HIGH ENERGY LITHIUM-ION VES CELLS AND BATTERIES PERFORMANCES

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ABSTRACT

Saft's Space VES range of lithium-ion cells have been designed specifically to meet the satellites on-board power need, while meeting the legitimate high levels of requirements for space products.

The purpose of the paper is to develop how the VES batteries designs have progressively evolved in order to accommodate the needs, requirements and constraints evolutions. The following topics will be presented:
▫ Description of the main design features of the VES Li-ion batteries.
▫ How the optimised battery configuration is selected against the required EOL power need or other constraints.
▫ Presentation of the batteries performances (electrical, mechanical, thermal, interface, weight, ...).
▫ Measures implemented in order to maintain these performances, and to guarantee the best product quality as per space standards.

1. INTRODUCTION

VES cells made their first space flight in 2003, and at end December 2010 there were 50 satellites in orbit which are powered with VES Li-ion batteries. In the meantime, other VES batteries were already delivered worldwide to Customers to be integrated into 22 additional satellites. And finally, with the current batteries manufacturing activities dedicated to 24 satellites, it is a total of **96 satellites** that are or will be operating with various designs of Saft VES Li-ion Batteries.
The current Li-ion VES cells range, including three cell formats, allowed and still allows to propose **a large range of Battery designs configurations**, all specifically designed to meet the satellite end-of-life (EOL) power need without any penalizing over-designed at beginning-of-life (BOL). Over the last ten years, these VES battery designs have evolved offering customers various possibilities to match, with the right accuracy, their needs and constraints. In the meantime, the energy needs have increased, as well as other requirements such as for instance mechanical levels.

The Li-ion VES Batteries can adapted from a large panel of possibilities, based on the required energy and on the Customers requirements in terms of electrical and mechanical interface constraints.

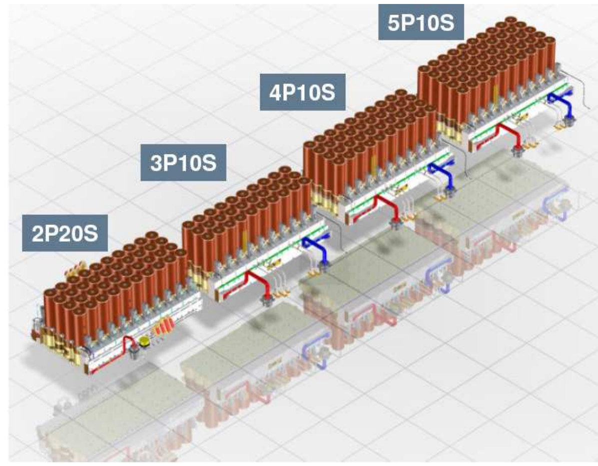

Figure 1. Example of VES Batteries configurations

2. THE SAFT LI-ION VES CELLS RANGE

The current range of Saft lithium-ion cells comprises three formats of high-energy cells: VES100, VES140 and VES180.

Figure 2. Saft High-Energy Li-ion VES Cells

From industrial cells designed for electrical vehicles application, Saft had qualified specific terminal and feed-through for Space environment which guarantee a cell He leak rate lower than 10^{-7} $cm^3.atm.s^{-1}$. The cell container design is compliant with the requirements of leak before burst.
The initial design of cell called 'S' have been completed by a second design called 'SA' with electrodes jelly-roll attached to cell container for a higher mechanical environment handling capability. Thus it is now among the four VES cells that the battery architecture can be established: VES100S, VES140S, VES140SA and VES180SA.

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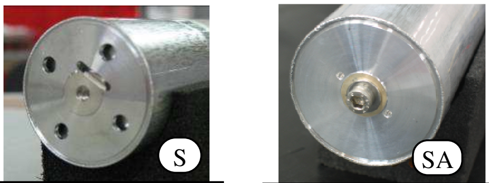


VES100S VES140S VES140SA VES180SA

Main cells characteristics are summarised in Tab 1.

	VES100 S	VES140 S	VES140 SA	VES180 SA
Date Of Qualification	Dec. 2003	Feb. 2001	June 2007	Dec. 2008
Nameplate capacity [Ah]	26	40	40	45
Guaranteed capacity [Ah]	26	38.5	38.5	45
Mean voltage @ C/1.5 [V]	3.6	3.6	3.6	3.6
Max End Of Charge Voltage[V]	4.1	4.1	4.1	4.1
Energy @C/2 / 4,1V / 20°C [Wh]	90	138	138	173
Specific energy [Wh/kg]	110	124	124	156
Weight [kg]	0.81	1.11	1.11	1.11
Internal impedance [mΩ]	4	3	3	2.6
Applications	LEO / MEO / GEO			

