Advantages of Lithium-Ion Batteries For Underwater Vehicle Applications

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Characteristics of the AUV and its demand for improved power sources

Increased Number of Pay Loads	Demands more **energy** and reduces available **volume** for power sources **(Energy/Volume)**
Higher Depth Rating	Increased vehicle weight reduces **weight** allocation to the energy source **(Energy/Weight)**
Faster Speed	Increases propulsive **power**
Longer Mission	Demands more **energy**

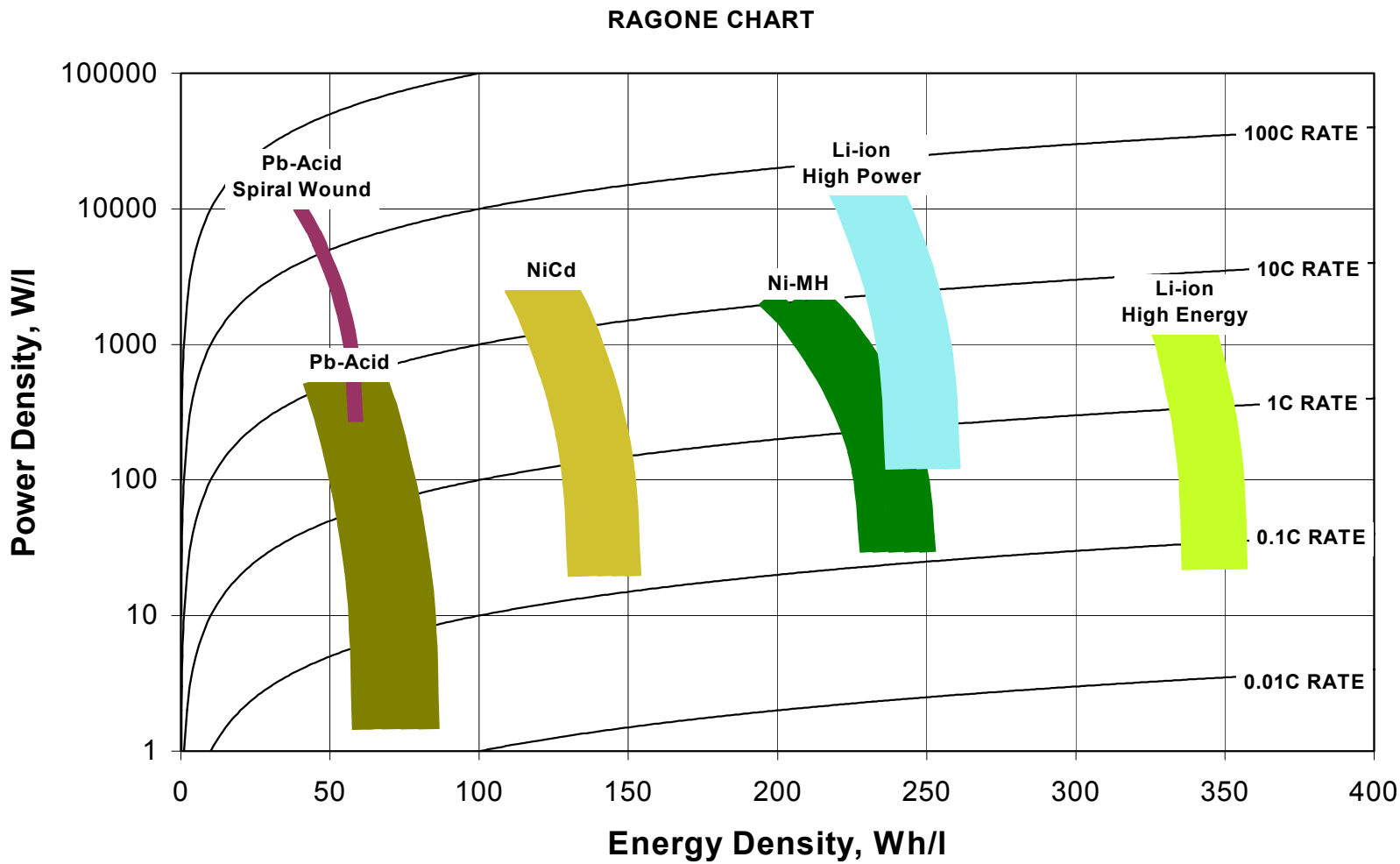
Energy Systems

- **Lead Acid**
  - Low Specific Energy (Wh/Kg)
  - Low Energy Density (Wh/l)
  - Loss of capacity at low temperatures
  - Generation of Hydrogen gas during charging and high rate discharge

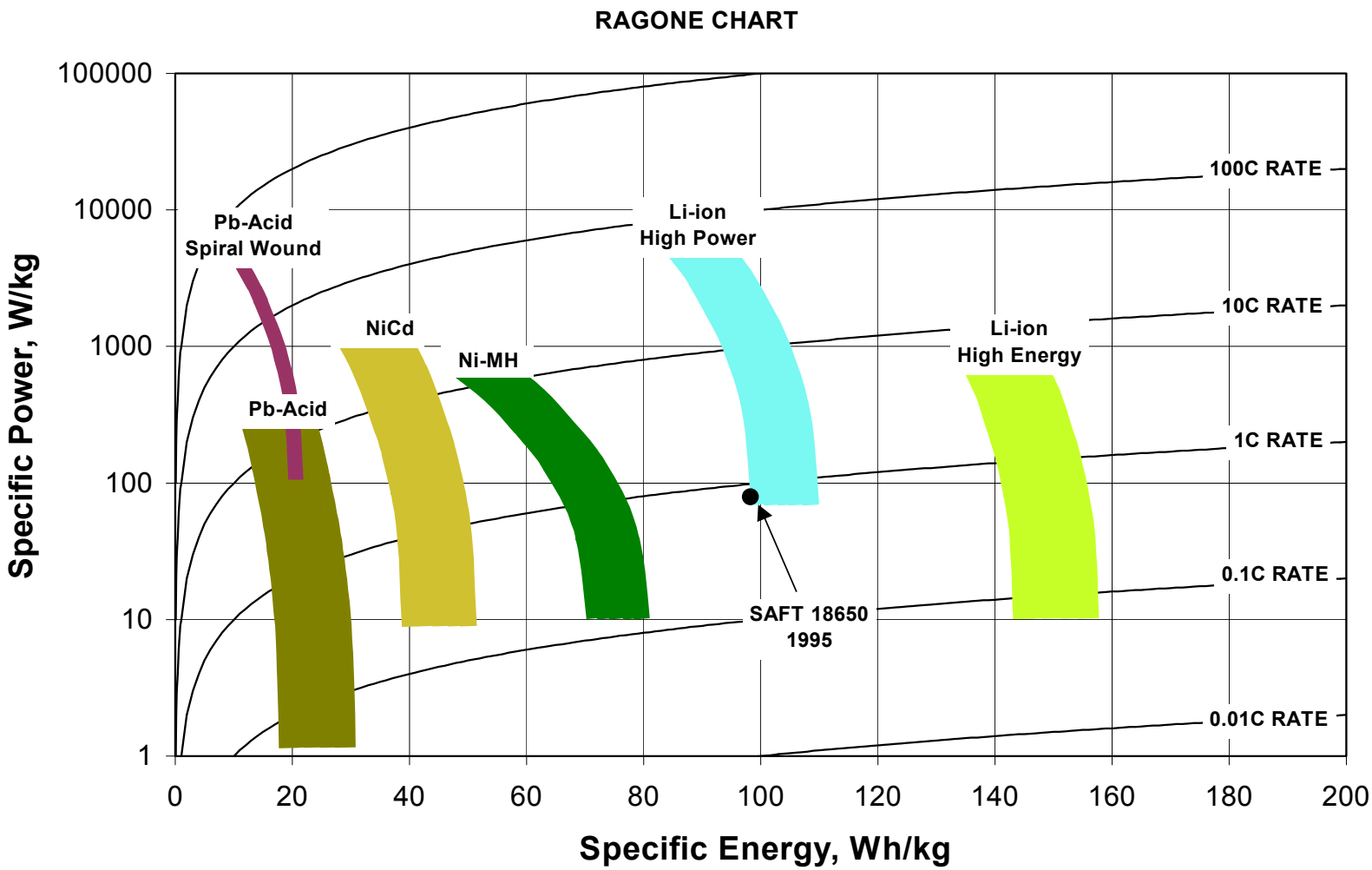
- **Nickel Cadmium**
  - Low Specific Energy (Wh/Kg)
  - Low Energy Density (Wh/l)
  - Memory effect
  - Poor shelf Life

