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Saft lithium-ion energy and power storage technology

Michael Saft [a,*], Guy Chagnon [a], Thierry Faugeras [b], Guy Sarre [b], Pierre Morhet [b]

[a] *Saft Advanced Technology Division, 107 Beaver Court, Cockeysville, MD 21030, USA*
[b] *Saft, 111 Boulevard Alfred Daney, 33074 Bordeaux, Cedex, France*

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Abstract

Since they were first introduced in the early 1990s, lithium-ion batteries have enjoyed unprecedented growth and success in the consumer marketplace. Combining excellent performance with affordability, they have become the product of choice for portable computers and cellular phones. Building on the same energy and life cycle attributes which marked their consumer market success, but adding new high power storage capability, lithium-ion technology is now poised to play a similar role in the transportation sector. With major programmes in both high capacity and high power lithium-ion technology, Saft has developed a family of products which can address the power and energy storage needs for vehicles, utilities, aviation, satellites, and other applications where light weight, long life, and excellent energy or power storage capabilities are needed. Although further development and refinements are underway, Saft has made a major commitment to bring this technology to the market with the establishment of a major pilot and research facility in Bordeaux France. This paper discusses the performance of this family of products and their potential applications. © 1999 Elsevier Science S.A. All rights reserved.

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1. Introduction

In 1993, under the sponsorship of the European Community and the French Ministry of Industry, Saft initiated a programme to develop a lithium-ion electric vehicle battery. Since then, Saft has evolved the technology through four generations of electro-chemistry. Today several vehicles are in road test in Europe using Saft lithium-ion batteries. As part of this evolution, Saft has developed an integrated modular concept to provide both design flexibility and packaging efficiency. With abuse tolerance being a primary objective of Saft's programme, the batteries currently being road tested have demonstrated an energy density of 100 W h kg^{-1} at the battery level, with a target of achieving 120 W h kg^{-1} by the summer of 2000.

In 1996, concurrent with, but independent of, the EV programme, Saft undertook a Phase I programme under the sponsorship of the Partnership for a New Generation of Vehicle (PNGV) to evaluate the applicability of lithium-ion technology for use as a power storage device for Hybrid Electric Vehicles (HEVs). During this programme, Saft demonstrated that a properly designed lithium-ion cell could exhibit outstanding power characteristics, and concurrent excellent cycle life. In 1997 Saft was awarded a Phase II programme to scale up the technology to a module level. Since then Saft has developed and demonstrated two cell sizes (6 A h and 12 A h), and an air-cooled 50 V integrated module.

Currently, Saft has integrated the experience and knowledge gained through its High Power and High Energy programmes to develop a new type of Dual Mode Cell which exhibits high energy and high power capabilities and is targeted for Hybrid Electric Vehicles designed to have significant, pure electric drive, autonomy.

2. High energy lithium-ion

Saft's initial development lithium-ion EV batteries focused on prismatic designs. After initial evaluation, it was

* Corresponding author

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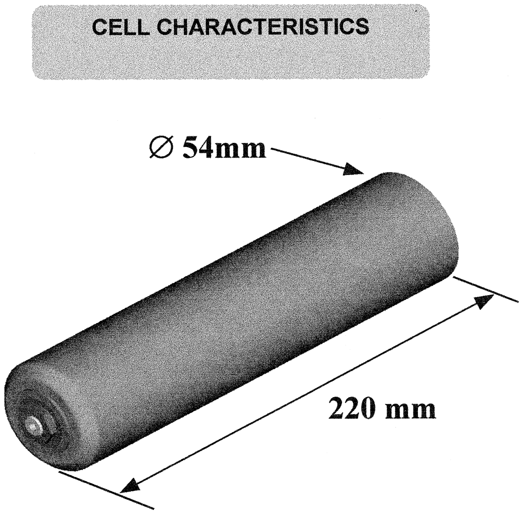

Fig. 1. Saft lithium-ion cell.

Table 1
Saft lithium-ion cell performance

Electrical characteristics	
Nominal voltage (V)	3.6
Capacity at C/3 rate (A h)	44
Specific energy (W h kg^{-1})	138
Energy density (W h dm^{-3})	304
Specific power (W kg^{-1})	> 300
Power density (W dm^{-3})	642
Mechanical characteristics	
Diameter (mm)	54
Height (mm)	220
Weight (kg)	1.07
Volume (dm^3)	0.5
Operating conditions	
Operating temperature range (°C) as provided by the thermal management system	−10/+45
Transport or storage temperature range (°C)	−40/+65
Voltage limits:	
on charge (V)	4
during discharge (V)	2.7

determined that a cylindrical form factor offered both performance and manufacturing advantages, specifically with respect to quality control, automated assembly and reproducibility on an industrial scale. Fig. 1 shows the current cylindrical design. Table 1 shows a chart of the high-energy lithium-ion cell performance data.