Table 1. Main VES Cells characteristics

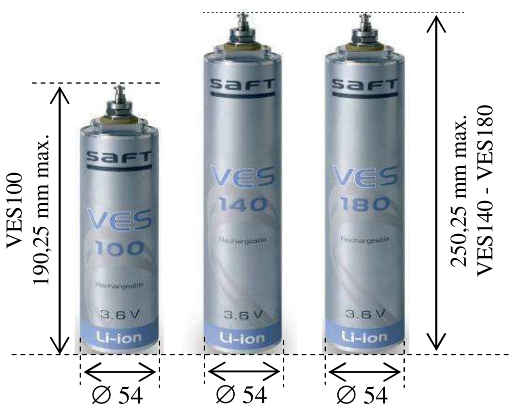


Figure 3. VES100-140-180 Cells Dimensions

The common interface dimensions allow developing and qualifying a generic range of Li-ion batteries with a wide range of similar and re-usable mechanical interface properties and behaviours. Both Saft and its partners can take benefit of qualification results and in-orbit heritage. Generic qualification data package are available that cover almost 80% of the customer requirements.

The range of satellite power demands covered by Saft with the batteries using these Li-ion cells is extensive and complete as presented in Fig. 4; each satellite power demand is satisfied with the exact battery without excess embarked mass, due to the small increment of energy capability provided by the qualified range of cells. A very good optimisation of energy sources on board the satellites is achievable thanks to the batteries range proposed by Saft to its customers.

Fig.4 shows the GEO satellites power need coverage by the range of VES batteries, considering 20% margin of energy at end of life, and in failure case.

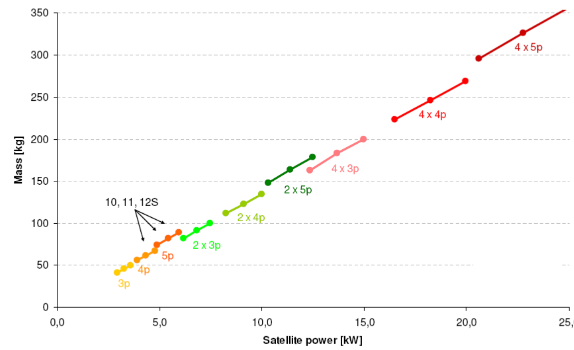


Figure 4. Satellites power need coverage

3. MAIN DESIGN POSSIBILITIES AND FEATURES OF VES BATTERIES

Fig.5 presents a typical complete Saft battery module, whose detailed design will be developed in this chapter.

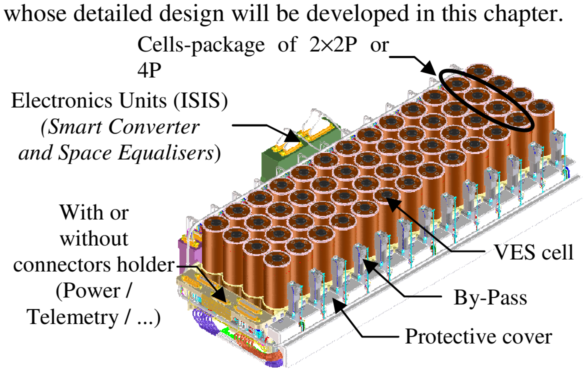
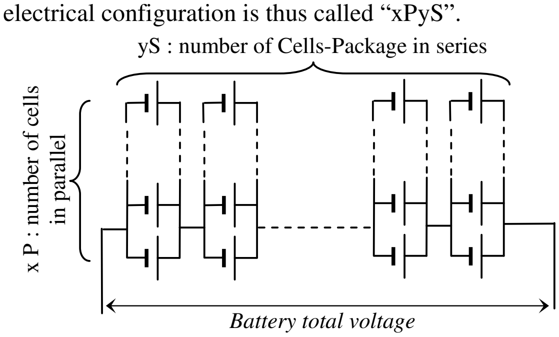


Figure 5. Example of VES Battery architecture

❒ ***Main VES batteries design features:***

The electrical configurations of the batteries are based on a combination of x cells assembled in parallel, which lead to a Cells-Package called “xP”, and then y cell-packages are connected in series. The battery module electrical configuration is thus called “xPyS”.

