

AFRL-PR-WP-TP-2007-215

**AIRCRAFT BATTERY DESIGN
PROJECT FOR IMPROVED ULTRA
LOW TEMPERATURE
PERFORMANCE (POSTPRINT)**



**John K. Erbacher, Gary J. Loeber, Sarah M. Owens,
and Cameron A. Riepenhoff**

NOVEMBER 2006

Approved for public release; distribution unlimited.

STINFO COPY

© 2006 SAE International

**The U.S. Government is joint author of the work and has the right to use, modify,
reproduce, release, perform, display, or disclose the work.**

**PROPULSION DIRECTORATE
AIR FORCE MATERIEL COMMAND
AIR FORCE RESEARCH LABORATORY
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251**

REPORT DOCUMENTATION PAGE				<i>Form Approved</i> OMB No. 0704-0188	
<p>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YY) November 2006		2. REPORT TYPE Conference Paper Postprint		3. DATES COVERED (From - To) 07/22/2005 – 09/12/2006	
4. TITLE AND SUBTITLE AIRCRAFT BATTERY DESIGN PROJECT FOR IMPROVED ULTRA LOW TEMPERATURE PERFORMANCE (POSTPRINT)				5a. CONTRACT NUMBER In-house	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER 62203F	
6. AUTHOR(S) John K. Erbacher, Gary J. Loeber, and Sarah M. Owens (AFRL/PRPS) Cameron A. Riepenhoff (University of Dayton Research Institute)				5d. PROJECT NUMBER 3145	
				5e. TASK NUMBER 22	
				5f. WORK UNIT NUMBER 9Q	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Electrochemistry and Thermal Sciences Branch (AFRL/PRPS) Power Division Propulsion Directorate Air Force Research Laboratory, Air Force Materiel Command Wright-Patterson Air Force Base, OH 45433-7251			8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-PR-WP-TP-2007-215		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Propulsion Directorate Air Force Research Laboratory Air Force Materiel Command Wright-Patterson AFB, OH 45433-7251				10. SPONSORING/MONITORING AGENCY ACRONYM(S) AFRL-PR-WP	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-PR-WP-TP-2007-215	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES Conference paper submitted to the Proceedings of the 2006 SAE Power Systems Conference, published by SAE International. © 2006 SAE International. The U.S. Government is joint author of the work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. PAO Case Number: AFRL/WS 06-2249; Date cleared: 21 Sep 2006. Paper contains color.					
14. ABSTRACT The AFRL, Electrochemistry and Thermal Sciences Branch has evaluated numerous aircraft battery designs and chemistries since the 1960s. Recent experiments on advanced battery chemistries have shown poor performance at ultra low temperatures below -20 °C. Aircraft battery designs stress low weight and volume and maximum capacity. One design concept uses lower capacity cells in a series parallel configuration to reduce overall battery resistance and should also improve ultra low temperature performance. Our organization has begun experiments with series-parallel cell designs to evaluate the concept and to solve low temperature performance issues. Progress, observations on the effect of different chemistries, and the impact on aircraft battery characteristics are discussed.					
15. SUBJECT TERMS Aircraft Batteries, Parallel Design, Ultra Low Temperature					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT: SAR	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON (Monitor) Gary J. Loeber 19b. TELEPHONE NUMBER (Include Area Code) N/A
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			

Aircraft Battery Design Concept for Improved Ultra Low Temperature Performance

John K. Erbacher, Gary J. Loeber, and Sarah M. Owens

Air Force Research Laboratory, AFRL/PRPS, Wright-Patterson AFB, OH 45433-7251

Cameron A. Riepenhoff

University of Dayton Research Institute – Metals and Ceramics, Dayton, OH 45469-1614

Copyright © 2006 SAE International

ABSTRACT

The AFRL, Electrochemistry and Thermal Sciences Branch has evaluated numerous aircraft battery designs and chemistries since the 1960s. Recent experiments on advanced battery chemistries have shown poor performance at ultra low temperatures below -20°C . Aircraft battery designs stress low weight and volume and maximum capacity. One design concept uses lower capacity cells in a series parallel configuration to reduce overall battery resistance and should also improve ultra low temperature performance. Our organization has begun experiments with series-parallel cell designs to evaluate the concept and to solve low temperature performance issues. Progress, observations on the effect of different chemistries, and the impact on aircraft battery characteristics are discussed.

