT

REMAINDER OF BATTERY

Optimum Combinations of
(~0.1 um Lithiated Metal OR ~0.25 um Solid Electrolyte) LAYER
AND
~0.25 um SPE LAYER
PAIRS

~ 0.25 um SPE
~ 0.1 um Lithiated Metal

~ 1 um SPE

~0.2 um to 1 um Solid Electrolyte

LITHIUM

SUBSTRATE

VERY THIN, Plasma Treated, Interfacial Layer
Cycle Life Comparison: Protected vs. Non-Protected

- **Control no ASL**
- **Protected by ASL**

Discharge Capacity (mAh) vs. Cycle
Lithium/Sulfur Discharge/Charge Chemistry

The diagram illustrates the specific capacity vs. voltage relationship for lithium/sulfur batteries. The specific capacity, in mAh/gm Sulfur, is plotted on the x-axis, while the voltage is plotted on the y-axis.

Key points include:
- **Operating region**: The range where the battery operates effectively.
- **Potential region**: The voltage range where the battery transitions between different sulfur states.
- **1st discharge capacity, region excluded thereafter**: The initial discharge capacity is noted, and it is excluded from subsequent cycles.
- **Potential sulfur states**: The diagram shows the transition from $S_8$ to $Li_2S$, $Li_2S_6$, $Li_2S_4$, $Li_2S_3$, $Li_2S_2$, and $Li_2S$ as the battery undergoes discharge.

The specific capacity values are marked at various voltage levels, with notable points at approximately 800 mAh/g and 600 mAh/g.
Li-S Compared to Other Systems

Energy Density Comparisons

- Dotted lines show projected energy densities
- Planar lithium includes Li Polymer & Advanced Li Ion
- One gram of lithium metal in alpha-6 design

Future Performance Region

Wh/Kg

Gravimetric Energy Density

Wh/l

Volumetric Energy Density

Future Performance Region

Li-S, December 2001

Li-S, December 2003

Planar Lithium

Prismatic Li Ion

Cylindrical Li Ion

NiCd

NiMH
Development Status of 3 Battery Systems for the X-38 Crew Return Vehicle

by

Eric Darcy/NASA-JSC

Presented at the

2001 NASA Aerospace Battery Workshop, Huntsville, AL
Crew Return Vehicle (CRV)

- 28V NiMH
- 270V NiCd
- 32V Li/MnO₂

De-orbit Propulsion Stage (DPS)
32V DPS Li Battery
32V DPS Li Battery

• Design Features (Vendor: Friemann & Wolf, Duisburg, Germany)
  – Li/MnO$_2$ 31Ah cell (P/N M62), 365g, 42 mm dia, 133 mm tall
    • At C/7 starting at 30 °C $\Rightarrow$ 245 Wh/kg, 487 Wh/L
  – Battery String = 12 cells in series
  – Battery Module = 12 strings in parallel
  – Similar to ASTRO-SPAS battery design that flew on 4 Shuttle missions
    • Li/SO$_2$ cells replaced with identically sized Li/MnO$_2$ cells (20% more Wh)
    • Provisions for added battery capacity gauge circuit
    • Provisions for improved internal thermal conductivity and capacitance
  – Flight Battery Set = 4 Battery Modules
  – Voltage: Open Circuit = 40V, Closed Circuit = 24-33V
  – Capacity starting at 0 °C = 350 Ah/battery module
  – Capable of adiabatic discharge at 50A/module for 7 hours starting at < 30 °C
    • Composite phase change material heat sink sealed in base of battery
    • Provides >3300 kJ of latent heat at 42-44 °C
  – Battery Module Size
    • 590 mm wide, 580 mm deep, 223 mm tall $\Rightarrow$ 169 Wh/L
    • 91.5 kg $\Rightarrow$ 141 Wh/kg
M62 Cell Design Features