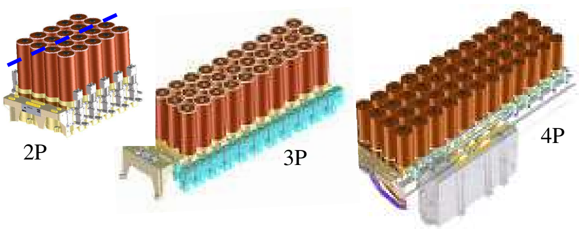


The following table summarizes the extended configurations available with their levels of maturity:

	2P	3P	4P	5P
VES100S		**i-o**	**Q**	**D**
VES140S	**Q**	**i-o**	**i-o**	**D**
VES140SA		**i-o**	**i-o**	**D**
VES180SA	**Q**	**Q**	**i-o**	**Q**
ITAR By-pass	**Q**	**i-o**	**Q**	**D**
Non-ITAR By-pass	**Q**		**Q**	**D**
Bypass free		**i-o**		
Electronics for Balancing & bypass control	**D**	**D**	**Q**	**D**

Legend:

i-o	*Qualified configuration operating **in –orbit***
Q	***Q**ualified configuration*
D	*Configuration under **D**evelopment*
	Not yet needed



The battery design is based on a common mechanical architecture which smallest common item is the cells package. A cells package is made of x cells assembled in a mechanical structure by gluing.

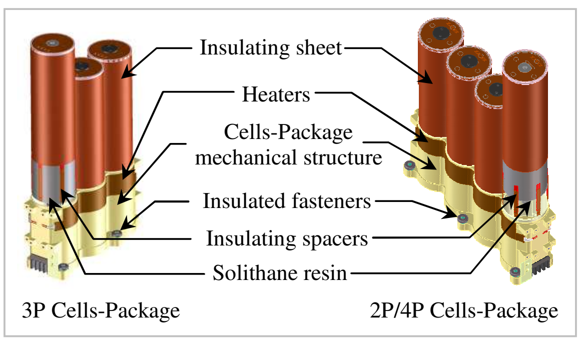


Figure 6. Cells-Package description

❒ ***Designs for cells electrical connections:***

Several designs are available for cells electrical parallel connection (using cables or bus-bars), and also for electrical series connexion.
Saft had started cells paralleling only using <u>cables design</u> with strict conformity to ESA derating rules regarding current handling capability.
In the configuration of fig.7, the series connexion and parallel wiring of cells are realized together through parallel wires and series connexion bus bars.

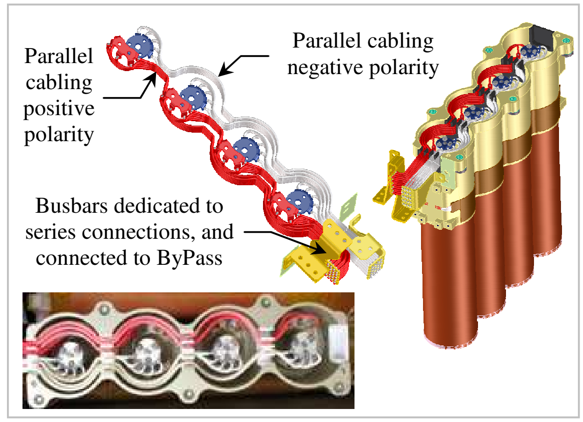


Figure 7. Cabling for parallel cells connections

The qualification of VES180SA cell, allowing higher power demand and consequently increased current, and also necessity to extend to 5P the number of cells in parallel during its VES180SA dedicated battery design qualification, Saft has decided to propose generic <u>busbars</u> for both cells paralleling and cells packages series connexion.
The generic battery design qualified offers more flexibility and better control of side effects of increased current intensities. The reduction of battery internal resistance is noticeable. Thanks to these generic busbars, it has been possible to Saft to derive an extension of battery range from existing battery design.
Battery mechanical structure rigidity, thermal capacity and exchange surface have been increased to cope with high specific energy VES180SA cells, while limiting significantly Joule effects produced by higher current intensities.

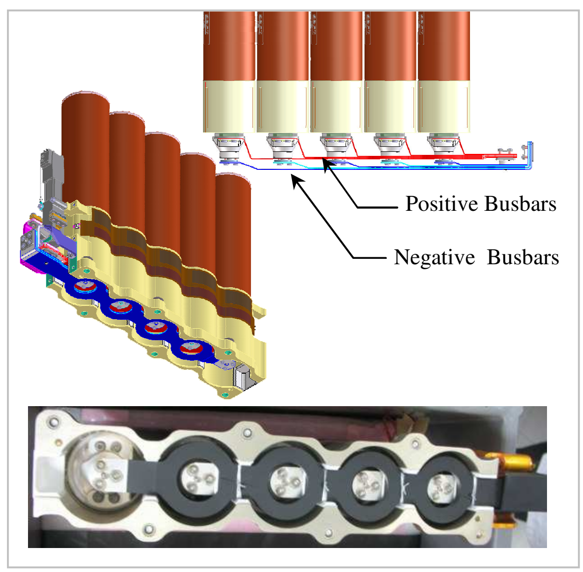


Figure 8. Busbars for parallel cells connections

These choices allow Saft to keep flexible and compact the battery while increasing power delivered by battery by roughly 20%.