Having decided on a cylindrical cell design, Saft next tackled the issue of physical packaging within the automotive envelope. Compounding this challenge was the realization that individual carmakers have different energy and voltage requirements, yet all were unanimous in their desire to have the lowest possible cost for the product. Conventional wisdom would dictate different designs for the various customer voltage requirements, but such a strategy would by necessity have lead to a reduction in standardization with associated higher manufacturing costs, exactly the opposite of what is needed by the industry.

Facing this challenge, Saft developed an innovative solution. Utilizing a common six-cell, module, Saft engineers incorporated design flexibility by providing the capa-

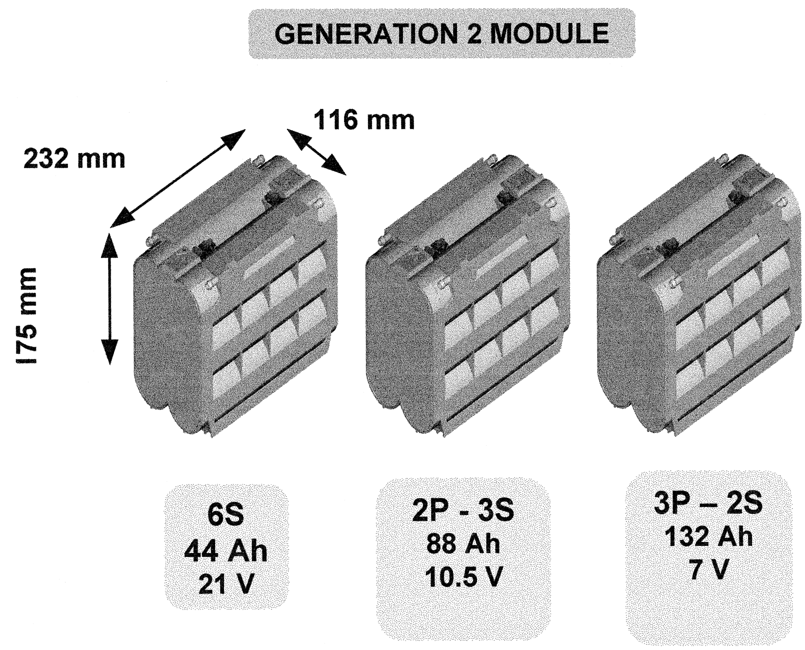

Fig. 2. Flexibility of the lithium-ion module design.

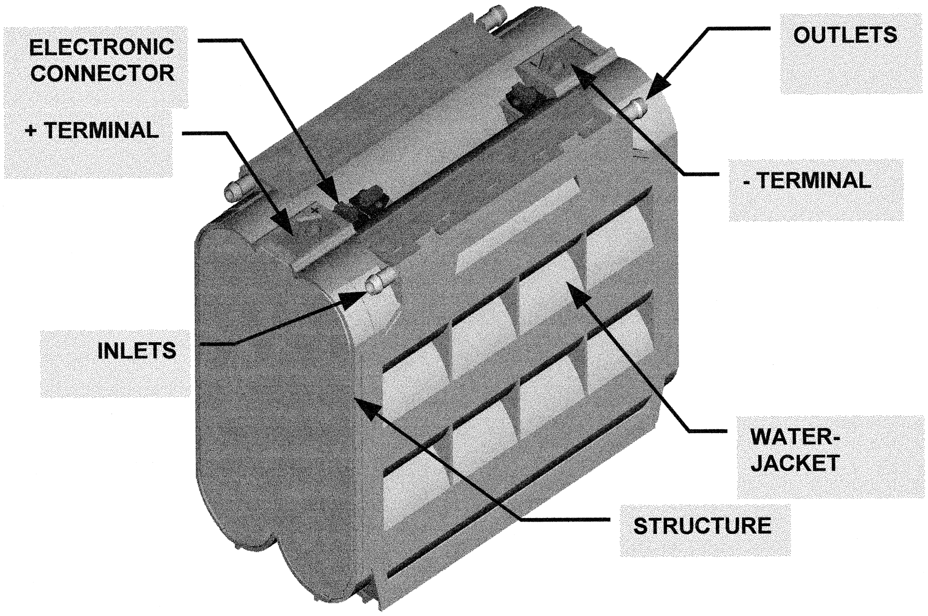

Fig. 3. Schematic of lithium-ion module.

bility for the same module to be provided with three different voltages and capacities by internally connecting the cells in various, but fixed, series and parallel connections. Thus the standard Saft module can be supplied in 21, 10.5 or 7 V configurations providing design flexibility without compromising industrial manufacturing efficiency. Module dimensions and the ability to reconfigure the module for its three design voltages is illustrated in Fig. 2.