- Li foil anode, 10 g
- MnO$_2$, carbon, binder cathode mix, 160 g
- Double layer, polypropylene separator, 20 g
- Cylindrically wound coil with anode in contact with case, positive insulated from case with PTFE spacers
- Non-corrosive, organic electrolyte (with LiClO$_4$ salt)
- Glass-to-metal positive feed-thru
- Hermetic seal achieved by laser weld of lid to deep drawn can
- 304L SS can & lid with safety vent operating at 150 to 250 psia
32V DPS Li Battery Module (without cover)

X38 HEAT SOURCE
positions of heat sources

24 x 1.75 W
diodes of Diode Block

discharge max time = 7 h

12 x 12 x 1.85 W
M62 Cells

12 x 2 x 0.25 W
PTC of String PCB

11/27/01
Eric Darcy/281-483-9055
32V DPS Li Battery Module
Adiabatic Discharge Possible with PCM Heat Sink

• Two Main Components of Battery
  – Upper Deck: Cells, polyswitches, and diodes dissipates heat
  – Base: PCM heat sink absorbs heat

• Thermal design requirements
  – High heat capacitance
    • Use latent heat of phase-change material (248 J/g) at 42-44 °C
    • Cp of composite heat sink ~ 2 J/g/C
  – Adequate thermal conductivity (Max ΔT < 9 °C)
    • Conductive Al sleeves around base of each cell
    • Thermally conductive glue to bond sleeves/shell to battery base
    • Conductive Carbon Fiber Core Material with 90% porosity’
      – Increases thermal conductivity of pure PCM by factor of 50
PCM Composite Heat Sinks

- Carbon-fiber core body
  - High thermal conductivity
  - Light honeycomb structural properties
  - Capillary control of voids relieves stress
- Lightweight packaging
  - Packaging mass = 20-50% of total heatsink mass
  - Specific latent heat > 150 J/g for total package
- Technology own by Energy Science Labs, Inc (ESLI), in San Diego, CA
Carbon Fibercore Blocks for Qual Battery
Side view of carbon fibercore
Battery Module Base Housing
Carbon Fibercore Blocks on Lid of Base
Base cavities are lined with epoxy glue
Fibercore blocs are hand fitted and glued to the base cavities
Battery base filled with fibercore blocks
Ass’y and Acceptance of PCM Heat Sinks

- Lid is glued onto housing to complete unfilled assembly
- Vacuum baked to remove moisture
- Thermally shocked cycled followed by helium leak check
- Vacuum back-filled at 90 °C with liquid $n$-docosane ($\text{C}_{22}\text{H}_{46}$)
- Thermally cycled to measure capacitance with 350W heat source in two orientations
Melting Heat Sink Characteristics

- Average of 4 Flight Heat Sinks
  - 3596 kJ of latent heat at 42-44°C
  - Melting over ~3.5 hours at 300W
  - Specific latent heat = 133 J/g (includes structural mass of base)
  - Specific latent heat = 184 J/g (without 7.5 kg base mass penalty needed for battery w/o PCM)
- Battery Module Base = 27 kg
  - 14.5 kg (54%) PCM
  - 3.6 kg (13%) fibercore
  - 1.3 kg (5%) cover
  - 7.4 kg (27%) base housing
Assembly of Cell Strings

Bypass diode
Qty 1/cell

Picofuse
Qty 1/diode

Polyswitch (not shown) Qty 2 in parallel/string

Kleber Scotchweld 2216

Thermofuse
Qty 4/string
Electrical Schematic of Cell String

- 12 cells (P/N M62) in series
- 1 bypass Schottky diode/cell rated at 9A
- Each cell protected from a shorted diode failure by 7A fuse
- 2 polyswitches in parallel trip above 7.5A at 20 °C or at ~82 °C with 4.2A
- 4 thermofuses/string open at 90 to 100 °C
Battery Module Front Panel Box

