

Technical Overview of a Safe, Configurable, Pressure Tolerant, Subsea Lithium Ion Battery System for Oil and Gas Deep Water Fields

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A growing trend in efforts to build more effective and efficient subsea chokes, completion and work-over control systems, and marine well containment systems in oil and gas deep water fields is to replace hydraulics with electrical drives. Electrical drives have advantages such as faster, smoother, and more precise valve control, including real-time feedback on valve position and performance. However, such electrical driven valves require higher peak electrical power to operate than one can effectively supply via a cable when the valve is thousands of meters below the surface of the sea. Local batteries deployed subsea near the valves and subsea control modules can serve the peak power needs, or even backup power needs. But heretofore the classic sealed lead acid battery technology of 1900 is too heavy, too big, and does not last long enough to make these solutions as practical or efficient as desired.

The subsea Oil and Gas deep water field equipment industry needs battery solutions that deliver more electrical capacity at less weight and smaller size than old technology sealed lead acid ("SLA"). They want to tap what battery industry expert Cerina Mikolajczak from Tesla Motors calls the "awesome Lithium-Ion technology" advantage [1], such as four times (4X) the energy density of SLA, yet the batteries need to be safe, reliable, and easy to use in subsea deployment. Also, achieving configurable size and capacity flexibility, long lasting subsea operating life, subsea pressure tolerance, and pre-certified testing for subsea oil and gas standards and international shipping standards are very important. Further, saving project execution time and cost by avoiding custom battery development is preferred. So this is not just an ordinary battery at all. These needs are summarized below and in also in Table 1.

Meeting these needs challenged the Southwest Electronic Energy Group ("SWE") R&D team to create SWE SeaSafe™, a safe, modular, flexible and reliable battery system leveraging unique safety and reliability features derived from years of intensive research and industry lessons learned.

SWE SeaSafe Lithium-Ion batteries deliver longer life and longer missions than lead acid:

- Four times (4X) more energy
- Six times (6X) more available energy at colder temperatures typical of the seabed.
- Eight times (8X) longer cycle life.

SWE SeaSafe Lithium-Ion is as safe as SLE and is more reliable than SLA batteries:

- Lithium-Ion does not outgas during charge. SLA does.

- SWE incorporates smart, automatic, autonomous battery management in each battery module that is constantly watching, balancing, and preventing charging and discharging errors. SLA does not.
- SWE SeaSafe provides health and status reporting on demand. Most SLA batteries leave you guessing.

These benefits provide a superior solution for subsea applications, such as

- Longer operating life for deep sea oil and gas infrastructure electronics, lights, and backup
- Safer, longer lasting missions for MUVs.
- Lighter weight and local instant power for ROVs.
- Deeper dives and longer missions for AUVs.

Li Ion is Superior for Modern Subsea Apps			LI ION BREAKTHROUGHS
App		Need	
Deep-Sea Oil & Gas Infrastructure		• Electronic control – Primary and back-up • Longer life • More reliable	
MUV (Manned Underwater Vehicle)		• Safe operation • Deeper dives • Longer observation times • Lighter weight	
ROV (Remotely Operated Underwater Vehicle - Hybrid & Untethered)		• Electric powered manipulators • Local energy/power • Lighter weight	
AUV (Autonomous Underwater Vehicle)		• Longer survey runs • Deeper dives • Lighter weight	

Li Ion Breakthroughs vs Sealed Lead Acid

- 4X more capacity
- 8X longer cycle life
- 1/4X weight
- 6X more usable capacity @ seabed temperatures

Table 1. Subsea Applications That Could Benefit From Lithium-Ion Batteries

Subsea Oil and Gas Completion and Work Over Control Systems Battery Requirements

While Woods Hole Oceanographic Institute (WHOI) provided requirements guidance and feedback on the SeaSafe modules to meet their world leading subsea vehicle pressure tolerant battery needs, let's take a closer look at how these modules are also designed to fully address the demanding requirements of subsea Oil and Gas completion and work over systems that are going to remain operating for years on the ocean floor. For this reason, typical generic requirements of such completion and work over systems drive extra robustness and certifications and are highlighted in Table 2.

