ABSL's COTS Li-Ion Cell Suite Development
2007 NASA Battery Workshop

Tami Max, Sales Manager
720 300 8817, tami.max@abslspace.com

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Objective

- Explain ABSL's programs for identifying and qualifying Li-Ion COTS cells for space use.
- Show some of the benefits this approach to space batteries provides.
- Provide a briefing on the current status of ABSL's next generation COTS cells.

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ABSL Space Battery Experience

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Launches Powered by ABSL Lithium Batteries

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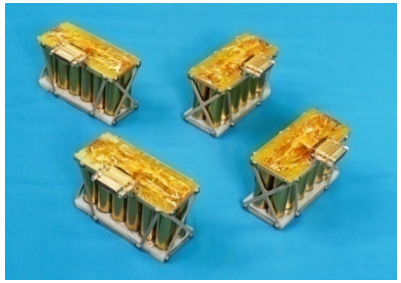

ABSL has the most launches of Li-ion batteries with 32 spacecraft powered by ABSL batteries without ANY failures

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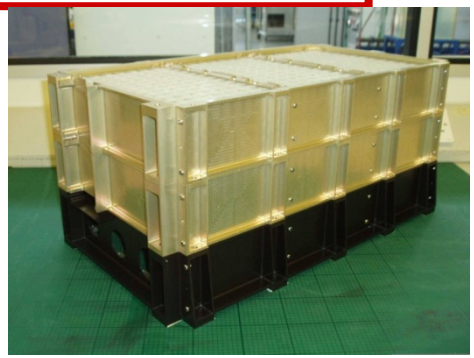

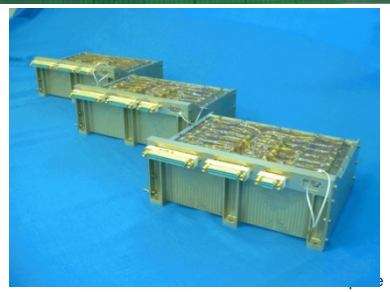

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Contracts/Launches "at a glance"

- 6 space qualified cell (3 launched)
  - Lithium-ion secondary
  - Lithium primary
- 32 s/c launched
  - LEO, MEO, GTO, HEO, Interplanetary
  - Including NASA, AFRL, DOE, ESA missions
  - Longest serving LEO Li-ion (6+ years, >30k cycles)
  - Three 10 yr LEOs on orbit
- Contracts for 80+ spacecraft and launchers
  - 2 GEO launches in 2008
  - 1st Launch Vehicle flight in 2008
  - Many more NASA missions, MDA, AFRL, ESA…

U.S. Customers

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Rest of the World Customers

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The ABSL COTS Approach

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Contents

- ABSL Space Battery Experience
- The ABSL COTS Approach
  - What is the COTS Approach?
  - Process Overview
  - The Details
- ABSL's Next Generation COTS Cells

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What Is the COTS Approach?

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- ABSL's COTS Approach is a proven process for providing space qualified Li-Ion batteries using commercial off-the-shelf (COTS) Li-Ion Cells.
  - Encompasses everything from identifying candidate COTS cells, to high fidelity design and qualification testing of space batteries.
  - Mitigates the risk of using of COTS cells for space applications to provide customer confidence in the end product.
  - Leverages the immense size of the commercial industry to provide cutting edge performance and security of supply.

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The ABSL COTS Approach

- Cell Assessment & Qualification
  - *Identify the best COTS cells to meet future space battery needs and qualify them to space industry standards.*
- The Cell Suite
  - *Readily provide a broad range of battery capabilities and security of supply.*
- Lot Acceptance Testing (LAT)
  - *Ensuring consistency of cells batch to batch, maximizing the value of comprehensive cell characterization and life test programs.*
- Life Test Program
  - *Enabling unmatched EOL performance predictions capabilities.*
- Standardized Battery Design, Build, & Qualification
  - *Leveraging the consistency and predictability of ABSL's COTS cells to efficiently optimize and qualify battery designs for any mission.*

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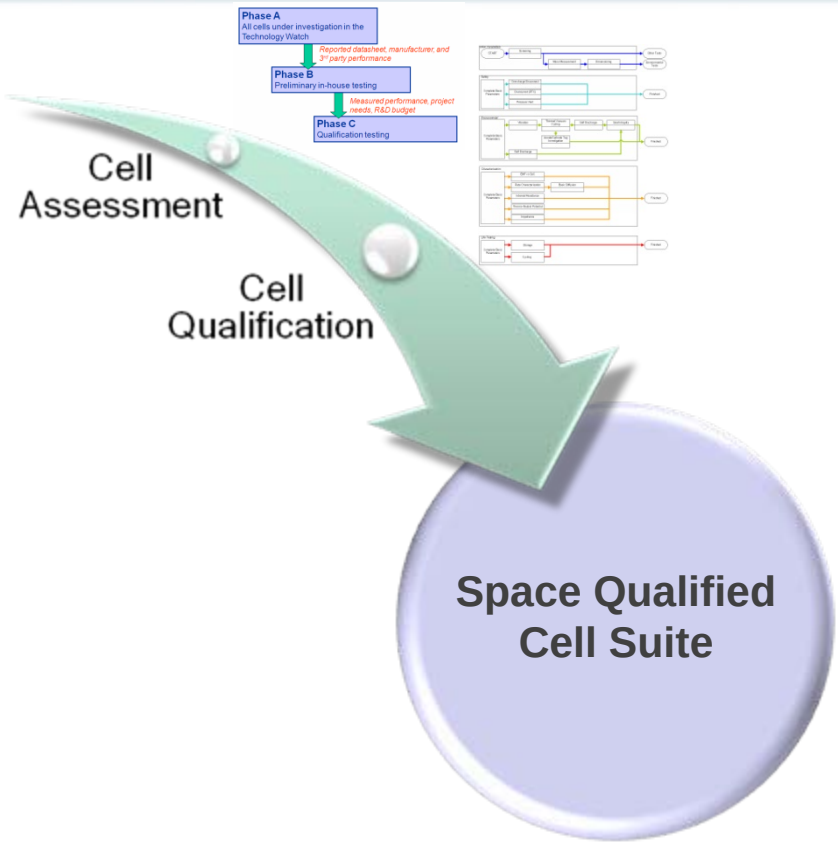
COTS Cell Cycle



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Cell Assessment

Phase A
All cells under investigation in the Technology Watch

Reported datasheet, manufacturer, and 3rd party performance

Phase B
Preliminary in-house testing

Measured performance, project needs, R&D budget

Phase C
Qualification testing

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Phase A: Technology Watch Database

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Microsoft Excel - Small Cell Database.xls