❒ *By-pass systems with current carrying capabilities:*

Battery present 'State Of Art' includes a by-pass device to cope with cell failure and avoid jeopardizing rest of battery, it is most of the time mandatory to remove any cell having high internal impedance from the battery serial circuit. By-pass systems are implemented in Saft batteries. The main requirements for by-pass selection are multiple: avoid open circuit on battery serial circuit, be compatible with derating rules, have no unmitigated single point failure when coupled to battery and avoid failure propagation leading to loss of mission or safety issue.

Two main by-pass devices are used in the battery design presented in this chapter: Historical ITAR by-pass device which current handling capability is 150A; and non-ITAR by-pass device capable of 200A current handling. Two others by-pass devices are qualified for use in Li-ion batteries using others architectures and more cells in parallel, their current handling capabilities are 400A for ITAR Device and 480A for Non-ITAR device.

By-pass Devices				
Regulations	ITAR	ITAR	NON-ITAR	NON-ITAR
Maximum Weight	60 g	265 g	115 g	320 g
Rated Current	150A	400 A	200 A	480 A
Flight Experience	from 2005	from 2004	from 2009	not yet

Saft Li-ion battery design are also available using the same elementary cells package from 3P to 4P based on discrete diodes, these customized designs were qualified, delivered and are well operating in orbit since 2006.

❒ *Space Electronics*

Saft has teamed up with German company called ASP 'Advanced Space Power equipment' electronics specialist to provide, on request, an "all in one" modular energy storage system with <u>intelligent autonomous cell balancing management</u>. See Fig. 9

For any Saft battery, Saft can include in battery design integrated balancing system dedicated to optimize the available energy during all the life of the battery. This is achieved by associating a battery management system, named 'ISIS' for Intelligent Surveillance Integrated System, to the battery module. The system is compliant with ESA regulations (i.e. single-point failure tolerant, hot redundancy) and ITAR free and was qualified with support of CNES and DLR. ISIS systems is composed of two items called "Space Equalizers" (SE) and "Smart DC/DC converter". Each Cells-Package is equipped with a SE supplied by the "Smart DC/DC converter".

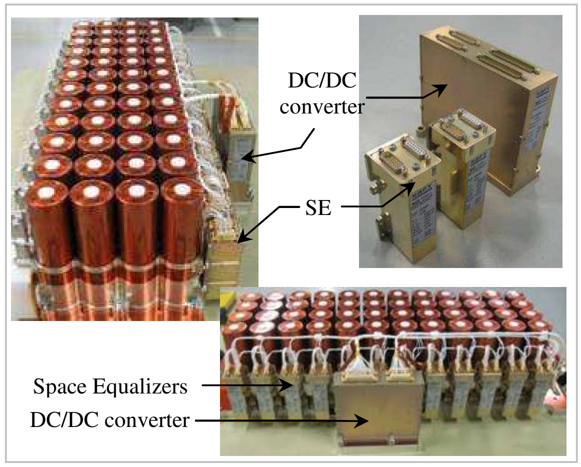


Figure 9. Battery electronic management system

The functions of the Space Equalizers (SE) are:

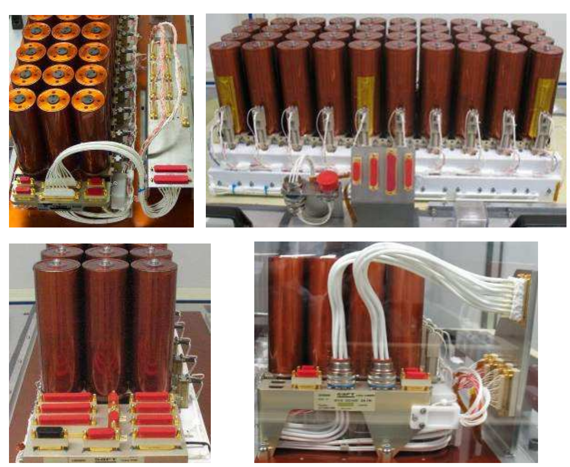
- Balancing which optimizes battery life and available energy,
- By-pass activation & function control to remove weak or failed cells package from the serial circuit.
- Disposal / (Discharge) function available to inert a cell package after bypass and end of life of satellite

And the functions of the Smart DC/DC converter are:

- Supply voltage for each SE.
- Smart charge signal: Command for PCDU or on-board computer to decrease charge voltage taking into account by-pass activation.