- **Silver-Zinc**
  - Limited Cycle Life (<50) and reduces down to 15 cycles at higher rates
  - Poor Shelf Life
  - Longer charge time
  - High Cost

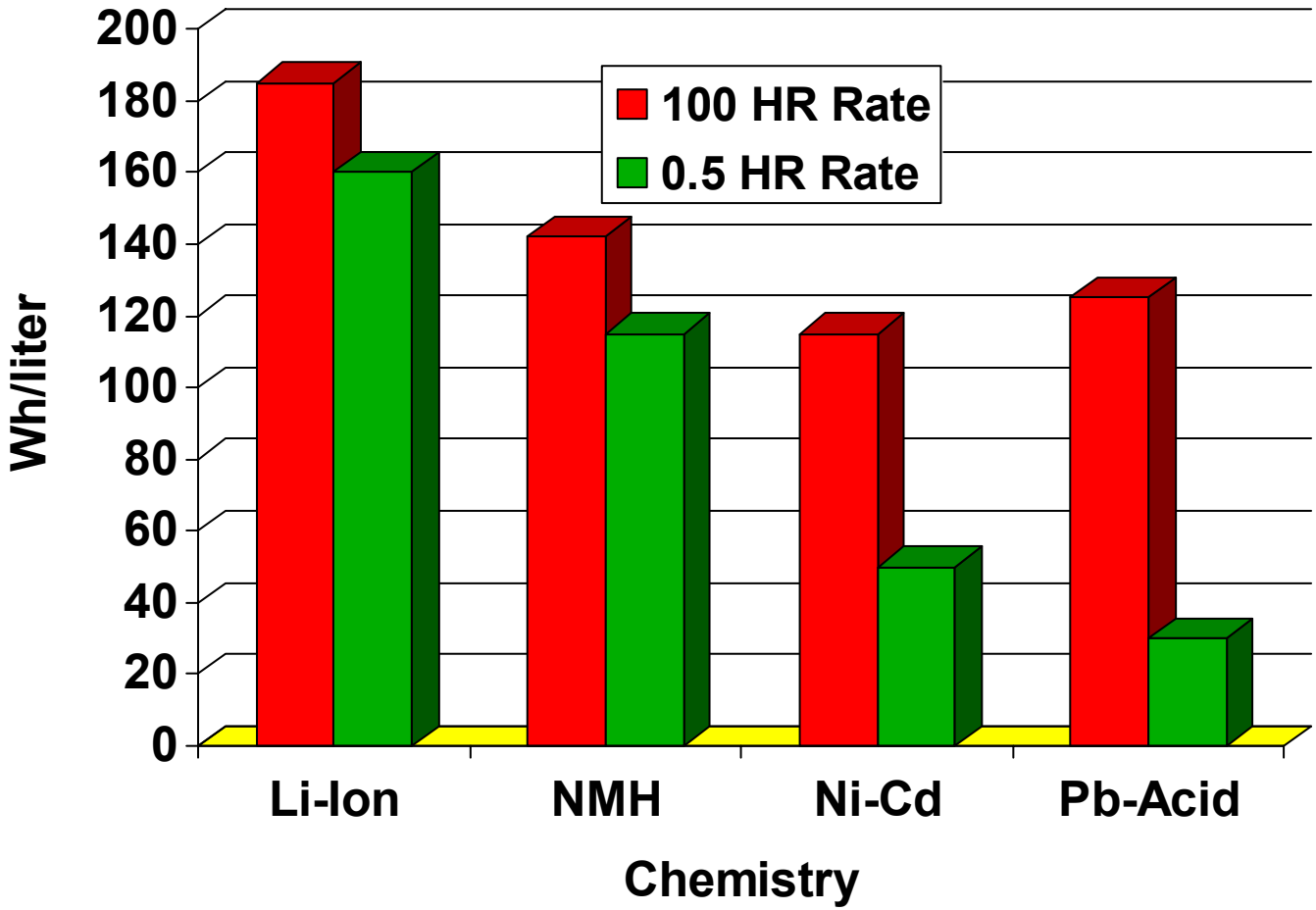
RAGONE CHART
(Volumetric)



RAGONE CHART
(Gravimetric)



Technology Comparison at Module Level



Advantages of Saft lithium-ion

- **Higher Cell Voltage** – One lithium-ion equivalent to three Ni/Cd or NMH
  3.6 Volts for Li-Ion Vs. 1.2V for NMH & Ni/Cd
- **Excellent Energy Density** – (a) Extended service hours (b) Lower in weight (c) smaller in size
- **Superior Power Capability –** (a) 1350 W/Kg (b) 2900 W/liter
- **Low Self Discharge or Superior Charge Retention**
- **No Memory Effect** (a) Li-Ion can be shallow discharge any depth without any degradation (b) Shallow cycling improves the cycle life up to 1,000,000 cycles
- **Fast Charge Capability** (a) 80% of full charge in one hour (b) 97% of full charge in Two hours
- **Cycle Life & Calendar life** (a) >3000 cycles at 100% depth of discharge (80% cap. Remaining) (b)15 years as calendar life
- **Broad Operating Temperature Range :** –20C to +60C
- **Hermetically sealed -** No out gassing
- **Maintenance free**

Advantages of SAFT Li-Ion over Ag/Zn System

- High Energy
- Excellent Cycle life, wet life & calendar life
  - Capacity loss: <0.05%/cycle Vs. 0.9%
  - >3000 cycles for Li-Ion and less than 50 cycles for Ag/Zn
  - Calendar life >10 years whereas <2 years for Ag/Zn
- Lower life cycle cost
- Reliability– Lower number of cells required
- Maintenance free
- Fast charge & no need of purging
- No need for balancing charge on each cycle
- Easy to incorporate state of charge indicator

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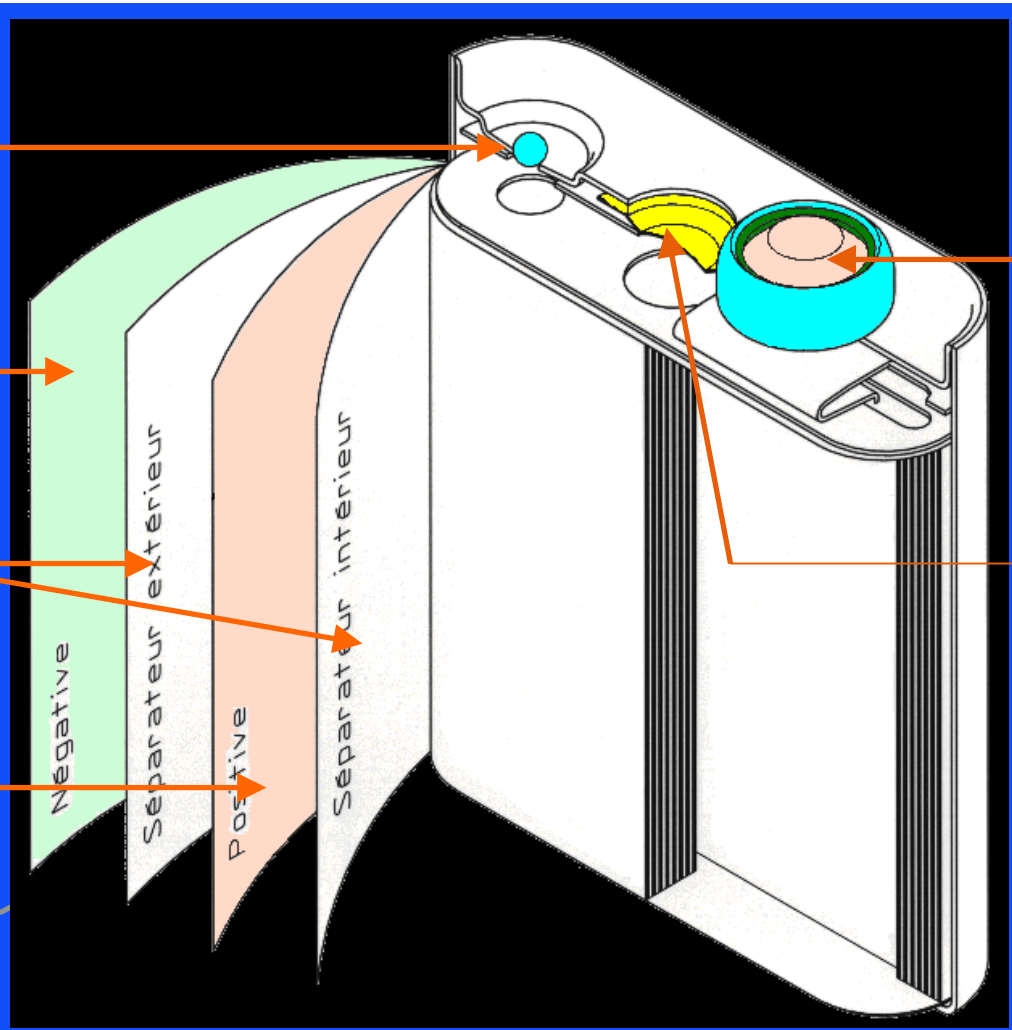
Chemistry