D1 Data Sheet

	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Diameter	Height	EoCV	EoDV	Capacity	Energy	Mass	Energy Density	Capacity Density	Volumetric Capacity	Current Density	Volumetric Current	Max Continuous Current	Max Disch
2	18.2 mm	65.1 mm	4.2 V	3. V	2.55 Ah		46. g		55.435 Ah/kg	150.566 Ah/m³				
3	18.6 mm	65.2 mm	4.2 V	3. V	2.55 Ah		46.5 g		54.839 Ah/kg	143.938 Ah/m³	105.376 A/kg	276.588 A/m²	4.9 A	1.92
4	18.6 mm	65.2 mm	4.2 V	3. V	2.45 Ah		45.5 g		53.846 Ah/kg	138.294 Ah/m³	102.418 A/kg	263.04 A/m²	4.66 A	1.90
5	18.4 mm	65.1 mm	4.2 V	3. V	2.43 Ah		46.1 g		52.711 Ah/kg	140.378 Ah/m³	104.121 A/kg	277.29 A/m²	4.8 A	1.97
6	18.6 mm	65.2 mm	4.2 V	3. V	2.35 Ah		45. g		52.222 Ah/kg	132.649 Ah/m³	100. A/kg	254.009 A/m²	4.5 A	1.91
7	18.2 mm	65.1 mm	4.2 V	3. V	2.4 Ah	9. Wh	46. g	195.652 Wh/kg	52.174 Ah/kg	141.709 Ah/m³	104.348 A/kg	283.418 A/m²	4.8 A	2.
8	18.4 mm	65. mm	4.2 V	2.75 V	2.4 Ah		46. g		52.174 Ah/kg	138.858 Ah/m³	104.348 A/kg	277.717 A/m²	4.8 A	2.
9	18. mm	65. mm	4.2 V	3. V	2.2 Ah		43. g		51.163 Ah/kg	133.007 Ah/m³	51.163 A/kg	133.007 A/m²	2.2 A	1.
10	18.24 mm	65. mm	4.2 V	3. V	2.4 Ah	8.9 Wh	47. g	189.362 Wh/kg	51.064 Ah/kg	141.305 Ah/m³	85.106 A/kg	235.509 A/m²	4. A	1.66
11	18.4 mm	65.1 mm	4.2 V	3. V	2.35 Ah		46.5 g		50.538 Ah/kg	135.757 Ah/m³	98.925 A/kg	265.737 A/m²	4.6 A	1.95
12	18.3 mm	65.2 mm	4.2 V	2.8 V	2.2 Ah		44. g		50. Ah/kg	128.287 Ah/m³	75. A/kg	192.431 A/m²	3.3 A	1.5
13	18. mm	65.2 mm	4.2 V	3. V	2.25 Ah		45. g		50. Ah/kg	135.613 Ah/m³	95.556 A/kg	259.171 A/m²	4.3 A	1.91
14	18.25 mm	65. mm	4.2 V	2.75 V	2.4 Ah	9.552 Wh	48. g	199. Wh/kg	50. Ah/kg	141.15 Ah/m³	100. A/kg	282.301 A/m²	4.8 A	2.
15	18.4 mm	65.1 mm	4.2 V	3. V	2.2 Ah		44.5 g		49.438 Ah/kg	127.091 Ah/m³	96.629 A/kg	248.406 A/m²	4.3 A	1.95
16	18.3 mm	65.2 mm	4.2 V	2.8 V	2.1 Ah		43. g		48.837 Ah/kg	122.456 Ah/m³	73.256 A/kg	183.684 A/m²	3.15 A	1.5
17	18.6 mm	65.2 mm	4.2 V	3. V	2.05 Ah		42. g		48.81 Ah/kg	115.715 Ah/m³	92.857 A/kg	220.141 A/m²	3.9 A	1.90
18	17. mm	65. mm			1.65 Ah		34. g		48.529 Ah/kg	111.836 Ah/m³	97.059 A/kg	223.673 A/m²	3.3 A	2.
19	18.6 mm	65.2 mm	4.2 V	3. V	2.15 Ah		44.5 g		48.315 Ah/kg	121.36 Ah/m³	91.685 A/kg	230.302 A/m²	4.08 A	1.89
20	18.25 mm	65. mm	4.2 V	2.75 V	2.2 Ah	8.694 Wh	46. g	189. Wh/kg	47.826 Ah/kg	129.388 Ah/m³	95.652 A/kg	258.776 A/m²	4.4 A	2.
21	18.25 mm	65. mm	4.2 V	2.75 V	2.2 Ah		46. g		47.826 Ah/kg	129.388 Ah/m³	86.957 A/kg	235.251 A/m²	4. A	1.81
22	18.4 mm	65.5 mm			2.15 Ah		45. g		47.778 Ah/kg	123.444 Ah/m³				
23	18.2 mm	65. mm	4.2 V	2.75 V	2.2 Ah		46.2 g		47.619 Ah/kg	130.1 Ah/m³				
24	18.2 mm	65. mm	4.2 V	3. V	2.2 Ah	8.25 Wh	46.5 g	177.419 Wh/kg	47.312 Ah/kg	130.1 Ah/m³	86.022 A/kg	236.545 A/m²	4. A	1.81
25	18.5 mm	65.5 mm	4.2 V	3. V	2.2 Ah		47. g		46.809 Ah/kg	124.953 Ah/m³	93.617 A/kg	249.907 A/m²	4.4 A	2.
26	32.4 mm	58.5 mm	4.2 V	2.75 V	4.2 Ah		90. g		46.667 Ah/kg	87.079 Ah/m³	140. A/kg	261.237 A/m²	12.6 A	3.
27	18.2 mm	65. mm	4.2 V	3. V	2. Ah		43. g		46.512 Ah/kg	118.273 Ah/m³	139.535 A/kg	354.818 A/m²	6. A	3.
28	18.3 mm	65.2 mm	4.2 V	2.8 V	2. Ah		43. g		46.512 Ah/kg	116.625 Ah/m³	69.767 A/kg	174.937 A/m²	3. A	1.5
29	18.5 mm	65.5 mm	4.2 V	3. V	2.15 Ah		47. g		45.745 Ah/kg	122.114 Ah/m³	91.489 A/kg	244.227 A/m²	4.3 A	2.
30	18.25 mm	65. mm	4.2 V	2.75 V	2. Ah	7.568 Wh	44. g	172. Wh/kg	45.455 Ah/kg	117.625 Ah/m³	90.909 A/kg	235.251 A/m²	4. A	2.
31	18. mm	50. mm			1.5 Ah		33. g		45.455 Ah/kg	117.893 Ah/m³				
32	18.1 mm	64.8 mm	4.2 V	2.5 V	2.1 Ah	7.766 Wh	46.5 g	167. Wh/kg	45.161 Ah/kg	125.95 Ah/m³	90.323 A/kg	251.899 A/m²	4.2 A	2.
33	18.3 mm	50. mm	4.2 V	2.8 V	1.4 Ah		31. g		45.161 Ah/kg	106.455 Ah/m³	67.742 A/kg	159.682 A/m²	2.1 A	1.5
34	18.2 mm	65.1 mm	4.2 V	3. V	2. Ah	7.4 Wh	44.3 g	167.043 Wh/kg	45.147 Ah/kg	118.091 Ah/m³	90.293 A/kg	236.182 A/m²	4. A	2.
35	18. mm	65. mm			2.2 Ah		49. g		44.898 Ah/kg	133.007 Ah/m³	89.796 A/kg	266.014 A/m²	4.4 A	2.
36	18.2 mm	65. mm	4.2 V	2.75 V	2. Ah		45.2 g		44.248 Ah/kg	118.273 Ah/m³				
37	18. mm	65. mm			1.9 Ah		43. g		44.186 Ah/kg	114.87 Ah/m³	88.372 A/kg	229.739 A/m²	3.8 A	2.
38	18. mm	50. mm			1.5 Ah		34. g		44.118 Ah/kg	117.893 Ah/m³	88.235 A/kg	235.785 A/m²	3. A	2.
39	18.3 mm	64.8 mm	4.2 V	3. V	2. Ah		45.5 g		43.956 Ah/kg	117.345 Ah/m³	43.956 A/kg	117.345 A/m²	2. A	1.
40	18.3 mm	64.8 mm	4.2 V	2.75 V	2. Ah		45.5 g		43.956 Ah/kg	117.345 Ah/m³				
41	18.5 mm	50. mm	4.2 V	3. V	1.4 Ah		32. g		43.75 Ah/kg	104.166 Ah/m³	87.5 A/kg	208.331 A/m²	2.8 A	2.
42	18.3 mm	49.8 mm	4.2 V	3. V	1.4 Ah		32. g		43.75 Ah/kg	106.883 Ah/m³	43.75 A/kg	106.883 A/m²	1.4 A	1.
43	18.3 mm	49.8 mm	4.2 V	2.75 V	1.4 Ah		32. g		43.75 Ah/kg	106.883 Ah/m³				
44	18.1 mm	49.3 mm	4.2 V	2.5 V	1.5 Ah	5.52 Wh	34.5 g	160. Wh/kg	43.478 Ah/kg	118.249 Ah/m³	86.957 A/kg	236.498 A/m²	3. A	2.
45	14.3 mm	65. mm	4.2 V	2.75 V	1.05 Ah		24.2 g		43.388 Ah/kg	100.581 Ah/m³				
46	17. mm	67. mm	4.2 V	2.8 V	1.6 Ah		37. g		43.243 Ah/kg	105.21 Ah/m³	64.865 A/kg	157.815 A/m²	2.4 A	1.5
47	18.1 mm	64.8 mm			1.9 Ah	7.392 Wh	44. g	168. Wh/kg	43.182 Ah/kg	113.955 Ah/m³				

Complete Database / High Rate Cells / High Capacity Cells

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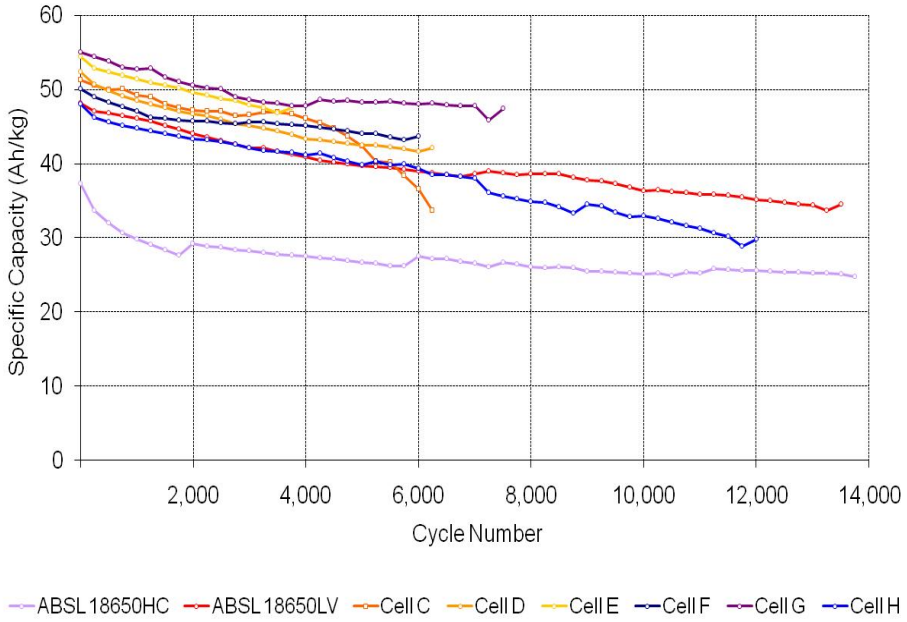
Phase B: In-House Testing

- All Phase B cells are screened and assessed for consistency and build quality
- Specific test regime depends on the cell, but any test is fair game: performance characterization, temperature sensitivity, safety, etc.
- Lifetesting is initiated as early as possible for promising candidates
- This helps identify the best future mission applications of candidate COTS cells



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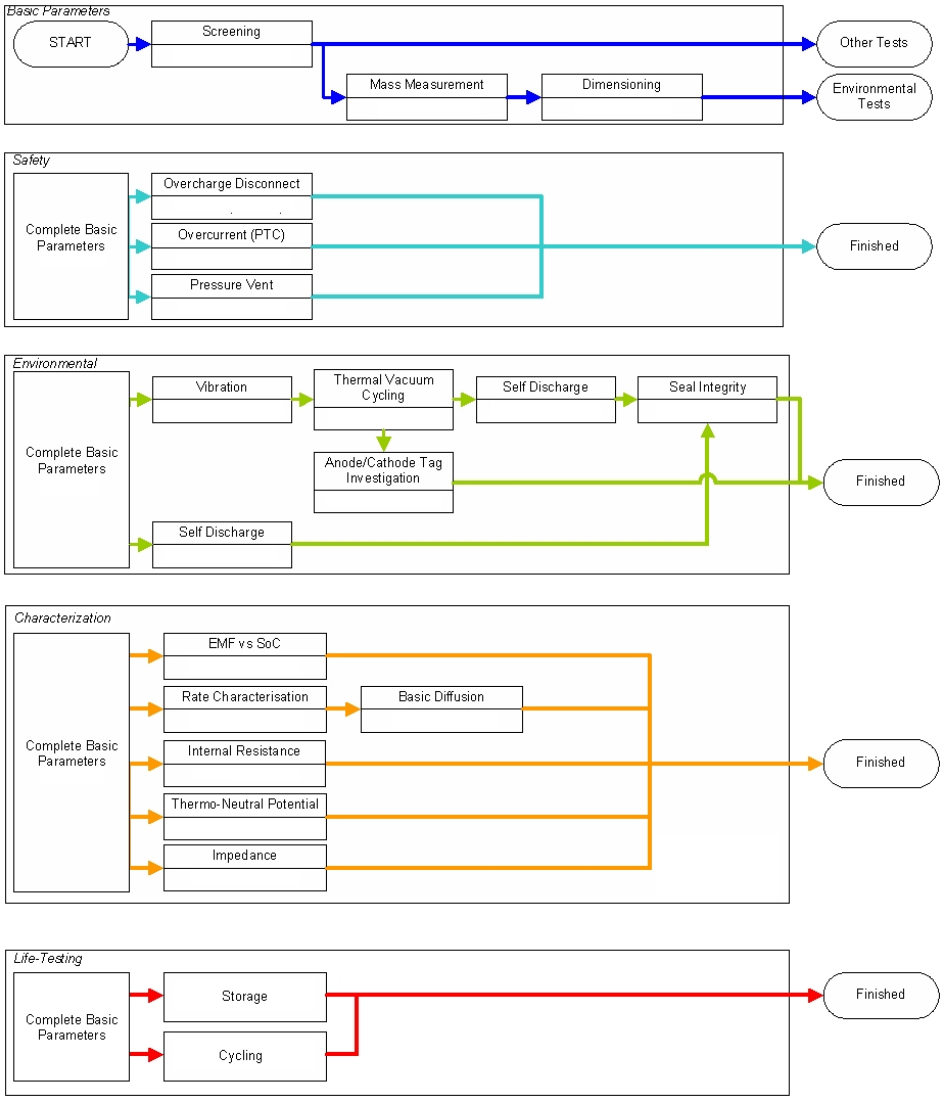
Phase C: Cell Qualification