INTRODUCTION

The Air Force Research Laboratory (AFRL), Electrochemistry and Thermal Sciences Branch (PRPS) has evaluated numerous aircraft battery designs and chemistries since the 1960s. Recent experiments on advanced battery chemistries [1] have shown poor performance at ultra low temperatures below -20°C . Aircraft battery designs have emphasized low weight, small volume, and maximum performance at minimal costs over the temperature range -40° to $+60^{\circ}\text{C}$. Since the mid 1990s the temperature range has increased on new aircraft procurements such that some batteries are expected to perform at temperatures lower or higher than the above range depending on the application.

Based on the weight, volume, performance and temperature criteria battery designers typically use serial cell connections with the minimum number of cells and connectors to improve reliability and provide a robust low cost battery such as in Figure 1. However, if the desired performance at ultra low temperatures is not

met, design changes are necessary. These design changes typically reduce the overall capacity of the cell and result in what is referred to as a high power design. Such a design will typically have a higher price than a regular battery due to use of special materials, designs, and packaging.

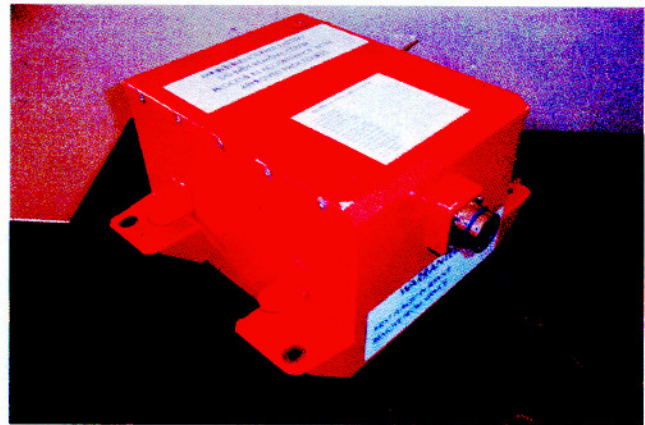


Figure 1. Typical VRLA Aircraft Battery

Some of these design changes include using higher capacity cells, thinner cell plates (increases the surface area for the chemical reaction) within the cells, square versus rectangular cells (shorter current path), and specially designed electrolytes for low temperature operation (higher conductivity). All of these result in a non standard cell or battery which increases costs. In most cases, these measures have the desired effect and enable the battery to meet the performance requirements of the particular aircraft system.

PARALLEL-SERIES DESIGN CONCEPT

One concept that appears to have been overlooked in designing a battery for low temperature performance is to use lower capacity cell packs in a parallel-series configuration which significantly reduces battery resistance and should also improve ultra low

temperature performance. Equation 1 describes the general resistance of a parallel circuit and is used to describe the internal resistance of a battery. In equation 1, R_t is the total resistance of the circuit (battery), R_1 is the resistance of the first circuit element (cell pack) and R_2 is the second cell pack, etc.

$$1/R_t = 1/R_1 + 1/R_2 + \dots + 1/R_n \quad (1)$$

Based on equation 1 the resistance of a battery will decrease as the number of cell packs in parallel increases. For ultra low temperature performance you want the internal resistance of the battery as low as possible consistent with minimizing the number of cells to comply with weight and volume restrictions of the design. For instance if each cell has the same resistance then placing them in parallel will reduce the battery resistance by a factor of three and should show markedly better low temperature performance compared to one cell being tested by itself. This design concept improves low temperature performance because the load across the battery is shared over the number of cell packs in parallel which effectively increases the surface area for the chemical reaction or, to put it another way, it reduces the current density within the battery improving low temperature performance. Naturally, there is a physical limit to the reduced battery internal resistance which is dependent on the number of interconnects electrolyte resistance, etc.