- *Positive*: Mixture of Metal oxides
- *Negative*: Graphite, Lithium ions are inserted during charge
  (no *metallic* lithium, no *dendrite* formation)
- *Electrolyte*: LiPF6 salt + organic solvent mixture
  alkyl carbonates (PC,EC,DMC) + proprietary additive)
- *Separator*: microporous PP and PE
- *Cell case*: Ni Plated CRS/Aluminum
  - CRS – Case Negative
  - Al – Case Positive
- *Assembly*: Spiral wound electrodes
- Seal: Hermetically sealed

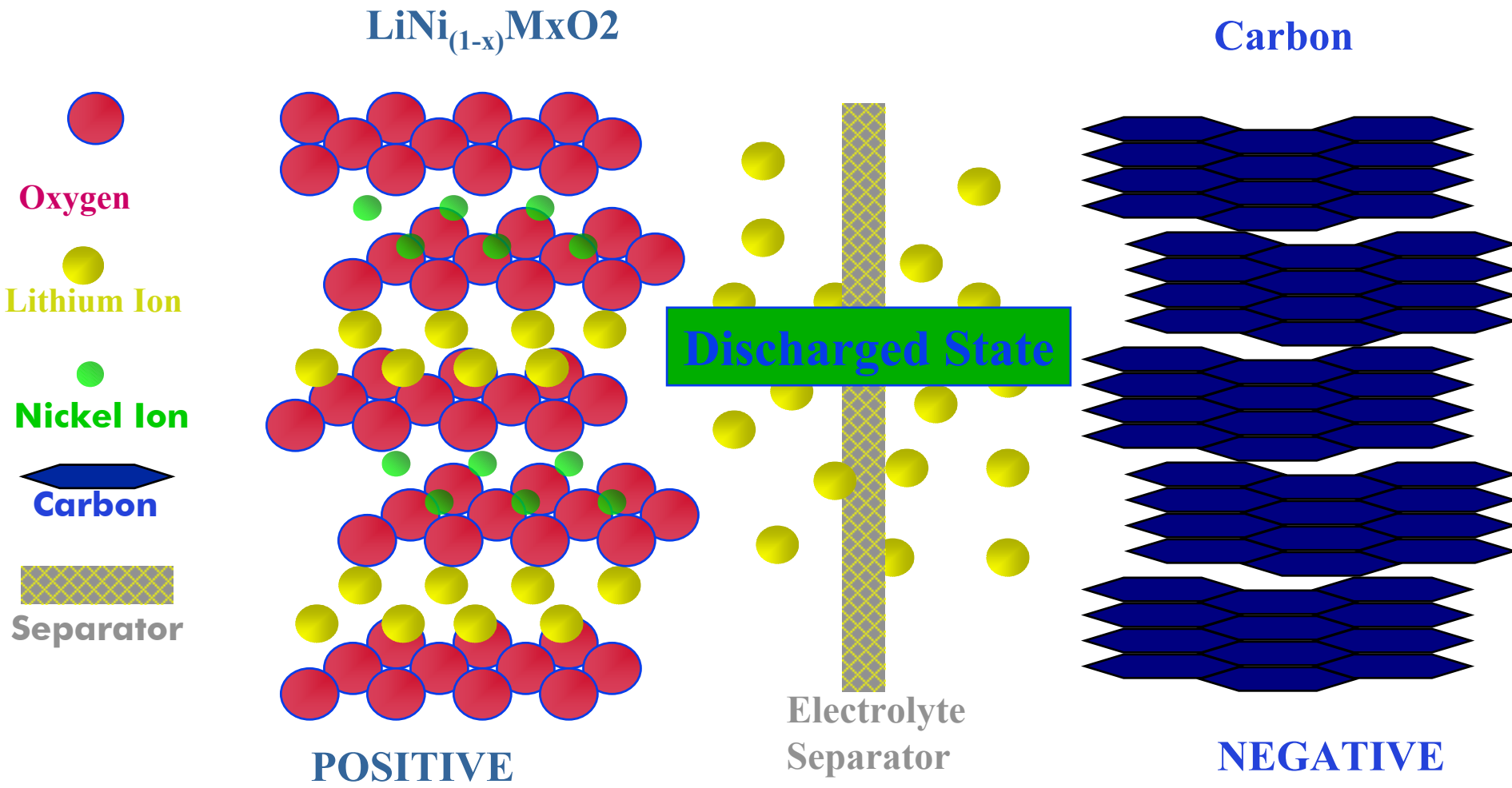
SAFT LITHIUM-ION TECHNOLOGY

Medium Prismatic (MP) *Cell Assembly - Jelly Roll*



SAFT TECHNOLOGY

Intercalation Process - I

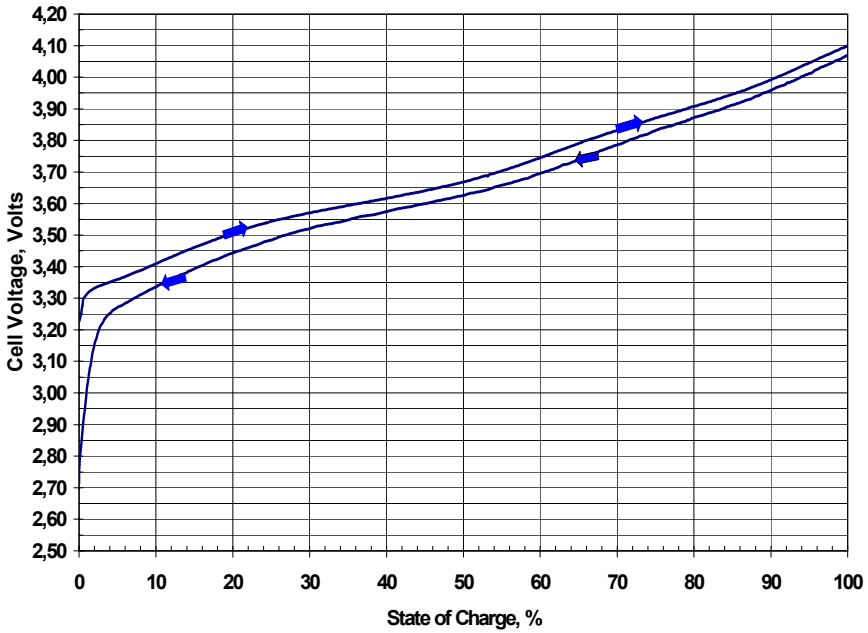


Saft Li-Ion Cell Range

Cell Type	Diameter (mm)	Length (mm)	Mass (kg)	Maximum Operating Voltage (V)	C/3 Capacity @ Max. Voltage (Ah)	Total Energy @ C/3 (Wh/kg)	Total Energy @ C/3 (Wh/l)	Pulse Power (W/kg)	Maximum Recommended Current
HP18650	18.2	65.4	0.042	4.1	1.0	86	212	N/A	6C
HPDD	34	122	0.24	4.1	9.0	135	300	N/A	2C
HP6	47	104	0.38	3.9	8	75	158	1420	10C
HP12	47	178	0.68	3.9	16	85	187	1430	10C
HP30	54	208	1.05	3.9	31	106	234	1190	8C
HE44	54	220	1.125	4.0	44	140	275	N/A	2C
HE100	67	366	2.7	4.1	115	150	314	N/A	2C
MP24	145 x 147 x 21		1.067	4.0	24	81	223	N/A	4C