- Basic Parameters
- Safety
- Environmental
- Characterization
- Endurance



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ABSL Cell Suite

Cell	Energy Density	Attributes	Space Qualified	Space Proven	Space Application
ABSL18650HC	130 Wh/kg	Excellent and Characterised Cycle Life	✓	✓	All space programs
ABSL18650HR	100 Wh/kg	Very high current delivery >10 C	✓	2008	High Power
ABSL18650LV	174 Wh/kg	High Energy Density, low temp performance	✓		Low temp, mass pushed
ABSL33111PR	450 Wh/kg	High energy and structural integrity	✓	✓	Primary batteries
ABSL 26650HC	120 Wh/kg	Excellent cycle life	✓	✓	Retired
ABSL 18650LVF	175Wh/kg	High Energy Density	✓		Retired

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The Cell Suite: ABSL 18650HC

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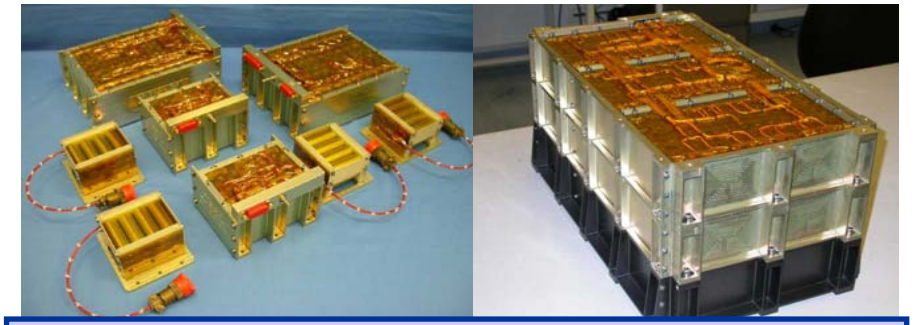
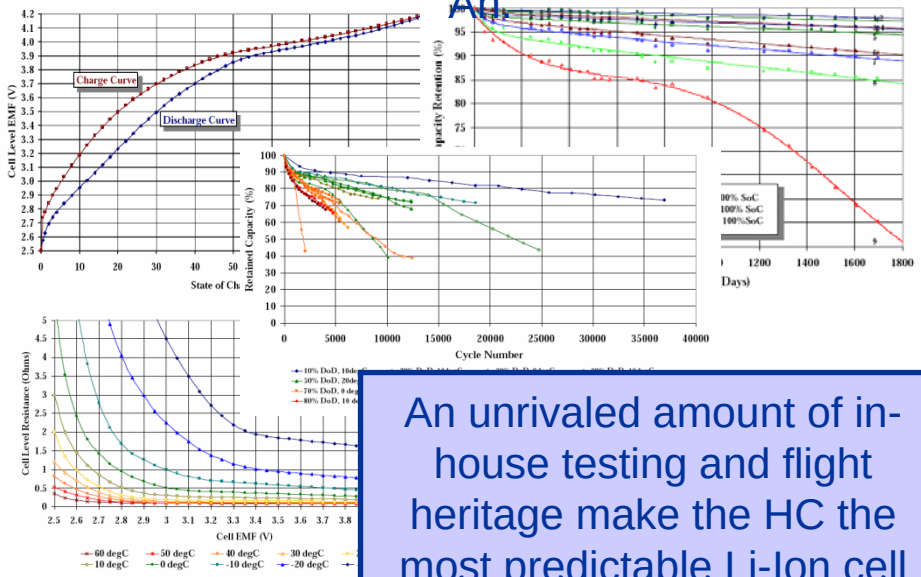
- **Description:** A proven, long-life COTS cell with excellent energy density.
- **Qualification**: The best characterized and understood Li-Ion cell for space, qualified to a broad range of temperatures and vibration environments to meet the needs of nearly any mission.
- **Lifetesting**: A wide range of varied parameters across both storage and operational conditions have been tested.
- **Heritage**: 30 missions flown, and more than 6,000 cell years in space without failure



The HC cell has been employed in batteries ranging from several Ah to more than 100 Ah.



An unrivaled amount of in-house testing and flight heritage make the HC the most predictable Li-Ion cell available for space.

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The Cell Suite: ABSL 18650HR

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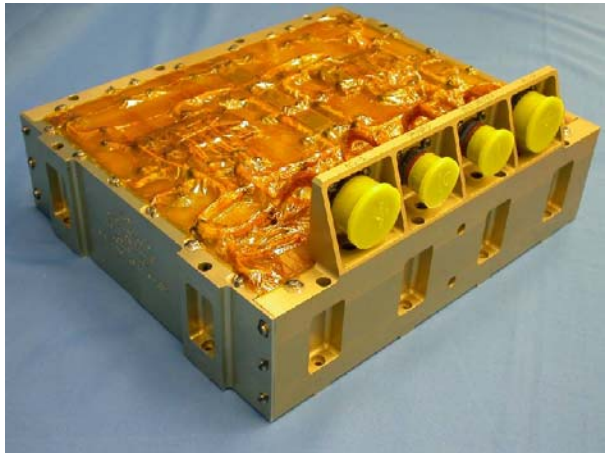
- **Description:** An extremely robust, high power cell for satellites and launch vehicles.
- **Qualification**: Focus on high rate characterization, qualified to extremely harsh temperature and vibration environments.
- **Heritage**: World's first space-qualified 270V Li-Ion battery set to fly in 2008.
- **Characterization**: Extensive testing has proven that the HR is an excellent cell choice for high power applications.



Employment of the HR cell in ABSL's 270V TVC battery is crucial to providing the required performance.

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The Cell Suite: ABSL 33111PR

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- **Description:** US manufactured high rate, high energy density (450 Wh/kg) Lithium Sulfuryl Chloride primary COTS cell.
- **Qualification**: Qualified for the rigorous vibration environment of atmospheric re-entry missions.
- **Heritage**: Successfully completed the FOTON-M3 Earth return mission in September, 2007

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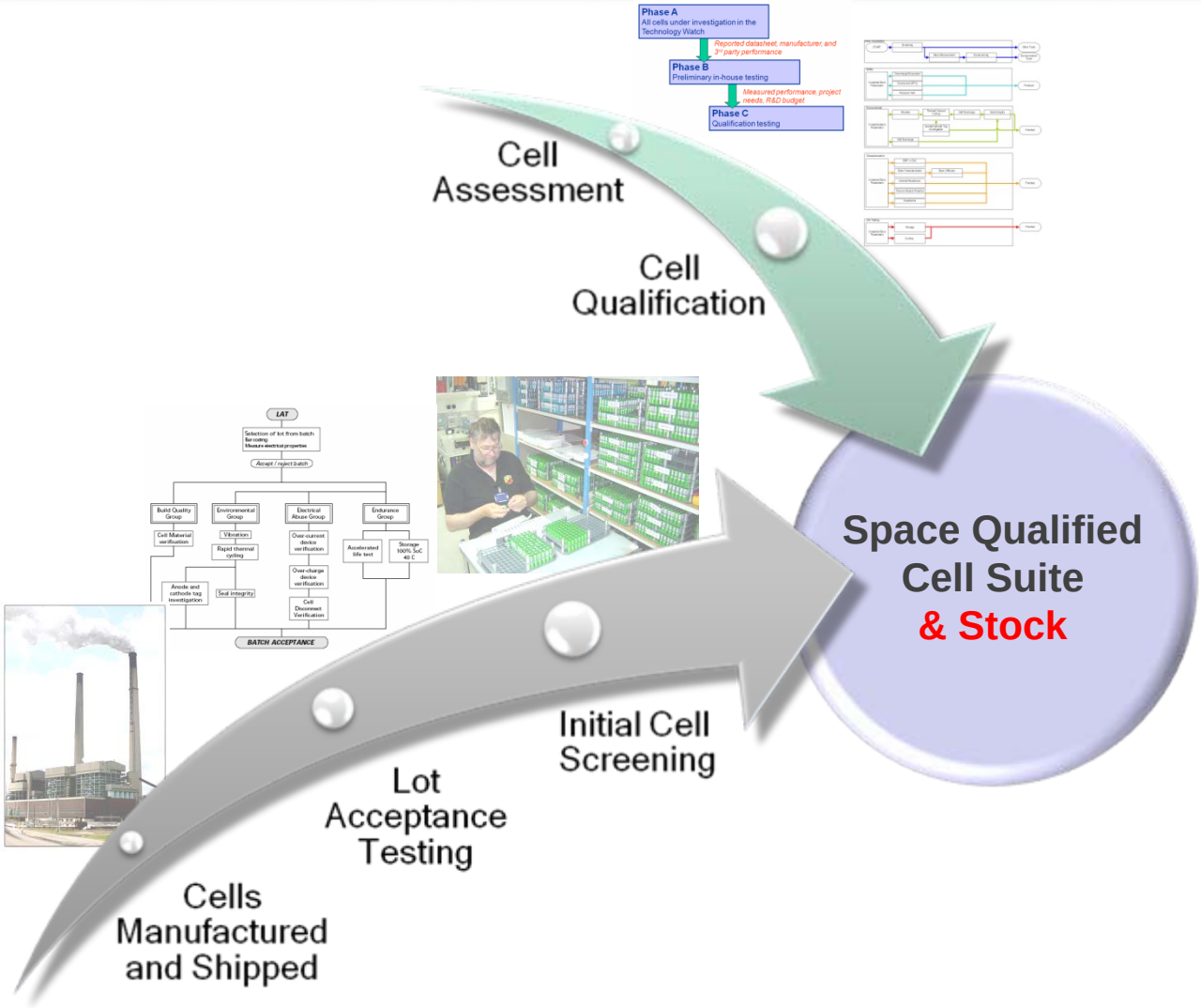
COTS Cell Cycle