Saft's innovative design places individual cell monitoring and control at the module level, effectively utilizing a hierarchical approach for cell, module, and battery control. Each module is designed to monitor and control the charge and discharge of the individual cells contained within the module as well as communicate information to the next higher level battery and vehicle control systems. Additionally each module is designed to provide over-charge detection and short-circuit protection. The entire system is further designed to allow individual module by-pass, thus allowing the battery to continue to power the vehicle even if an individual cell or module fails. This added feature further enhances the user-friendliness of the Saft system. The module is liquid cooled, thus providing more precise

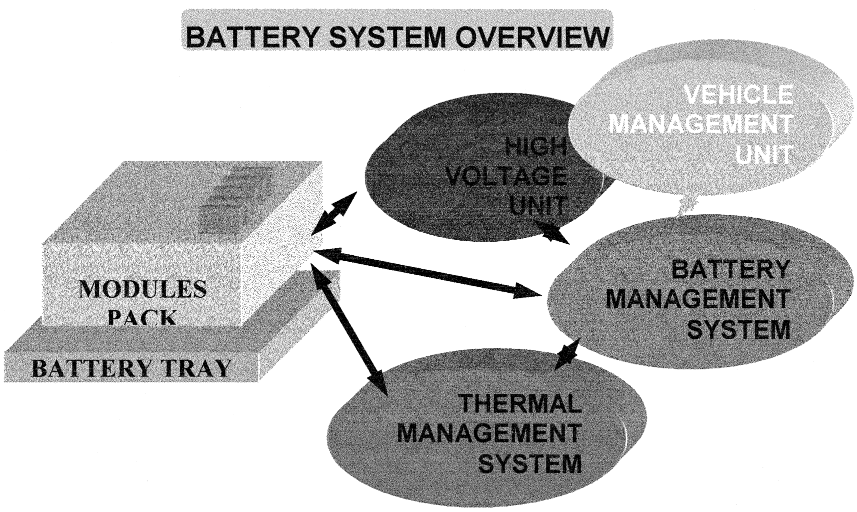

Fig. 4. Saft lithium-ion. 'Total Battery Package'.

Table 2
The performance at module level of current electrochemistries

Specific energy (W h kg^{-1})	138 (ECE 15) 120 (D/2)
Energy density (W h dm^{-3}) (ECE 15)	223
Specific power (W kg^{-1}) (80% DOD)	230
Cycle life (80% DOD)	1000 cycles performed
Safety (EUCAR procedure)	flames fumes

Table 3
Performance of the high energy battery system

Specific energy (W h kg^{-1})	105 (ECE 15) 95 (D/2)
Energy density (W h dm^{-3}) (ECE 15)	119
Specific power (W kg^{-1}) (80% DOD)	200
Cycle life (80% DOD)	200 cycles performed
Safety	not yet tested

and effective thermal management for both warm and cold weather operation as well enabling fast charging strategies. A more descriptive view of the Saft module is shown in Fig. 3.

The modules are further combines into an integrated battery pack which incorporates the modules, the thermal management system and the centralized electronic controls. This design philosophy is straightforward as illustrated in Fig. 4. The concept is to provide a self-contained unit, which provides the needed energy, with all the controls and management functions, integrated into the package. Effectively this becomes an energy black box, which is then installed on the vehicle. As specific battery designs are considered proprietary by our customers, illustrations of specific pack designs are not possible within the scope of this paper.

3. Performance

Summaries of the performance for Saft's chemistry at the module and battery level are contained in Tables 2 and 3.

Specific cycle data are given in Ref. [1].

4. Abuse tolerance

For any EV battery system to be utilized in a commercial vehicle it must not only provide acceptable performance at affordable cost, but it must also exhibit acceptable tolerance to abuse conditions. Saft has viewed accept-

Table 4
Electrical abuse test requirements

	Radiant heat	Thermal stability	Thermal insulation	Overheat	Thermal shock	Elevated temp. store	Extreme cold temp.	Fire test
UN (transportation)					T1–T2 48 h 75°C 6 h −20°C 24 h RT			
USABC	890°C for 10 min	5°C increments, each 30 min		thermal control removed. 20 cycles at C rate	+80°C/−40°C for 6 h 5 cycles	2 months storage at 60/80°C	0° −20°C −40°C	
EUCAR								2 min on fuel fire