SAFT TECHNOLOGY

Cell typical voltage profile



- **The Open Circuit Voltage (OCV) is a function of the state of charge, and almost independent of the temperature**
- **The OCV increases with the state of charge (Gas gauge feasibility)**
- **Cycling voltage limits (typical 4.1/4.0/3.9V-2.5V)**
- **No affect on electrolyte by the electrochemical reaction**
- **100% faradic efficiency on charge**
- **No out gassing (hermetically sealed cells)**

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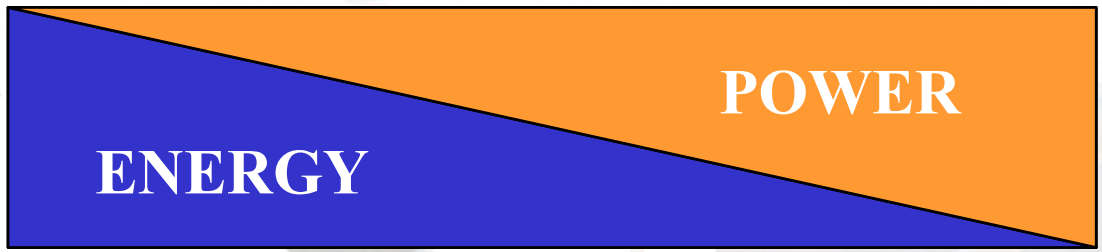
Performance Range

Cell Name	High Energy	Dual Mode	High Power
	HE44	HP30 MR26T	HP6 HP12



Energy (Wh/kg)	140	106	85	75
Power (W/kg)	300	1100	1350	1350
P/E Ratio	2 to 3	8 to 10	10	25

Applications	EV	HEV w/ZEV	HEV PA/Starter

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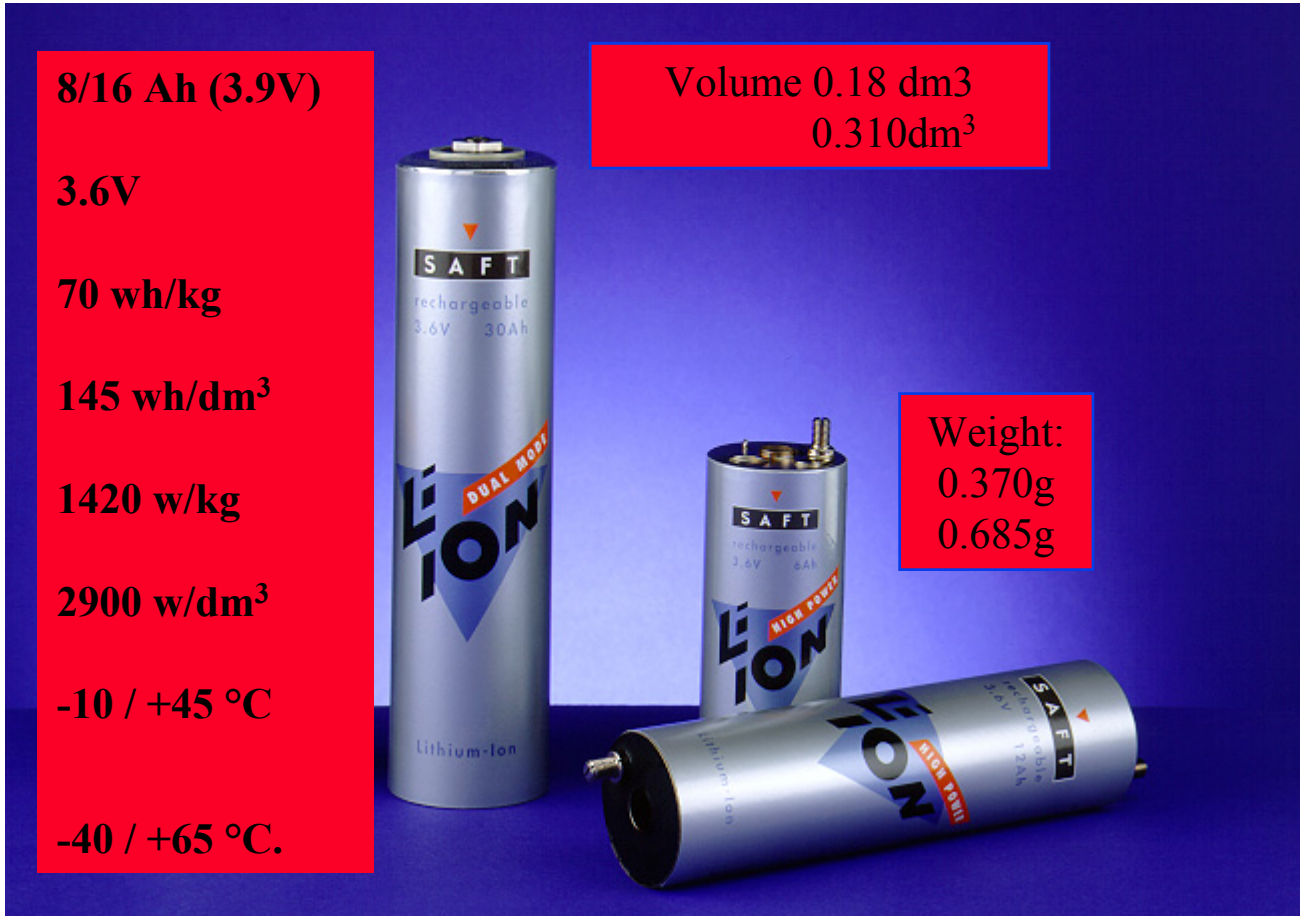
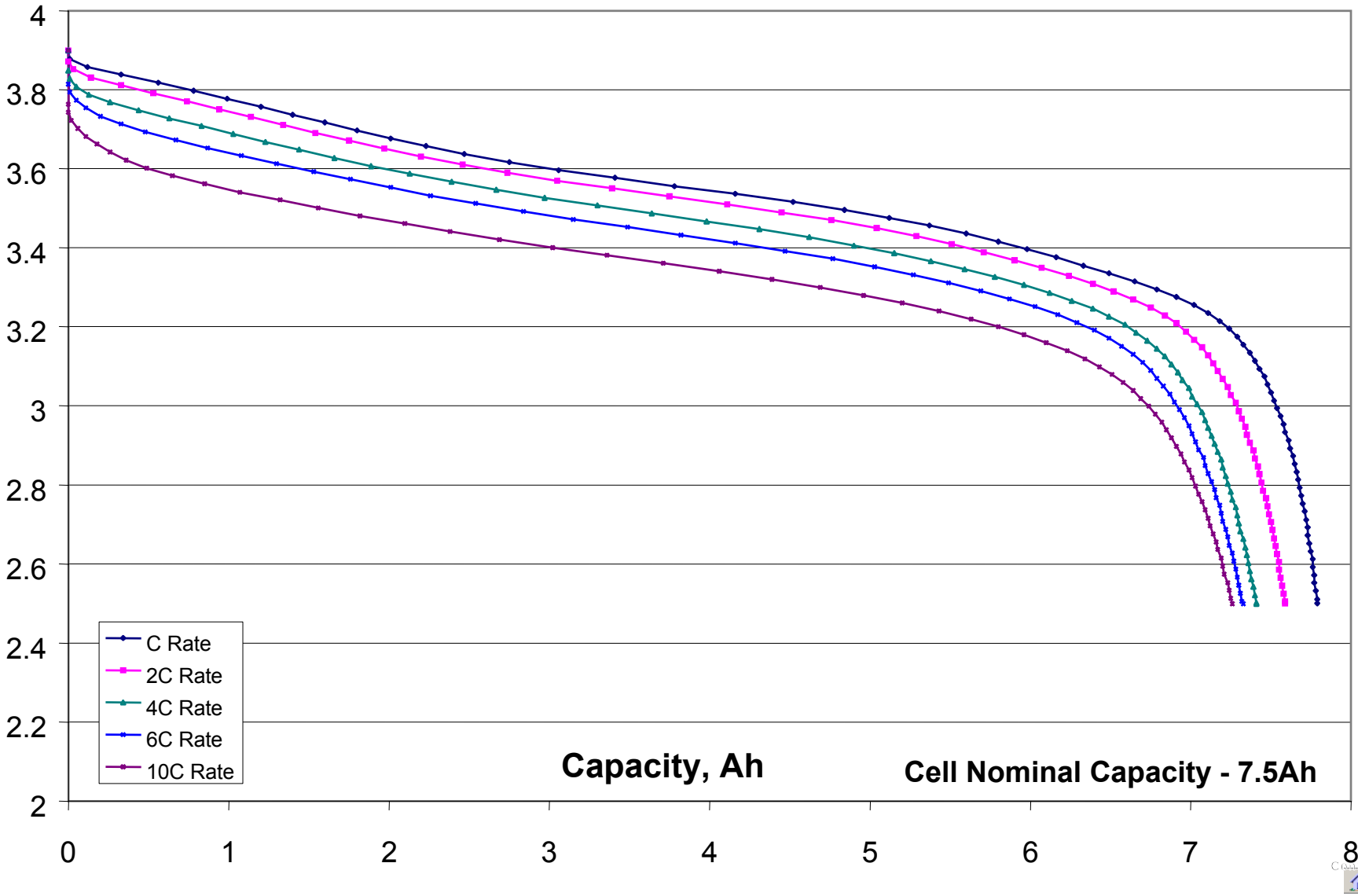
« High power » cells

