ICTINEU 10Kwh Pressure-tolerant Li-po battery qualification for 6.000m.

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Abstract

The Ictineu pressure tolerant li-po batteries were designed to provide the ICTINEU 3, a manned submersible for 1.200 meters depth, with a very compact high power, high density energy system. The batteries have undergone a certification procedure under GL rules, they have undergone a long series of certification tests, and they have been fully validated both in laboratory and in real operational conditions. They have proved a high performance and endurance, completely fulfilling the expectations, so they are ready to go into the market. As the battery units are modular and plug&play, they are easy to implement in any kind of vehicle, manned and unmanned, as well as in underwater stations and platforms.

The requests of several clients for deeper applications have brought the company to perform a new series of tests in order to qualify the batteries for higher depths. The last series of tests has been performed together with Ifremer as part of a li-po battery development for 6.000m depths. Also after checking clients specific needs, some functionalities of the battery have been improved and several updates applied for easier implementation and better performance. The company expects to obtain the DNV-GL type approval for the updated design. The company envisions li-po batteries as the definitely solution for deep water applications seeking for a radical weight reduction and performance increase.

OVERVIEW

During the design of the ICTINEU 3 submersible a particular lack was detected if a really highly operational vehicle was to be achieved: the need for a more efficient and powerful battery system than those existing models based on lead-acid batteries, and more efficient, lighter, compact and safer than those in pressure tight containers. The result of a 5 years development (2008-2012) is a compact li-po module at 148VDC, 70Ah and 10,36 Kwh, fully submersible to 1.200m as it is, that can be connected in parallel with other modules.

The battery cells are of the Lithium-polymer type (LiPO), providing 2x to 5x energy densities with respect to classical (Lead-acid, Ni-Ca or Ni-MH) types. The chosen cells are high energy ones and they allow charges up to 2C rates (i.e. 140 A) and discharges up to 5C continuous rate (i.e. 350 A) and 8C peak rates (i.e. 560 A). When integrated in the Ictineu battery (on base of the application needs), they are limited to 0,5C charge rate (35 A) and 1.14C discharge rate (80 Ah) offering a high safety factor and avoiding the cells abuse. The battery enclosure contains all the power, control and safety systems already imbibed, so in this way a very compact and light-weight battery module has been achieved: it weights 114 kg in air and 49,64kg in water, and can be installed in a room of 44 x 60 x 27.5 cm (17.16 x 23.4 x 10.7 inch), being the real water volume displacement of 62 litres (16,38 gallon). The battery modules are oil filled, pressure compensated containers which provide extra savings in weight and volume as compared to batteries at atmospheric conditions housed in pressure-tight containers. For more details see reference (4).

APPLICATIONS

Battery application in the ICTINEU3 manned submersible.

The ICTINEU 3 is a work class vehicle with high capabilities for research, ocean observation and underwater intervention. It has been designed and built for 1.200 meters depth, and a crew of three (one pilot and two observers) under DNV-GL rules and certification. It is a small and lightweight vehicle (L x W x H = 4,8m x 2m x 3m and weight in air approx. 5300 Kg), but at the same time versatile and highly operational.

One of the goals in design was to provide the vehicle with ample, above-the-standard energy capacity in order to be able to perform almost unlimited missions in terms of time, navigated length and mission instrumentation. This reverts on improved operability, more safety and more comfortable dives. Another one of the critical goals was to reduce weight as much as possible so that transportation (by air, sea and road) and deployment is simplified, and costs reduced. The development has ended up with a battery that fulfils all this premises as well as the energy needs. Indeed, thanks to the li-ion-polymer battery system and its hydrodynamic design, the vehicle could travel about 20 miles underwater at a cruise speed of 1,5 knots.