Table 5
Mechanical abuse test requirements

	Altitude simulation	Shock test	Drop test	Penetration test	Rollover	Immersion	Crush test
UN (transportation)	T1 Pressure: 11.6 kPa for 6 h	T2–T3–T5 50 g, 11 ms					T4 $F \leq 10$ Kn rod
USABC		25 g, 30 ms 35 g, 51 ms 25 g, 60 ms	Height: 10 m dia: 150 mm	nail diameter: cell—3 mm module—10 mm	one turn, then stop 1 h for each 90°	2 h in salt water	$F = 1000 \times$ weight. dia. 150 mm
EUCAR							$F = 1000 \times$ weight. dia. 150 mm

Table 6
Specific energies of lithium-ion cells for tolerance of abuse

	Cell	Module
Penetration	103 W h kg^{-1}	89.5 W h kg^{-1}
Short-circuit (3 mΩ)	130 W h kg^{-1}	113 W h kg^{-1}
Over-charge C/10	130 W h kg^{-1}	113 W h kg^{-1}
Over-discharge C/2	130 W h kg^{-1}	113 W h kg^{-1}
Immersion		113 W h kg^{-1}
Crush		113 W h kg^{-1}
Fire test		113 W h kg^{-1}
Short circuit (2 mΩ)		113 W h kg^{-1}
Over-charge		113 W h kg^{-1}

Table 8
Lithium-ion performance objectives

	July 1999	September 2000	Ultimate goal
Specific energy (W h kg^{-1}) (D/2)	100	120	140
Specific power (W kg^{-1}) (80% DOD)	200	230	270
Cycle life (80% DOD)	600	800	1000
Safety (EUCAR procedure)	no flames	no flames no fumes	no flames no fumes

able abuse tolerance as a necessity throughout its development programme. With extensive testing Saft has learned that such performance is a combination of system and component design and engineering, coupled with an appropriate selection of materials. One of the challenges all developers have faced is the multiple criteria required from different world-wide agencies. Examples of the multiplicity of such tests are shown in Tables 4 and 5.

By incorporating comprehensive safety testing within its development programme, Saft has made major progress in developing a system that has demonstrated acceptable tolerance to abuse. Table 6 illustrates the specific energies at which cells demonstrate acceptable tolerance to abuse. Nonetheless, this is an ongoing area of focus and development as Saft strives to further improve safety performance.

5. Vehicle testing

The proof of any technology is when it is taken off the bench and put into its actual application. A major goal of Saft's programme has been to transfer its lithium-ion EV technology from the laboratory into actual vehicles as rapidly as possible. To meet this objective, two batteries, made with the Generation 1 modules, BMS and thermal management system, were tested on vehicles during 1998. These road tests are establishing the mechanical integrity of the module battery concept and the ability of the BMS to manage the battery in a automotive EMI environment. A brief description of the two test vehicles and incorporated system is shown in Table 7.

Table 7
Generation 1 lithium-ion battery road test summary

Project	VE 2000	Vedelic
Car	Renault Megane Scenic	Peugeot 106
Battery	30 modules 1 container 270 kg	14 modules 2 container 130 kg
Battery weight/vehicle weight	265 kg/1450 kg	130 kg/875 kg
Energy	28.9 kW h (ECE15)	13.5 kW h (ECE15)

6. Future development

As an ongoing programme, Saft's objectives are to simultaneously improve performance while concurrently driving down the cost of manufacturing. In addition to Saft's ongoing technical development effort, a major milestone in addressing the cost portion of this equation was Saft's investment and establishment of a lithium-ion pilot-production facility in Bordeaux, France. This state of the art facility is capable of assembling commercial quality cells, modules, and batteries using industrial scale equipment and processes, and began operation early in 1999. As to future performance, Table 8 shows Saft's targets for its high-energy lithium-ion battery system, both for the immediate future and long term.

7. High power lithium-ion

7.1. Background

The PNGV was established in 1994 with the objective of developing a vehicle with three times the fuel economy of current mid-size vehicles without compromising performance, safety and comfort standards. A key to this objective is utilization of hybrid drive systems that use an

Table 9
PNGV battery requirements

System	Power-assist. fast response engine	Power-assist. slow response engine	Dual mode
Energy (kW h)	0.3	3	8
Peak power (kW)	25	65	65
P/E ratio	83	22	8
Mass (kg)	40	65	115

Table 10
PNGV power-assist battery performance targets

	Low energy	High energy
Pulse discharge power (18 A/kW)	25	65
Peak regenerative pulse power (10 A/kW)	30	70
Total available energy at C/1 (kW h)	0.3	3
Life cycle for specific	200,000 for 25 W h	120,000 for 100 W h
SOC increment (cycle)	50,000 for 100 W h	20,000 for 600 W h
System weight (kg)	40	65
System volume (dm^3)	32	40
Temperature operation (°C)	−40/+52	−40/+52

energy storage device that can feed power back into the power train to provide energy for high power incremental loads, e.g., acceleration.