Battery Module Front Panel Box Zchn.Nr.: 49815-300.000
Summary of Battery Qualification

- Qualification was successfully completed on 4/11/01
  - Battery passed shock (20g, 11ms) and vibration tests (~7 grms, 3 min/axis)
  - Battery ran for > 7 hours at 50A under adiabatic TV conditions
    - Started at 30 °C, ran for 7 hrs, 28 min until cell temperatures reached 80 °C
    - PCM composite heat sink stabilized battery temperatures at 42-50 °C for 3.5 hours
  - Three “firsts” were achieved for manned spacecraft!
    - Largest (12 kWh) lithium battery module
    - Largest (3600 kJ) PCM heat sink
    - Largest lithium battery capable of adiabatic discharge
Voltage, Temperature vs Runtime during thermal vacuum adiabatic discharge of the Lithium Battery for the DPS of X-38
Discharge current at 50A with 74A, 1 min peaks every hour
Future Plans

• Flight battery production underway
  – Quantity of 4
    • All 4 PCM bases have passed all acceptance tests
  – Refurbishment of Qual unit also underway

• Delivery expected in March 2002

• Vaporizing heat sink alternative looks very promising
  – Completed SBIR Phase I with ESLI
  – Could reduce battery heat sink from 27 to ~10 kg
    • Replace 14.5 kg of melting wax with ~1.5 kg of vaporizing water
  – Will award Phase II in Jan 2002
Water Heat of Vaporization

- Water latent heat of vaporization is 10x higher than paraffin latent heat of melting
  - But only one cooling cycle

<table>
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<tr>
<th>Temp. (C)</th>
<th>Pressure (bar)</th>
<th>Heat-vap (kJ/kg)</th>
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<td>102</td>
<td>1.08</td>
<td>2252</td>
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</table>
Vaporizing Heat Sink (VHS) Concept

• Relief Valve
  – Allow coolant to vaporize through a pressure-relief valve whose P sets the heat sink T

• Conductive Wick
  – Assures that all coolant remains in good thermal contact with the heat transfer surface in microgravity

• Recuperator
  – Channel the expended low pressure vapor back through the heat transfer surface to better utilize the vapor (reheat, atomize)
Vaporizing Heat Sink Schematic

- Heat source
- Warm vapor at low pressure
- Pressure relief valve
- Liquid + vapor in gradient wick
- Fibrous heat exchanger
Prototype VHS with Wick and Recuperator
VHS Concept Demonstrated by Test

- Simple, uniform wick allows the heatsink to perform well against gravity (upside down, heater above)
- Thermal resistance in wick ($k \approx 1 \text{ W/K-m}$) causes steady increase in VHS temperature
  - Wick dries out across thickness
- Expect to reduce the gradient in either of two ways:
  - Higher conductance ($k \sim 5$)
  - Capillary gradient wick
28V NiMH Battery System Requirements

- **Specification Summary**
  - Closed circuit voltage: 24 to 33V
  - Power: 3.6 kW
  - Energy: 3.6 kW for 3 hours = 10.8 kWh
  - Capacity: 387 Ah at 129 A rate to 24V while >10 °C
  - Charger built into each battery module using X-38 28V bus power
    - C/8 charger rate using < 3.5 kW power consumption
  - Capacity gauge circuit built into each battery module
    - Measure battery voltage, current, and temperature
    - Calculates and tracks %Ah remaining
    - Communicates to
      - DAU via a RS-422 interface
      - GSE via a RS-232 interface
  - Total mass: < 335 kg (738.5 lbs)
  - Max crate dimensions: 34.31” depth, 25.37” width, 12.13” height
28V In-Cabin Battery for V201