The ICTINEU 3 power system uses four modules in parallel, in a 3+1 redundant layout, which results in a 148VDC, 70Ah, 40,84 kWh system. It has been dimensioned for an average consumption per 8hours mission of 21kWh, and a 20kW peak discharge in case of an emergency. Each battery can be controlled and monitored externally, having all the desired data (cells temperature, SOC, SoH, cells voltage, current, etc. and). In the ICTINEU 3 vehicle, all the available parameters are constantly monitored by the managing computer, and can be registered in a data-base. They can be displayed in the main monitor at any time, and alarms are configured so they will clearly display and sound whenever any parameter gets to the (pre-defined) safety limits. In parallel a dedicated panel will display redundant voltage and current values, which are obtained independently of the internal BMS system. This panel offers as well the possibility to switch on-off each battery module in case of emergency and to operate them manually, performing the system pre-charge and start process independently of the BMS which allows the possibility to force the manoeuvre if required.

Two battery modules installed

ICTINEU 3 manned submersible

Other applications.

After the suitability and performance of the batteries has been validated satisfactory on the ICTINEU 3 manned submersible, the company has decided to put the batteries on the marked in order that other vehicles and platforms can use this technology which development (long and costly) is not in the hands of all organisations.

The modularity and pnp based system make this batteries a choice for other underwater applications, or even the use in harsh environments as, due to they nature, they protect the components from small particles and from corrosion. The most suitable applications are manned submersibles, autonomous vehicles, underwater observatories, underwater work stations and hybrid vehicles. For large vehicles it offers a big advantage as each unit contains a high amount of energy compared to existing underwater li-po batteries. For small vehicles and gliders they appear to be too large, though other smaller versions can be developed from the current model.

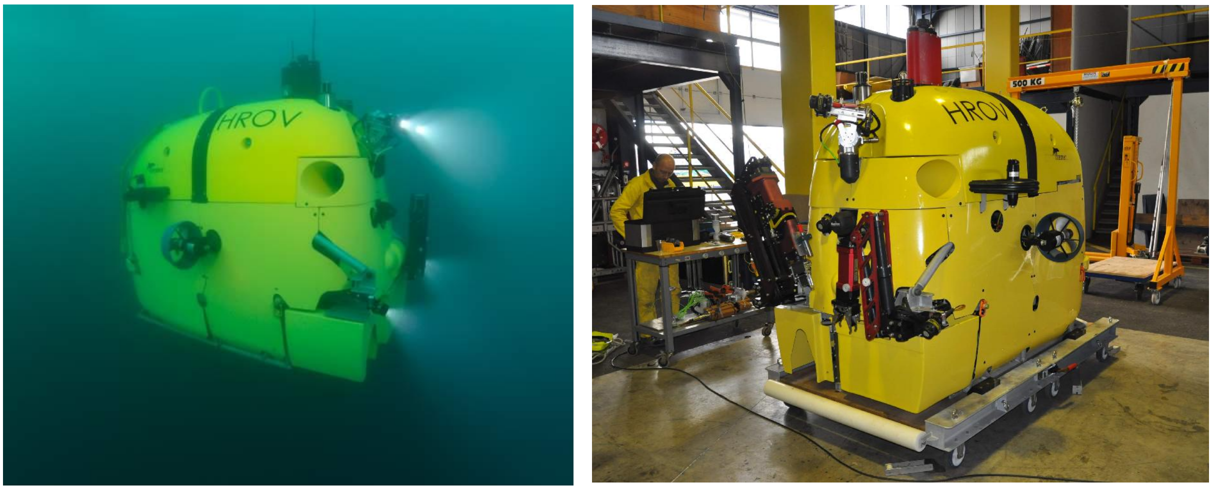
Another interesting application is that of the oceanographic instrumentation where still disposable alkaline cells are used, with the consequent inefficiency and environmental impact, as for ensuring the mission new cells are used for each campaign or dive. The inconvenient for this application is yet the price, which proves to be critical for most scientific teams, although a single battery would provide many years of service for most applications as li-po cells ensure long life cycling (up to 3000 cycles). Nevertheless, the application is feasible and simple.

