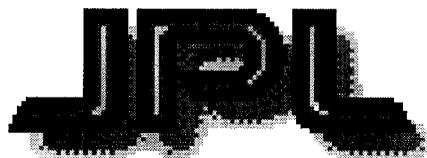


Li-Ion Cells for Terrestrial Robots

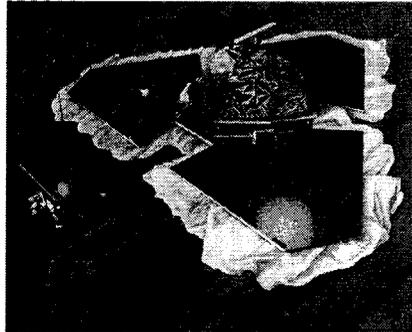
by

**K. B. Chin, M. C. Smart, S. R. Narayanan, B. V.
Ratnakumar, L. D. Whitcanack, E. D. Davies, N. S. Raman
and R. Surampudi**

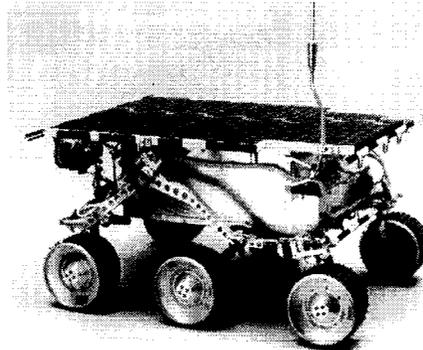


Electrochemical Society Fall Meeting, Orlando, FL, OCT. 11-18, 2003

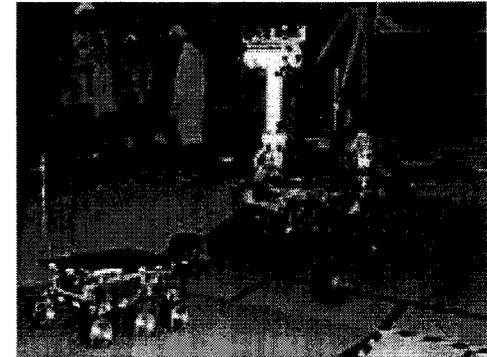
Batteries for NASA/JPL Robotic Missions



**Mars Pathfinder
Lander**



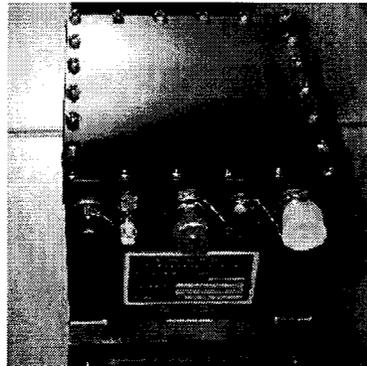
**Mars Pathfinder
Rover- Sojourner**



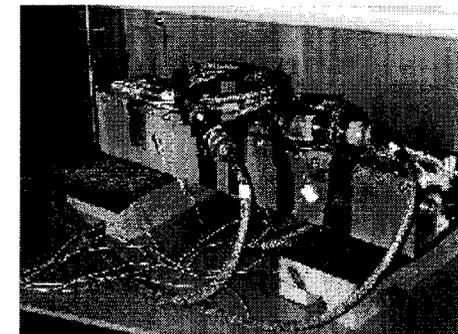
**Mars Exploration Rover
vs. Sojourner**



**Sojourner Lander Batteries
SAFT Li-SOCl₂
28 V and 12 Ah; 1.2 Kg**



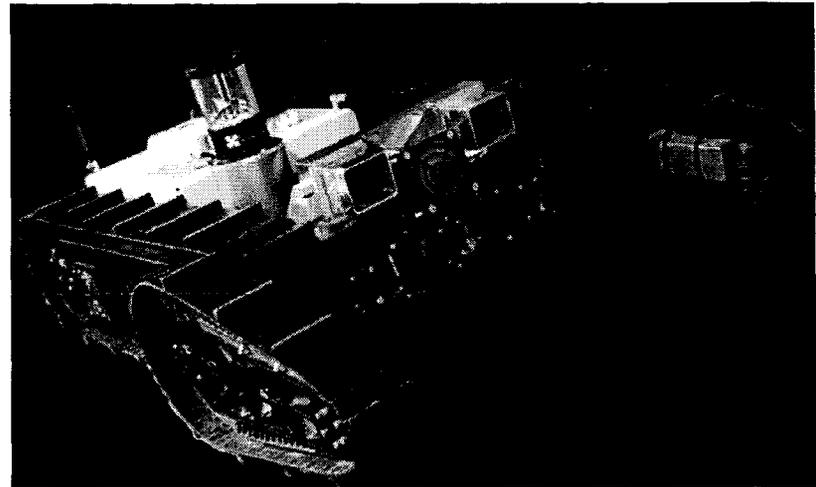
**Mars Pathfinder Battery
BTS Silver-Zinc
28 V, 40 Ah; 15 Kg**