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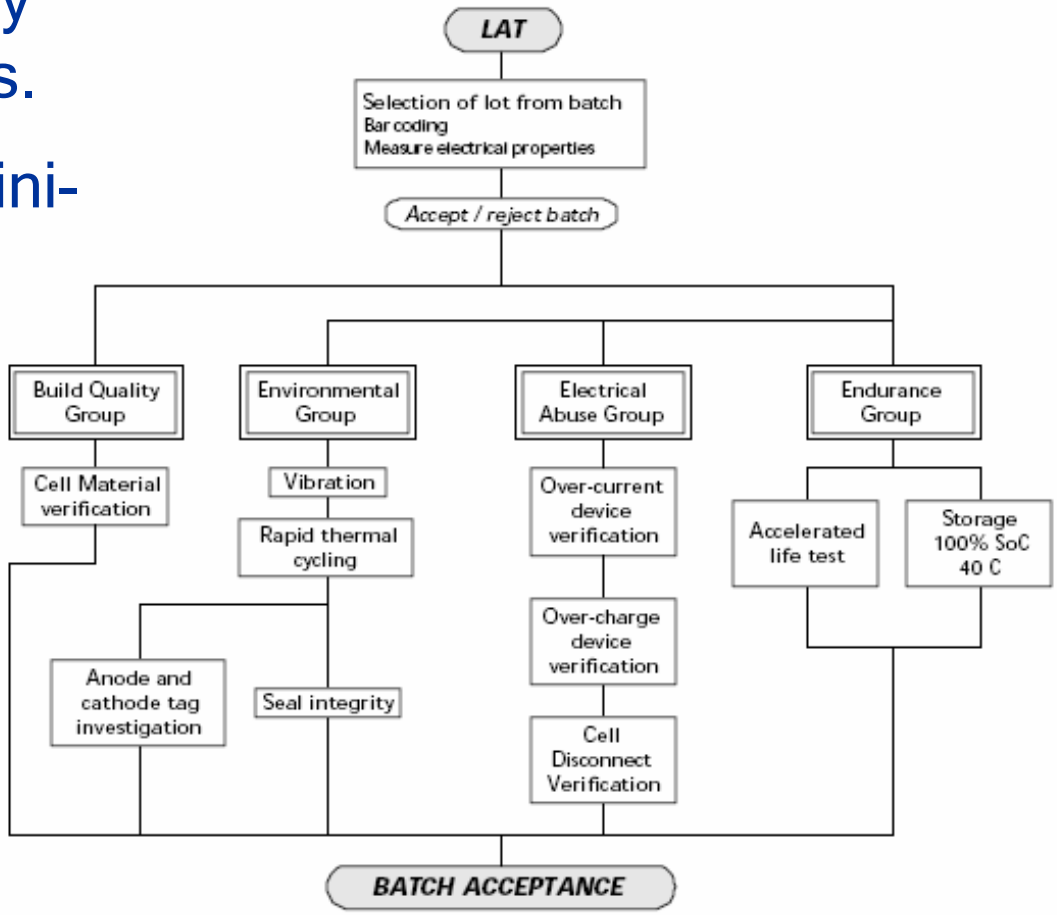
Lot Acceptance Testing (LAT)

- Build variability is the key risk for using COTS cells.
- LAT = Zero-tolerance mini-qualification program
- Ensures predictable performance batch to batch.



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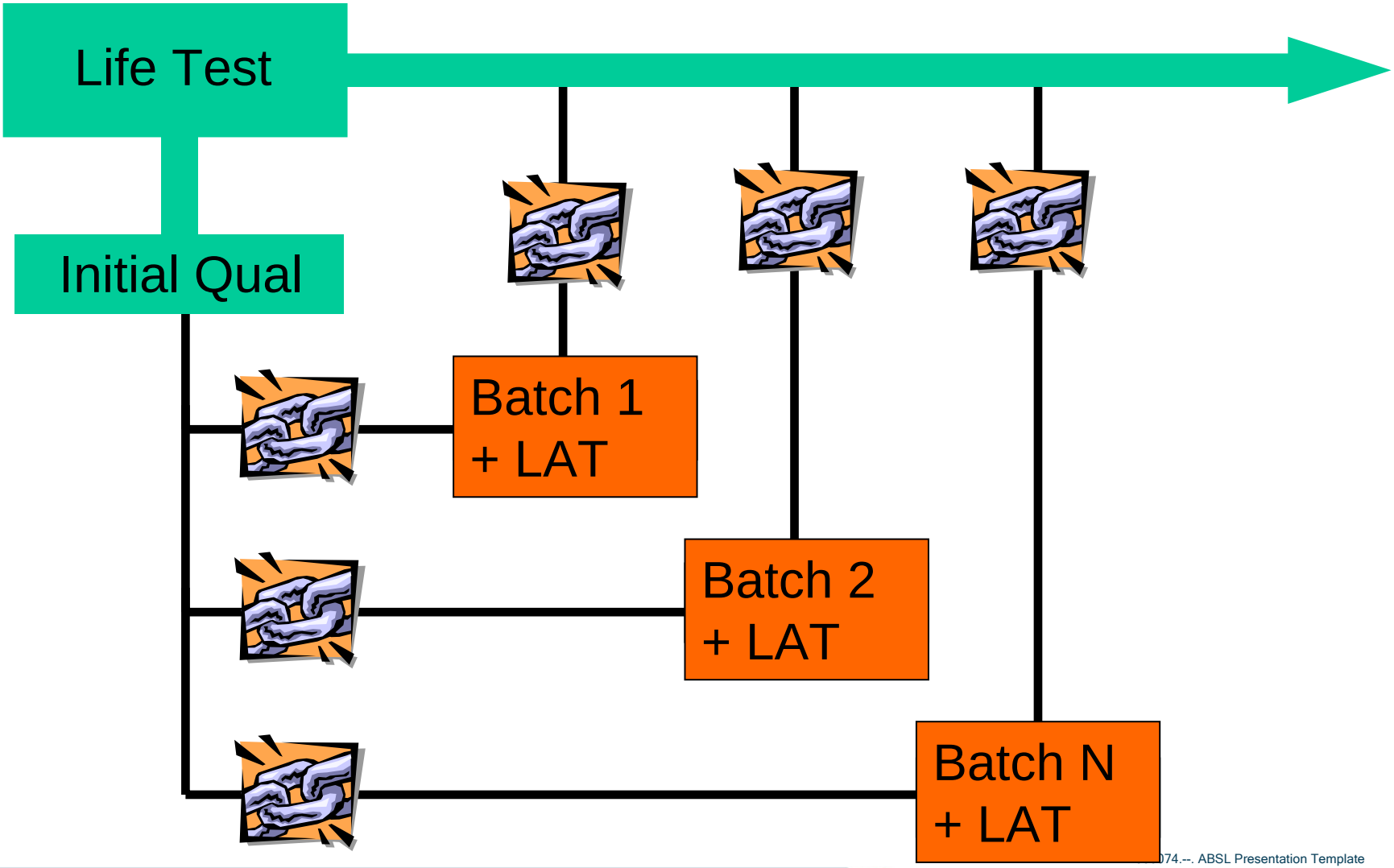
Life Test Program



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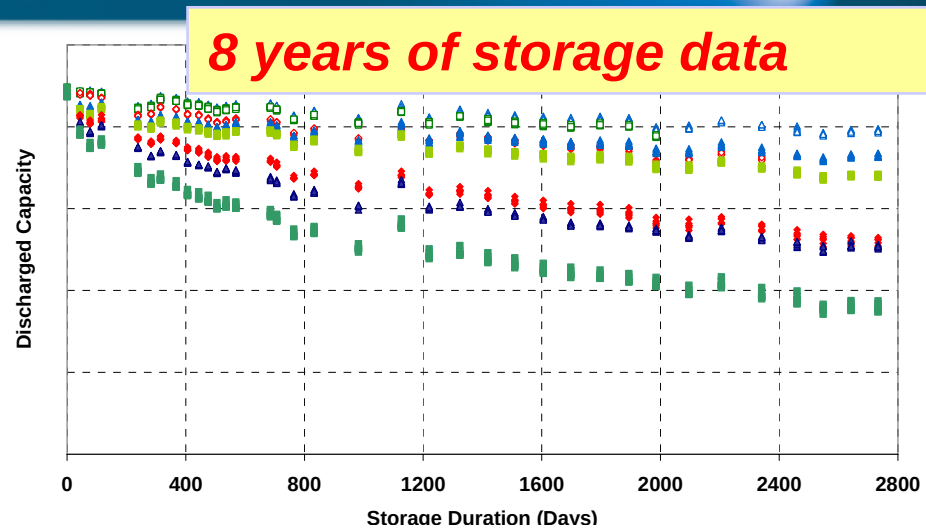
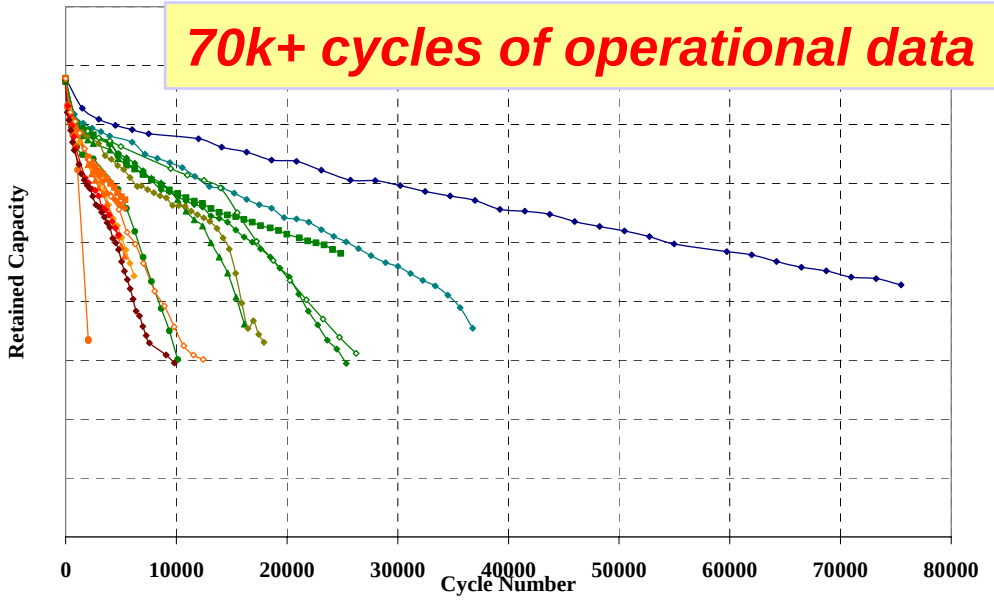
Life Test Program

- A wide range of varied parameters across both storage and operational conditions are tested
  - Storage
    - Temperature
    - SOC
  - Operational:
    - Orbital profiles
    - Temperature
    - DOD
    - Charge/Discharge rate
    - Charge management regimes





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Stockpiling

- Assured access to cells is critical
- Short Term (0 to 3 years)
  - ABSL buy 10k's of cells at a time maintain rolling stock
  - Last-time buy agreements
- Long Term (3+ years)
  - Cell stockpiling
  - Cell selection
  - Diverse cell suite
  - Commitment to qualify new cells