The application on underwater observatories can play as well an important role, mainly in temporary observatories, but also in long-term or permanent observatories. It can be a particularly interesting alternative in those cases where a long and expensive cabling infrastructure is needed, if alternative communication/download means can be used instead. This is often the most complex part of the project which requires not only a big expense in deployment and logistics, but also it is time consuming and a long delay factor due to environmental and legal bureaucratic trap.

Case studies.

Several submersible operators, AUV operators and developers, instrumentation providers, oceanographic centres and offshore companies have showed interest on the Ictineu batteries, and some projects have already been developed. The wide range of users and applications require the study of different installation configurations as well as specific developments to adapt the battery design to each client needs.

A particular case study has been analysed with Ifremer as the French institution is evaluating the implementation of the Ictineu batteries in their new HROV vehicle. The H-ROV is an underwater vehicle, powered by onboard Li-ion batteries, which can be deployed in both teleoperated mode (ROV), via a light optic fibre cable deployed from a depressor or a cage, and in autonomous mode (AUV) with an optional acoustic communication link. It has been conceived for coastal applications (up to 2500m) and to be used from small vessels without dynamic positioning, as it is small (2,2m length) and lightweight (1,5t). The development of li-po pressure tolerant batteries for this vehicle has been studied based on initial requirements: 18kWh, 150V, 120Ah, max. discharge rated current 60A and a charge time of 8 hours. A configuration of one single battery was preferred though several modules in parallel, in series or a combination of both was also suitable. An autonomy of 8 to 12 hours was required, and a lifetime of 5 years with at least 500cycles and a mean of 100 cycles per year.



HROV Ifremer

The result from the study shows that two batteries in parallel are the most suitable option, as no re-design or engineering are needed which makes the production time shorter and more economic. It fully fulfils the given requirements, both which are mandatory and those which are desirable. A pressure tolerant li-ion battery is expected to offer far more autonomy for the same weight of the present batteries installed in the vehicle, which shows an interesting improvement.

The study could be also applied to other existing or future vehicles at Ifremer, as different voltage cases have been studied.

In the frame of future applications, Ifremer has decided as well to qualify the Ictineu li-po batteries for 6.000 meters depth. In this sense a preliminary battery project is undergoing at the time of this article is written, which includes a set of tests on components and on a battery prototype, as well as a safety study. Tests will be explained in more detail in the following paragraph *Certification procedures.*

The following table is an example that shows the different configurations that can be feasible from the standard type:

	Requirement			Ictineu proposal							
Architecture	Nb of modules	Module Voltage	Module energy	Current	Proposal	Cell capacity	Nominal tension per module	Total energy per module	Total system energy	New box	Battery system size approx
L1 : one battery	2	150,00 V	18 – 25 kWh	60 A	P1	70,00 Ah	148,00 V	10,36 kWh	20,72 kWh	No	275 x 1220 x 440 mm
	1				P2	150,00 Ah	148,00 V	22,20 kWh	22,20 kWh	Yes	265 x 1070 x 440 mm
					P3	150,00 Ah	148,00 V	22,20 kWh	22,20 kWh	Yes	480 x 610 x 440 mm
					P4	70,00 Ah	148,00 V	20,72 kWh	20,72 kWh	Yes	275 x 1070 x 440 mm
L2a: parallel association	2-4	150,00 V	9 - 12.5 kWh	60 A	P1	70,00 Ah	148,00 V	10,36 kWh	20,72 kWh	No	275 x 1220 x 440 cm
L2b : serial association	3	48,00 V	6 - 8.5 kWh	60 A	P1	200,00 Ah	48,10 V	9,62 kWh	28,86 kWh	Yes	250 x 1830 x 440 mm
					P2	200,00 Ah	48,10 V	9,62 kWh	28,86 kWh	Yes	320 x 1410 x 440 mm
					P3	150,00 Ah	48,10 V	7,22 kWh	21,65 kWh	Yes	255 x 1410 x 440 mm
L3a : parallel and serial association	6	48,00 V	3 - 4.5 kWh	80 A	P1	70,00 Ah	48,10 V	3,37 kWh	20,20 kWh	Yes	380 x 1410 x 440 mm
					P2	80,00 Ah	48,10 V	3,85 kWh	23,09 kWh	Yes	395 x 1410 x 440 mm

Other case studies and projects have been done according to client requests which include voltages as high as 236,8VDC (236,8 VDC, 40Ah, 9,44 kWh) for an underwater vehicle, or as small as 24V for oceanographic instrumentation.

