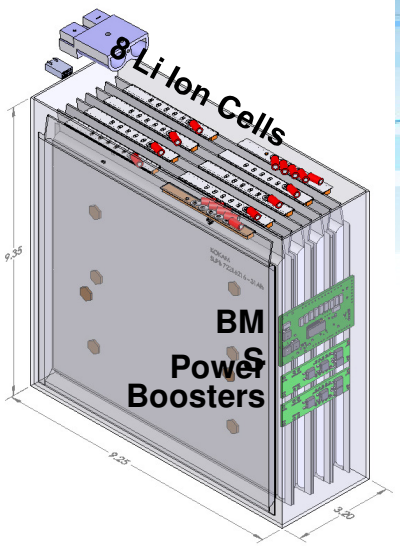
Pressure Testing SeaSafe Li-Ion Cells, Modules, and Systems – A Case History

SOUTHWEST ELECTRONIC ENERGY GROUP
Advanced Battery Solutions

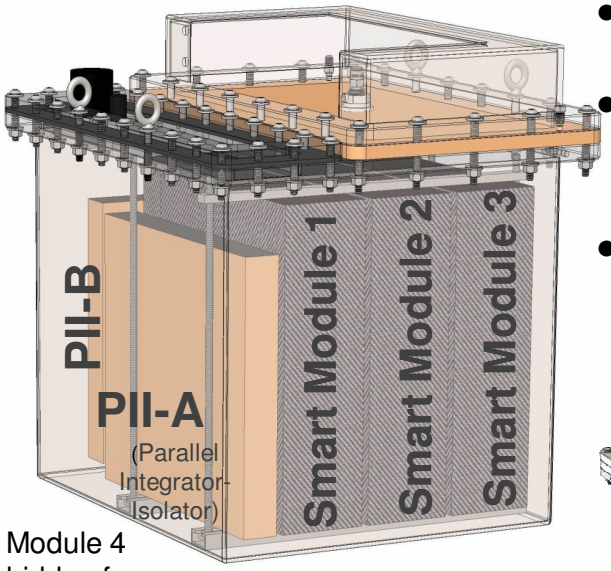
David White and Leon Adams

Southwest Electronic Energy Group

- Introduction to SWE SeaSafe
- SeaSafe Pressure Test History
- Details of 6 Most Recent Tests
- Future Test Plans
- Summary
- Acknowledgements



29V Smart Module
Internal View



Module 4 hidden from view

SeaSafe 4-Module System
Internal View

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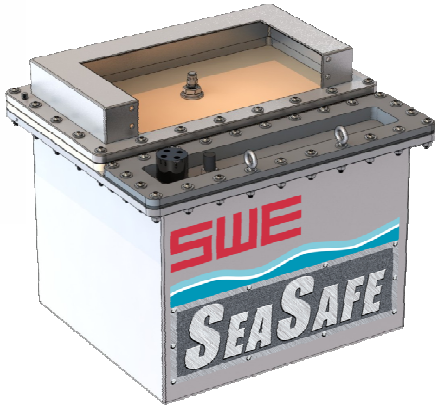
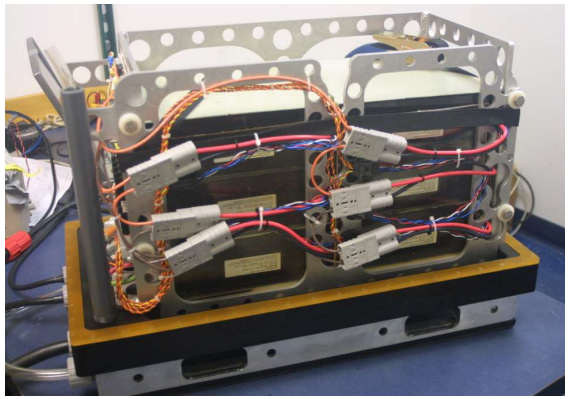
About SWE SeaSafe:

- Pressure Tolerant Autonomous Smart Module Building Block w/RS-485 Modbus Com Port.
- Std 29V Module w/8 Series, 31Ah Li-Polymer Cells.
- Smart Module w/All Best Practice BMS Functions.
- 4-Module Pressure Tolerant 316 Stainless Steel Battery System Building Block is Standard.
- Custom Battery Systems for AUVs, ROVs, & MUVs are Supported.





SeaSafe Test History

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Test	Description	PSI	Location & Date	Operator	Result
A	Lithium Polymer Cell - Korean	10,000	DSPL – 02/2010	DSPL	Passed
B	Lithium Polymer Cell - Korean	10,000	DSPL – 02/2010	DSPL	Passed
C	SeaSafe Lithium Polymer Module – 1 (Korean cells)	6,000	WHOI – 01/2013	WHOI	Passed
1	SeaSafe Lithium Polymer Modules – 4 (Korean cells)	10,000	SWRI – 02/2013	SWE/SWRI	Failed; ReDesign
2	SeaSafe Lithium Polymer Module – 1 (Korean cells)	10,000	SWRI – 05/2013	SWE/SWRI	Passed
3	SeaSafe Lithium Polymer Modules – 4 (Korean cells)	10,000	SWRI – 06/2013	SWE/SWRI	Passed
4	SeaSafe Lithium Polymer U.S. Cells	10,000	SWRI – 10/2013	SWE/SWRI	Passed
5	SeaSafe Lithium Polymer U.S. Cells	20,000	SWRI – 10/2013	SWE/SWRI	Passed