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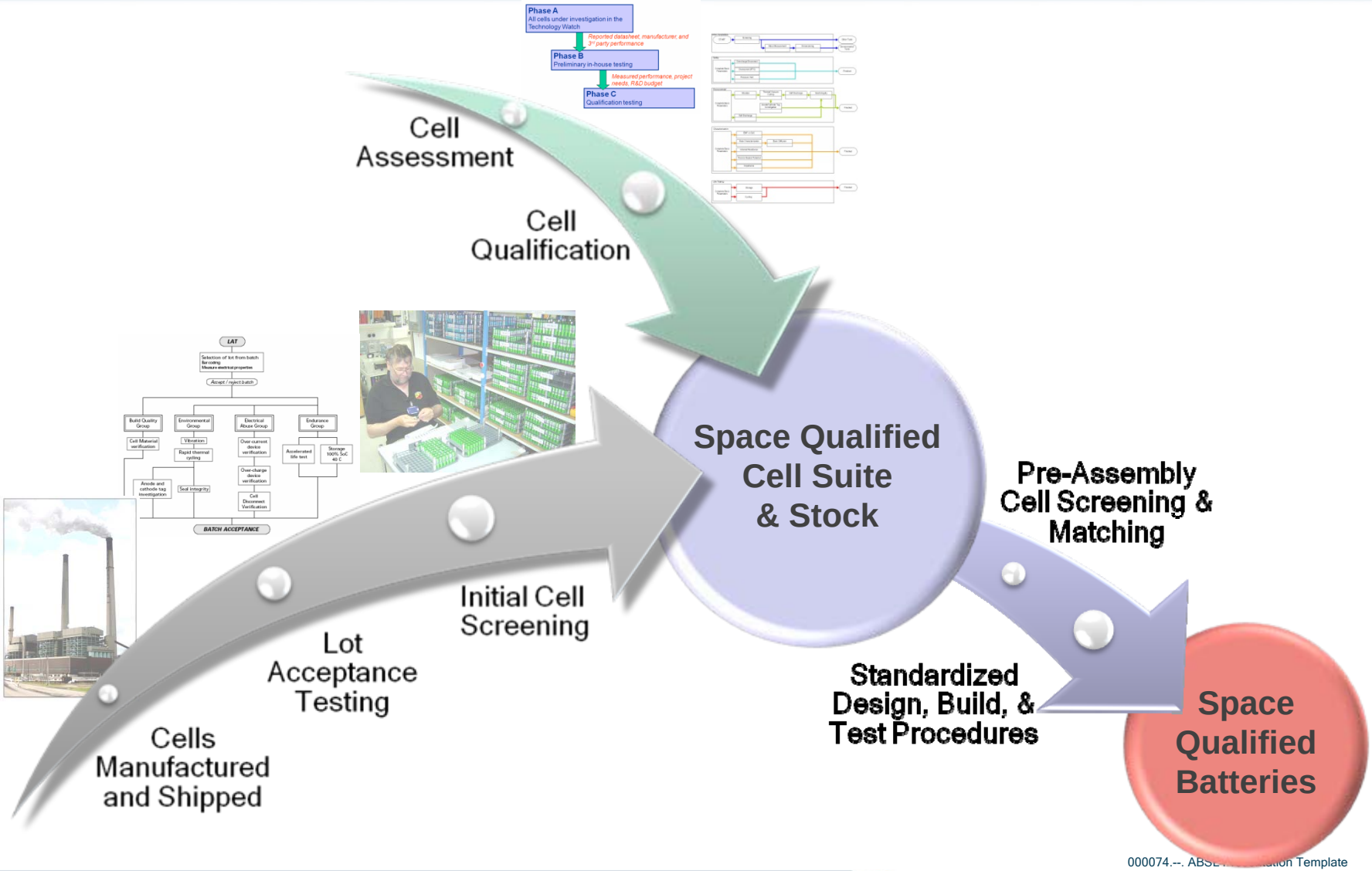
COTS Cell Cycle



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Cell Screening

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Cell Screening Timeline

- In addition to performing a LAT on a sample of each batch, *all* cells are screened *twice*.
- The first screening is on receipt of the cells from the manufacturer, the second is just before use of the cells.
- This approach allows two opportunities to identify cells with abnormally high self-discharge rates.

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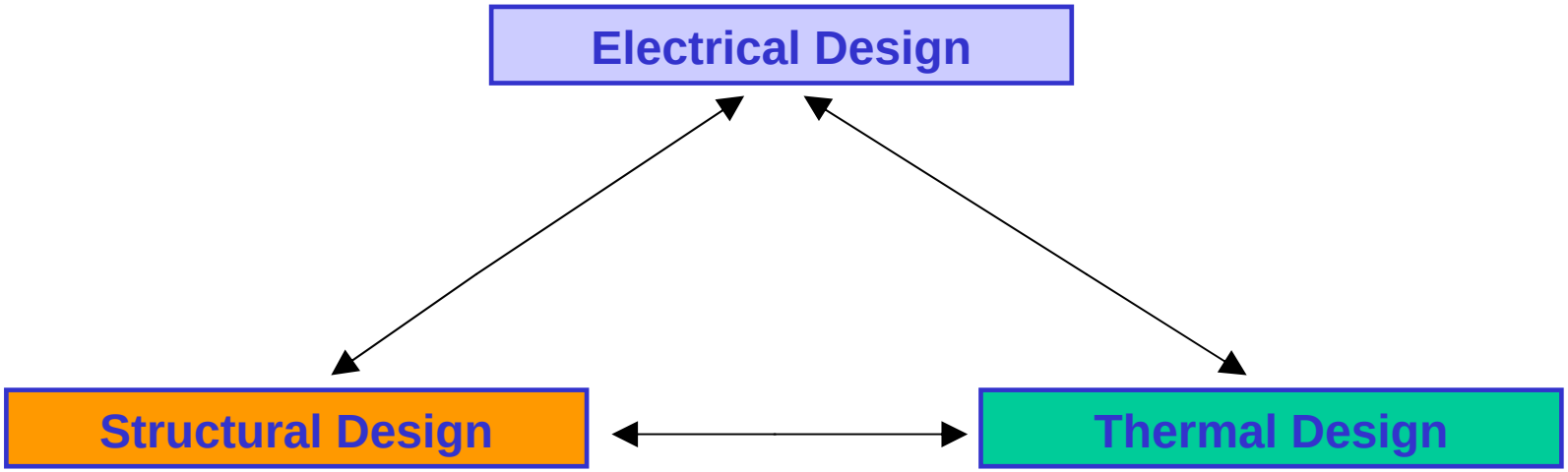
Standardized Battery Design

- Battery performance is highly dependant on the complex interplay of electrical, thermal, and structural design aspects.
- For optimal results, all three disciplines must be approached collectively through iteration.
- Strong expertise in all aspects is critical for excellence.



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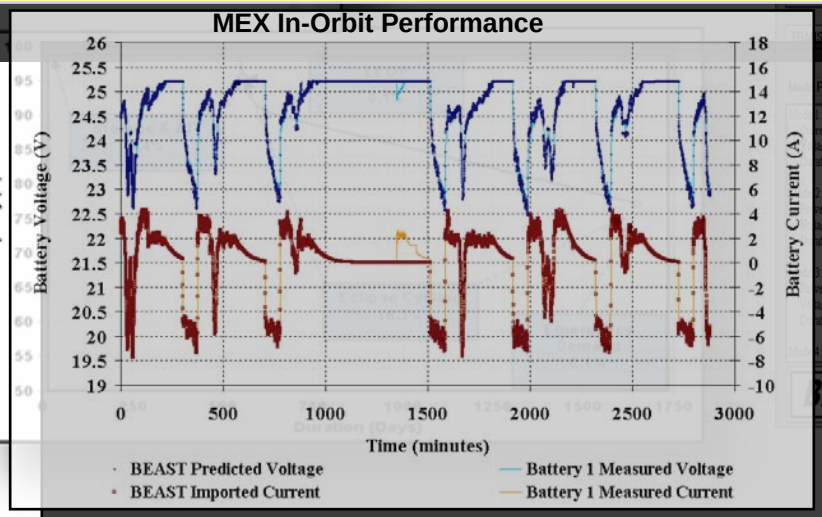
Standardized Battery Design

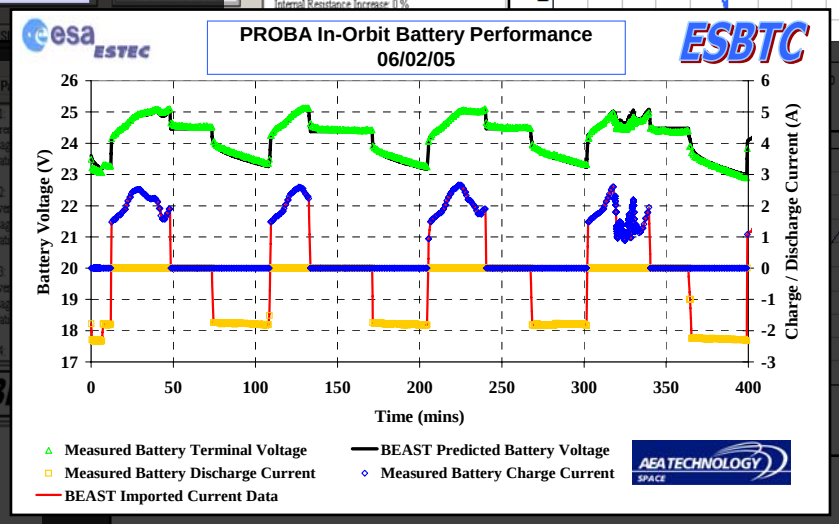
Electrical Design

LIFE → *EOL Capacity & Resistance* → BEAST

LIFE ← *DOD* ← BEAST

Comparison against in-orbit telemetry shows a high degree of accuracy for complex mission profiles and long mission durations.