Oil and Gas Subsea Completions and Work-over Control Systems BATTERY REQUIREMENTS	SWE SeaSafe BATTERY MODULE DELIVERS
⊙ Safe, Reliable Operation ⊙ Pressure tolerant to 3000 m sea depth ⊙ Voltage range From 24 Volts ⊙ Voltage range To 360+ Volts ⊙ High Current (power) ⊙ 100 recharge cycles ⊙ Discharge Temperature: -20C to +50C ⊙ Charge Temperature: 0C to 60 C ⊙ Subsea chargeable ⊙ Protection and balancing internal ⊙ Diagnostic information logged externally ⊙ Battery Status software with GUI preferred ⊙ International Shipping Safety certified (UN DOT 49CFR 173.185) ⊙ Design of Subsea Equipment standard compliant (ISO 13628-6:2006) ⊙ High Quality Manufactured ⊙ Rugged Case such as 316 Stainless Steel	⊙ Patented BMS for Top Safety, Reliability ⊙ Pressure tolerant to 6000 m sea depth ⊙ 24V Module X 1Series = 24 Volts ⊙ 29V Module X 12 Series ≈ 350V ⊙ 40 A continuous Current, 90 A pulse ⊙ 1000+ recharge cycles ⊙ Discharge Temperature: -40C to + 85C ⊙ Charge Temperature: -2C to 60C ⊙ Subsea chargeable ⊙ SWE BMS: Internal protection, balancing ⊙ SWE BMS: Modbus access to battery status on demand, log external; CANbus optional interface ⊙ SeaSafe Observer battery status software with GUI ⊙ International Shipping Safety certified (UN DOT 49CFR 173.185) ⊙ Design of Subsea Equipment standard compliant (ISO 13628-6:2006) to Battery relevant tests (shock) ⊙ ISO9000-2008 Quality Compliant ⊙ Rugged 316 Stainless Steel Case

Table 2. Subsea Battery Requirements Delivered by SeaSafe Battery Modules

More Details on SeaSafe Subsea Battery Solutions

SeaSafe battery solutions are implemented in two commercial off-the-shelf battery product configurations with support software to monitor and maintain these battery solutions.

These are:

- SWE SeaSafe Smart Battery Modules, which are easy to use Lithium-Ion battery module building blocks,
- SWE SeaSafe Battery System, a pressure tolerant battery system constructed using a pressure equalization case designed to hold 4 SeaSafe Modules with Parallel Integrator Isolators (“PIIs”),
- SeaSafe Observer, a PC based status software to monitor the health and status of battery modules and/or systems.

Subsea Battery Modules

The SeaSafe Smart Battery Module shown in Figure 1 is the heart of the solution. They are available in a 29 Volt @ 28 Ah size or a 24 Volt @ 28 Ah size. The modules are based on industrial grade long lasting Lithium-Ion polymer cells. Safety, reliability, flexibility, and ease of use are achieved because each and every module has its own, built-in autonomous Battery Management System (“BMS”) with SWE patented safety protection. No external connections or controls are required to manage critical safety features. Multiple modules can be connected in series for total battery system voltage and/or parallel for total battery system amp-hour capacity. Modules are specified and are tested pressure tolerant to 6,000meter sea depth. Maximum State-of-Charge (“SOC”) is configurable and is managed by the BMS to optimize extended operating life of up to 15 years. Charge is provided by off-the-shelf constant voltage/constant current power supplies. The module enclosure is fiberglass. It is filled with thermally conductive, flame retardant polyurethane potting material. In addition to its thermal benefits, the potting material also dampens shock and vibration. The modules can be configured in customer designed cases or within a SWE supplied SeaSafe battery case. Summary specifications for the SWE SeaSafe Battery Module are shown in Table 3.



Figure 1. SeaSafe Module

		SeaSafe Modules	
		29V	24V
Cells in series		8	7
Dimensions (in)	H	9.4	9.4
	W	3.2	3.2
	L	9.3	9.3
Weight (lbs)	Total Module (air)	20.0	20.0
	Total Module (sea)	9.7	9.7
Voltage (V)	Min	24	21
	Nom	29	25
	Max	32	28
Current (A)	Max Dschg (continuous)	40	40
	Max Dschg (30s pulse)	75	75
	Max Dschg (1s pulse)	90	90
Power (W)	Dschg (nom)	1160	1015
Capacity @ 90% SOC	Ah	28	28
	Wh	812	711

Table 3. SeaSafe Module Specifications

The SeaSafe Module has been UN DOT International Shipping certified to UN DOT 49CFR 173.185. Also, SeaSafe meets the design of Subsea Equipment standard compliant (ISO 13628-6:2006) in the battery relevant shock tests.