- NiMH 3.7Ah cell (P/N TH-4000) from Toshiba, Japan
  - Cell used in EMU helmet light battery
  - Cell extensively performance and abuse tested for X-38
  - Demonstrated 308 Wh/L, 90 Wh/kg at C/4 rate and 25 °C
  - 52 g, 17 mm diameter, and 67 mm long
- Battery String = 24 cells in series
- Battery Module = 16 strings in parallel
- Flight Battery Set = 8 Battery Modules in a Crate
  - Estimated at 300 kg, 173 L ⇒ 48 Wh/kg, 83 Wh/L
- Voltage: Open Circuit = 33.6V, Closed Circuit = 24-33V
- Capacity starting at 10 °C = 474 Ah
- Capacity gauge and charger circuit in each module accepting 28V
  - One charge control chip (ICS1702) per string using reverse pulse charging
  - One capacity gauge control chip (MTA11200) per module
- Battery Vendor: Yardney Technical Products, Pawcatuck, CT
**LIMITED CONTROL**

This document is valid only if accompanied by related procurement or test documentation (purchase order, work order, etc.).

**Issued by Drawing MAY 12 2000 and Change Control**

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**NOTES:**

1. MFG. PER YP-197
2. REMOVE AND DISCARD ORIGINAL SHRINK WRAP AND INSULATOR.
3. IDENTIFY PER YEC-933, CLASS F, TYPE VS.
4. INSULATE ITEM 1 USING ITEM 4.
5. RESISTANCE WELD PER YP-897

---

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<th>ITEM</th>
<th>QTY</th>
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<th>PART NO. OR IDENTIFYING NO.</th>
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<td>3</td>
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<td>50951 INSULATOR</td>
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<td>50953 DIODE ASSEMBLY</td>
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<td>1</td>
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<td>50943 CELL, NI-MH</td>
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**Yardney**

**CELL/Diode Assembly**

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**ENDNOTES**

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**11/27/01**

**Eric Darcy/281-483-9055**
28V, 50 Ah NiMH Battery Module
28V Flight Battery Stack and Crate

ASSEMBLY

25.37”  34.31”

12.13”
Status and Future Plans

• Battery vibration failure during qualification forced a redesign
  – Battery charge & gauge panel design flaw was root cause
• Re-test is this week at YTP
• Assembly of 8 flight battery modules to follow after completion of qualification
270V Battery Module Requirements & Status

• Performance Requirements
  – 270 +30/-70V during discharge, 306-350V during charge
  – Divide into 3 batteries modules each capable of 5.07 Ah (4.10 Ah for EMAs)
    • 6A for 1640 sec
    • 6A baseline with 170A, 100 ms peaks every 1 sec for 220 sec
    • Four 6A to 55A ramps over 15 sec for untwisting the parafoil
    • Four 6A to 45A ramps over 15 sec for steering the parafoil
    • One 6A to 45A ramp over 7 sec for the flare
  – 34.85 kW max peak power/battery module
  – Outside cabin, vacuum exposed for 3 years (14 days for V201)
  – Mass < 85 kg/battery module
  – Not to exceed volume; 25.25” wide x 16.25” deep x 6.75” tall
  – All 3 battery modules located in nose of vehicle

• Development Status
  – Contract awarded to AZ Technology (Huntsville, AL)-SRI (Arab, AL)
  – Assembly of qualification battery module nearly complete
  – Prototype 270V string charging and discharge performance validated
  – Completed cell acceptance on 5700 cells
V201 Nose Equipment

- Pressure Port (2)
- SPU
- PEB
- Forward Bulkhead
- 270 V Batteries (3)
- Air Data Modules
- Ballast #2 332 lbs.
- Ballast #4 (2) 178 lbs. each
FBM internal block diagram

Battery Analog Signal Conditioning

Isol

Battery string 1
Control logic
Kilovac
CBPC

Battery string 2
Control logic
Kilovac
CBPC

Battery string 3
Control logic
Kilovac
CBPC

Battery string 4
Control logic
Kilovac
CBPC

Dchg Pwr

1

J2

Battery Analog Signal Conditioning

BASC

MCF: Master Current Fault (any string)
MTF: Master Temperature fault (any string)
CCx: Charge control for string x
ATx: Analog temperature for string x
MFR: Master fault reset
Baseline Design of 270V Battery