Test #C – WHOI Custom Battery System on 3D Video ROV

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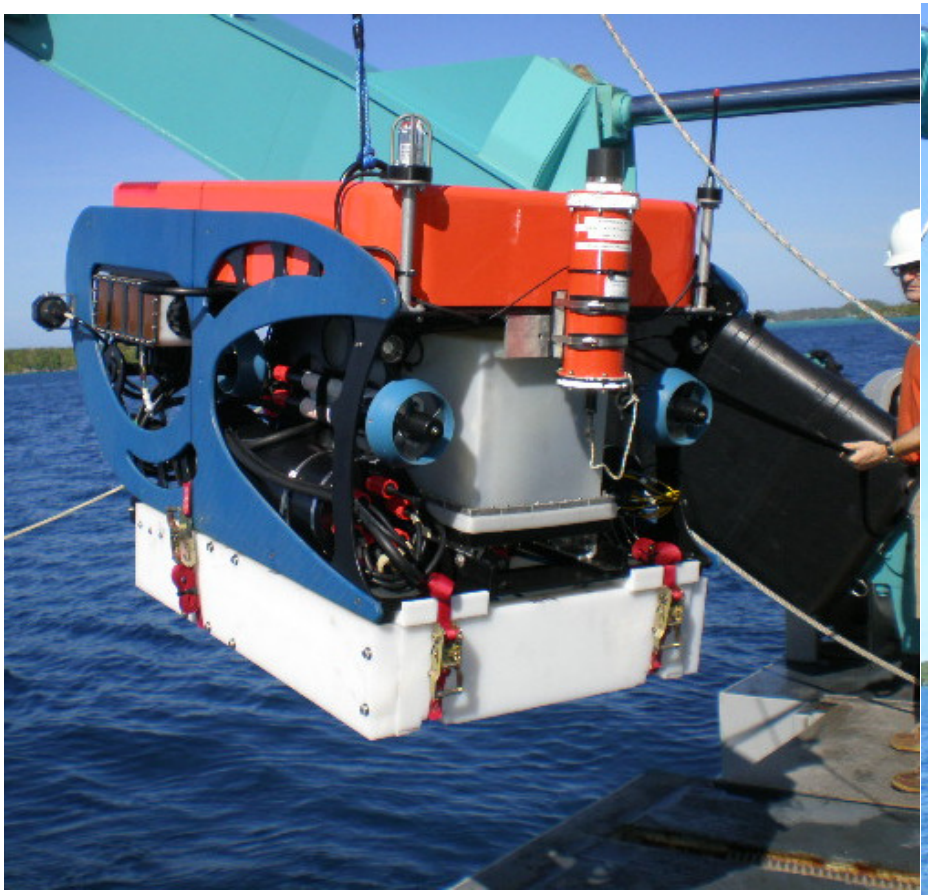
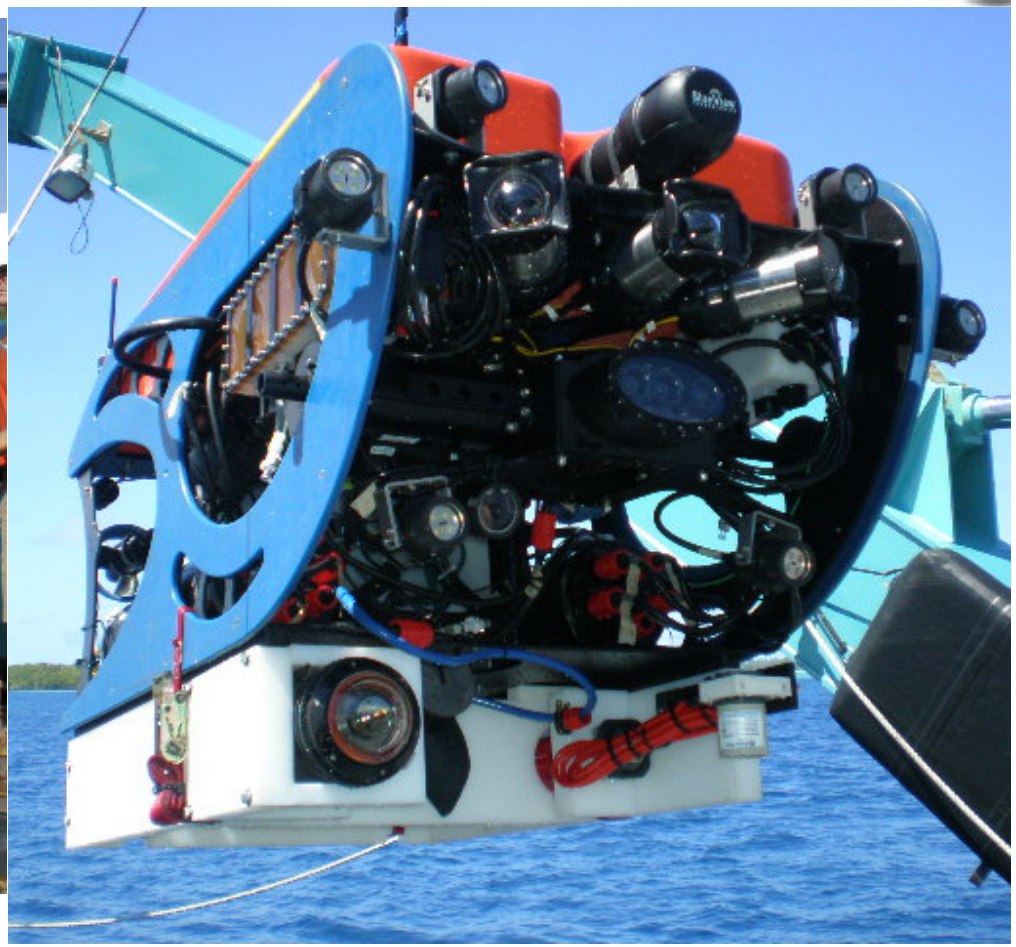