The advantage of such a system is that it permits the main engine to work within a narrower power band thus optimizing efficiency and improving fuel economy. However, unlike a pure Electric Vehicle (EV) which requires the capability for high-energy storage and moderate power for long deep-discharge cycles, a hybrid system places a premium on the ability to store and deliver power and high cycle life during shallow depths of discharge.

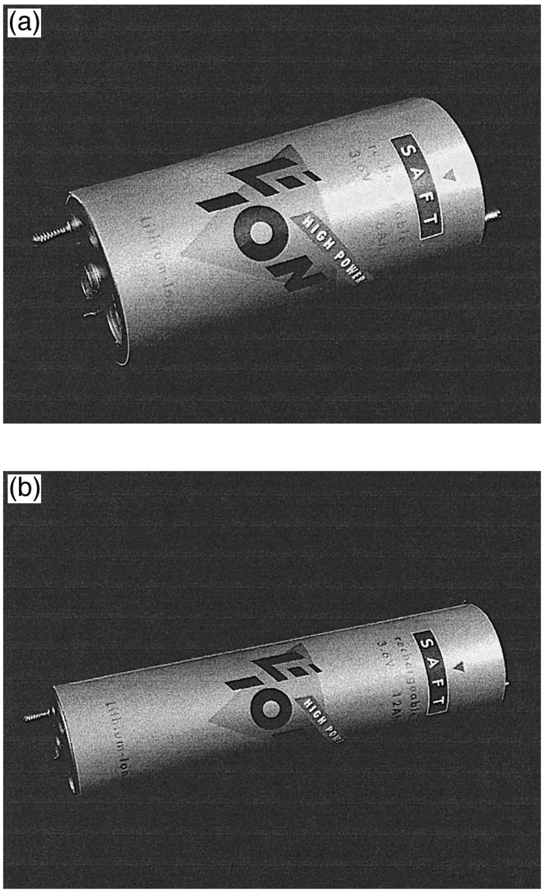

Fig. 5. (a) 6 A h cell. (b) 12 A h cell.

For HEV's there are two classes of storage that must be addressed: power-assist with a relatively small battery, and dual mode with larger capacity batteries capable of enabling HEVs to operate in both hybrid and pure electric modes. Within the domain of power-assist HEVs there are fast response (internal combustion) and slow response (fuel cells or turbines) engines. The difference as it relates to power and energy storage is that in a fast response engine the Auxiliary Power Unit (APU) can provide power for a limited duration, thus sharing the load with the energy storage device. In a slow response engine, the energy storage system provides all the power during periods of acceleration. Finally, for a dual mode system, the energy storage device must provide sufficient energy to give pure electric operation for limited periods of time. The consequence of these operational modes on the battery system is illustrated in Table 9 and the respective PNGV battery technical requirements for power-assist battery systems in Table 10. These represent performance requested at the initiation of the programme in 1996.

In addressing these challenges under its Phase I PNGV programme, Saft was able to demonstrate with lithium-ion technology a peak power handling capability in excess of 1300 W kg^{-1} during both charge and discharge, concurrent with a cycle life of over 140,000 cycles for a specified test profile. Based on these results, Saft was awarded a

Table 11
Characteristics of the high-power cells

	6 A h	12 A h
Electrical characteristics		
Nominal voltage (V)	3.6	3.6
Capacity at C/3 rate (A h)	6.5	13
Specific energy (W h kg^{-1})	64	70
Energy density (W h dm^{-3})	135	150
Specific power (W kg^{-1})	1500	1350
Power density (W dm^{-3})	3100	2900
Mechanical characteristics		
Diameter (mm)	47	47
Height (mm)	104	180
Weight (g)	375	680
Volume (dm^3)	0.18	0.31
Operating conditions		
Operating temperature range (°C) as provided by the thermal management system	−10/+45	
Transport or storage temperature range (°C)	−40/+65	
Voltage limits:		
on charge (V)	3.9	
during discharge (V)	2.1	

Phase II contract to scale up the technology to larger size cells and modules.

7.2. Phase II programme

Under its Phase II contract, Saft developed two sizes of high-power lithium-ion cells, 6 A h and 12 A h, and the associated air-cooled modules. A picture of these cells is shown in Fig. 5a and b with their dimensions and nominal performance in Table 11.