- Cell: SubC NiCd from Sanyo (P/N CP-2400SCR)
  - New cell design intended to replace Sanyo’s N-1900SCR

- Battery String = 210 cells in series
- Battery Module = 4 strings in parallel
- Flight Battery Set = 3 Battery Modules
- Voltage: Open Circuit = ~285V, Closed Circuit = 200-280V
- Redundancy Plan: Consistent with EMA 2 failure tolerance
- Estimated Battery Module Mass = 85 kg
- Mass and volume estimates do not include interface to bulkhead
Prototype 270V String Validation Test

EMA/Winch Profile 7 Battery Voltages
270V Prototype String #03XB50, Dsch 1
4-string Design Profile currents plus 2.4A residual discharge

Battery Voltage (V)

time (min)

0 10 20 30 40 50 60 70

140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0 300.0

baseline EMA/Winch
Performance and capacity retention test

EMA/Winch Profile 7 Battery Voltages
SRI 2400CSUHP040 36V Battery
3 hour vs 14 day rest
4-string Design Profile currents plus 2.4A residual discharge

Graph showing battery voltage over time for 3 hour and 14 day rest conditions.
Comparison of N-1900SCR and CP-2400SCR

<table>
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<tr>
<th>ATTRIBUTE</th>
<th>N-1900SCR</th>
<th>CP-2400SCR</th>
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<tr>
<td><strong>Physical</strong></td>
<td></td>
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<tr>
<td>Size dia X ht (in)</td>
<td>0.873 X 1.651</td>
<td>0.870 X 1.673</td>
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<td>Mass (g)</td>
<td>55</td>
<td>58</td>
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<td><strong>Design</strong></td>
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<td>Electrode types (neg/pos)</td>
<td>Sinter/sinter</td>
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<td>Jellyroll winding lead</td>
<td>180° opposed lead</td>
<td>&gt;360° pos lead</td>
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<td>Can wall thickness (in)</td>
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<td>Vent mechanism</td>
<td>Spring backed disk</td>
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<td>Vent Pressure (psig)</td>
<td>230 to 290</td>
<td>190 to 310</td>
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<td>Burst Pressure</td>
<td>910 to 950</td>
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<td><strong>Performance, typical</strong></td>
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<td>1C Capacity (A-h)</td>
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<td>Eff. Internal Resistance (80ms pls)</td>
<td>4.8</td>
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High Power Cell Evaluation
Typical Cell Voltage and Re vs. DOD at Room Temp.
Sanyo N-1900SCR NiCd Cs Cell
1C baseline current w/10C, 80ms pulses @ 10% DOD intervals

Old Cell
New Cell

High Power Cell Evaluation

Typical Cell Voltage and Average Re (w/min, max range) vs. DOD at Room Temp.

Sanyo CP-2400SCR Cs Cell, Date Codes "DK" & "DL"; n=12
1C baseline w/10C 80ms pulses @ 10% DOD intervals

New cell provides 20% more Ah for only 1% more volume and 7% more mass
Cell Acceptance

Cell Preparation – remove sleeves, clean as necessary, serialize all cells

Residual Discharge

Open Circuit Voltage
All cells

Cold Charge, Discharge
All Cells

High rate charge, 3-day rest, discharge with Re Pulse
All Cells

Phenolphthalein leak check
All Cells

Physical Measurements, Visual Inspection – Mass and dimensions
All Cells

Passing Cells

Rejected Cells

Low

Low Capacity

Low Capacity, high Re

Seal/vent Leaks

Out of Spec., Visual Defects

High

Eric Darcy/281-483-9055
Cell Acceptance

270V X-38 Cell Acceptance
Sanyo CP-2400SCR; Date Code EK
Cycle 1 capacity Distribution; n=5699