❒ *Battery Interfaces with satellite*

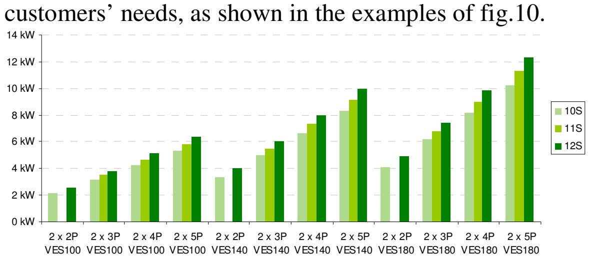
Several electrical interfaces are proposed for the battery module depending of customer requirements. Connectors and threaded contact plugs can be set on battery assembly facing almost any direction and axis. Shape of connectors (rectangular or circular), inter-connectors distances, altitudes, number, levels of redundancy are some of the parameters that can be decided together and customized.



Functions of the electrical interfaces are power, signal telemetries, pyrotechnic outputs, command signal interfaces, on ground or in-orbit monitoring of heaters, thermal sensors, balancing shunts.
Batteries including electronics are also equipped with connectors for converters and space equalizer if necessary. Batteries which electronic system is delocalized in the satellite and managed by customer provide any interface connector needed for the purpose of battery management.

4. SELECTION OF OPTIMIZED BATTERY CONFIGURATION

Thanks to all the possibilities described in previous chapter, with different cells, and different xPyS battery configurations, Saft can propose the most suitable to the customers' needs, as shown in the examples of fig.10.



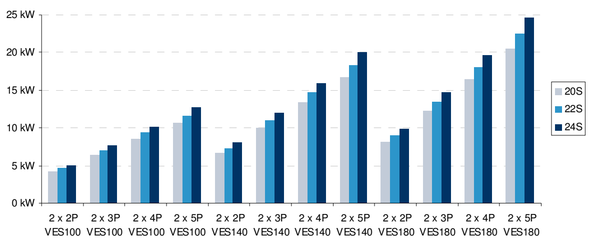


Figure 10. Battery configuration versus satellite need

Since beginning of year 2009, a very helpful software developed by Saft called: 'Saft Li-ion Model_SLIM' is available to all the Space community to initiate a battery selection and prepare discussion and exchanges with Saft teams and specialists. This Saft Li-ion Model:

- Predicts the End Of Life parameters for LEO/MEO and GEO missions at battery level
- Is based on **electrochemical** characteristics: energy, capacity, EMF, Internal Resistance, End Of Charge Voltage (EoCV)…
- Is a **macroscopic** model based on energy (global at cell level)
- Uses **fading and calendar law** effects on energy and internal impedance versus time, temperature, end of charge voltage….
- Uses mission figures: power, duration, Depth of Discharge (DoD), end of charge voltages, temperatures during eclipses and solstices, cell failures
- Gives cell and battery **voltage profiles**, **energy evolution** through the life time (nominal and failure cases)
- Was checked by **comprehensive DPAs** (Destructive Physical Analysis), and has been **correlated** with existing cycling and calendar tests, is validated by **in-orbit results.**

This software allows all the community obtaining from a set of mission parameters inputs such as:

- Eclipse and solstice power
- Mission profile: DoD versus days
- Eclipse and solstice temperatures
- Eclipse and solstice EoCV
- Battery configuration and characteristics

a complete set of characteristics and key data including for any cycles of the battery life:

- Discharge and charge curves;
- Internal impedance;
- Voltages and State of Charge.
- Energy ; Energy loss;

5. PRESENTATION OF BATTERIES PERFORMANCES

❒ *Beginning Of Life Batteries Performances*

Typical electrical performances obtained on previous manufactured batteries are provided hereafter.

Example of battery
3P12S VES140S
(ITAR By-Pass)

L×W×H: 795×230×265mm
Weight: 48,5kg +/-1,5kg

Discharged energy from 4,1V to 2,7V under constant discharged power (P=2780W)	
Temp.	Batteries average measured values
10°C	Average : 4 610 Wh
20°C	Average : 4 975 Wh
35°C	Average : 5 420 Wh
40°C	Average : 5 535 Wh
Battery internal resistances at 60%DOD	
Temp.	Batteries average measured values
10°C	Average : 25 mΩ
20°C	Average : 21 mΩ
35°C	Average : 16 mΩ
40°C	Average : 15 mΩ
Battery actual measured weights (kg)	
Weight	Average : 48,0 kg

Discharged energy from 4,1V to 2,7V under constant discharged power (P=3130 W)	
Temp.	Batteries average measured values
15°C	Average : 4 630 Wh
20°C	Average : 4 810 Wh
35°C	Average : 5 225 Wh
Battery internal resistances Ri at 60%DOD	
Temp.	Batteries average measured values
15°C	Average : 22 mΩ
20°C	Average : 20 mΩ
35°C	Average : 15 mΩ
Battery actual weights (kg)	
Weight	Average : 47,5 kg