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Standardized Battery Design

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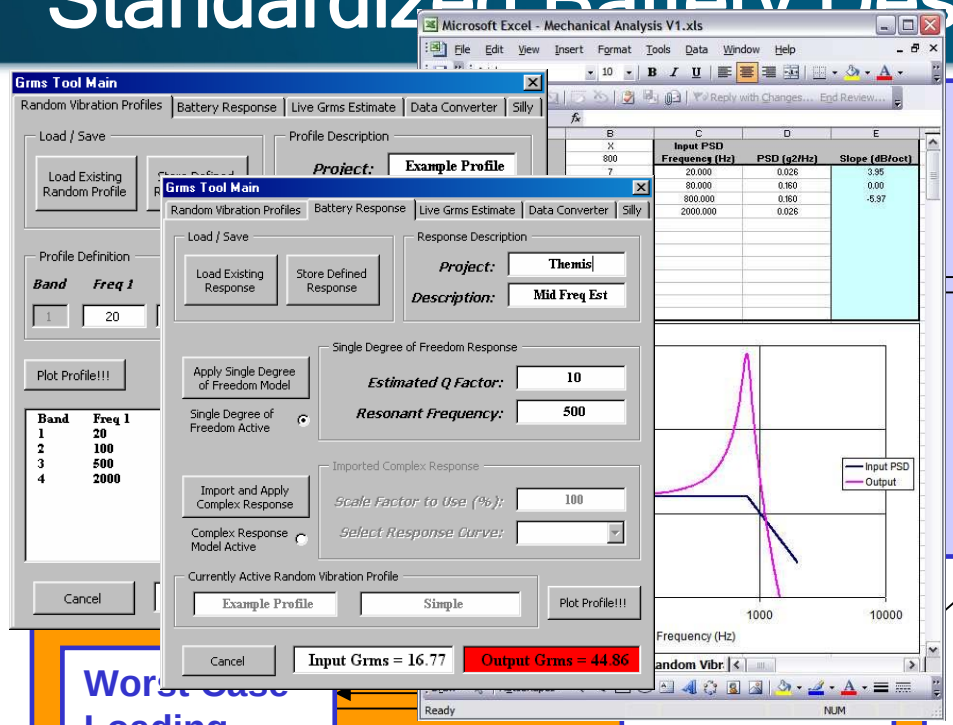


EOL Capacity & Resistance

DOD

BEAST

Battery Configuration

Worst Case Loading

Max Deflection & Stress

Cell Level Vibration

Cell Level Vibration

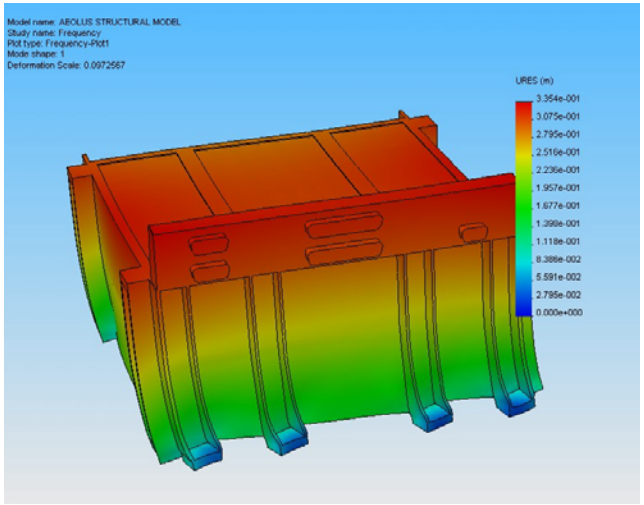
Structural Design

Random Vibration

Natural Frequencies & Mode Shapes

Modes & Frequencies

Structural Design



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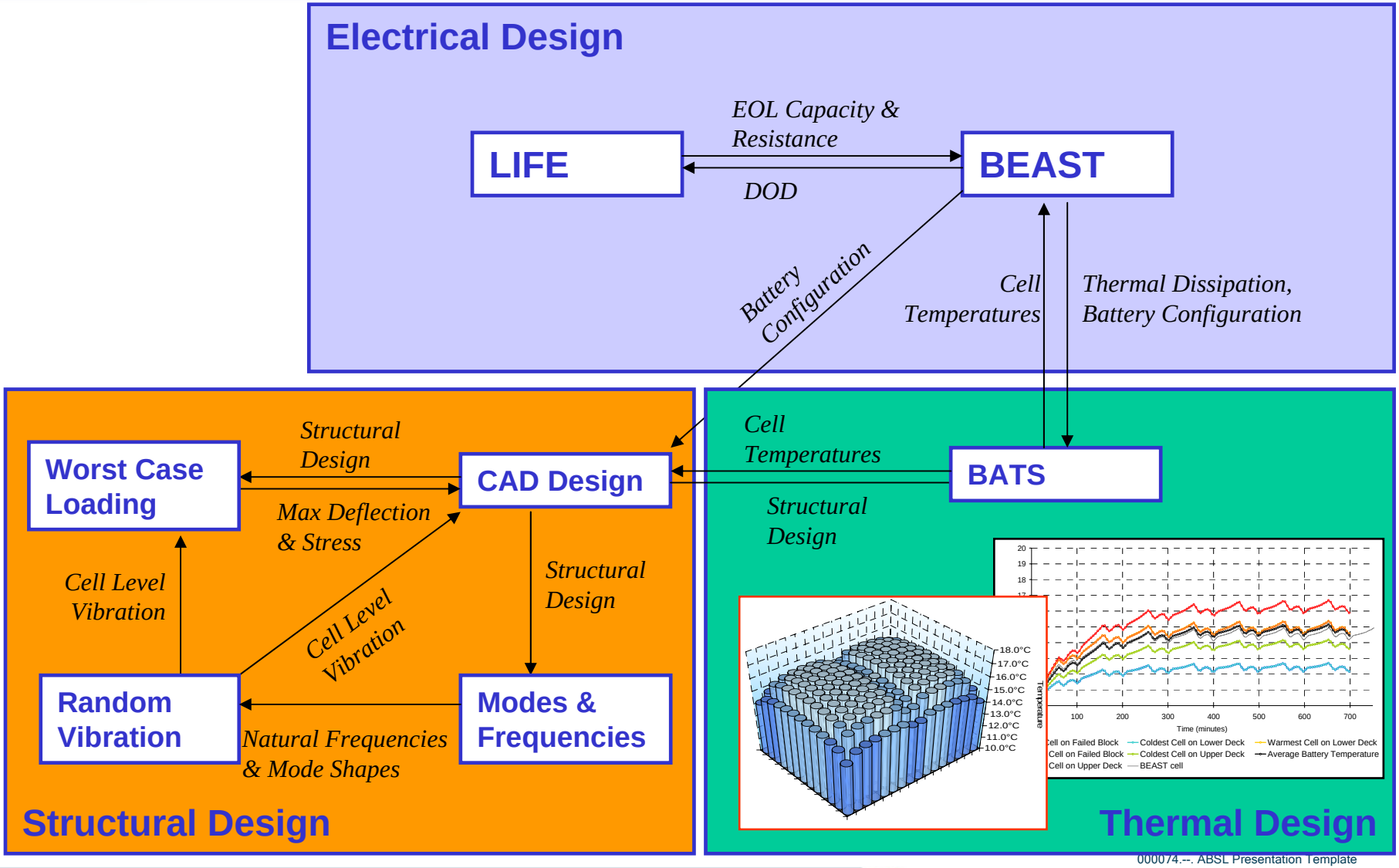
Standardized Battery Design



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Standardized Battery Build

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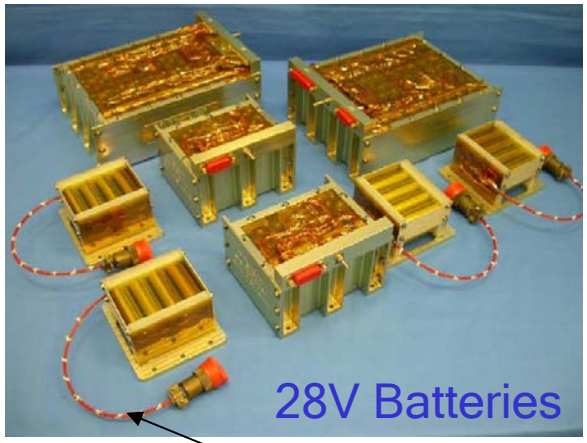

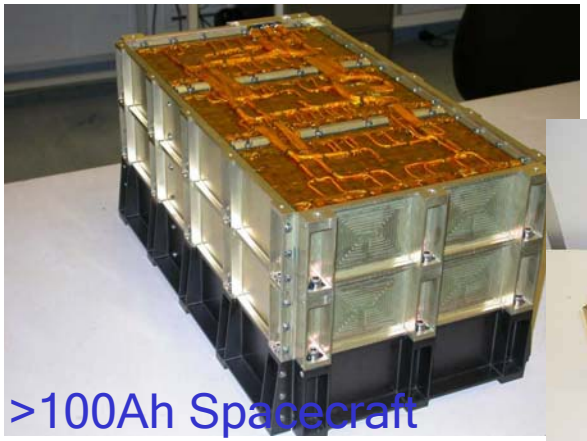

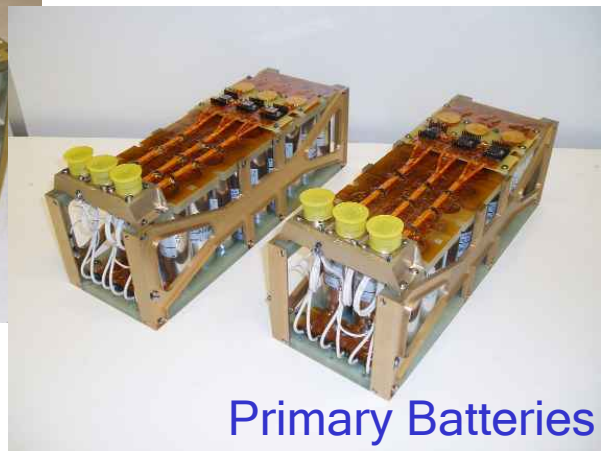

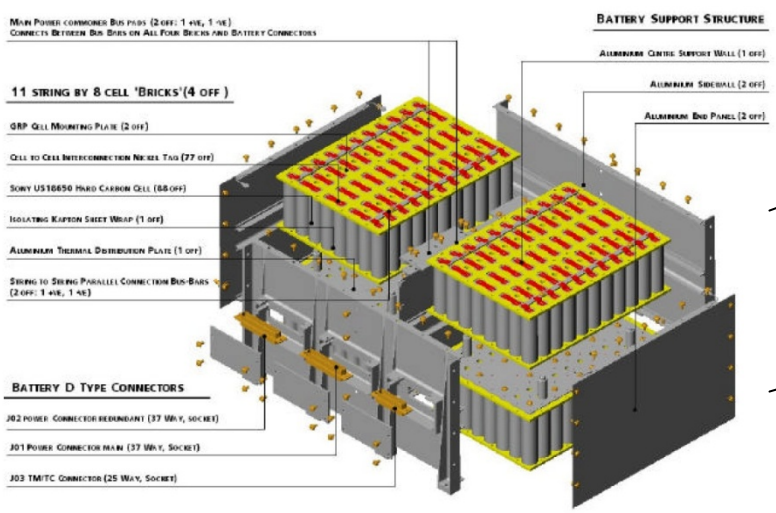

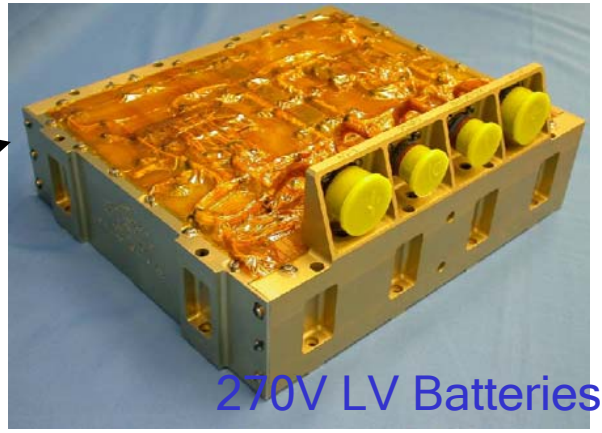

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Space Battery Qualification

Design & Analysis, Build

Inspection

ICD Verification, Functional Checks

Structural Testing

LLS, HLS, Random Vibration, Shock

Thermal Testing

Operational & Non-Operational Thermal Cycling in Vacuum

Additional Testing

Mission Specific

- Custom batteries qualified to different levels at customers' request.
- ABSL has pre-qualified "build to print" designs as well, to reduce cost and lead time.