Average = 2.247
Std Dev = 0.040

Capacity (A-h)

Frequency (no. cells)
Cell Acceptance Summary

Cell Acceptance Testing for Sanyo CP-2400SCR Cs NiCd Cells
for 270V X-38 Battery Modules

Sanyo Cell Lot Identification "EK" (Nov., 2000)
Summary, all cells n=5700

<table>
<thead>
<tr>
<th>OCV Chk (P/F)</th>
<th>1st Cycle Cap. (A-h)</th>
<th>2nd Cycle Cap. A-h</th>
<th>Int. Res. (mohms)</th>
<th>Leak Test (P/F)</th>
<th>Mass Chk (P/F)</th>
<th>Dimension Chk P/F</th>
<th>Visual Defect (P/F)</th>
<th>Cyc1 minus P/F</th>
<th>Calc V @42.5A</th>
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<td>&lt;2.10</td>
<td>&lt;2.00</td>
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<td>3</td>
<td>71</td>
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Short Circuit Test

Sanyo CP-2400SCR NiCd 6-Cell Stick
Short Circuit; 0.005 ohm Ext. Circuit Resistance
270V Prototype Construction

Stick short circuit tests results in no smoke, flames, or fire!

11/27/01 Eric Darcy/281-483-9055
30-Cell Bundle – after short circuit test!
Short Circuit Test

Sanyo CP-2400SCR NiCd 30-Cell Bundle
Short Circuit; 0.105 ohm Ext. Circuit Resistance
270V Prototype Construction

30-cell bundle short circuit tests results in no smoke, flames, or fire!

11/27/01
Eric Darcy/281-483-9055
Pallet Drop Battery

- Half-Battery (2, 270V strings)
- Package in Pelican Case
- Powered parafoil winches during pallet drop tests of 7500 sq.ft parafoil in near Yuma, AZ
- Excellent performance using 30 cell bundle as building block
- Good shock tolerance
Future Plans

- Manuf Readiness Review in late Nov
- Complete Qualification in Jan 2002
- Deliver Qual Module in Jan 2002
  - Perform corona test with EMA and HVSU at Moog
  - Integrate into V131R for drop test with 270V winches
  - Use it for EMA, Winch, and Ironbird testing
- Deliver 4 Flight Battery Modules by May 2002
Small Cell Battery Approach Works!

• High Safety
  – Small cells are safer than larger cells
  – Protective devices necessary are small and available

• Good Performance
  – Automated production of commercial cells are highly homogenous

• Low Cost and Rapid Development
  – Low total cell cost more than offsets cell screening costs needed
  – No cell development needed, only characterization
  – Cell and string level testing applicable to total battery
The new high tech commercial devices, like cellular phones, digital cameras, laptops, camcorders and palm pilots require more energy and power than the devices we have been using in the past. The manufacturers of small cylindrical cells want a significant share of these large new markets and are, therefore, making cell improvements to meet these new requirements. For these devices, they are concerned with operation in the 0.5-2.0 watt range. The cell improvements began in the late 1990’s with the Duracell Ultra, Energizer e², Panasonic digital and similar improvements by other manufacturers to their standard product line.

Since the aerospace community may have some interest in these commercial products, we have attempted with this paper to present performance information for recently developed small cell technologies. Comparisons between manufacturers will not be made. The paper will be concerned only with the present state of the technologies.

The date presented in this paper, unless otherwise indicated, represents the discharge data for the median cell of a group of from 6 – 15 standard cells. We will start with the standard “AA” as the baseline. Figure 1 shows the performance for various discharge rates at 24°C. Performance begins to degrade at rates shorter than the 100 hour rate and at the 10 hour rate only about ½ the cell capacity is delivered to a reasonable cutoff voltage. Figure 2 shows the performance of the same type cells at the 1000 hour discharge rate as a function of temperature. Performance begins to degrade below 0°C and below –20°C less than ½ the capacity is delivered. Only ½ the capacity is delivered at 90°C at this rate but at 70°C the full capacity is delivered.