Rear of 3D Video ROV Shows Battery System in White Box at Center.



Front (Business End) of 3D Video ROV Shows Camera Lens and Light Sources. Battery Provides More Power Than the Tether Alone for this High Power Operation.

Test #1 – SeaSafe Case w/4 Battery Modules

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PURPOSE:

- Obtain Bulk Modulus of Compensation Fluid Thru 10,000psi
- Verify Functional Operation of Case & Modules Thru 10,000psi

PROCEDURE:

- Bulk Modulus Test First 2 Days - @ 23°C then @ 0°C
- Functional Tests & Cycle Tests of 4 Series Modules Next 2 Days

RESULTS:

- Thermal Run Away of One Module on 2nd Day of Tests (Other 3 modules failed safe)
- Thorough Failure Analysis of All 4 Modules
- Design Out Pressure Sensitive Component on BMS
- Improve Module Fail Safe Redundancy Design

Test #1 – Fluid Bulk Modulus Characterization Test Setup

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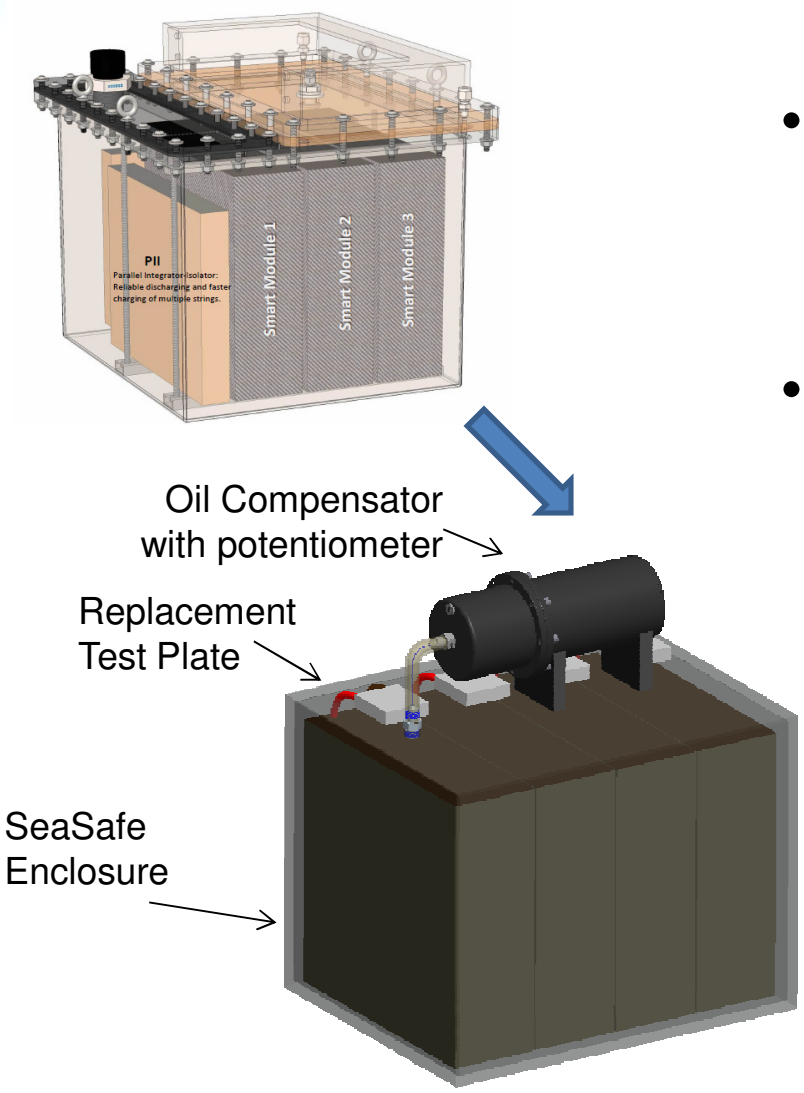

- Purpose:
  - Characterize the change in module volume as a function of Depth
- Approach
  - Replace SeaSafe Case Compartment Lid with a solid test plate with port fitting
  - Plumb fitting to instrumented compensator
  - Record compensation volume change as a function of depth at two temperatures (23℃ & 0℃)