**MER Rover Rechargeable
Battery- Yardney Li Ion
28 V, 16 Ah. 7.5 Kg**

Tactical Mobile Robots

- **Used as Military “Point Men”**
 - **Surveillance of Enemy Terrain**
- **4 to 6 Month Operation**
- **Easily Deployable**
 - **Light Weight**
 - **“Backpackable”**
 - **Manageable Size**
 - **~16 Inches in Length**
- **Highly Maneuverable and Agile**
- **Durable and Long Operating Life**
- **Tolerant to moderately high temperatures**



TMR Design Example by I-robot



Batteries for TMR – Tactical Mobile Robots

Design Requirements

- **Power Loads**
 - **Base Load in Watch Mode: 80 W (45% duty cycle)**
 - **Travel/Running Mode: 120 W (45% duty cycle)**
 - **Stair Climbing Mode: 350 W (10% duty cycle)**
- **Energy Content: 720 Whr**
- **Operating Time: > 6 Hours continuous**
- **Weight: < 7 Kg**
- **Volume: < 4.6 Liters**



Batteries for TMR – Tactical Mobile Robots

Operational Requirements

- **High Specific Energy and High energy density**
- **Extreme Thermal Operating Environment (-20°C to 55°C)**
 - **Able to withstand Abusive Operating Conditions for Worst-Case Scenario!!**
- **Excellent Rate Capability even after cycling**
 - **Up to C rate**
- **Moderate Cycle Life**
- **Nearly Commercial Off the Shelf (COTS)**

Battery System selected for Evaluation

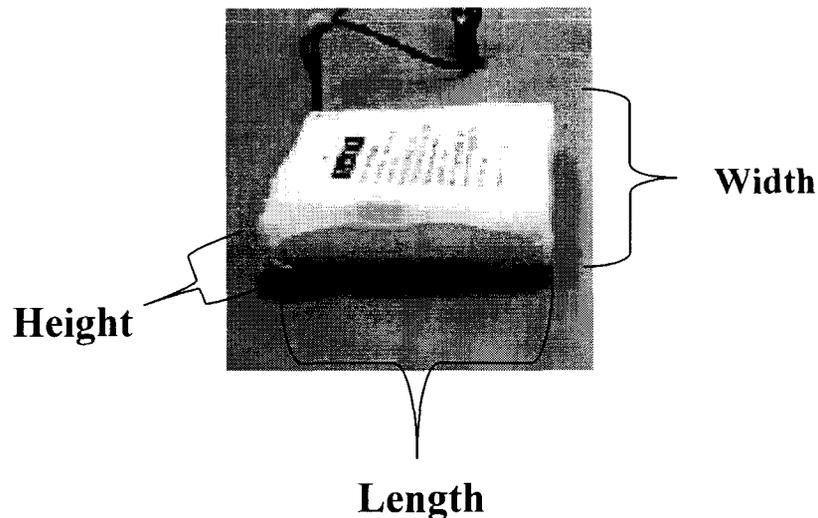
- **5 Ah Li ion Cells from SAFT, France**
 - **MP 5 (wound Prismatic)**
 - **Provide packing efficiency similar to any prismatic, without any additional external constrainers**

Li-Ion Proposed Cells & Battery

SAFT Prismatic MP 5 Ah Series

Cell Properties

- Length = 6.2 cm
- Width = 5.8 cm
- Height = 1.4 cm
- Cell Mass = 155 gm
- Nominal Voltage = 3.6 V
- Rated Capacity = 5 Ahr



Proposed Li ion Battery Characteristics

- Configuration : 8S 2P (Two parallel strings of eight cells in series)
- 10 Ah, 28 V and ~ 280 Wh
- Operating Voltage = 24-32 V
- Estimated Mass = ~3.2 Kg (~8 lbs)
- Estimated Volume = ~1.6 Liters