The feedback received from clients and end-users have shown the importance of some issues for the easiness of the installation and maintenance on the user side. The conclusion after an extensive review of the system says that there is place for updates and improvements on the battery configuration and design that will provide more safety, easiness of use and installation to the end user. This will be described in the following paragraph.

Advantages and disadvantages for the application on other vehicles and platforms.

Any choice is never perfect as there are always advantages and disadvantages on the final result, but for the application in the Ictineu 3, the system showed clearly far more advantages than disadvantages. This advantages are also applicable to other vehicles, instruments and underwater platforms. Though many might seem obvious, following the most relevant are described.

Advantages:

Flexibility: as a modular, on the shelf and pnp system, it is very easy to adapt to each user needs. As a custom taylored system, many different configurations can be achieved to adapt to several voltages and powers, with few re-engineering required (see the example table above). A number of modules can be connected in parallel.

High energy: more than 10kWh in a room of 44 x 60 x 27.5 cm (17.16 x 23.4 x 10.7 inch) weighing 114 kg in air and 49,64kg in water offers a much more efficient system, up to 5 times higher than typical lead-acid systems. If compared to other lithium systems, it offers the highest energy solution in the market, which reduces the number of units to be installed, and so the installation time, maintenance, number of connections and risk of failure.

Compact and pnp: the battery units have all they need for a safe use: power, control and safety systems already imbibed in a sealed box, including the end connectors. For simple applications, the battery module can be controlled just with two switches/signals, one for charge and one for discharge and the battery will be monitored and protected by the imbibed systems (BMS). Only signal and power connectors are needed. But if desired, the system can be continuously controlled and monitored externally as the battery outputs a huge set of parameters.

Additional advantages for MUV: if the vehicle so configured, a forced start can be done bypassing the BMS in order to take control of the battery in case of the BMS failure. This allows to force a deeper discharge in case it is needed (for example in case of an emergency, taking for granted the pilot knows well the system safety limits).

Disadvantages:

Weight: 114kg can be a high weigh to handle at the time of moving it for installing-deinstalling each unit. Nevertheless, a simple hand crane is enough for a quick manipulation by a single operator.

Installation of modules in series: this is not possible with the current design. Though, it is being analysed for future implementation, and can be developed under client request.

Charging connexions: up to now, the modules are designed adapted to the Ictineu 3 configuration where the charge is done through the internal vehicle system, with no dedicated charging cable for signals. Improvements will be implemented in future units to solve this inconvenient (see following section)

Transportation and national regulations may limit the air shipping and/or other transportations and uses.

Improvements to apply on new Ictineu battery units.

In order to offer a higher degree of flexibility to the end users applications and vehicles operation, and for a better and easier integration, the next battery modules will include the following characteristics:

Independent power and signal connectors for charging (charger connectors) and discharging (load connectors): it is not necessary to unplug the battery from the vehicle to charge it.

Ictineu battery modules allow to charge and discharge simultaneously giving a very high degree of flexibility on the vehicle's operability. This will allow to charge the battery while doing set-up jobs, programming or discharge data from the vehicle without the necessity of an auxiliary or alternative power unit.

Faster charging times: balancing cells is a time consuming process, in the new Ictineu improved battery modules the battery cells will start balancing before the end of the charging process, reducing significantly the necessary time to complete the process to charge and balance the battery cells.