Test #1 – Failure Analysis Highlights

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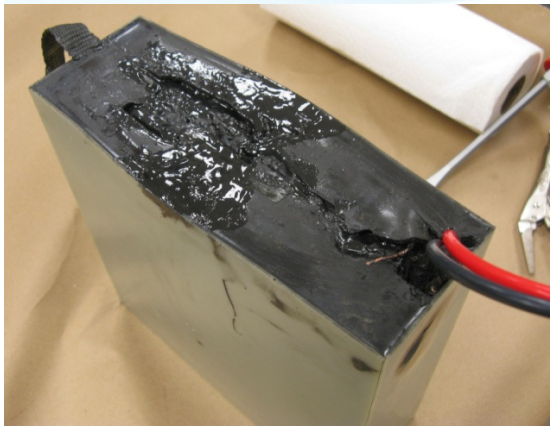
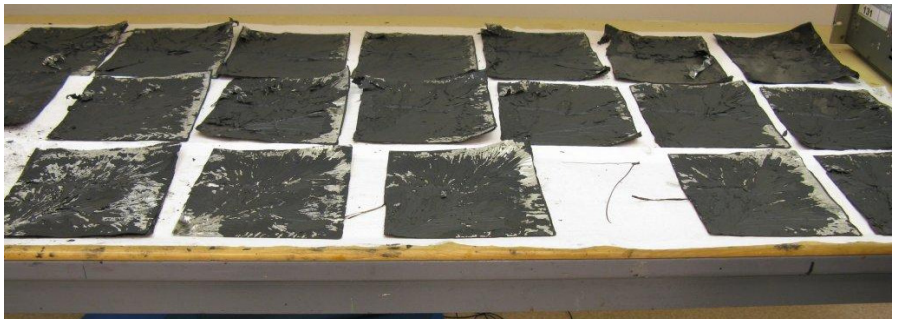
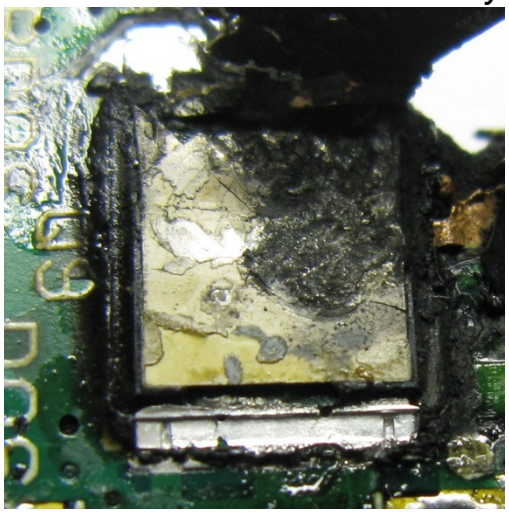


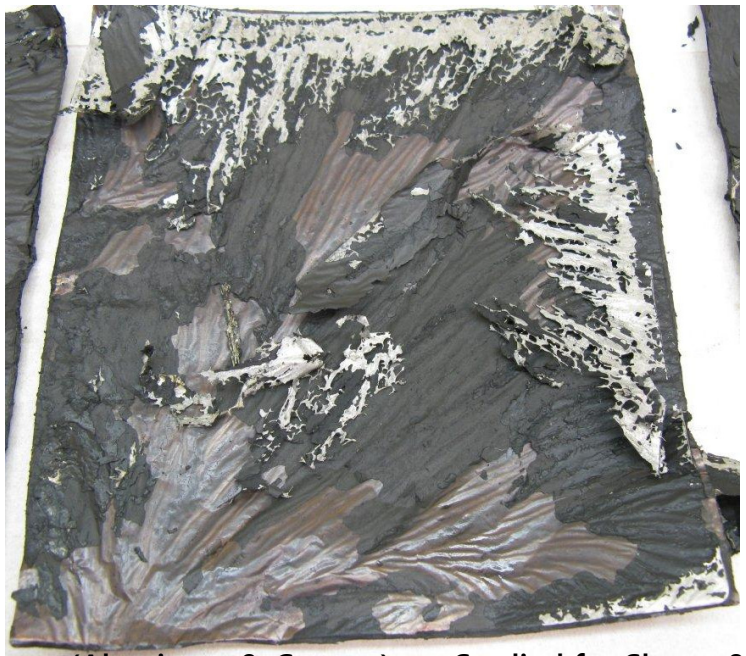
Component Failure => Intense Intermittent BMS Short w/All Cells Heating Simultaneously. Only one of 4 Modules Goes Into Thermal Runaway.



Module is Disassembled & dismantled. All Inside Layers of Each Cell (8 ea.) are Studied - Cell 7 is Shown.



Suspect Components on BMS are dismantled & Studied – This High Power Component Has Cracked From Exposure to High Pressure.



Current Collectors (Aluminum & Copper) are Studied for Shorts & Temp. Analysis.
NOTE: Aluminum Has Melted (660°C) but Copper (1085°C) has Not Melted.

Test #2 – SeaSafe Case w/1 Battery Module

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PURPOSE:

- Verify Functional Operation of Case & Redesigned Modules Thru 10,000psi @ 23°C.
- Verify Functional Operation After Multiple Pressure Cycles.