- Capacity @ C/3 & 21C
- Nominal voltage
- Specific energy
- Volumetric energy
- Specific power
- Volumetric power
- Operating temperature range
- Storage temp. range



HP-6 Rate Capability (Continuous Discharge)



SAFT TECHNOLOGY

« High energy » cell

- Capacity @ C/3 & 21C
- Nominal voltage
- Specific energy
- Volumetric energy
- Specific power
- Volumetric power
- Operating temp. range
- Storage Temp. range

41 Ah

3.6V

140 wh/kg

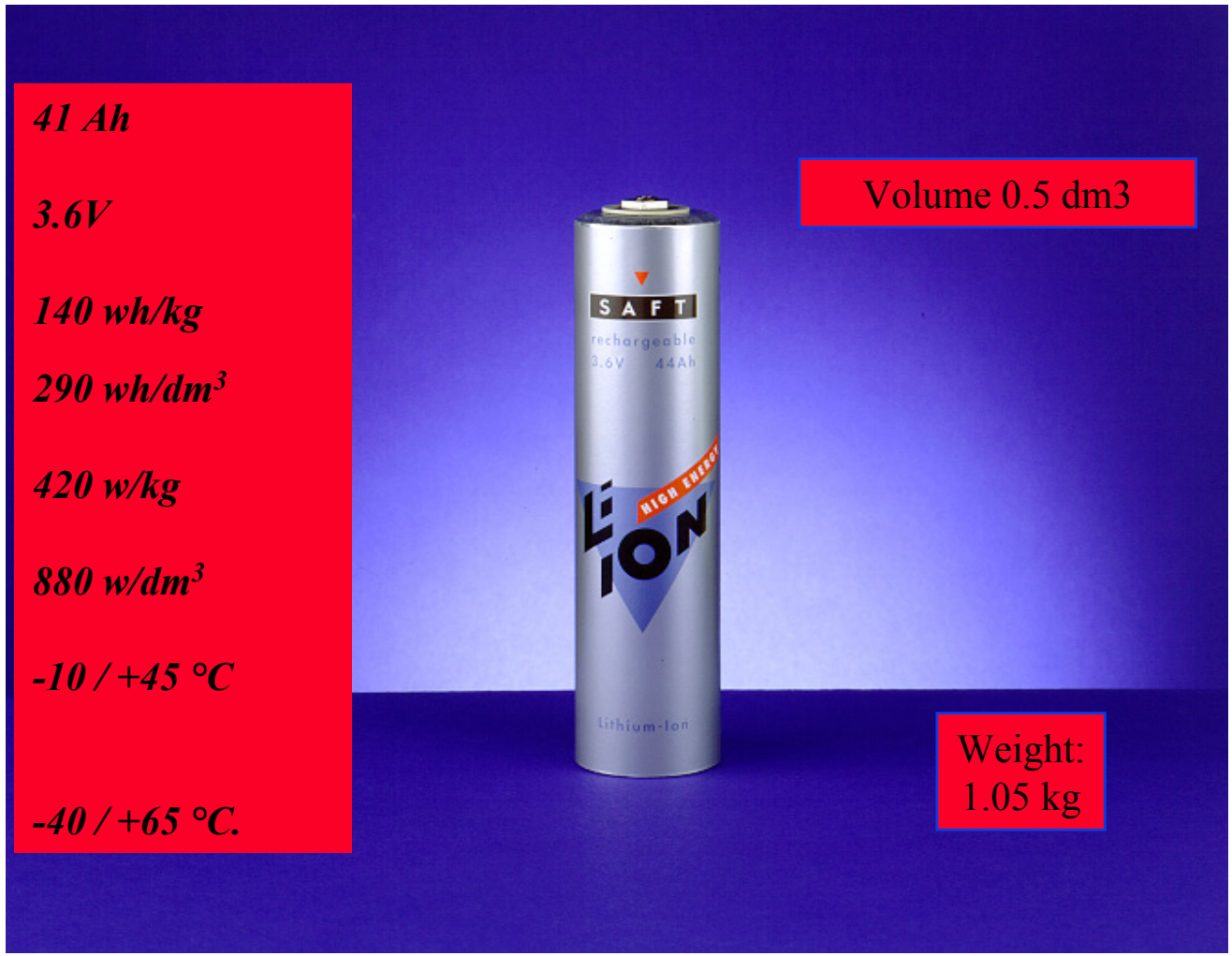
290 wh/dm³

420 w/kg

880 w/dm³

-10 / +45 °C

-40 / +65 °C.