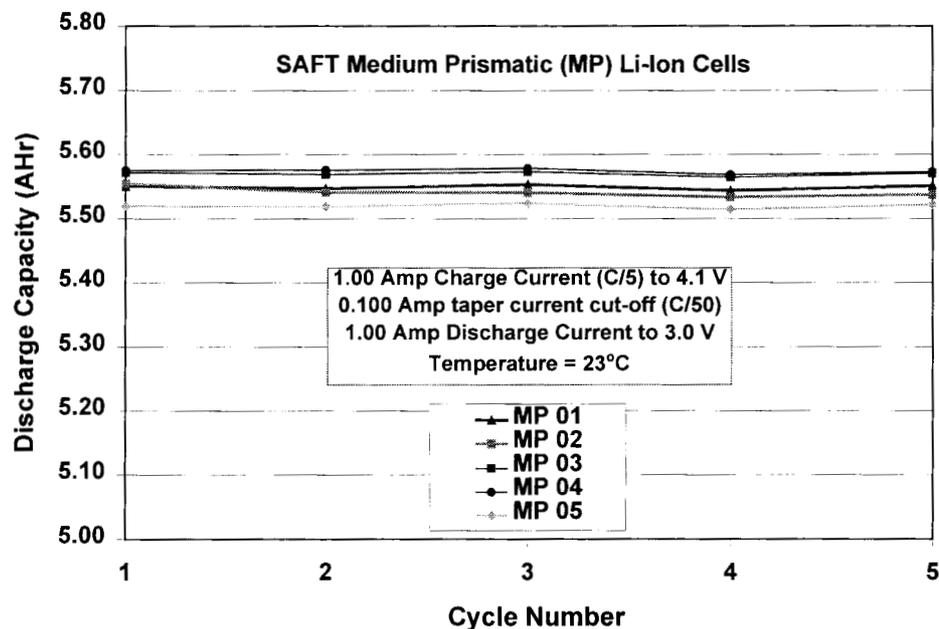
Outline of Cell Evaluation

- Capacity determination from initial characterization cycles at 25°C
- Discharge Rate capability was determined as a function of cycle life (repeated after every 100 cycles).
- Electrochemical impedance Spectroscopy
 - As a function of state of charge
 - As a function of cycling
- Cycling over **EXTREME** operating range
 - Worst-Case Scenario: 100% DOD Cycling at to 55°C
- DPA of cells (future work)

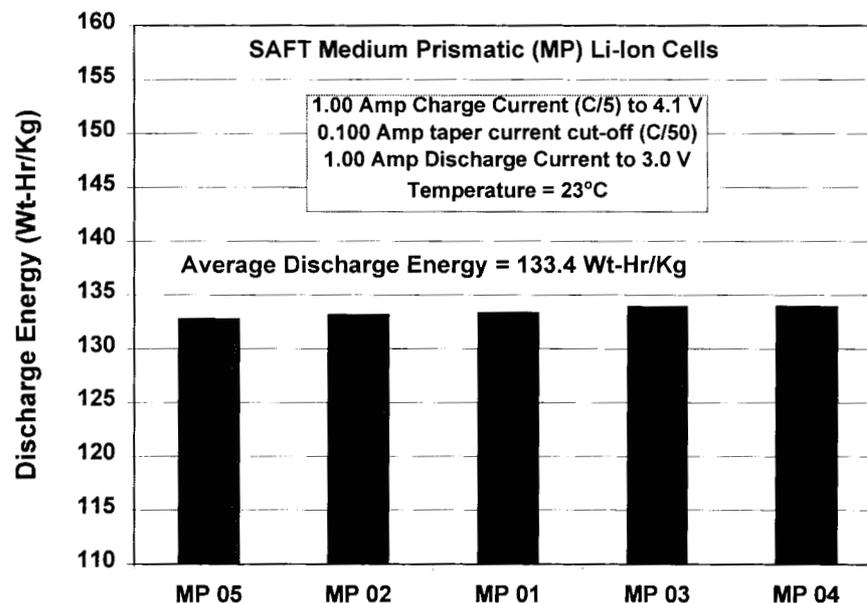


SAFT 5 AH (MP) Li-Ion Cells Characteristics of Conditioning Cycles

Discharge Capacity (Amp-Hour)



Specific Energy (Wh/kg)