Example of battery
4P13S VES100S
(ISIS + By-Pass)

L×W×H : 855×425×210mm
Weight : 61,4 kg

Test temperature	10°C	20°C	30°C
Discharged energy at cst current C/2 (52A)	4120 Wh	4520 Wh	4820 Wh
Ri (mΩ) 80%DOD	34 mΩ	23 mΩ	16 mΩ

Example of battery
4P12S VES100S
(ISIS + By-Pass)

L×W×H: 794×425×210mm
Weight: 56,9 kg

Test temperature	10°C	20°C	30°C
Discharged energy at cst current C/2 (52A)	3770 Wh	4140 Wh	4425 Wh
Ri (mΩ) 80%DOD	32 mΩ	22 mΩ	15 mΩ

Example of battery
4P12S VES140S
(Non-Itar By-Pass)
L×W×H: 807×290×265mm
Weight: 64,5kg +/-1,8kg

Discharged energy at constant power (P= 4180W) from 4,1V to 2,7V			
Test temperature	10°C	20°C	30°C
Discharged energy	5880 Wh	6380 Wh	7160 Wh
Ri (mΩ) 60%DOD	18 mΩ	15 mΩ	10 mΩ

Example of battery
3P9S VES180SA
(Non-Itar By-Pass)

L×W×H: 685×235×265mm
Weight: 39,3 kg max

Test temperature = 20°C	Batteries average measured values
Discharged energy at cst power (1560W) from 3,95V to 2,7V	3 860 Wh
Ri (mΩ) 60%DOD	Average : 11 mΩ
Battery actual weights (kg)	Average : 37 kg

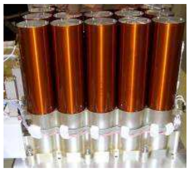
Example of battery
4P9S VES180SA
(with diodes)
L×W×H: 758×290×265mm
(Hmax with diodes: 460)
Weight: 55,2 kg max

Discharged energy down to 2,7V under constant discharged power at +20°C	
1) Nominal mode simulation : P=3425W, charge at 4,0V	average : 5 625 Wh
Battery internal resistances Ri at 60%DOD	average : 6 mΩ
2) Degraded mode simulation : P=3850W, charge at 4,1V	average : 6 290 Wh
Battery actual weights (kg)	
Battery actual weights (kg)	52,9 kg

Example of battery
2P20S VES180SA
(Non-Itar By-Pass)

L×W×H: 641×400×265mm
Weight: 58kg +/-2kg

Discharged energy from 4,1V to 2,7V under constant discharged power (P=3860 W)	
Temp.	Batteries average measured values
10°C	Average : 6 420 Wh
20°C	Average : 6 830 Wh
30°C	Average : 7 190 Wh
Battery internal resistances Ri at 60%DOD	
Temp.	Batteries average measured values
10°C	Average : 32 mΩ
20°C	Average : 28 mΩ
30°C	Average : 25 mΩ
Battery actual weights (kg)	
Weight	Average : 57,8 kg



Example of battery
5P10S VES180S
(Non-Itar By-Pass)

L×W×H : 650×396×268mm
Weight : 74kg +/-2,5kg

Discharged energy at constant power (P=2250W) from 4,1V to 2,7V on QM model 5P5S VES180SA			
Test temperature	10°C	20°C	30°C
Discharged energy at constant power	4035 Wh	4270 Wh	4642 Wh
Ri (mΩ) 60%DOD	3.2 mΩ	2.7 mΩ	2.3 mΩ

❒ *Mechanical Environment qualification*

The Saft Li-ion cells range have been qualified in battery configuration. Therefore, the presentation hereafter of cells mechanical environment qualification directly characterizes the battery range mechanical characterization. Nevertheless, only generic qualifications are presented in the table.
Several customers have already asked for higher qualification levels for quite all cells of the range.
This case is managed between Saft and customer through dedicated qualification vehicles. Higher qualifications levels coverage is not a concern.