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The ABSL COTS Approach

- Cell Assessment & Qualification
  - *Identify the best COTS cells to meet future space battery needs and qualify them to space industry standards.*
- The Cell Suite
  - *Readily provide a broad range of battery capabilities and security of supply.*
- Lot Acceptance Testing (LAT)
  - *Ensuring consistency of cells batch to batch, maximizing the value of comprehensive cell characterization and life test programs.*
- Life Test Program
  - *Enabling unmatched EOL performance predictions capabilities.*
- Standardized Battery Design, Build, & Qualification
  - *Leveraging the consistency and predictability of ABSL's COTS cells to efficiently optimize and qualify battery designs for any mission.*

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ABSL's Next Generation Cells

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Contents

- ABSL Space Battery Experience
- The ABSL COTS Approach
- ABSL's Next Generation COTS Cells
  - Next Gen Summary
  - Cells G & F
  - ABSL 18650LV

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Next Generation Cells

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Current Next-Gen COTS Cell Status:

- More than 140 COTS cells currently in Phase A (Technology Watch Database)
- Approximately 10 COTS cells currently in Phase B (In-House Testing)
- Multiple COTS cell under investigation via cooperative efforts with NASA/ESA
- One COTS cell starting Phase C (Cell Qualification)
- One COTS cell about to complete Phase C (Cell Qualification)

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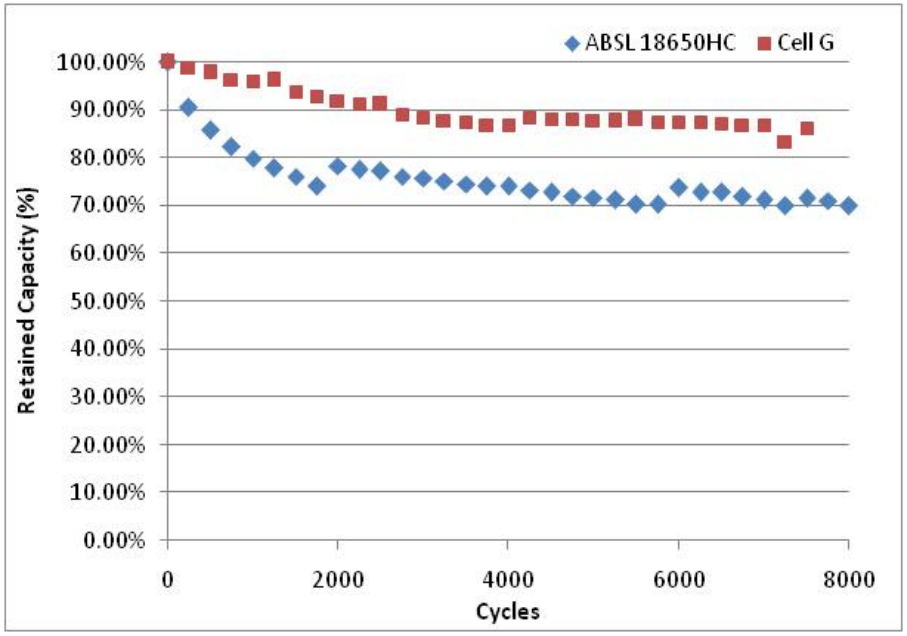
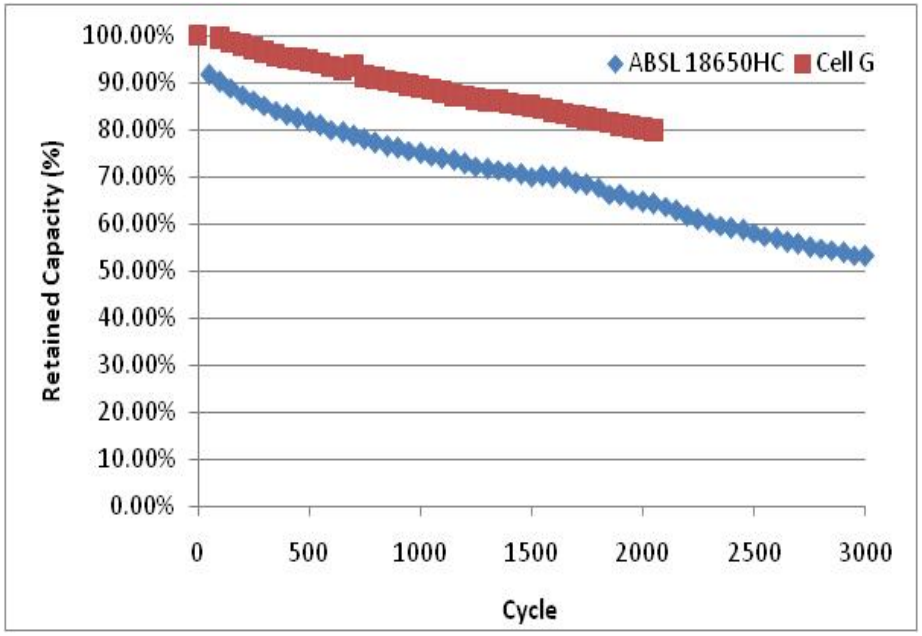
Next Gen Cells: Phase B

- "Cell G": Lifetesting

20% DOD LEO



100% DOD



Cell G shows improved percent capacity retention performance relative to the HC at both low and high DOD

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Next Gen Cells: Phase B

ABSL SPACE PRODUCTS

- "Cell G": Additional Completed Characterization
  - Consistency & Build Quality Testing
  - Capacity at Temperature, -40° C to 60° C
  - Rate & Pulse Characterization, up to 3C
  - Resistance Characterization, -40° C to 60° C
  - Overcharge Testing
- ABSL has assessed prototype rather than production cells
- Further testing & characterization planned upon initiation of full-scale production

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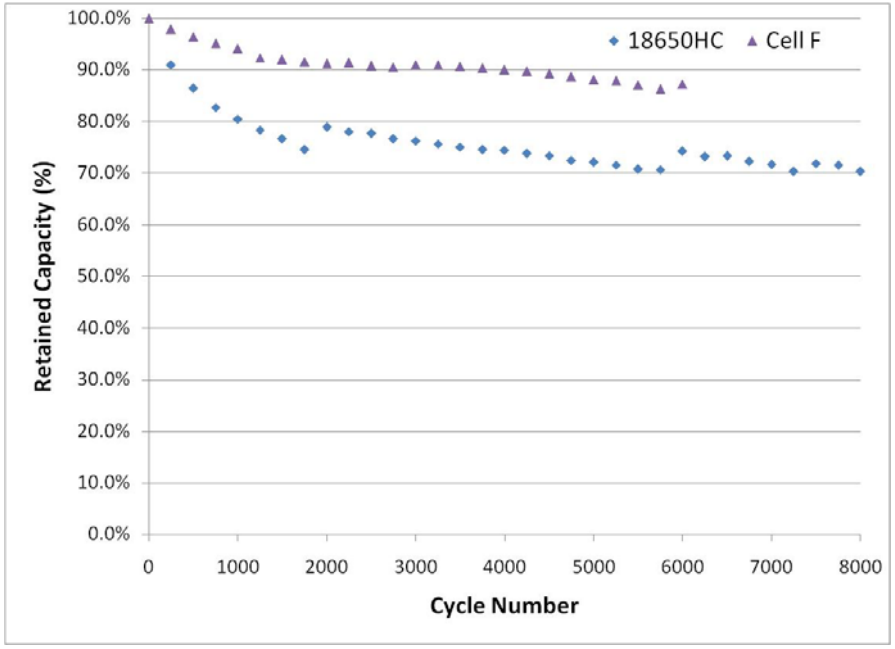
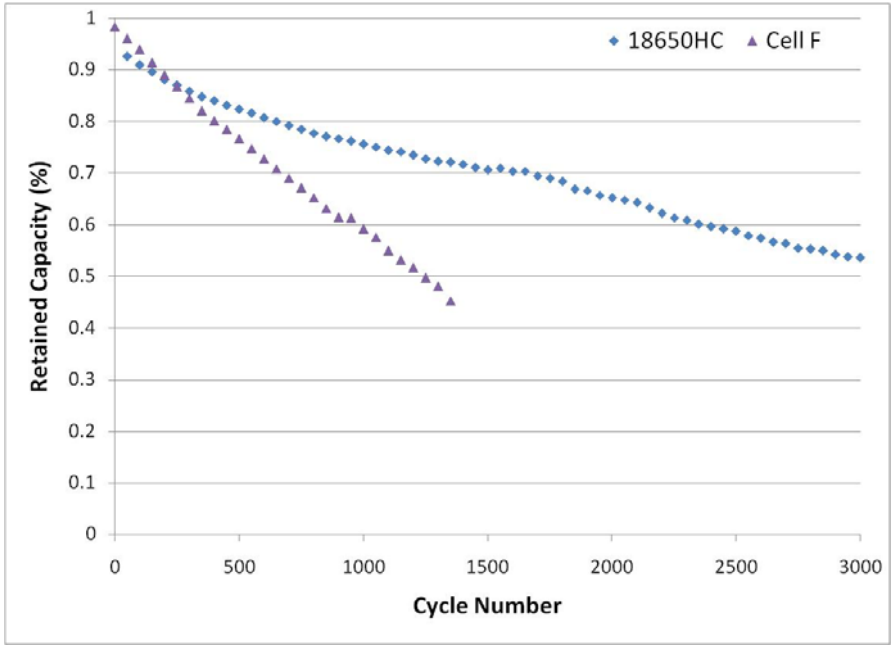
Next Gen Cells: Phase B

- "Cell F": Lifetesting

20% DOD LEO



100% DOD



Cell F shows improved percent capacity retention performance relative to the HC at low DOD, but not at high DOD

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Next Gen Cells: Phase B

ABSL SPACE PRODUCTS

- "Cell F": Additional Completed Characterization
  - Consistency & Build Quality Testing
  - Capacity at Temperature, -40° C to 60° C
  - Rate & Pulse Characterization, up to 7C
  - Resistance Characterization, -40° C to 60° C
  - Overcharge Testing
- More tests are currently underway
- A full BEAST cell model will be available Dec. 2007