Figure 3 shows the performance of the high tech “AA” cells at various discharge rates. To a 0.8 volt cutoff and the 31.6 hour discharge rate the cells deliver a capacity of about 2.7 Ah, while the standard cells deliver about 2.4 Ah. At the 3.16 hour rate the high tech cells deliver 1.3 Ah while the standard cells deliver 0.8 Ah. At the 1000 hour rate (Figure 4) the high tech cells perform like the standard cells, which is no great surprise because they are designed for rates of less than 10 hours.

Manufacturers use essentially the same technology in their “AAA”, “C”, and “D” cells as they do in their “AA” cells, so these cells are supposedly a scale up or down of the “AA” cells with the same label. This does not necessarily mean that the performance of other cell sizes is just a multiple of the “AA” size. It only means that the technology is the same.
One other cell size that will be mentioned is the “AAAA” (Quad A) size. In the past this cells size has only been used in 9 V batteries and has not been offered commercially. It is now being offered commercially for applications like medical devices, laser pointers, target sites, personal safety devices, pen lights, etc. It performs similar to the high tech alkaline cells at various temperatures. At the 1000 hour rate it delivers about 700 mAh to a 0.8 volt cutoff. At the 31.6 hour discharge rate at 24°C the performance drops off by about 20%, which is similar to the performance of the high tech “AA” alkaline cells, (see Figures 9 & 10).

The Li/FeS$_2$ cell technology presently comes in the “AA” cell size and is only sold by Energizer. It is being marketed as a cell for cameras. The open circuit voltage of these cells is about 1.8 volts and at low discharge rates discharges at two plateau voltages (see Figure 5). At low rates this cell only delivers about 2.5 Ah but even at the 1 hour rate the cell still delivers more than 2.0 Ah above 0.8 volts. The alkaline high tech cells cannot deliver 2.0 Ah at discharge rates shorter than the 10 hour rate. At the 1000 hour discharge rate over 2.0 Ah of capacity is delivered at temperatures as low as –40°C., (see Figure 6).

“AAA” size Li/FeS$_2$ cells have been made in evaluation quantities, but it does not appear that this cell will be produced until a significant market is developed for it. At the present time, the “AA” Li/FeS$_2$ cell sells in the commercial marketplace for 2 to 3 times more than that of the alkaline high tech cells. Its outstanding performance in the camera market (which will be shown later in the paper) may justify its higher cost.

Because of their high cell voltage (greater than 3.0 volts), good pulse capability and high energy density Li/MnO$_2$ 2/3A cells and CR2 cells were developed. The 2/3A cell contains the maximum amount of lithium metal that can be shipped uncontrolled. Because of the good performance capabilities of the Li/MnO$_2$ technology the smaller CR2 cell was marketed. The 2/3A cell has a rated capacity of about 1800 mAh while the CR2 has a capacity of about \( \frac{1}{2} \) that. At rates greater than the 500 hour rate the 2/3A cells deliver most of their capacity above 1.7 volts. There is then a gradual drop off in delivered capacity from the 500 hour rate to the 0.5 hr rate where about 1.0 Ah of capacity is delivered. For such a small cell this is an excellent capacity for a cell operated at 2.6 A (0.5 hr rate). At the 1000 hr rate as a function of temperature, the 2/3A cell performance falls off about 20% at –20°C & 90°C. At –40°C, the performance drops off another 10%, (see Figures 7 & 8). Performance of the CR2 cells is similar to those of the 2/3A, (see Figures 11 & 12).