Subsea Battery Systems

SWE SeaSafe Battery Systems are built with SeaSafe battery modules installed in a SWE designed, subsea ready, pressure equalized case. Up to four SeaSafe modules can be configured-to-order within one case in a series/parallel combination of modules to meet voltage and amp-hour capacity needs, delivering up to 132 Volts or 112 Amp hours maximum. Multiple cases can be stacked and connected to increase voltage and/or amp-hour capacity. The system is pressure tolerant down to a 6,000meter sea depth. The pressure equalized case is built rugged from 316 stainless steel and incorporates Seacon Wet-Con connectors standard with ODI and others optional. The 316 stainless steel case has a translucent urethane bladder, that equalizes the pressure of the ocean depth with the battery modules that are immersed within the case in pressure compensation oil. The case holds 1 to 4 SeaSafe Smart Modules, 1 to 4 PIIs, and is pressure validated down to 6000 meter depth. The dimensions are 14.8" x 15.6" by 17.8". Multiple cases can be connected in series and parallel to increase voltage and/or increase amp hour capacity of the battery system beyond the single case maximum of 132 Volts or 112 Amp hours.

When SeaSafe battery modules are connected in a series string, many autonomous safety features are redundant, thus increasing reliability. For example, if one string of two series connected modules is accidentally shorted, both modules are monitoring the shorting current and there are two opportunities for the short to be autonomously interrupted. Although not required, we recommend the SeaSafe Parallel Integrator Isolator ("PII") be used when the battery system has parallel strings of modules or cases. The PII is an "ideal" diode ORing circuit, and enables increase in battery system amp-hour capacity with redundancy. If one string should fail, other parallel strings will continue to function normally, thus increasing system reliability. The PII also allows faster charging of multiple strings and isolates multiple strings during discharge thereby preventing potential high current discharge from one parallel string into another. One PII is used with each module string connected in parallel. PIIs are not needed for single string configurations. PIIs dissipate over an order of magnitude less heat at high current than the typical diode ORing circuit because actual diodes are replaced with "ideal" diodes.

Intelligent Battery Management System

The brains of the SWE SeaSafe battery modules and systems are a patented, autonomous intelligent battery management system (BMS) with a unique suite of safety and reliability features. The BMS assures safe operation, protect the module's cells from damage, allows a more reliable distributed battery system architecture, and prolongs cell life. There are numerous, autonomous safety and reliability features in the SeaSafe BMS as follows:

- 1) Three types of intra and inter-module balancing to assure cell safety and reliability,
- 2) Patent pending algorithms to detect internal cell shorts to notify and/or prevent failures that might lead to a cell's going into thermal runaway,
- 3) Algorithms to prevent formation of metal dendrites subsequent to copper dissolution ,
- 4) Configurable, autonomous control of charge level within each battery module to extend battery cycle life and safety,
- 5) Thermal control of cells and modules to assure battery safety and extend operating life,
- 6) Short circuit fuse protection for safety redundancy should BMS electronics fail, and
- 7) Classic Lithium Ion safety features that are configurable to your application and mission.

These include custom thresholds for:

- Over and under voltage detection and prevention
- Excessive charge and discharge current detection and prevention
- Ensuring charge is allowed only within the temperature window defined by the cell specification.
- Ensuring discharge occurs only within the temperature window specified by the customer's mission requirements.
- Detecting and preventing short circuits

- Allowing high current pulse discharge to prevent nuisance power interruption.

Robust Battery System Packaging to Stand Up to the

Ocean and Handling

SeaSafe Battery Systems are built with smart battery modules installed in a subsea ready pressure equalized case.