For these cells to become the basis for a commercial product, three criteria have to be met. First performance

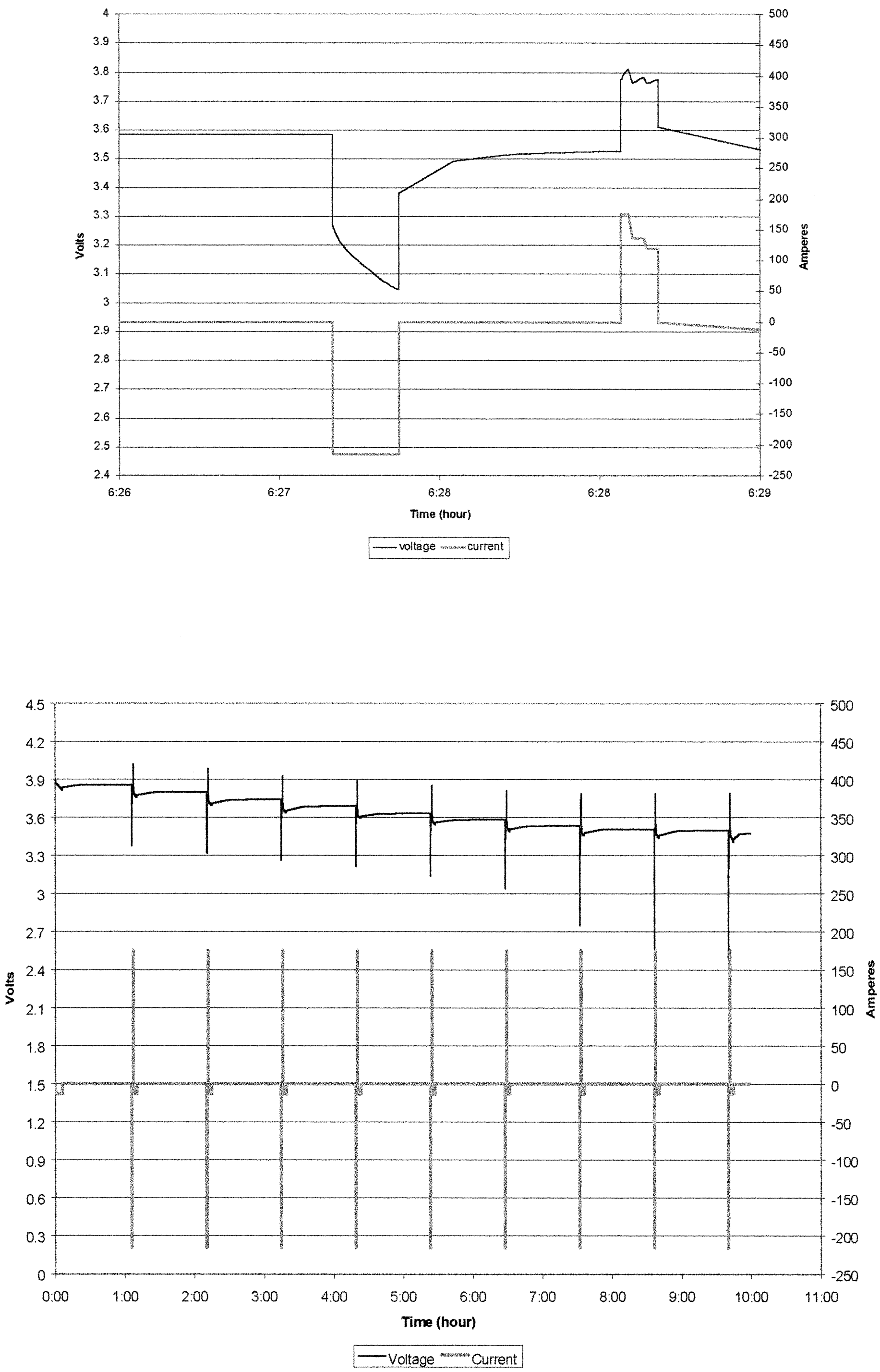

Fig. 6. High-power test profiles. Pulse currents and voltages against time.