PROCEDURE:

- Step Test Chamber to 10,000psi – Discharge and Charge Battery Module at 10,000psi.
- Cycle Test Chamber Continuously from 60psi to 10,000psi while Continuously Discharging and Charging Battery Module.
- Characterize Module's Cells Before and After Pressure Test.

RESULTS:

- Battery Module Performed All CHG & DSG Functions @ 10,000psi
- Completed 9 Full Pressure Cycles w/CHG & DSG w/o any Failures.
- No Cell Damage Observed After Comparing Pre and Post Characterization of Cells That Had Undergone 9 Pressure Cycles.

Test #2 – Post Test Photo

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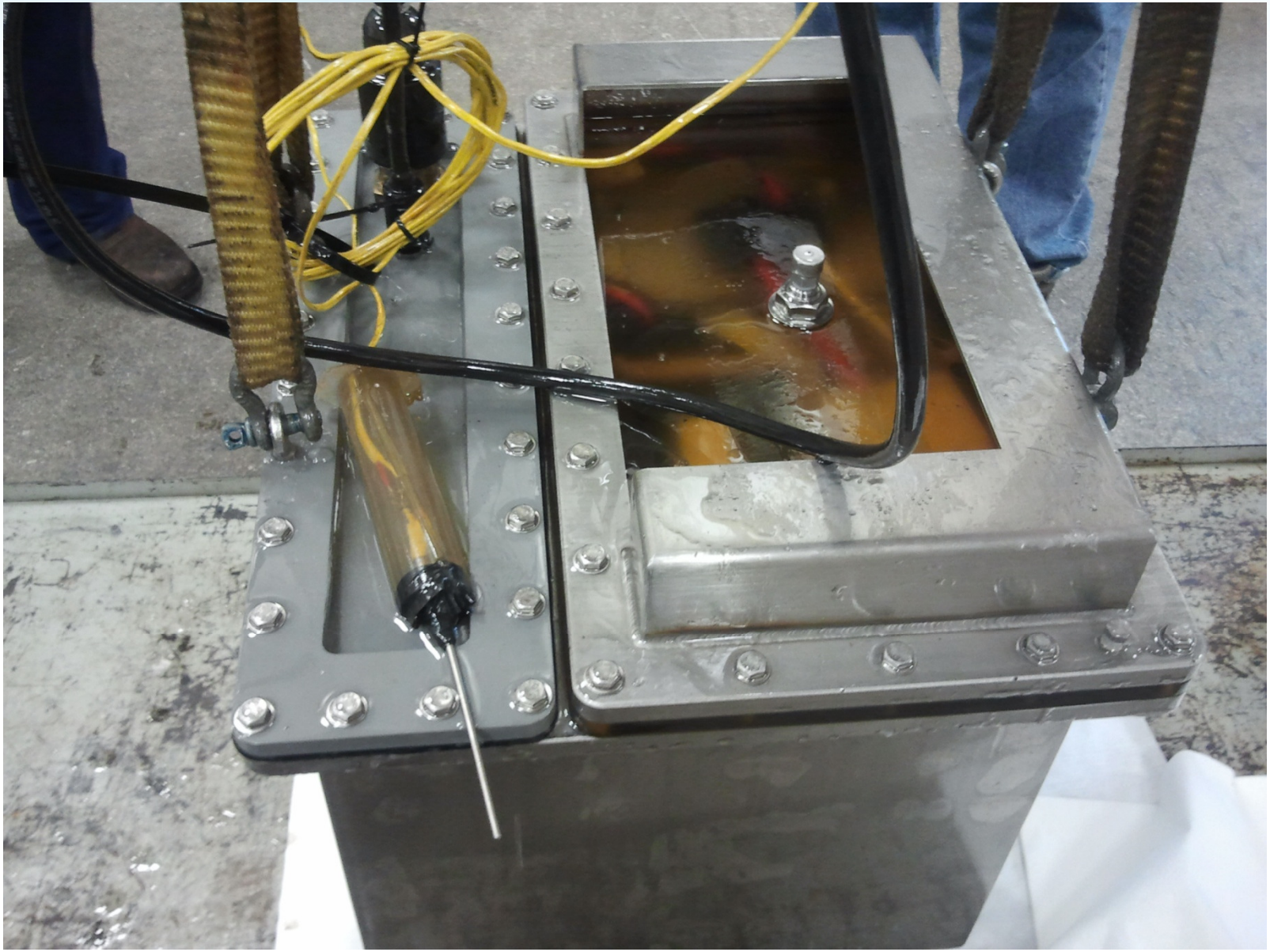

Test #3 – SeaSafe Case w/4 Battery Modules

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PURPOSE:

- Verify Functional Operation of Case w/4 Series Connected Modules & 1 High Voltage PII Thru 10,000psi @ 0°C.
- Verify Functional Operation of Utility (Single Module) & System (4 Simultaneous Modules) Software.
- Verify Functional Operation of System HW & SW After Multiple Pressure Cycles.

PROCEDURE:

- Step Test Chamber to 10,000psi – Discharge and Charge 4 Series Connected Battery Modules Thru PII at 10,000psi @ 0°C.
- Cycle Test Chamber Continuously from 60psi to 10,000psi while Continuously Discharging and Charging Battery System Thru PII @ 0°C.
- Characterize Module's Cells Before and After Pressure Test.