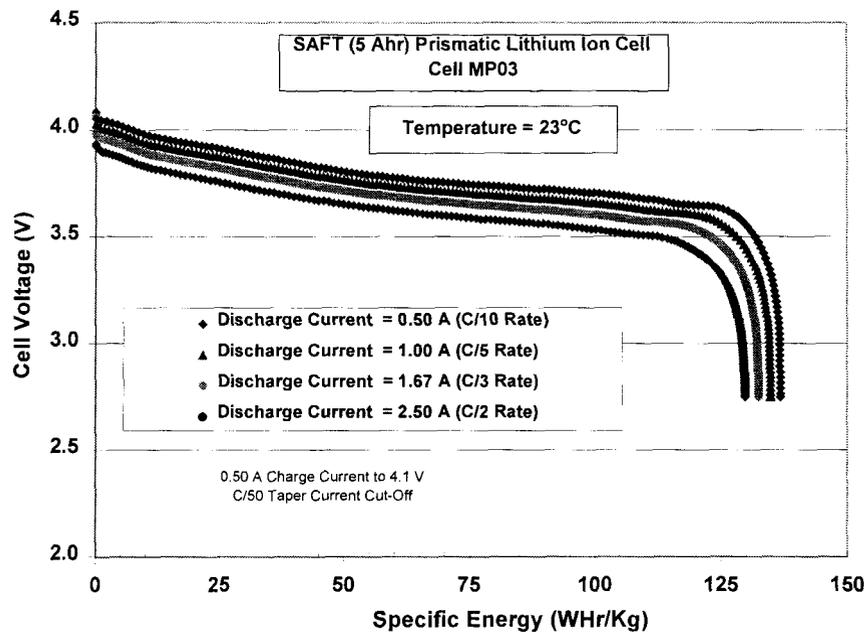


- Cell specific energy over 130 Wh/kg

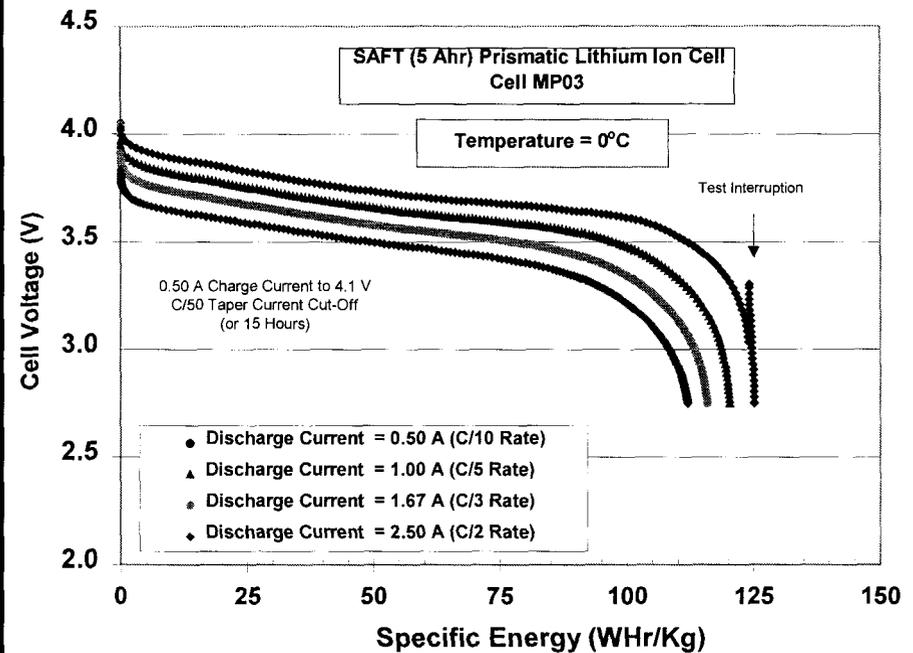


SAFT 5 AH (MP) Li-Ion Cells Rate Capability Before Cycling

Rate Capability at 25°C



Rate Capability at 0°C

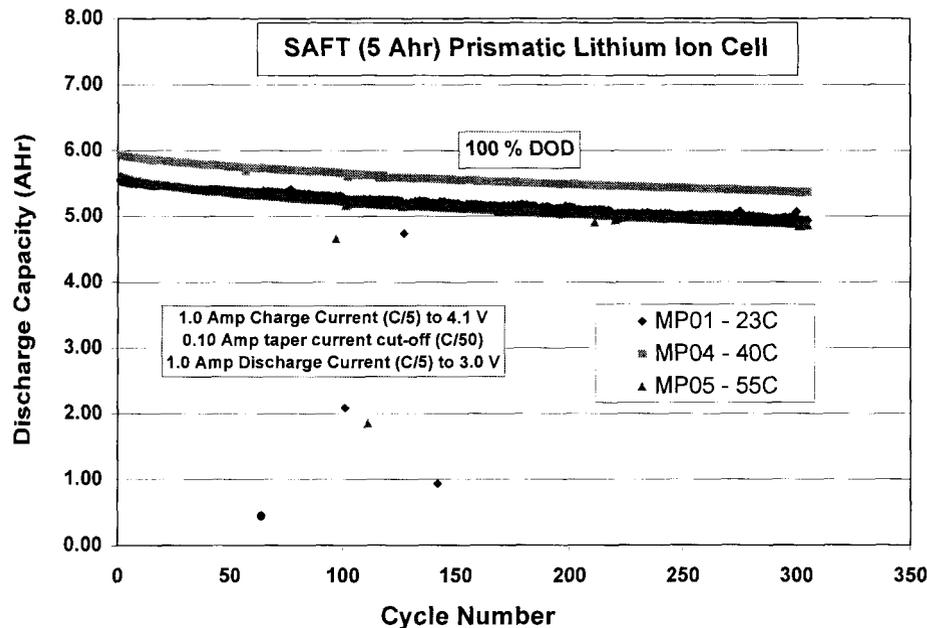


- Specific energy \geq 120 Wh/kg even at 0°C and C/2 rate.