The pressure equalized case is built rugged. The body is constructed from 316 stainless steel known for its superior corrosion resistance and its thermal properties to dissipate any heat from within the battery modules to the ocean. It incorporates a rugged glass infused plastic connector plate that is fitted with Seacon Wet-Con connectors standard, or with ODI or other connectors of choice. The SeaSafe battery case is shown in Figure 2.

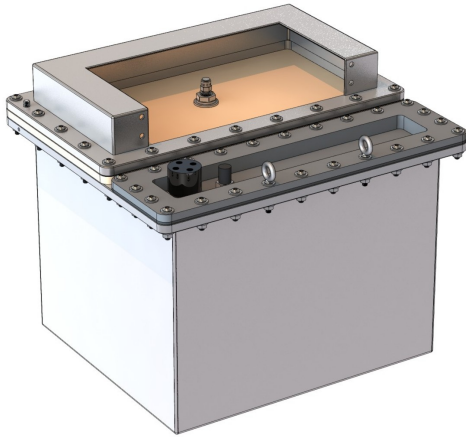


Figure 2. SeaSafe Pressure Equalized Case

The transparent view of the case in Figure 3 shows the battery systems holds up to four Smart Modules configured to order in any series/parallel combination to meet voltage and amp-hour capacity needs. Each system delivers up to one hundred thirty volts or one hundred twelve amp-hours maximum, with one, two, three or four Smart Modules in series to achieve voltage and in parallel to achieve amp-hour capacity.

Examples shown in Figures A, B, C illustrate voltage and amp-hour capacity combinations of four twenty-nine volt modules in a SeaSafe Battery System.

System A in Figure <number> shows four modules in series for one hundred and sixteen volts and twenty-eight amp-hours.

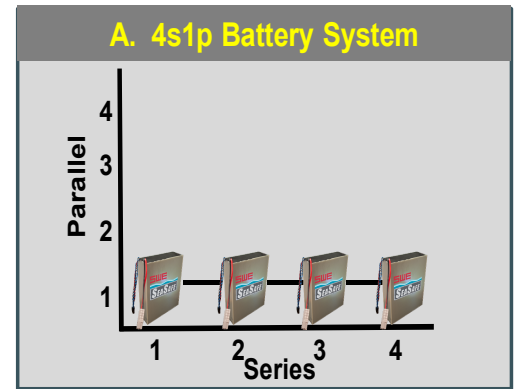


Figure A. System A - 4s1p Battery System

In System B shown in Figure B, all four modules are connected in parallel delivering twenty-nine volts and one hundred twelve amp-hours.

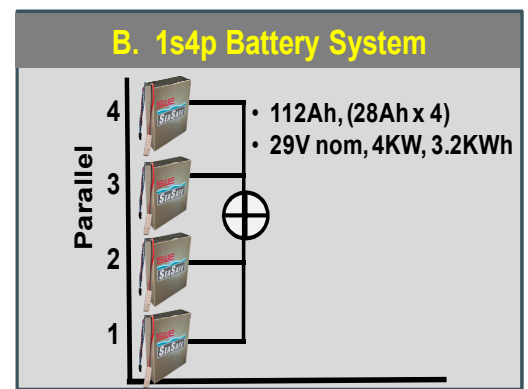


Figure B. System B - 1s4p Battery System

For the System C example shown in Figure C there is a combination of two modules in series and two in parallel providing fifty-eight volts and fifty-six amp-hours of capacity.

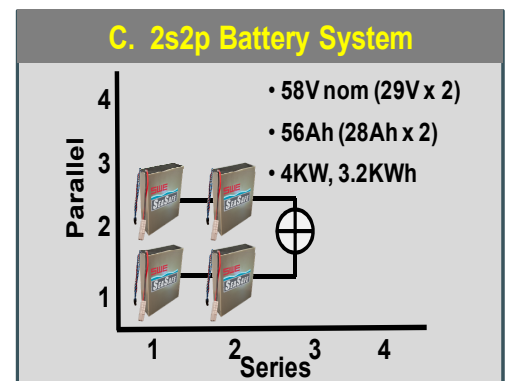


Figure C. System C - 2s2p Battery System

All the systems are pressure tolerant down to a six thousand meter sea depth.

Also included in the case is room for two Parallel Integrator Isolators, or PIIs.

Such modularity enables these systems to feature low repair times. If needed, modules can be replaced anywhere in the system, easing maintenance.