To provide a rough idea of how the different cells, described above, perform in pulse applications consider Figure 13. This chart shows how the different technologies perform in the ANSI photoflash test. The ANSI photo flash test had been 1.8 ohms applied 15 seconds/minute until the voltage dropped to 0.9 volts. The new ANSI photoflash test is 1 A applied 10 seconds/minute; 1 hour/day. The flashes obtained for the cells tested under the 1.8 ohm regime are shown in red, while the flashes obtained in the 1 A test are shown in blue.

We hope that the data presented in this paper will give the user some insight into the changing world of battery cells in the commercial market place and help the user select the right battery for his application.
Battery System Studies in a Virtual-prototyping Environment

Presented by Roger A. Dougal

Contributors:
Zhenhua Jiang, Shengyi Liu, Roger A. Dougal, Lijun Gao,
John W. Weidner, Ralph E. White
Outline

- Introduction to VTB
- Battery Models in VTB
- Satellite power system simulations
- Comparisons of different configurations
- Interactive demonstration
Virtual Test Bed

- Is an environment for integrating the work of interdisciplinary teams
- Provides a “common language” for expression of problems and solutions
- Enables virtual prototyping and tuning of complex dynamic systems

Capture domain-specific expertise and preserve utility of existing models and modeling skills

Advanced visualizations increase comprehension
VTB accelerates interdisciplinary system design by integrating knowledge.
VTB facilitates interdisciplinary and distributed team work by **capturing** and **amplifying** user knowledge at every step of the system modeling and simulation process.
VTB uniquely supports all three types of object couplings, even for imported and hardware objects.

**Natural Coupling**
Enforce physical conservation laws

**Signal Coupling**
Directed flow of information through objects

**Data Coupling**
Pass data between objects
Advanced VTB Features

Variable Model Order

- Different types of studies require different levels of model detail
- VTB allows automatic model order reduction to speed computing. Resolution is appropriate to the particular study objective.
Battery Performance Models in a System Context

Charge Controller

Simulink
What is in a battery model?

- Electrochemical effects
- Thermal effects, including heat exchange with ambient
- Pressure effects
- Transient response characteristics
- ...full diffusion based physics....on the way
Charge/Discharge Characteristic Tests
Models capture known physics

NiH$_2$ battery: discharge curves

Temp effects
1C rate  
T=250K

T=350K

Rate effects
0.5C
4C

Hysteresis effects
1C rate
charge
discharge
Models capture known physics

Lithium ion batteries
Polystor

Rate effects

0.2C
0.5C
1.0C
1.5C
2.0C

Rate effects

0.2C
1.0C
2.0C

Temp effects

45 °C
34 °C
23 °C
10 °C
0 °C
-10 °C
-20 °C

Rate effects

280mA
700mA
1000mA
1400mA
2800mA

Sony US18650—Constant current discharge

Sony US18650—Discharge characteristics on temperature (700mA)

Sony US18650—Discharge characteristics on temperature (700mA)

280mA
700mA
1400mA
2800mA

280mA
700mA
1400mA
2800mA

280mA
700mA
1400mA
2800mA
Models capture known physics

Unexpected data?

Nov 25, 80°, sunny, breezy

280mA
700mA
1000mA
1400mA
2800mA

45°C
34°C
23°C
10°C
0°C
-10°C
-20°C

0°C
-10°C
-20°C

280mA
700mA
1000mA
1400mA
2800mA
System Comparisons
Design Alternative 1: Add Supercapacitor
Design Alternative 2: Use Flywheel instead of Li battery
Power profiles – Li battery

- Solar array
- Resistive load
- Transmitter
- Battery

Graph showing power profiles with labels for solar array, resistive load, transmitter, and battery.
Battery voltage and current

![Graphs showing battery voltage and current over time.](Image)
Battery state of charge
Terminal Voltages of energy storage devices

Battery w/Super cap

Battery

Flywheel
Comparison of the bus voltages
VTB belongs to the users

- Download software
- Get the latest models
- Develop/submit your own models
- Contribute to the software development effort!
Demonstration