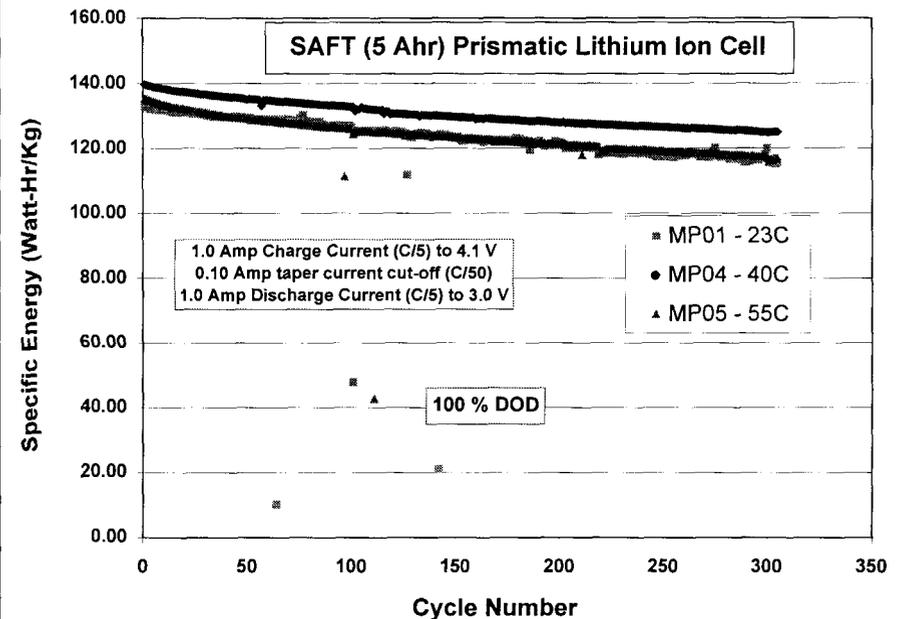


SAFT 5 AH (MP) Li-Ion Cells Cycling to 100% DOD

Capacity Retention During Cycling



Specific Energy During Cycling

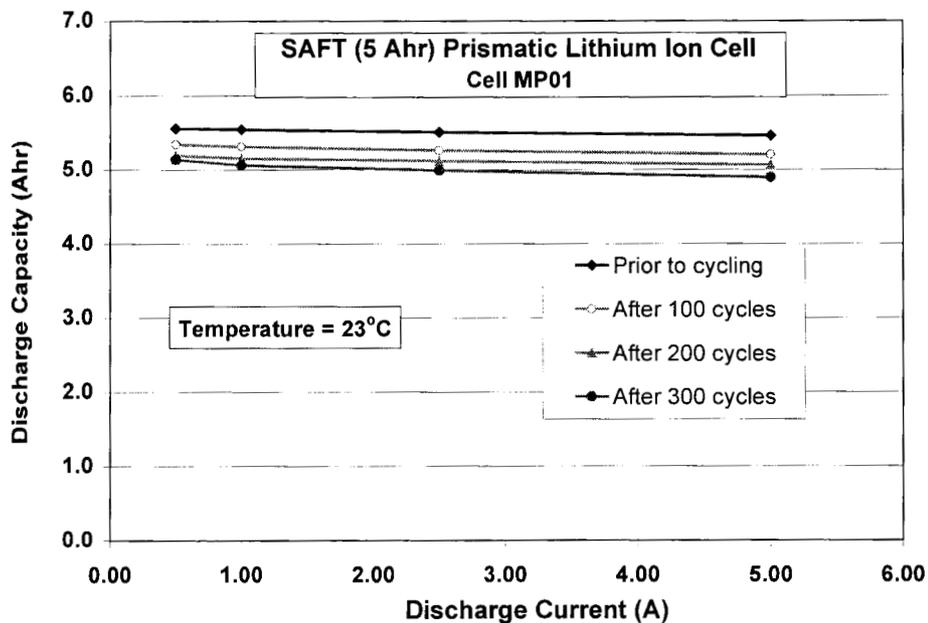


- About 120 Wh/kg available through 300 cycles even at moderately high temperatures.
- More than adequate for the intended application.