Extensive Test to meet the subsea needs

The photo in Figure 5 shows the SeaSafe battery system in the 316 stainless steel case being lowered into a pressure chamber to undergo hyperbaric pressure testing at Southwest Research Institute (“SWRI”). The exhaustive hyperbaric pressure test conducted in the 30 inch hyperbaric chamber at the SWRI test laboratory included nine complete pressure cycles up to 10,000 psi and back down to zero psi while continuously performing live charge and discharge cycles. The 10,000 psi pressure provides for 6000 meter sea depth pressure plus margin. The pressure test was preceded by exhaustive functional testing and a sophisticated external shorts test validating the module automatically shuts off safely for currents in excess of 90 amps.

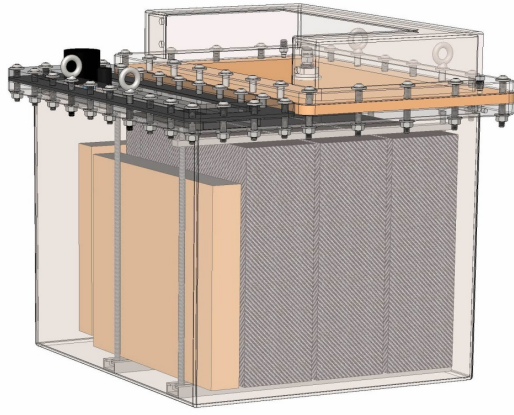


Figure 3. SeaSafe Pressure Equalized Case Transparent View

Battery system scale is not limited to a single four module battery system. Battery cases can be stacked to configure much higher voltage, higher Amp-hour capacity, and higher power battery systems for massive power backup or other substantial requirements.

The diagram in Figure 4 illustrates a larger 64 module battery system. A system of this scale provides high voltage, high capacity, high power, and ample redundancy.

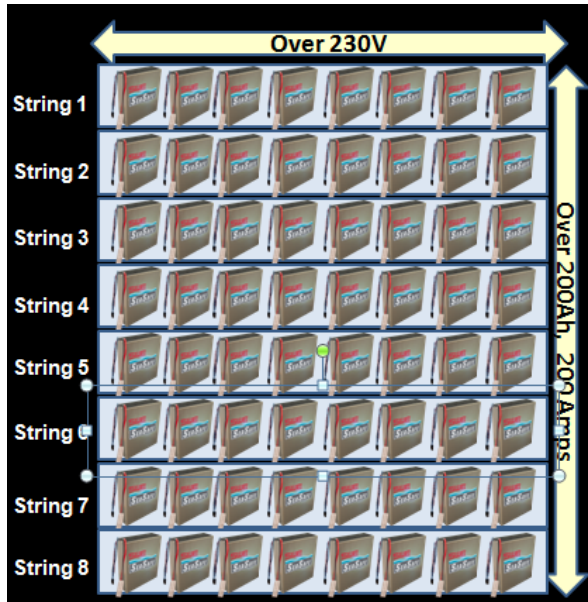


Figure 4. 8S8P Battery System Diagram

The 64 battery modules are configured in eight parallel strings. Each string has eight twenty-nine volt Smart Modules in series. The system delivers over two hundred thirty volts, two hundred amp-hours of capacity and two hundred amps of current. This system will keep running at reduced capacity if one or more strings go down allowing the mission to continue.



Figure 5. SeaSafe Case Being Lowered Into Pressure Test Chamber

Observing Battery Status Real Time or Post Mission

Both SeaSafe products (modules and subsea ready battery systems) are supported by SeaSafe Observer, a PC based health and status monitoring software package with a graphical user interface.

SeaSafe Observer PC software is a useful support software tool to monitor the status of SeaSafe Smart Modules or SeaSafe Battery Systems. In fact, it was utilized to monitor the battery systems and collect status data during the battery system pressure tests previously described. Battery status checks can be run after the mission is completed and/or real-time during the mission, whichever is appropriate for your objective. It should be noted that real time monitoring and an active communications link are for mission information purposes only, and are not required for autonomous safe, reliable battery operation.

SeaSafe Observer delivers status at three levels based on your needs:

- Multiple SeaSafe Battery System cases connected together,
- Single SeaSafe Battery System case, or
- Module Level when multiple SeaSafe Battery modules are in a custom configuration.