RESULTS:

- Battery System (4S Modules) Performed All CHG & DSG Functions @ 10,000psi
- Completed 9 Full Pressure Cycles w/CHG & DSG w/o any Failures.
- Noted That Continuous CHG & DSG Increased Cells' Temperature by about 10°C.
- No Cell Damage Observed After Comparing Pre and Post Characterization on Battery Module That Had Undergone 18 Full Pressure Cycles.

Test #3 – Pre Test Photos

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Full Instrumentation Prior to Pressure Testing Includes LVDT to Measure Equalization Bladder Depression w/pressure.

Measuring in-water weight of Battery System Prior to Pressure Testing.

Tests #4 & 5 – SeaSafe U.S. Manufactured Cells

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PURPOSE:

- Verify Lithium Polymer Cells (2 ea.) Manufactured in the U.S.A. Can Discharge and Charge at Both 10,000psi (Test 4) and at 20,000psi (Test 5)

PROCEDURE:

- Pot 2 U.S.A. Manufactured Cells and Place Them in a Bag Filled with Mineral Oil for Pressure Equalization. Discharge & Charge Cells at both 10,000psi (1st day Test 4) & 20,000psi (2nd day Test 5).
- Cycle Test Chamber from 60psi to 10,000psi (1st day Test 4) while Continuously Discharging and Charging Battery System. Repeat at 20,000psi (2nd day Test 5).
- Characterize Test Cells Before and After Pressure Tests.

RESULTS:

- U.S.A. Manufactured Cells Performed CHG & DSG Functions @ 10,000psi and @ 20,000psi Without Failure.
- After Initial CHG & DSG at Full Pressure Only One Subsequent Full Pressure Cycle w/Continuous CHG & DSG was Performed. Both Performed w/o Failure.
- No Cell Damage Observed After Comparing Pre and Post Characterization on U.S.A. Manufactured Cells That Had Undergone Both 10,000psi and 20,000psi Full Pressure Cycles.

Tests #4 & 5 – Photos Part 1

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Two Cells Bagged and Filled w/Mineral Oil Prior to Pressure Testing.

Pressure Test Chamber Able to Test Up to 30,000psi!

Tests #4 & 5 – Photos Part 2

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Cells Carried in Girl Scout Tote Bag Being Lowered Into Pressure Test Chamber.

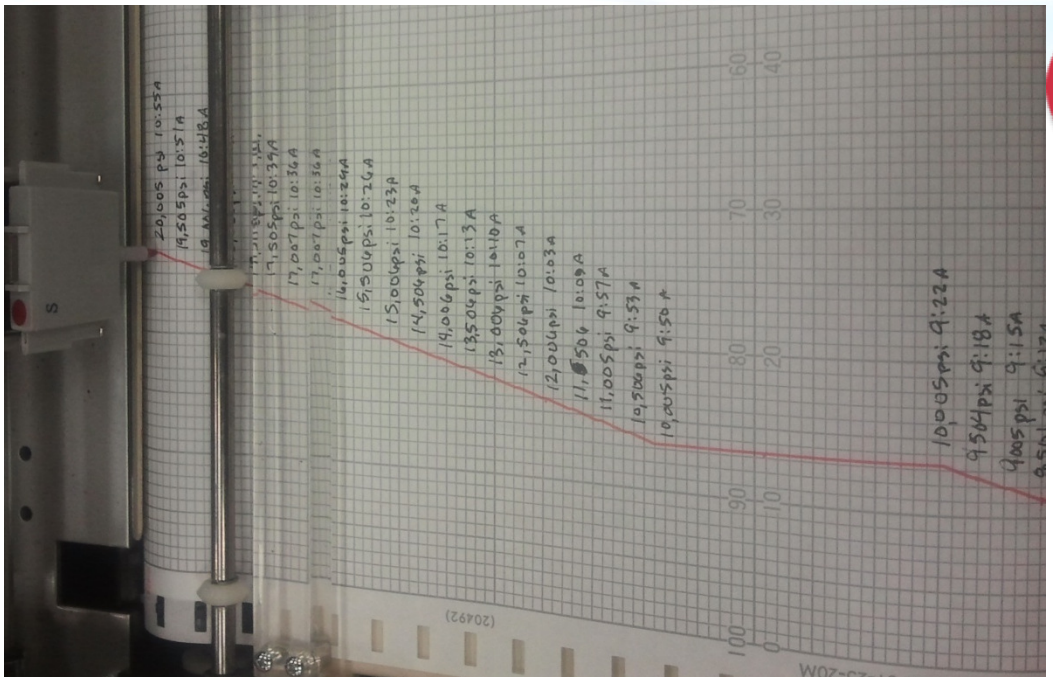

Chart of Pressure Going All the Way to 20,000psi.

Cells Look OK at Completion of Both 10,000psi Pressure Tests and 20,000psi Pressure Tests.