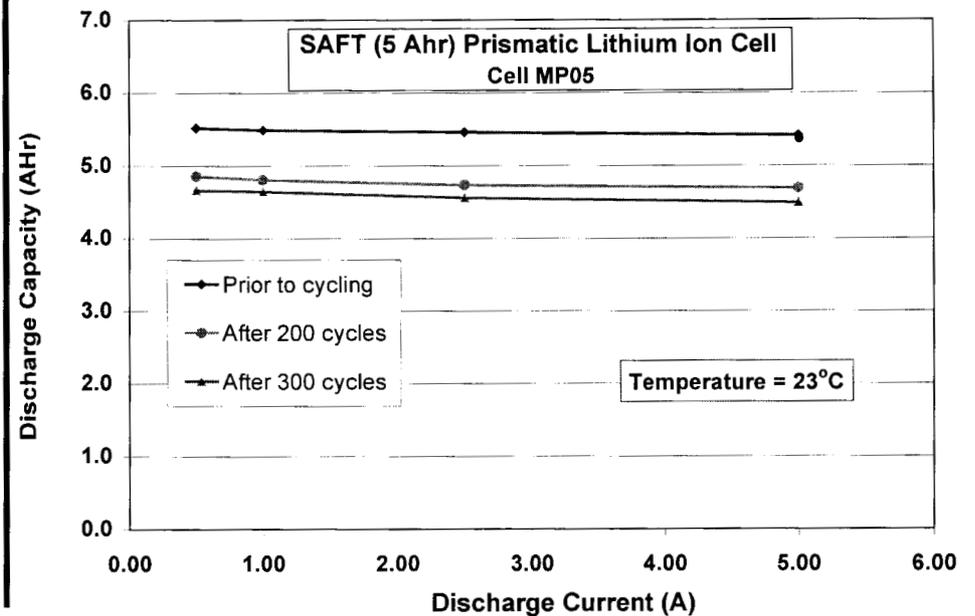


SAFT 5 AH (MP) Li-Ion Cells Rate Capability After Cycling to 100% DOD

Rate capability During cycling at 25°C



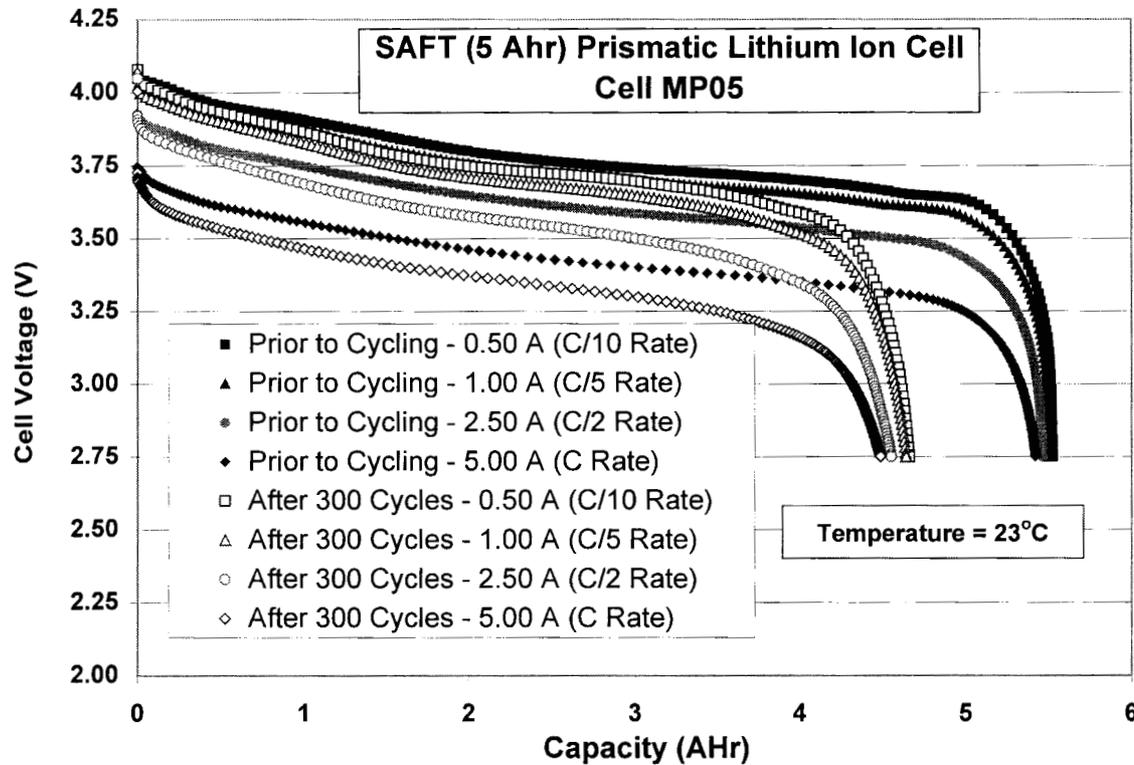
Rate capability During cycling at 55°C



- Good rate capability during 300 cycles even at moderately high temperature.
- Satisfies a critical mission driver.