Concerning safety, also some measures are being implemented:

In order to avoid electrical shocks, the Battery's charger power receptacle and the charger's plug will remain isolated till the charger's power plug has been plugged, even in the case the charger's control plug has been plugged and the charge enable signal has been enabled.

All the inputs and communication pins of the charger control receptacle and the battery's power connector will be isolated if there is no voltage coming from the charger's signals plug. This will avoid the battery to have control problems and/or high voltage leakages or even turn off unwittingly if ever the battery is submersed without the mandatory dummy sealing plugs.

In order to avoid matting errors, power and control connector pairs for the charger and the vehicle are not compatible (poka-yoke).

It is being studied as well the possibility to develop battery modules that can be connected in series, so that they can be charged and discharged as if they were a single unit.

CERTIFICATION PROCEDURES.

Certification is always a crucial point when talking of a manned underwater vehicle, and even more when we talk of the power system. Their use in unmanned vehicles and other systems is equally important as any battery will be manipulated either for installation/disinstallation, and charged regularly by human beings in human occupied facilities (workshops, ships). The certification and classification by a accredited certification agency is the best quality assurance that can be given to client and end-user.

The Ictineu 3 vehicle has been designed, built and tested under the Germanischer Lloyd "Rules for Classification and Construction -now under DNV-GL group- which means that the battery system has been analysed, tested and approved by the GL authority to be used in a manned submersible. As the battery system is now offered to other users and the number of customers and applications is very wide, it is of interest to provide to them all with a reliable product that fulfils the regulations and has its own type approval or certification. This will make more easy the integration of these batteries on manned vehicles subject to classification by any authority, and as well the integration in unmanned systems which have exigent certification rules.

Following are explained the different levels of certification and testing that the battery system has undergone and the ones expected in a near future:

A. Certification procedures for the application on the ICTINEU 3 MUV.

As there were no specific rules for the application of li-ion-polymer batteries in manned submersibles, a particular program was discussed and agreed between Ictineu Submarins and GL for the development and testing of the battery system. GL rules and recommendations have been applied as well as different standards (IEC, UL, UN), compelling those specific for lithium-ion batteries and those general to power systems. Following is a brief description of the test procedures:

Tests on cells:

> Electrical tests (short circuit, forced discharge, overcharge, according to UN). Performed by the cells manufacturer.
>
> Physical tests (altitude, temperature, vibration, acc. to UN).Performed by the cells manufacturer.
>
> Mechanical tests (shock and impact, acc. to UN). Performed by the cells manufacturer.
>
> Hydrostatic pressure tests. Performed by Ictineu at their own facilities.

Tests on cell packs:

> Sinusoidal vibration test according to the procedure defined on GL 2003, VI Rules for Classification and Construction. Additional Rules and Guidelines, Part 7 Guidelines for the Performance of Type Approvals, Subpart 2 Test Requirement for electrical / Electronic Equipment and Systems, Section 3.B.9. Vibrations. Test performed at Applus accredited laboratory by request of Ictineu.
>
> Hydrostatic pressure tests to pack and bms during discharge process. Performed by Ictineu at their own facilities

Tests on the battery management system (BMS):

> Temperature, vibration, EMC emission, EMC immunity, ESD immunity, CE compliance: 2006/95/EC Low-Voltage Directive (safety), CE compliance: 2004/108/EC Electromagnetic Compatibility Directive (EMC). Performed by the BMS manufacturer.
>
> Hydrostatic pressure tests and cycling to bms during operation.
>
> Hydrostatic pressure tests and cycling to passive components and control board. Performed by Ictineu at their own facilities.

Tests on the battery enclosure materials:

> A 1000ºC flame test was performed on a set of samples with different material configurations representative of all the battery composite parts. Test performed at Applus accredited laboratory by request of Ictineu.
>
> Hydrostatic pressure tests. Performed by Ictineu at their own facilities.