Other Validation Tests

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- Several Years of Design Validation & Continuous Improvement Design Over Multiple Similar Projects
- Extreme Custom Needs => Unique Designs w/ Validation
- UN DOT 38.3 Certification Test Completions
- ISO 13628-6 2006 Certification Test Completion

Potential Future Test Plans

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- Continuous Improvement Tests as Needs Arise
- Testing of BMS 20,000 psi
- Testing Smart Battery Module to 20,000 psi
- Testing Battery System(s) to 20,000 psi
- Testing on Alvin or Other MUV/HOV
- 3rd Party Tests/Certs As Required
  - ABS, LR, BV, DNV, GL, NK, RS, etc.
  - Navsea
- Testing Custom Battery System Designs to Meet Challenging New Requirements

Summary

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- 4 Yrs Cell, Module, & System Li-Ion Pressure Tests
- Multiple Pressure Test Houses
- 3rd Party & Partner Pressure Testing
- Continuous Improvement via Pressure Test to Failure
- Design Validation via Pressure Test Successes
- Testing Beyond Immediate Needs (i.e., 20,000 psi)
- Complementary Internal & 3rd Party Lab Testing
- Validation Thru Broad Experience & Unique Challenges

Acknowledgement

SOUTHWEST ELECTRONIC ENERGY GROUP
Advanced Battery Solutions

THE AUTHORS WOULD LIKE TO THANK
DANIEL GOMEZ-IBANEZ WITH
WOODS HOLE OCEANOGRAPHIC INSTITUTION
FOR COLLABORATION IN DEVELOPING,
PRESSURE TESTING, AND IN-WATER TESTING
SWE SEASAFE LITHIUM-ION BATTERY SYSTEMS

Extensive Testing and Certification

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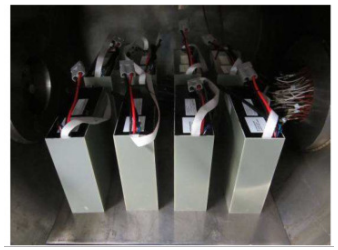
International Shipping Safety Certified - UN Manual of Test and Criteria Section 38.3

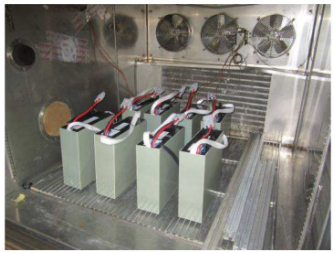
RESULT SUMMARY: The tested samples met the test requirements. See below breakout for tests performed.

Specification Section	Test Description	Results
T1	Altitude Simulation	Conforms
T2	Thermal Test	Conforms
T3	Vibration	Conforms
T4	Shock	Conforms
T5	External Short Circuit	Conforms
T7	Overcharge	Conforms

T1 – Altitude Simulation Test



T2 – Thermal Test

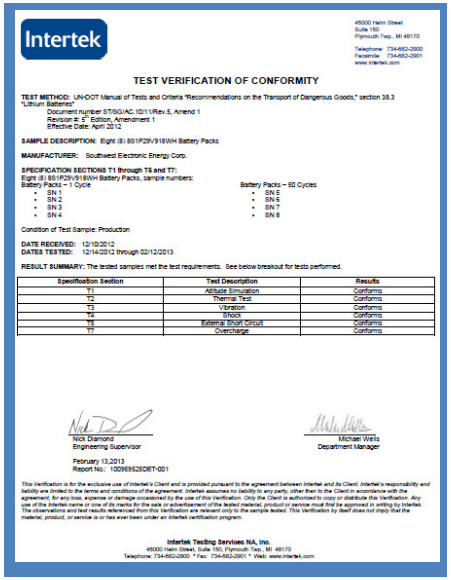


T1

T2

T5 – External Short Circuit

T5



Intertek

TEST VERIFICATION OF CONFORMITY

TEST METHOD: UN-DOT Manual of Tests and Criteria "Recommendations on the Transport of Dangerous Goods," section 38.3 "Lithium Batteries"
Document number ST/SG/AC.10/11/Rev.5, Amend 1
Revision # 5th Edition, Amendment 1
Effective Date: April 2012

SAMPLE DESCRIPTION: Eight (8) 8S1P29V918WH Battery Packs

MANUFACTURER: Southwest Electronic Energy Corp.

SPECIFICATION SECTIONS T1 through T6 and T7:
Eight (8) 8S1P29V918WH Battery Packs, sample numbers:
Battery Packs – 1 Cycle
- SN 1
- SN 2
- SN 3
- SN 4

Battery Packs – 50 Cycles
- SN 5
- SN 6
- SN 7
- SN 8

Condition of Test Sample: Production

DATE RECEIVED: 12/10/2012
DATES TESTED: 12/14/2012 through 02/12/2013

RESULT SUMMARY: The tested samples met the test requirements. See below breakout for tests performed.