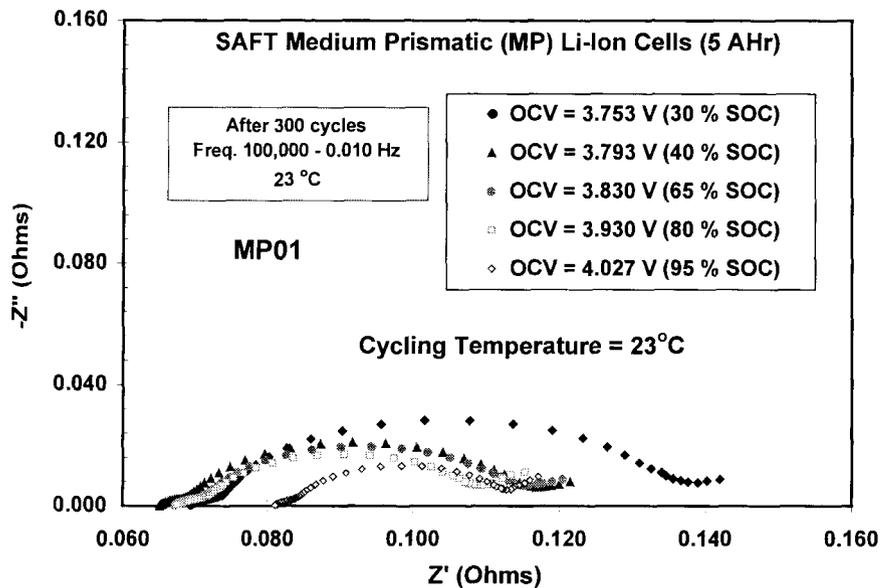
SAFT 5 AH (MP) Li-Ion Cells Rate Capability After Cycling to 100% DOD Worst-Case Scenario: Rate Capability During Cycling at 55°C



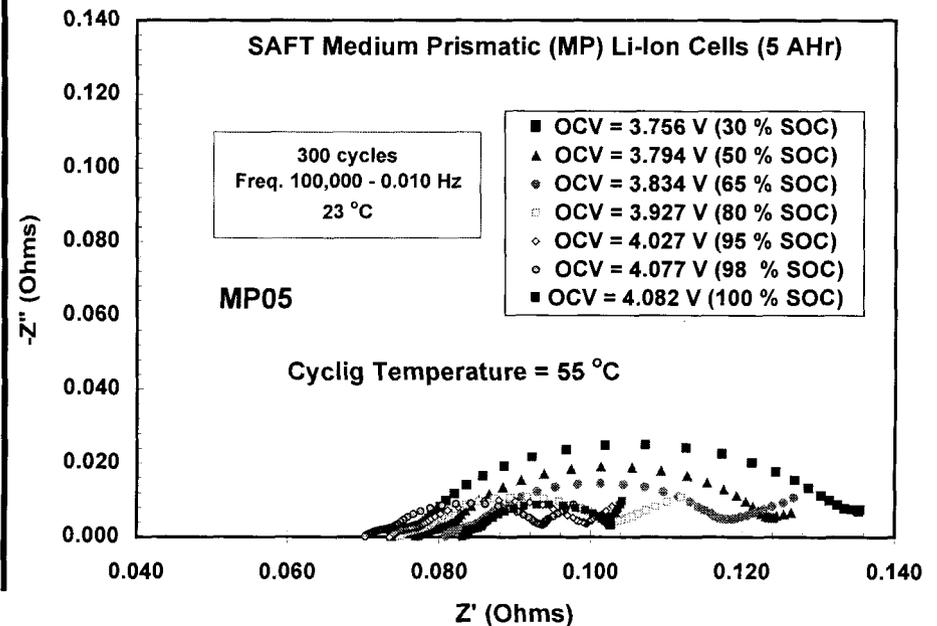
- **Good discharge capacity after 300 cycles at high temperatures.**
- **No indication of cell damage at high cycling temperatures.**