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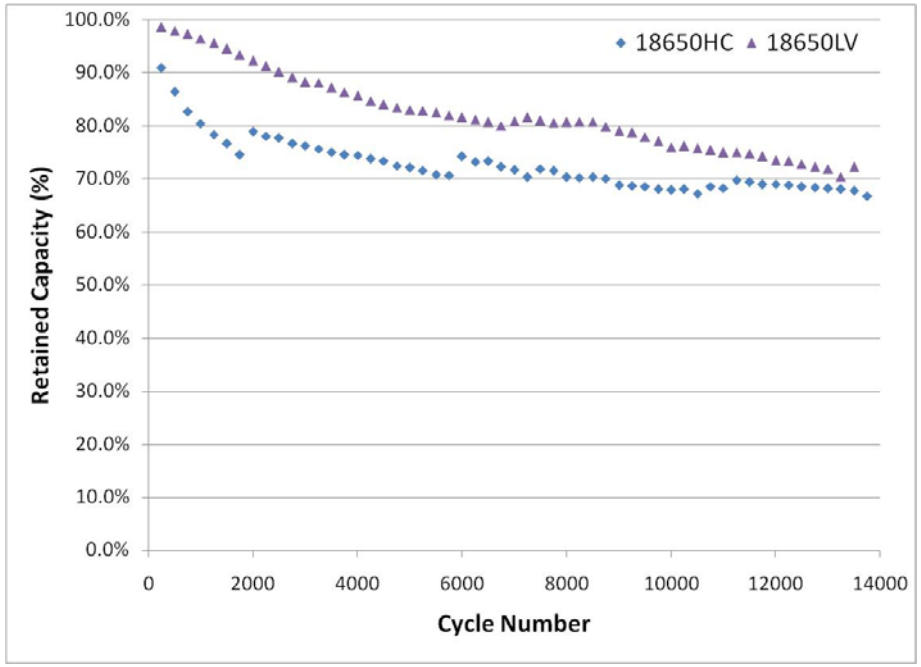
Next Gen Cells: Phase C

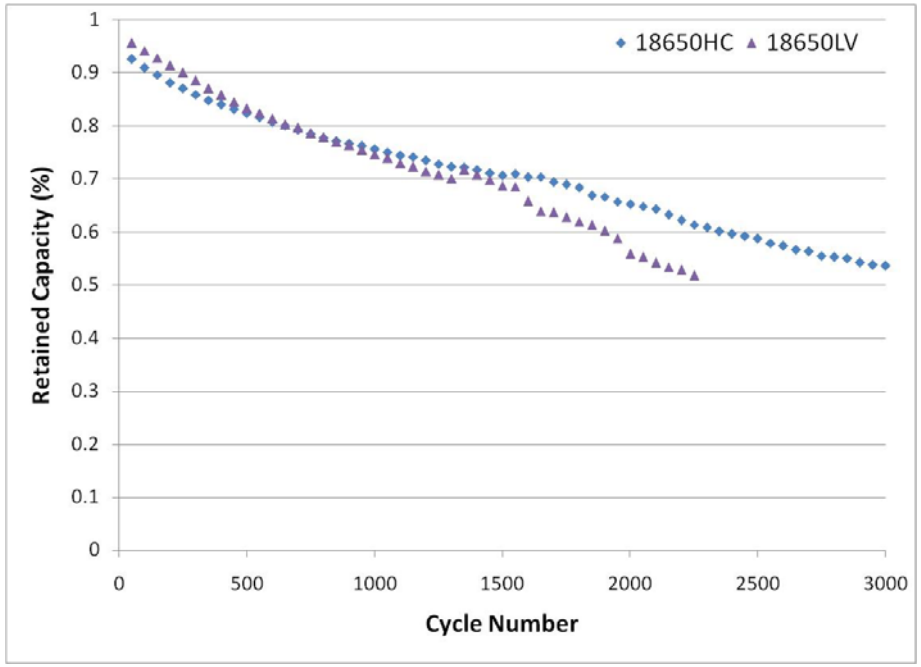
ABSL SPACE PRODUCTS

- ABSL 18650LV: Lifetesting

20% DOD LEO



100% DOD



The LV shows very similar percent capacity retention to the HC at both high and low DODs

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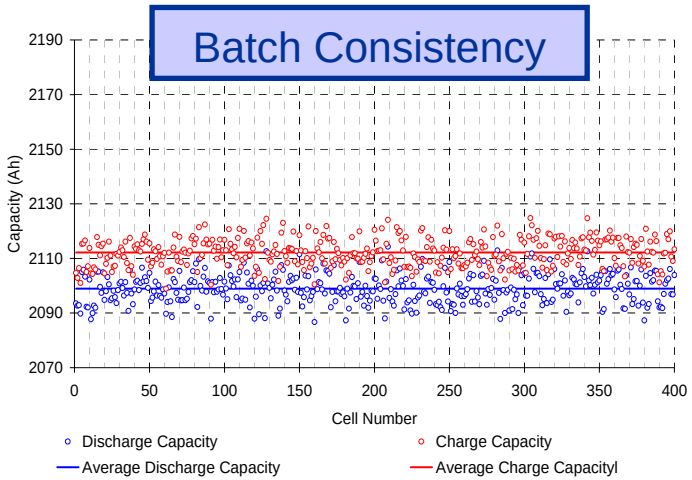
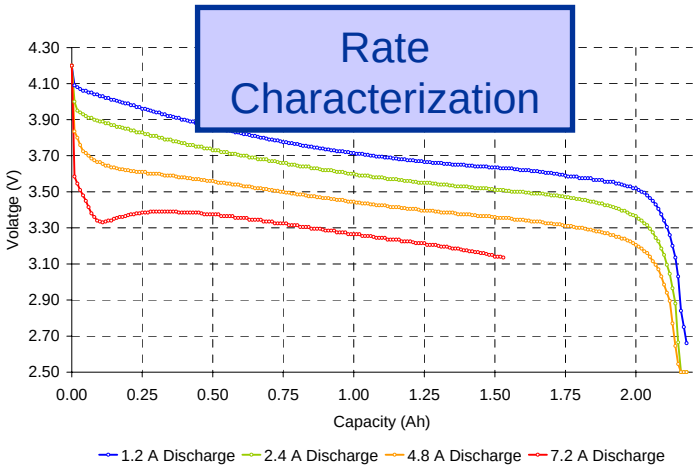
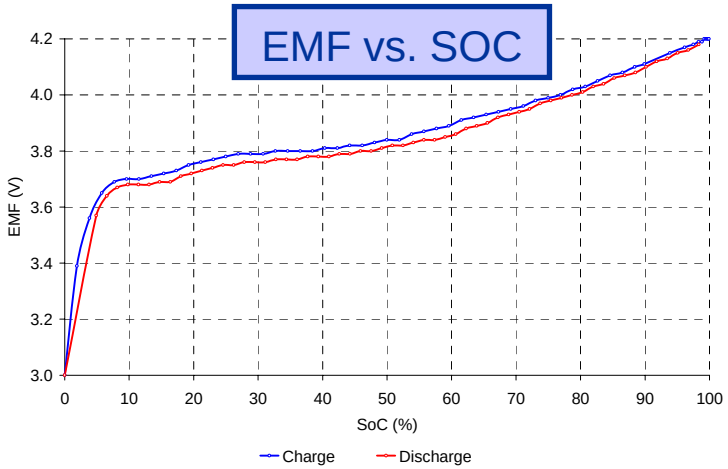
Next Gen Cells: Phase C

- ABSL 18650LV: Performance Characterization







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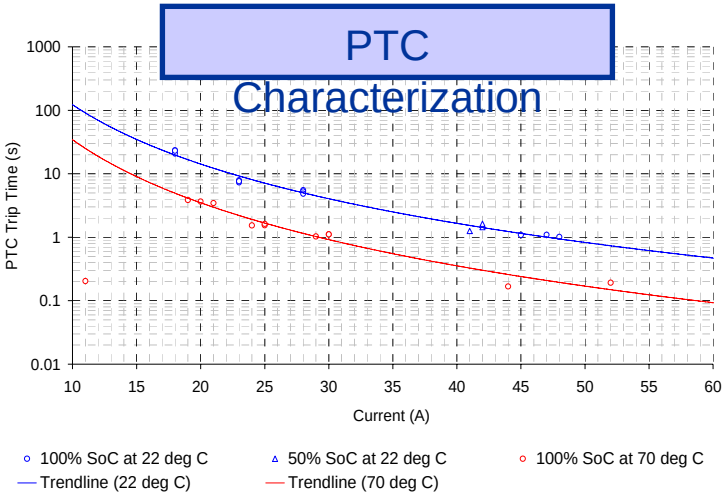
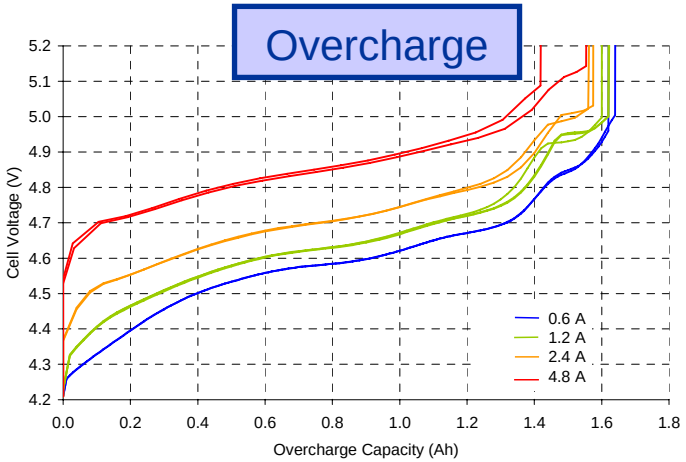
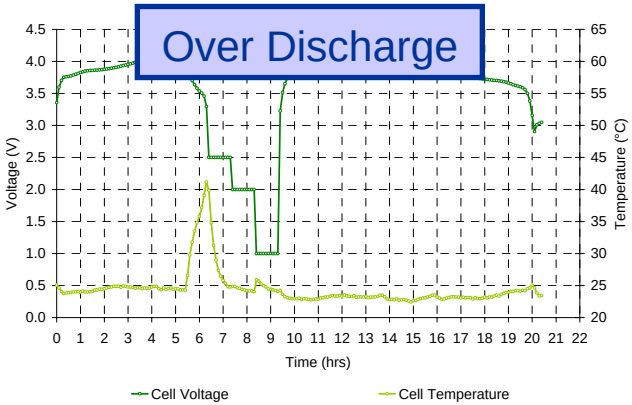
Next Gen Cells: Phase C

- ABSL 18650LV: Safety Testing







TV & Vibration & Safety testing is done – the key risk areas have been mitigated

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Next Generation Summary

ABSL SPACE PRODUCTS

- Currently ABSL has more than 140 COTS cells under investigation in Phase A.
- Approximately 10 COTS cells in are presently under going in-house testing in Phase B
- “Cell F” is about to graduate from Phase B to C
- The ABSL 18650LV has completed key portions of the qualification testing, and is ready for a mission!

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Questions?

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