VES100S – Mechanical Qualification Levels			
Sine Levels 2 oct/min per axis	Frequencies	Levels	sweep
// to the mounting plane (X-Y) – (⊥ cells axis)	5 -21.3 Hz	± 11 mm	1
	21.3-130 Hz	15 g	
⊥ to the mounting plane (Z) - (cell axis)	5-18.4 Hz	± 11 mm	1 Sweep
	18.4-130 Hz	20 g	
Random Levels 3 minutes per axis	Frequencies	Levels	g RMS
⊥ to the mounting plane (Z) - (cell axis)	20-60 Hz	+3 dB/oct	7.0
	60-100 Hz	0.12 g²/Hz	
	100-400 Hz	0.06 g²/Hz	
	400-2000 Hz	-5 dB/oct	
// to the mounting plane (X-Y) – (⊥ cells axis)	20-60 Hz	+3 dB/oct	6.7
	60-400 Hz	0.12 g²/Hz	
	400-2000 Hz	-5 dB/oct	
Shock levels	Frequencies	Acceleration	Toler.
All 3 axis (// and ⊥) (X-Y-Z)	250 Hz	60 g	[-0 dB, +6 dB]
	500 Hz	200 g	
	2000 Hz	1300 g	
	10000 Hz	1300 g	

VES140S – Mechanical Qualification Levels			
Sine Levels 2 oct/min per axis	Frequencies	Levels	sweep
All 3 axis (// and ⊥) (X-Y-Z)	5-22.3 Hz	± 10 mm	1
	22.3-100 Hz	20 g	
Random Levels 3 minutes per axis	Frequencies	Levels	g RMS
⊥ to the mounting plane(Z) - (cell axis)	20-50 Hz	+6 dB/oct	12.0
	50-400 Hz	0.2 g²/Hz	
	400-1200 Hz	-6 dB/oct	
	1200-2000Hz	0.02 g²/Hz	
// to the mounting plane (X-Y) – (⊥ cells axis)	20-64 Hz	+6 dB/oct	8.5
	64-450 Hz	0.08 g²/Hz	
	450-900 Hz	-6 dB/oct	
	900-2000 Hz	0.02 g²/Hz	
Shock levels	Frequencies	Acceleration	
All 3 axis (// and ⊥) (X-Y-Z)	100 Hz	30 g	
	400 Hz	200 g	
	2000 Hz	1300 g	
	10000 Hz	1300 g	

VES140SA / VES180SA – Qualification Levels			
Sine Levels 2 oct/min per axis	Frequencies	Levels	sweep
All 3 axis (// and ⊥) (X-Y-Z)	5-20 Hz	± 10 mm	1
	20-55 Hz	20 g	
	55-70 Hz	25 g	
	70-100 Hz	20 g	
Random Levels 3 minutes per axis	Frequencies	Levels	g RMS
⊥ to the mounting plane (Z) - (cell axis)	20-100 Hz	+3 dB/oct	17.3
	100-400 Hz	0.3 g²/Hz	
	400-2000Hz	-3 dB/oct	
// to the mounting plane (X-Y) – (⊥ cells axis)	20-80 Hz	+3 dB/oct	12.8
	80-100 Hz	0.093g²/Hz	
	100-1000 Hz	0.1 g²/Hz	
	1000-2000Hz	-3 dB/oct	
Shock levels	Frequencies	Acceleration	
All 3 axis (// and ⊥) (X-Y-Z)	100 Hz	30 g	
	400 Hz	200 g	
	2000 Hz	1300 g	
	10000 Hz	1300 g	

Saft realized all vibrations tests on its own equipments, available at test labs, which capabilities cover the total battery range 2P to 5P up to 13S.

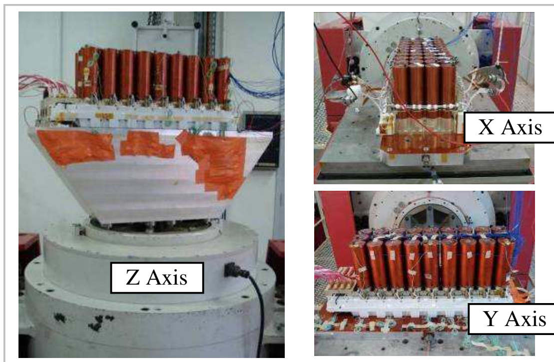
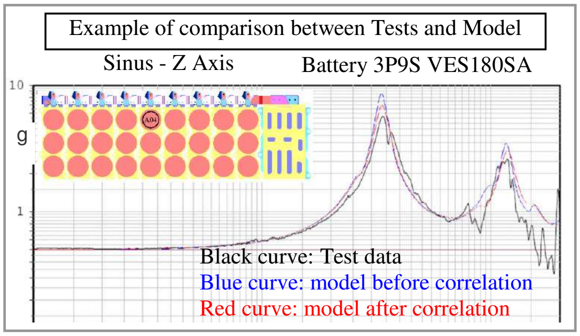


Figure 11. Battery vibrations testing

Acceleration tests and shock tests are realized under Saft Tests lab technicians and engineers' responsibility at subcontractor facilities, such as INTESPACE.
Based on extensive tests realized on batteries for many years, Saft has available correlated Mathematical Mechanical Model of many qualified batteries of its range. These models are used to predict battery behaviour during on-ground testing and satellite launch.