SAFT 5 AH (MP) Li-Ion Cells EIS After 300 cycles at different States of Charge

After cycling at 25°C

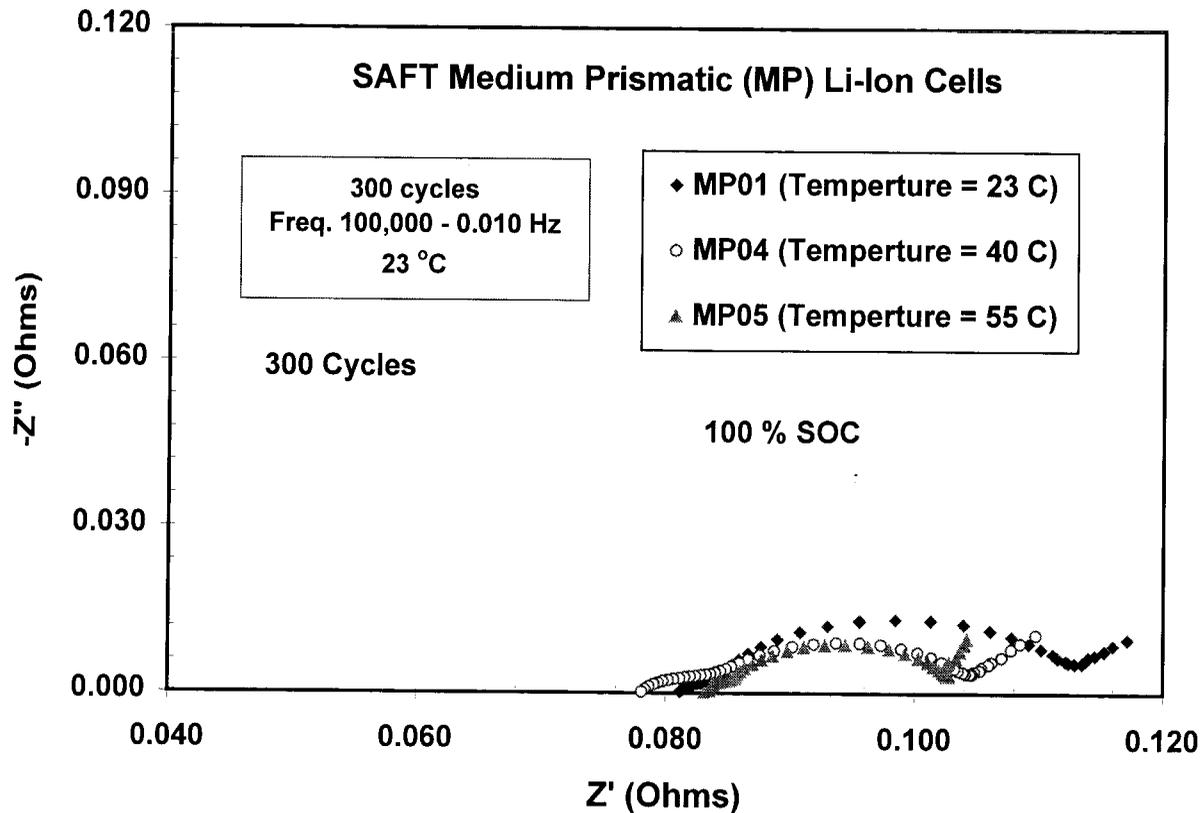


After cycling at 55°C



- Charge-Transfer Impedance (at Low Frequency) increase with decrease in state of charge.
- No noticeable difference in impedance between cycling at 23°C and 55°C.

SAFT 5 AH (MP) Li-Ion Cells EIS After 300 cycles at 100% State of Charge



- When the EIS measurements were performed (at 23°C) after cycling, only moderate impedance increase was observed for the cell that was subjected to cycling at 55°C compared to cells cycled at milder temperature.



Conclusions

- **SAFT prismatic wound 5 Ahr MP Series Cells are ideally suited for Tactical Mobile Robot battery design requirements.**
 - **Weight and volume of a 10 Ahr battery is approximately 3 Kg (8 lbs) and 1.6 Liters, respectively.**
 - **Specific Energy Exceeded 130 Whr/Kg.**
 - **Good Capacity Retention for required mission life.**
 - **No deleterious effects after extensive cycling even at EXTREME operating conditions.**



Acknowledgements

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration and was supported by NASA Code R Advanced Battery Technology Program and the Tactical Mobile Robotics Program from DARPA.