Observer delivers status to users with a user-friendly GUI (graphical user interface) or raw .csv file format for time-log storage and creation of custom reports. The GUI features a simple red/yellow/green stoplight letting operators know at a glance if the battery is in good operating condition, simply needs a charge, or requires maintenance to be scheduled. An easy-to-read dashboard of gauges provides amp-hour capacity, voltage, temperature, current, and alert messages. Communications bus and protocol are RS485/MODBUS. Real-time monitoring, an active communications bus, and manual intervention are not needed for safe operation of SeaSafe Modules and Battery Systems.

The SeaSafe Module Observer window and dashboard provides System Observer type information, but drilled down specific to a single Module within the system. In the screenshot example shown in Figure 6, module id 8 which is part of a 6 series, 1 parallel battery system is queried. The numbered references as shown in the diagram and described in Table 4 show the detailed status information available and associated with module id 8. It is noteworthy that you can pop up and drill back down on any one of the 6 modules and get a similar but unique status reporting or “observer” page.

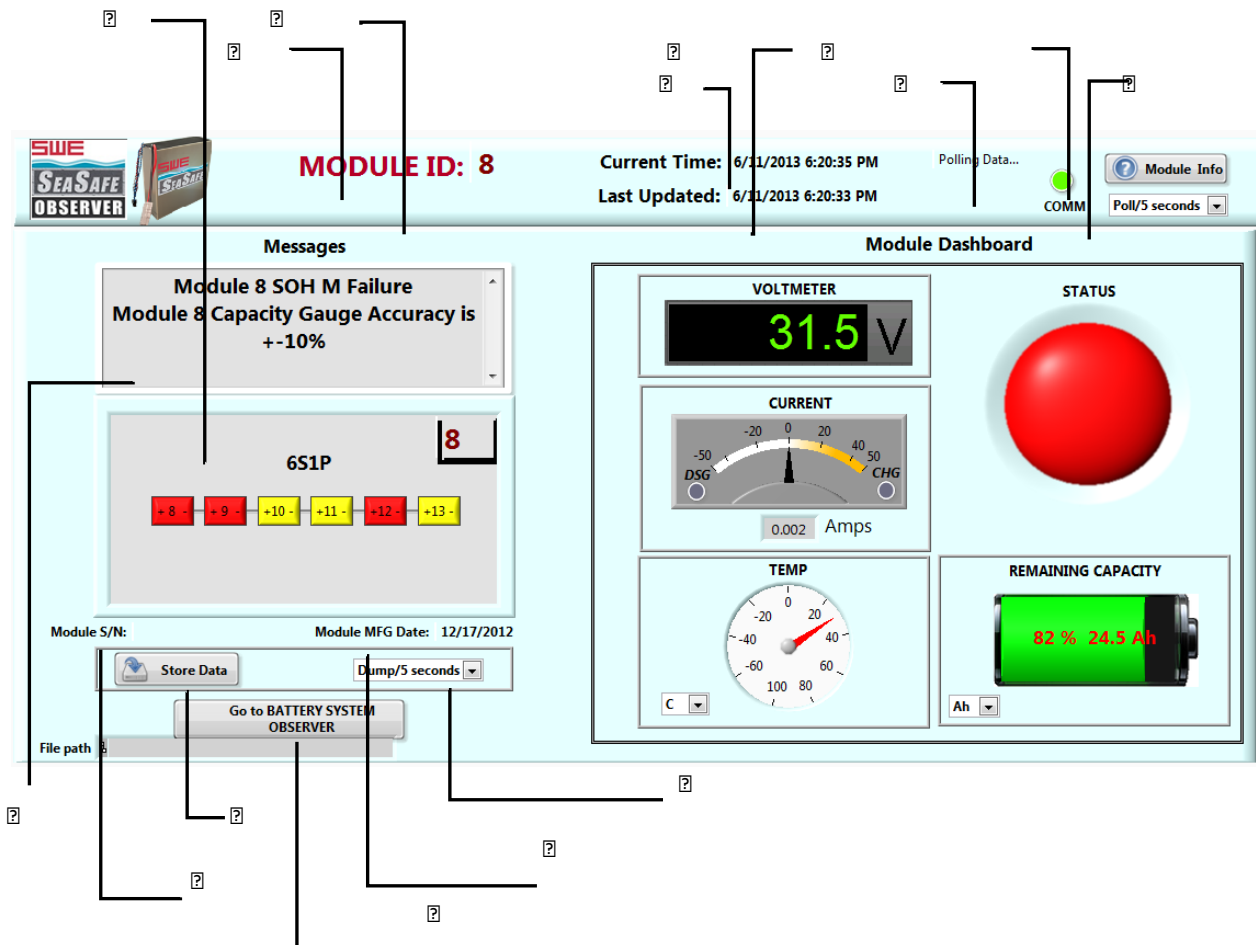


Figure 6. Module Monitor Window

Controls & Indicators		
	Name	Purpose
?	System Configuration Window	Illustrates the intermodule series/parallel hook-up. Click on a specific module to display it's status. The selected Module ID is displayed on the top right corner of this window.
?	MODULE ID	The ID of the selected module is also displayed here.
?	Battery System ID	ID of the System that houses the Module being observed. System ID default it is 1.
?	Current time	Current date and time of the PC running SeaSafe Observer.
?	Last updated	Shows the date and time when the screen was last updated.
?	Module Info	Opens up a pdf document with information regarding the Module currently being monitored.
?	COMM	This LED indicates whether or not the module under observation is connected to the system. Unlike Battery System Monitor, Module Monitor COMM only has 2 states of indication.  COMM Green LED indicates the module is connected to the system.  COMM Red indicates the module is disconnected from the system.