Dedicated condensed and reduced Mechanical Mathematical Models using international standards and codes can be delivered on request to predict with accuracy the Saft battery behavior in satellite model.

❒ *Thermal Environment Qualification*

All Saft batteries include passive items dedicated to battery thermal control. Batteries are equipped with thermal sensors, for access in real time to reference point temperatures, and heating resistances. All these items are glued on mechanical structures or cells containers. These passive elements are dedicated to be part of complete satellite thermal control and interface with satellite as agreed between Saft and Customers.

Thermal sensors references and heaters dimensioning are results of technical discussions and system level thermal analysis.

Two vacuum chambers are dedicated to satellites batteries tests at Saft. One is equipped for thermal balance tests, thermal cycling tests and in-orbit cycles tests, while the second is used for Corona and leak tests.

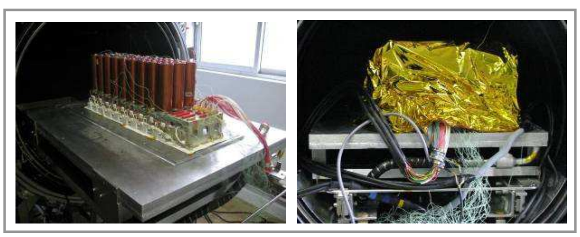


Figure 12. Preparation for thermal vacuum testing

These chambers allow Saft to correlate the Thermal Mathematical Models. The batteries thermal behavior during on-ground tests and in-orbit operation is therefore predictable with satisfactory accuracy.

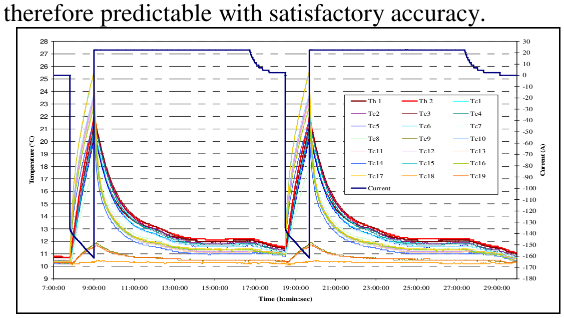


Figure 13. Cold cycle at 10°C in thermal vacuum

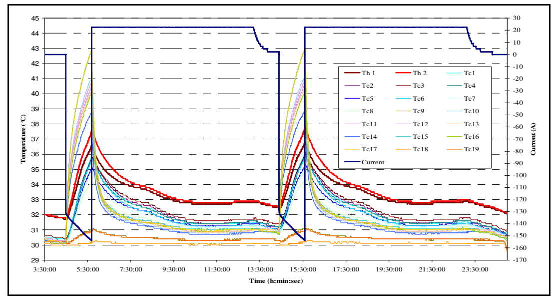


Figure 14. Hot cycle at 30°C in thermal vacuum

Dedicated condensed and reduced Thermal Mathematical Models using international standards and codes can be delivered on request to predict with accuracy the Saft battery behavior in satellite thermal model.

The qualified Li-ion cells temperature range is extended from -10°C to +60°C. Cells electrochemical definitions allow cells operation, in this temperatures range, taking into account cautions based on Saft expertise in Li-ion electrochemistry. Nevertheless, actual in-orbit operating temperature range is defined thanks to Life-Tests realized on cells and necessary margins included in 'State Of the Art' of in-orbit use of equipments.

Saft recommends in-orbit temperatures for cells in operation or in stand-by, depending of cells State Of Charge and type of mission (GEO Solstice or Equinox, LEO, MEO, launch, transfer orbit, ...).

6. CONTROL OF PRODUCTION QUALITY

In order to maintain the qualification status and to confirm the performances achieved during qualification programs, extremely fine surveillance and inspections were established, strictly followed and controlled by the Quality Department. These inspections start from the parts incoming controls, and check of the full and complete required traceability, then are pursued during each battery manufacturing step with the detailed recordings in Batteries log-book, and finally are ended by the completion of all the battery testing campaign.

And since the heart of the Batteries is the Cells, materials and processes used in Saft Li-ion Cells are especially meticulously managed under configuration. Regular MPCB's are performed at cell level in addition to the huge number of controls for each step of the manufacturing and the systematic quality inspection points.

Complete and detailed materials list, parts list and processes list are provided to customers. And full traceability from cell electrodes raw materials up to battery structure and components is always available.

And in case of any evolution, wherever the evolution occurred in the Battery or inside the cells, detailed analysis, validation by tests and justifications, are submitted to Customers for approval before any change implementation.