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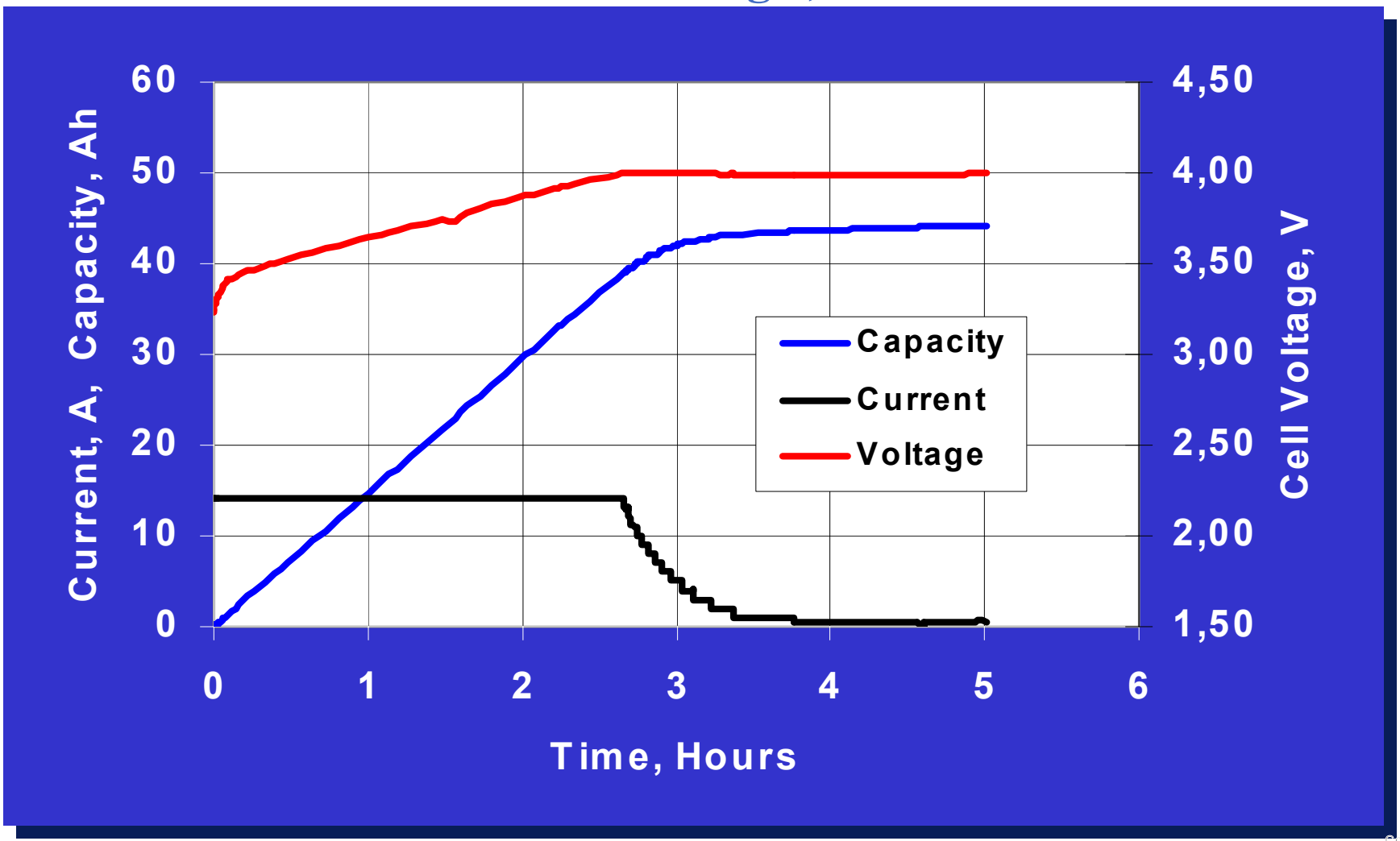
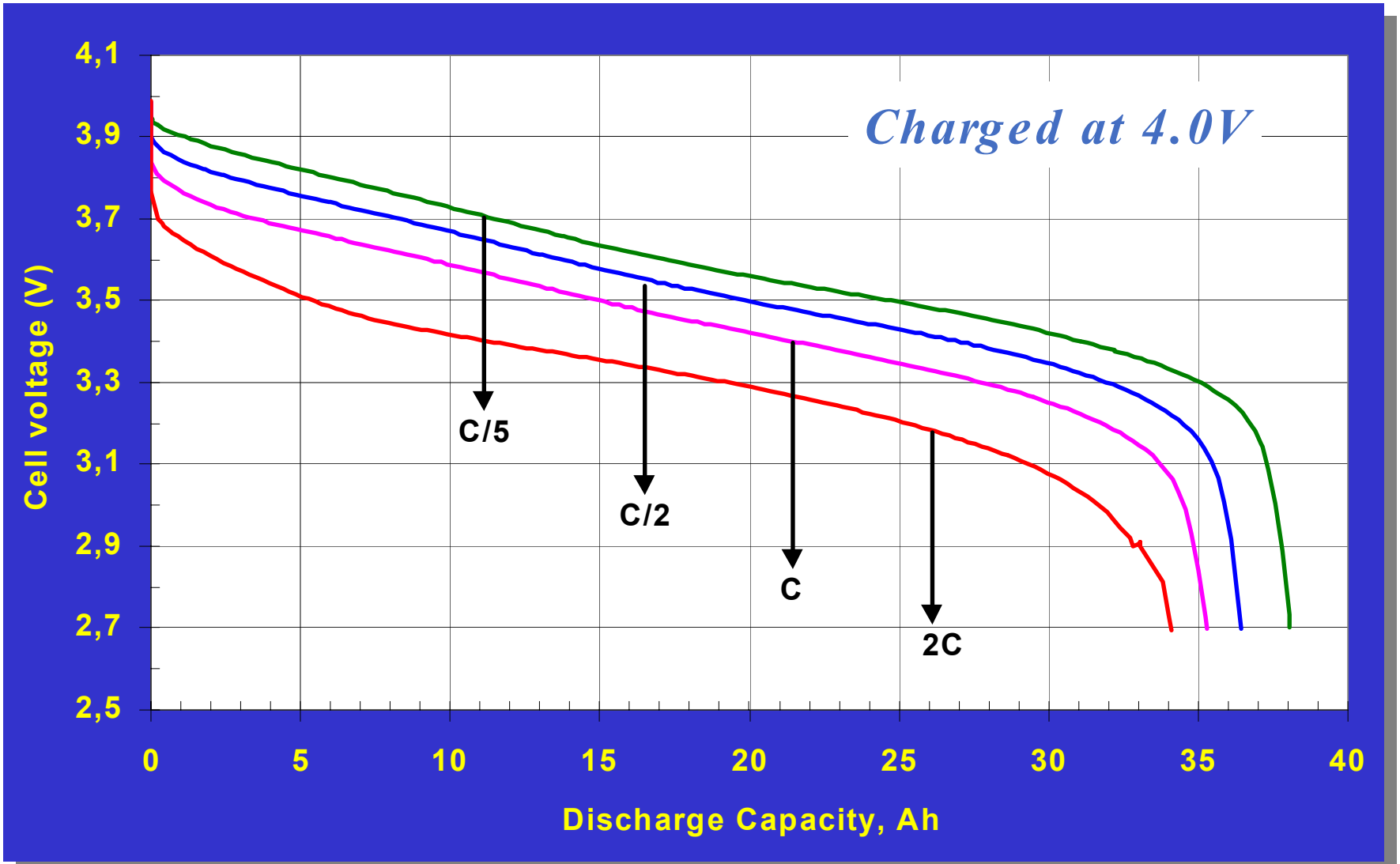
HE-44: Charge Behavior, 21C

CC / CV charge, C/3



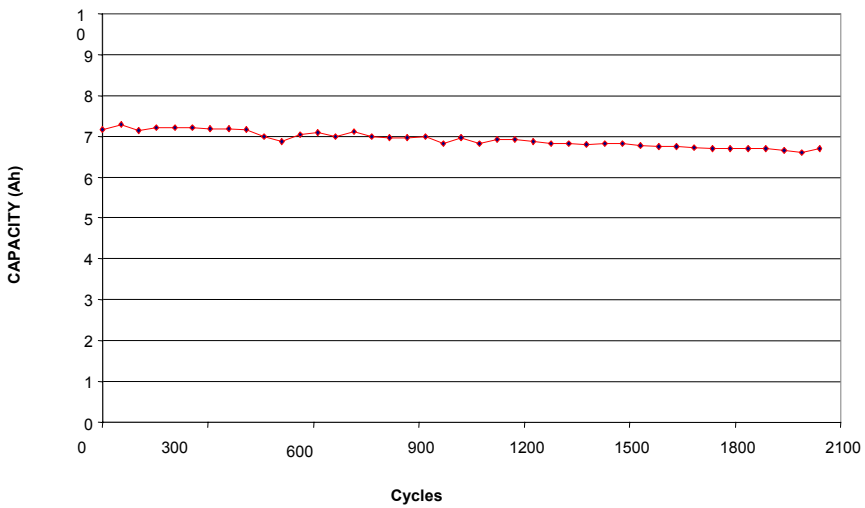
SAFT LITHIUM-ION TECHNOLOGY

HE-44: Rate Capability, 21C



High Power Lithium Ion Cycle Life & Calendar Life

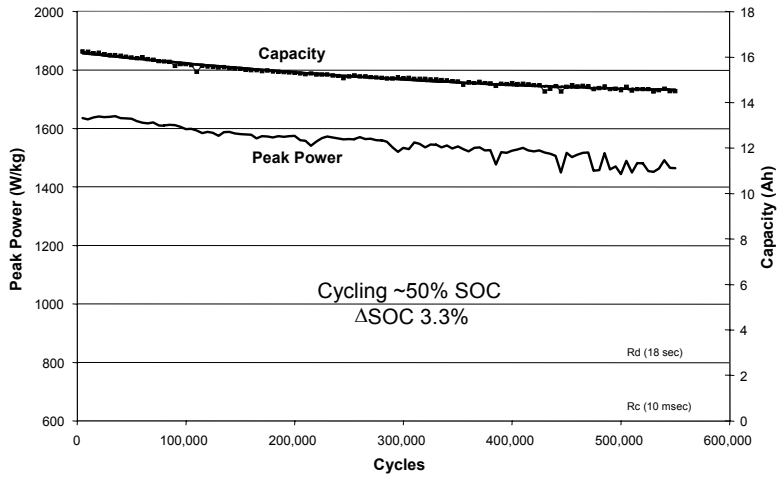
HP Cell Performance Under 100% DOD Cycle