Specification Section	Test Description	Results
T1	Altitude Simulation	Conforms
T2	Thermal Test	Conforms
T3	Vibration	Conforms
T4	Shock	Conforms
T5	External Short Circuit	Conforms
T7	Overcharge	Conforms

Nick Diamond
Engineering Supervisor

Michael Wells
Department Manager

February 13,2013
Report No.: 100969626DET-001

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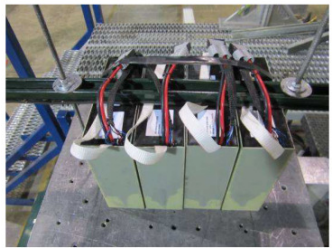
T3 – Vibration Test

T4 – Shock Test



T3

T4

T7 – Overcharge

T7

Extensive Testing and Certification

- **Design of Subsea Equipment standard (ISO 13628-6:2006) relevant to Batteries**
  - Testing per ISO 13628-6 2006
    - Shock per section 11.2.5.2.1 method Q2. Sinusoidal
    - Vibration per section 11.2.5.2.2 method Q2. Random

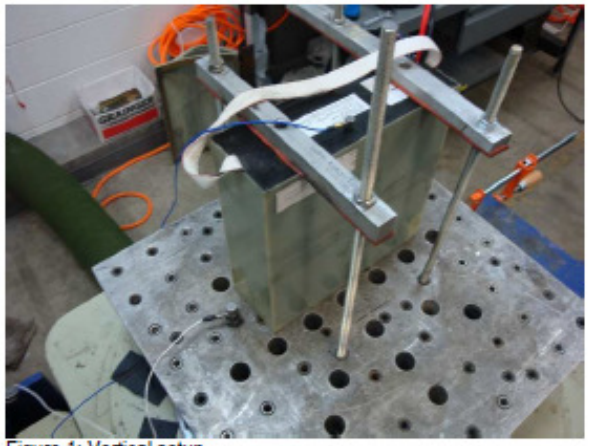
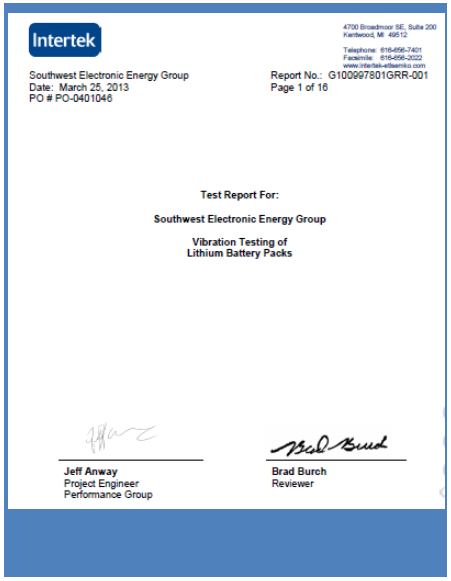


Figure 1: Vertical setup.



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Southwest Electronic Energy Group
Date: March 25, 2013
PO # PO-0401046

Report No.: G100997501GRR-001
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Test Report For:

Southwest Electronic Energy Group

Vibration Testing of
Lithium Battery Packs

Jeff Anway
Project Engineer
Performance Group

Brad Burch
Reviewer

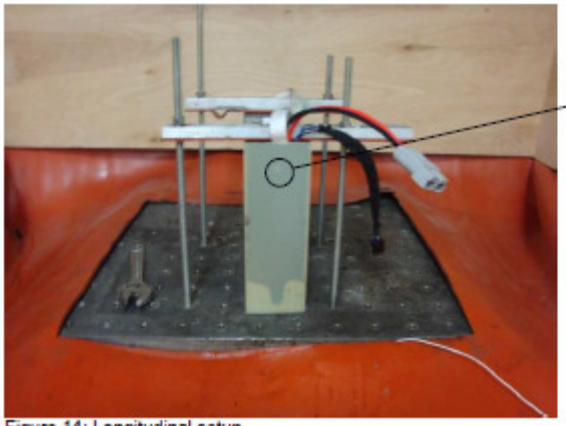

Figure 14: Longitudinal setup.

Backup- UN DOT 38.3 Tests

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Table 3. UN transportation tests

UN 38.3.4.1	Test T.1 – Altitude Simulation		Cells and batteries stored at a pressure of 11.6 kPa or less for at least six hours at ambient temperature
UN 38.3.4.2	Test T.2 – Thermal Cycling		Rapid thermal cycling between high- (75°C / 167°F) and low- (-40°C / -40°F) storage temperatures
UN 38.3.4.3	Test T.3 – Vibration		Vibration exposure: sinusoidal waveform with a logarithmic sweep from 7 Hz (1 g peak acceleration) to 200 Hz (8 g peak acceleration) and back to 7 Hz; 12 cycles, 3 perpendicular mounting positions
UN 38.3.4.4	Test T.4 – Shock		Shock exposure: half-sine shock, 150 g peak acceleration, 6 msec pulse duration, three shocks in positive and negative directions for each of three perpendicular mounting positions (total of 18 shocks)
UN 38.3.4.5	Test T.5 – External Short Circuit		Short circuit of less than 0.1 ohm at 55°C (131°F), 1 hour duration
UN 38.3.4.6	Test T.6 – Impact	N/A	15.8 mm diameter bar placed across cell center, and a 9.1 kg mass is dropped onto the bar from 61 cm height
UN 38.3.4.7	Test T.7 – Overcharge		Over current (2X manufacturer's recommended maximum) and over voltage (for 18 V packs or less, charge to the lesser of 22 V or 2X recommended charge voltage. For > 18 V packs, charge to 1.2X recommended charge voltage) charge (applied to battery packs only)
UN 38.3.4.8	Test T.8 – Forced Discharge	N/A	Over-discharge cells a single time