Tests on the complete battery unit:

> Sinusoidal vibration test according to the procedure defined on GL 2003, VI Rules for Classification and Construction. Additional Rules and Guidelines, Part 7 Guidelines for the Performance of Type Approvals, Subpart 2 Test Requirement for electrical / Electronic Equipment and Systems, Section 3.B.9. Vibrations. Test performed at Applus acredited laboratory by request of Ictineu.
>
> Transport random vibration simulation test according to standard ASTM D 4169-09: Standard Practice for Performance Testing of Shipping Containers and Systems. According to requirements of section 12.2 Schedule D - Stacked Vibration with parameters of section 12.4 Random Test Option – Truck. Test performed at Applus accredited laboratory by request of Ictineu.
>
> Hydrostatic pressure test. Performed by Ictineu at their own facilities.

B. Additional tests for 6.000m depth qualification.

Ifremer is interested to qualify the Ictineu li-po battery for their future applications. In a first step, tests are being performed on the several battery components in order to demonstrate survivability and full functionality of the battery critical elements under the worst working conditions: 2ºC and 624 bar maximum operational pressure (safety factor to be applied acc. to Ifremer). Tests are being performed at Ifremer laboratory at Ifremer Centre Méditerranée, la Seyne, France. Not all the tests performed for the battery certification have to be repeated for this qualification as they have no relation with the depth increase, although the cell properties and components functionality have to be checked after the tests.

Following a brief description of the test procedure for the first phase is given:

Hydrostatic pressure test on passive components and control board, 10 cycles.

Hydrostatic pressure test on BMS, 10 cycles.

Battery pack characterization (capacity and internal resistance values) before tests.

Hydrostatic and functional pressure test on BMS, battery control board and the battery pack, 2 cycles.

Hydrostatic and discharge under pressure test on BMS and battery pack, 2 cycles.

Hydrostatic pressure fatigue test on BMS, battery control board and the battery pack, 40 to 100 cycles.

Battery pack characterization (capacity and internal resistance values) after the tests.

C. DNV-GL Classification.

As explained, the company has the intention of obtaining a type approval from DNV-GL for a general application of the Ictineu battery. There are not yet specific rules for the certification and type approval of lithium polymer batteries, so as alternative to wait for the regulation authorities to produce them, a procedure must be defined by DNV-GL for this particular case. At this time the existing regulations are being reviewed in order to prepare a procedure. It is expected to be able to perform it during 2015.

CONCLUSIONS

The use of li-po pressure tolerant batteries shows as the best available solution for deep water applications where they will play an important role to radically reduce the weight of the vehicles as well as improve their performance and operability. The Ictineu batteries are suitable and provide many advantages for their implementation in manned and unmanned vehicles, as well as in instrumentation and subsea platforms and observatories.

Further to the validation and certification of the battery, Ictineu Submarins continues to update new functionality and provide better performance, as well as gathering data for a continuous monitoring and future improvements.

As a near future objectives, the Ictineu battery should achieve the DNV-GL type approval, and the qualification for 6.000m operation.

References

(1) Germanischer Lloyd, "Rules for Classification and Construction, I Ship Technology, 5 Underwater Technology, 2 Submersibles", edition 1998.

(2) Germanischer Lloyd, "Rules for Classification and Construction, I Ship Technology, 5 Underwater

Technology, 2 Submersibles”, edition 2009.

(3) Germanischer Lloyd, “Rules for Classification and Construction, I Ship Technology, 5 Underwater Technology, 3 Underwater Equipment

(4) Carme Parareda, Pere Forès, Miquel Àngel Rodríguez, *Pressure-tolerant Li-ion batteries, implementation and certification on MUV ICTINEU 3*, Underwater Intervention 2013, New Orleans USA, 2013.

(5) Vincent Rigaud, *From manned submersible to autonomous and hybrid systems. The ways from research to operational uses: Criteria, Trends and perspectives*, 2012

(6) Vincent Rigaud, *Nouveaux outils Gliders et HROV*