Actual: 3000 Plus cycles

Projection: >5000 cycles

HP Cell Performance Under Shallow Cycle



Projection: >1,000,000 cycles

«Medium range » cells

♦ *Capacity @ C/3*	*39/25 Ah*
♦ *Average voltage*	*3.6V*
♦ *Specific energy*	*135/115 wh/kg*
♦ *Volumic energy*	*280/245 wh/dm³*
♦ *Specific power*	*880/830 w/kg*
♦ *Volumic power*	*1850/1730 w/dm³*
♦ *Operating temperature*	*-10 / +45 °C*
♦ *Storage*	*-40 / +65 °C.*

Portable High Energy MP Cells

MP144350	MP174865	MP176065
2.3 Ah	3.6 Ah	6.0 Ah

High Power Lithium Ion Cell Behavior Under Abuse Test

Test Description		Test Results	Comments
External Short Circuit	HP6 HP12	Vent of electrolyte, no smoke Vent of electrolyte, no smoke	Cell design with fusible link reacting at very high power. Arching due to fusible link disconnect.
Nail Test/Internal Short	HP6 HP12	Smoke Smoke	A few "weld" sparks during penetration.
Heat Test (ramp up 150°C in 30 min. Event after>45 min.)	HP6 HP12	Smoke Smoke	
Crush	HP6 HP12	Vent only Smoke	
Impact Drop Test		No event	
Over Charge (100A charge current)		No event up to 4.6V per cell. Flame & smoke if voltage not limited	Event start depends on charge rate. More than 13 Ah can be overcharged in HP12 cell.
Over Discharge (current reversal)		No event	Typically the cell develops an internal short.
Salt Water Immersion (8 hours)		No event	Terminal corrosion. Voltage at end of test ~3.4V.
Fuel Fire (radiant heat 890°C)		Fire, no explosion	Case integrity fully kept. Test done by Sandia National Laboratory.

Protection Electronics

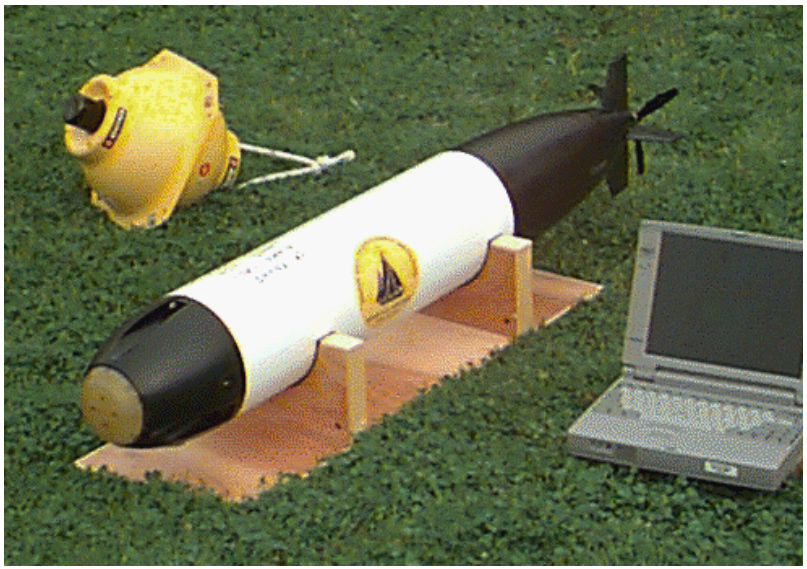
- Cell balancing of cells in series for maximum performance
- Over-charge protection
- Over-discharge protection
- Over current protection

Remote Environmental Monitoring UnitS (REMUS)

- Low cost autonomous underwater vehicle (AUV), ϕ: 7.5", L: ~ 54"
  - Coastal monitoring
  - Multiple vehicle survey operation
- Original mission used Pb/Acid but current requirement demands high energy
- Woods Hole Oceanographic Institution (WHOI) – Two phase program
  - Prototype for demonstration
  - Safety Evaluation
- SAFT Design –
    - Phase I: 7 MP176065 S X 2P, 26.6 volts, 250 Wh/module, 3 modules in parallel
    - Phase II: 4 Modules in parallel, Energy:1 KWh, 99 Wh/Kg at battery level
    - Batteries for both phases: Full protection electronics to prevent (a) Overcharge (b) Over- discharge © Over-current (d) Over- temperature
- Advantages of SAFT lithium Ion Vs. Pb/Acid (REMUS/SAHRV)
  - No gas generation – virtually eliminates the need to open/close pressure seal
  - Feasible to charge the battery in the vehicle
  - Longer mission time (2.6 times)
  - Greater number of cycles (~10 times)

REMUS/SAHRV lithium ion battery brick

First Underwater US Application
REMUS



REMUS Vehicle shown with Acoustic Transponder and Laptop

REMUS Vehicle

Note: REMUS is a 54” long, 7.5” diameter, low cost underwater vehicle used for coastal monitoring and survey operations.

Advantage of SAFT LiON Battery (Compared to the lead acid previously used)

- No gas generation during both charge and discharge (hermetic cell). Therefore, there is no need to open and close the vehicle pressure seal resulting in improved reliability and reduced labor.
- Ability to charge the battery directly in the vehicle inside a closed housing with built-in charger and monitoring circuit.
- Improved energy – a typical lead acid battery provides 380Wh or about 3.2 hours of mission at 5 knots. The prototype lithium ion battery provided 750Wh or 6.3 hours of mission. The final lithium ion battery will deliver 1000Wh or 8.3 hours under the same conditions, 2.6 times the mission duration of the lead acid.
- Projected high cycle life; more than 1000 cycles can be expected, depending on the mission profile.

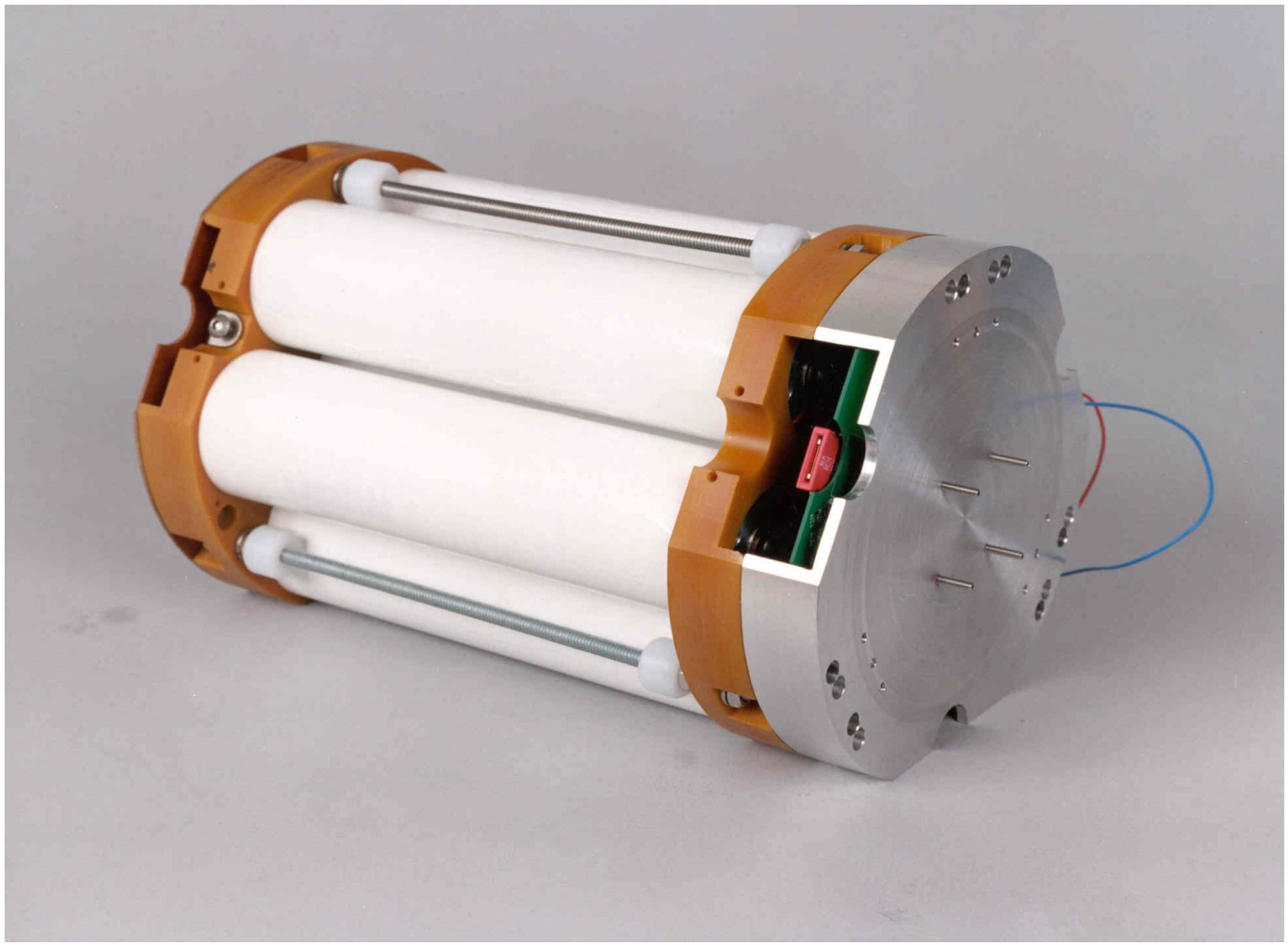
  Consequences:

  - Vehicle is more reliable (no need to open/close the seal), more user friendly (charging in vehicle), more efficient (no dead time between missions, no maintenance), and with increased mission time.
  - Significant reduction of the operating cost.

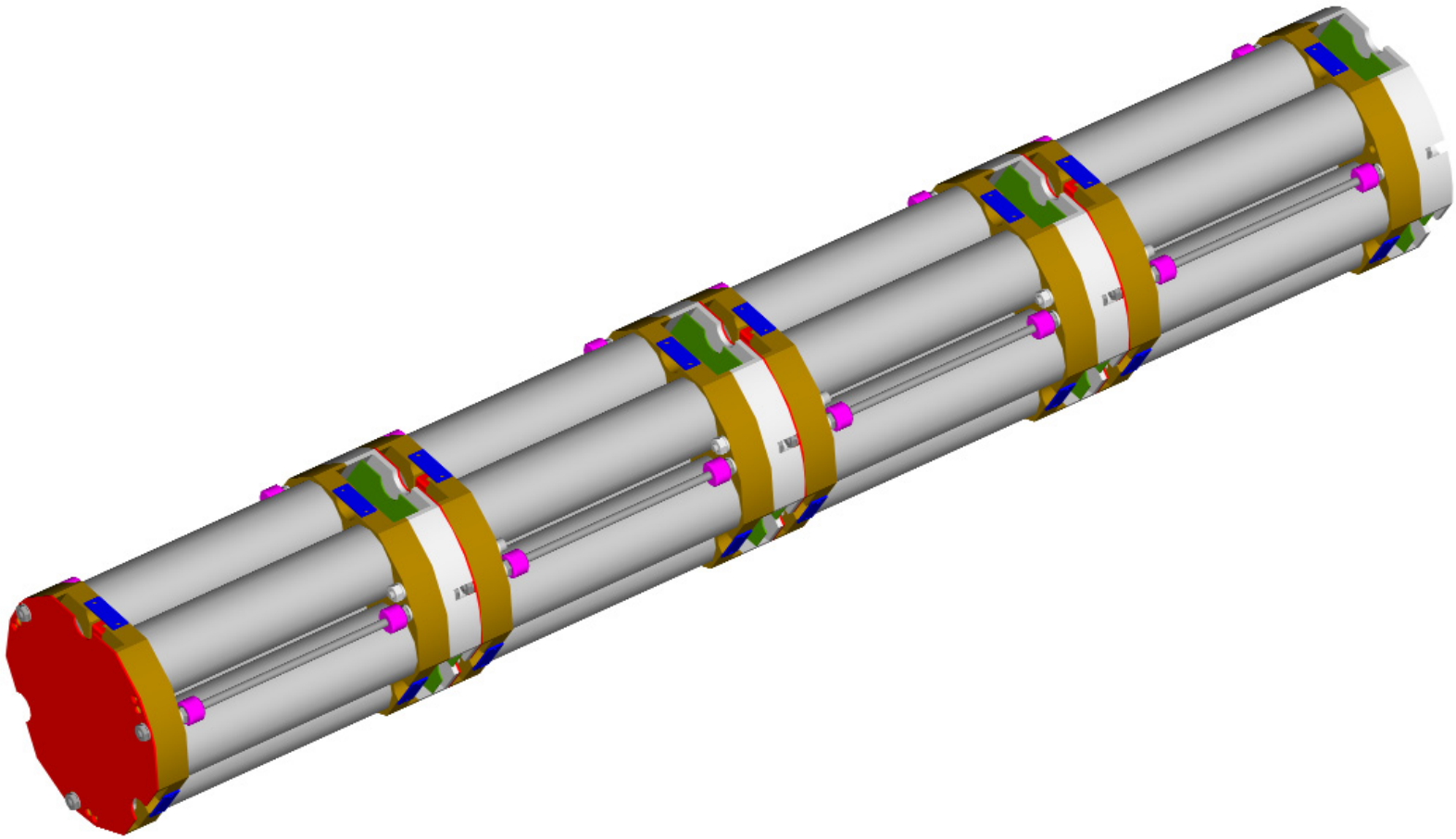
Semi-Autonomous Mapping System (SAMS)

- Developed by WHOI for Naval Oceanographic Office
  - Two vehicle operation – 12 hours mission duration each
- Reconfigured REMUS
  - Deep ocean floor mapping – 6 Km depth
  - Increase Deep sonar mapping rate – Four Times
- SAFT Approach –
  - Battery: 8 total number of modules connected in parallel, Energy: 8 KWh
  - Each Module: 25 volts nominal, ~1 KWh, configuration 7 HE 44 S, ϕ: 6.9”, L: 10.64”, Volume = 6.5 liters, Weight: 8.87 Kg, ED: 154 Wh/l and 113 Wh/Kg

SAMS 1 kWh lithium ion module



SAMS Battery Assembly



SAMS Requirements and Performance

Module size: 10.0” L X 7.0” Diameter	Actual: 10.643”L X 6.9” Dia.
Approximate module weight: 10 kg	Actual: approximately 8.9 kg
Operating Voltage: 21-28 Volts	
Discharge Life: 12 Hrs.	Actual: > 13 Hrs.
Load: 610W (4Kts) (76W per module)	
Typical Current: 24A (3A per module)	
Max. Current: 20A per module continuous, 50A, 1sec. pulses	
Environments:	
Operating Temperatures:	Discharge: -10^{o}C to +50^{o}C
	Charge -15^{o}C to +45^{o}C,
Pressure: 0-1 ATM	
Sinusoidal Vibration: Transportation	
Shock: Transportation	
Electronic protection:	Over charge: 29.4V & 28.7V
	Over discharge: 18.2V
	Over current: 30A fuse
	Balancing

HP12 Module Example: 28V Aircraft Battery

	17Ah NiCd 20 Cells	7.5 Ah Pbacid 2 Bat. = 15Ah 24 Cells	16Ah Li ion 7 Cells
Weight	16.60 kg	23.64 kg	7.36 kg
Specific energy	30 Wh/kg	15.23 Wh/kg	66 Wh/kg
Volume	8.62 L	10.94 L	5.47 L
Energy density	56 Wh/L	32.91 Wh/L	90 Wh/L

Li-Ion module

Advantages of Saft Lithium-ion batteries for Unmanned Vehicles

- Extended mission time – Three times comparing with Pb/Acid
- Improved speed
- Lower weight
- Smaller in size
- Increase in payload
- Capable of 85% as charge capacity in one hour
- No out gassing - Hermetically sealed cells
- No maintenance required
- Improved reliability
- Attractive life cycle cost

Contents