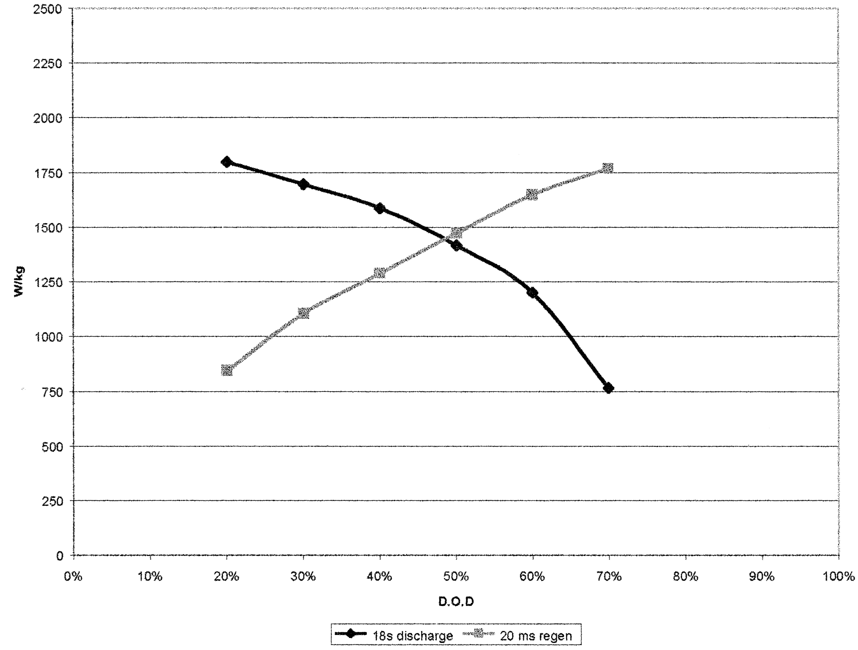

Fig. 7. Charge–discharge results.

must be deemed acceptable, secondly, they must be low in cost and lastly, they have to demonstrate acceptable to abuse. With respect to performance, as shown in Table 10, using a high-power test profile (Fig. 6) both cells show excellent power characteristics (> 1350 W kg^{-1} derived peak power) coupled with good energy density (64 and 70 W h kg^{-1} respectively, Fig. 7). In addition cycle life testing of 6 A h cells demonstrate that the results of Phase I were reproducible on samples of 6 A h cells (Figs. 6–8).

To fully characterize the abuse tolerance of the system, a series of tests were performed on more than 50 cells with all external and internal safety devices (e.g., fuses) removed. This demanding criteria enables a 'worse case' evaluation to be made, as it simulates performance if all external or internal fuse-protection fails. The abuse tolerance characterization was done following the USABC test procedure manual. The series of tests conducted included short circuit, overcharge, nail penetration, and 150°C heat-

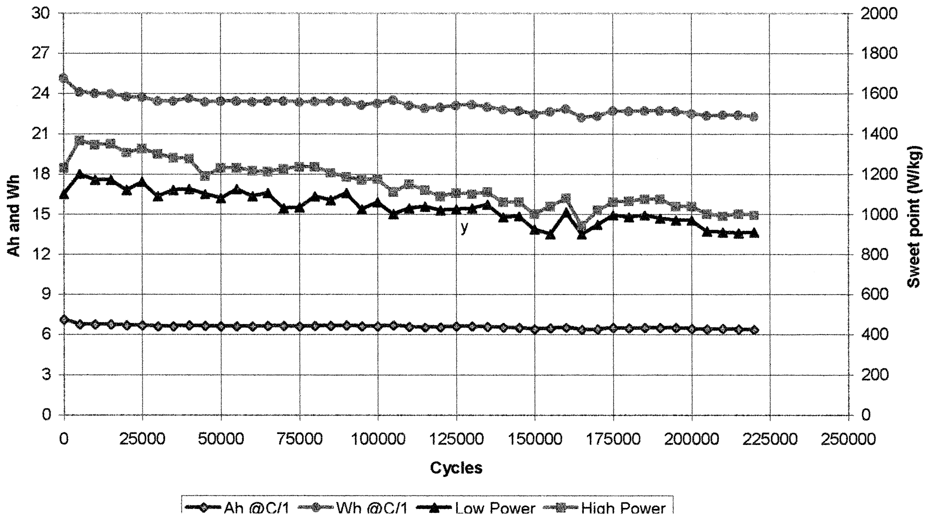

Fig. 8. Performance of 6 A h cell during 225,000 cycles.

Table 12
Abuse test results on 6 A h and 12 A h cells

Test description	Test results	Comments
Nail test (70 and 100% SOC)		
6 A h	smoke (max. temp.: 214°C)	A few ‘weld’ sparks during penetration
12 A h	smoke (max. case temp.: 288°C)	
Short circuit (70 and 100% SOC)		
6 A h	vent of electrolyte (max. case temp.: 109°C)	arcing due to (−) terminal rupture. Redesign successful.
12 A h	vent of electrolyte (max. case temp.: 70°C)	
Heat test (ramp up to 150°C in 30 min event after 45 more min)		
6 A h (70 and 100% SOC)	smoke (max. case temp.: 306°C)	
12 A h (100% SOC only)	smoke (max. case temp.: 334°C)	
Crush (70% SOC)		
6 A h	vent only (max. case temp.: 66°C)	
12 A h	smoke (max. case temp.: 241°C)	
Impact drop test (70% SOC)	no event	
Overcharge (total of 200% SOC, current rate 100 A)	no event (max. case temp.: 59°C)	
Over-discharge (current reversal)	no event (max. case temp.: 48°C)	
Salt water immersion (70% SOC—8 h)	no event (terminal corrosion–voltage at end of test about 3.4 V)	

1. 100% SOC corresponds to 3.9 V.
2. More than 50 cells have been tested to date.

ing test. During this series of tests, no flames or explosions were observed on either the 6 A h or 112 A h cells. A formal programme review concluded that cell abuse performance was considered ‘excellent’ for the HEV application with energy needs of up to 1 kW h. A summary of the testing for 6 A h and 12 A h cells is shown in Table 12. Fig. 9 shows a series of cells that have undergone several of these tests including crush and nail penetration.