?	Poll/time	This is a drop down menu, the operator can select between choices of how fast he wants to poll the data for the module. The options available are: • Poll/5seconds, Poll/minute, Poll/5minute, Poll/hour, Poll/day • Each poll results in a screen refresh.
?	Messages	Status messages regarding for the Module under observation.
?	Module S/N	Serial Number of the selected module.
?	Module MFG Date	Manufacturing date of the selected module.
?	Store Data	Dumps raw module data into a .CSV file on the host PC at a rate defined via the dropdown menu. Stop storage clicking this button again. More details are given in section 5 Data Storage (.csv file).
?	Dump/time	Select the raw data dump rate. A rate should be chosen that is equal or slower than the poll rate. Rate options available to the operator are: • Dump/5seconds, Dump/minute, Dump/5minute, Dump/hour, Dump/day
?	Go To Battery System Observer	Takes the user from “Module Observer” to “Battery System Observer”.

Table 4. Available Detailed Status Information Available from Figure 6.

Summary: Lithium Ion Battery System for Oil and Gas Deep Water Fields

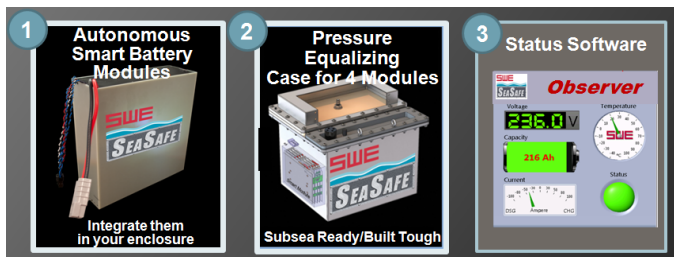


Figure 7. Summary SeaSafe Products

In summary, two subsea battery products are available to meet the needs of oil and gas deep water fields enabling electrical drive advantages such as faster, smoother, and more precise valve control or other electrical control and electrical backup solutions. These are illustrated in Figure 7. SeaSafe Smart Battery Modules and SeaSafe Battery Systems, in a pressure equalized case, are both supported by SeaSafe Observer software and optional PIIs. SeaSafe incorporates SWE Lithium Ion and a patented battery management system to deliver best in class safety and reliability that is autonomous. SeaSafe Subsea Battery solutions deliver four times more energy and eight times longer cycle life than SLA. SeaSafe can be configured to voltage and capacity increments to meet your electrical power needs and is sea depth tolerant down to six thousand meters.

REFERENCES

- [1] National Transportation Safety Board, Office of Aviation Safety, NTSB Battery Forum.