At the present time, Saft is completing development and evaluation of air-cooled 6 and 12 A h 47 V modules (Fig. 10). Module voltage for both will be a nominal 47 V, with the 12 A h system delivering 63 W h kg^{-1} and power density of 1250 W kg^{-1} or 1400 W dm^{-3}. Saft anticipates that bench and vehicle testing of these battery systems will occur during 1999. Although not discussed, the Saft high-power cells can support advanced ICE applications, including alterno-starters.

7.3. Dual mode lithium-ion programme

The concept of an HEV capable of pure electric operation has become an attractive option to the automotive industry. In part, this type of vehicle would couple the capability of meeting stringent air quality requirements in urban environments, with the ability to meet drivers needs for extended range, such as inter-city travel. The flexibility of this technology has been recognized by the staff of the California Air Resource Board, which have proposed sig-

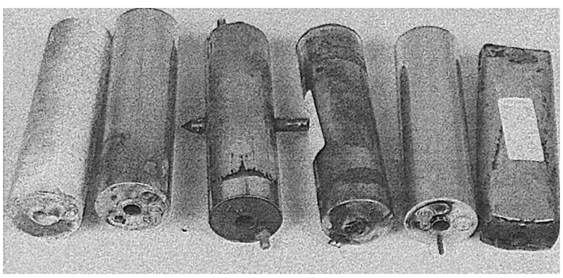

Fig. 9. 12 A h cells after abuse testing.

Fig. 10. 47 V air-cooled high-power module.

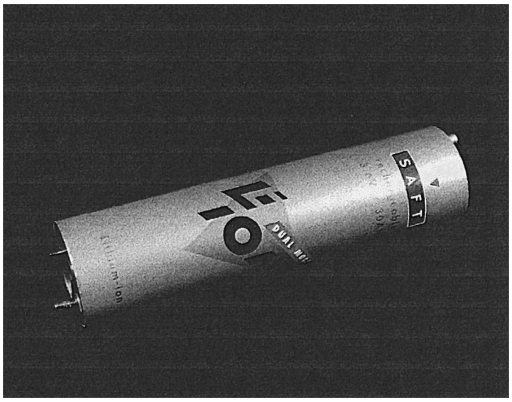

Fig. 11. Preliminary design of a dual mode cell.

nificant ZEV credits for vehicles which couple Super Ultra Low Emission operation in the ICE mode with a pure electric drive capability in excess of 17 miles.

To enable carmakers to design vehicles which can capitalize on the proposed CARB HEV requirements and/or their customer needs independent of mandates, Saft has coupled its High Power and High Energy capabilities to develop a preliminary Dual Mode cell. This preliminary cell design is intended to be either liquid or air-cooled; combining both high energy-density cells (100 W h kg^{-1}) with excellent power capability (950 W kg^{-1}). Fig. 11 shows this preliminary cell, and Table 13 summarizes the preliminary performance specifications and physical dimensions of the cell. Saft is in the process of modifying the design to meet specific carmaker requirements.

8. Conclusion

Saft has developed a family of lithium-ion cells, modules and batteries that provide the transportation industry with a full spectrum of performance for electric, hybrid-electric, and even internal combustion vehicles. Continuous development and refinement have moved the technology rapidly forward to where systems are currently undergoing vehicle testing and evaluation. A major commitment and programme is underway to industrialize these products so as to have adequate quantities available for the automotive industry to support the full range of advanced vehicles which will become a reality in the 21st century.

Table 13
Preliminary characteristics of the dual mode cell

Electrical characteristics	
Nominal voltage (V)	3.6
Capacity at C/3 rate (A h)	30
Specific energy (W h kg^{-1})	100
Energy density (W h dm^{-3})	220
Specific power (W kg^{-1})	950
Power density (W dm^{-3})	2.100
Mechanical characteristics	
Diameter (mm)	54
Height (mm)	220
Weight (g)	1.12
Volume (dm^3)	0.5
Operating conditions	
Operating temperature range (°C) as provided by the thermal management system	−10/+45
Transport or storage temperature range (°C)	−40/+65
Voltage limits:	
on charge (V)	3.9
during discharge (V)	2.1

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