PRACTICAL EXAMPLE

Suppose company ABC wants to design and produce an aircraft battery that operates at a nominal 28 VDC and has a 20 Ah capacity. We'll ignore the low temperature requirement for the moment. Using existing lead-acid cells operating at 2.2 V or nickel-cadmium (Ni-Cd) and nickel-metal hydride (Ni-MH) cells operating at 1.2 V or lithium-ion (Li-ion) cells at 4.0 V per cell one would need 11 lead-acid, 20 Ni-Cd/Ni-MH or 8 Li-ion cells in series to obtain the battery voltage and each cell would have to be 20 Ah in size to make up our theoretical battery. Using a series-parallel design one could use as many as 10 cell packs at 2 Ah per cell pack to make up the 20 Ah battery or any easy multiple in between 2 and 20. If the standard size cell company ABC already produces by the millions for the XYZ commercial application is 4 Ah then you could use five commercial cell packs in parallel. Hence you would not have to retool your production facility to make a nonstandard cell size (for you) nor would you have to charge an exorbitant amount for this special design battery to pay for the nonrecurring engineering (NRE) costs associated with the new cell design.

EXPERIMENTAL PROGRAM

During the last year PRPS experimented with parallel cell designs to evaluate the concept and to help solve

low temperature performance problems. Our preliminary results using available assets did show a marked improvement in ultra low temperature performance using two strings of cells in parallel [2]; however, further experiments were needed to eliminate an increased capacity effect and quantify the improvements.

Other areas that were not addressed were chemistry dependence of the concept and the optimum number of cell packs in parallel to maximize the effect consistent with application volume and weight restrictions. Questions that needed to be answered included:

- Is the concept valid across all battery chemistries?
- Does the effect vary depending on which chemistry you are using to design your battery?
- Does the overall battery weight and volume increase offset low temperature performance gains,
- How many cell packs in parallel maximizes low temperature performance, and
- What safety issues are associated with using a parallel-series configuration versus a series configuration, especially for Li-ion cells?

Our preliminary results [2] using available assets did show a marked improvement in ultra low temperature performance using two strings of cells in parallel; however, further experiments were needed to eliminate the increased capacity effect of the combined battery. Hence in designing the expanded test program we decided to address all these factors. However, because Li-ion chemistry is the hot chemistry for new aircraft batteries and the most expensive compared to legacy battery systems, PRPS elected to perform further experiments on Li-ion cells and use existing commercial production cells as the test specimens.

LITERATURE SEARCH

A literature search covering commercial and military battery articles and other publications over the last 50 years was conducted through the AFRL technical library. This search failed to identify any battery design and development programs that reported using a parallel-series cell design to meet low or ultra low temperature performance requirements.

TEST PLAN

PRPS elected to use 14 V half batteries for the test program to minimize budget expenditures and battery assembly required for the tests. This size allowed us to place four Li-ion cells in series to baseline the series interconnection resistance as there would be in a full size battery. Since the available capacities of commercial Li-ion cells varied somewhat a 19 Ah battery capacity was selected for the test. If the cells from one manufacturer exceeded this capacity by several Ah we could do an initial discharge to reduce the assembled

battery capacity to the target 19 Ah before conducting the low temperature part of the test in accordance with the test procedure reported earlier [2].

Test Assets

SAFT prismatic Ni-MH 28 V, 22 Ah batteries were available from previous work [2], but had to be split into 10 cell strings to make half batteries. Additional Li-ion test assets were identified from available commercial cylindrical and rolled prismatic cell designs. These cells were obtained from Panasonic, Inc. and SAFT America, Inc. In addition, some commercial Li-ion polymer cells were also chosen to ascertain if there is a cell internal design impact on the parallel cell pack battery design. The Li-ion polymer cells are available in several sizes available from Kokam America, Inc. Representative selected test cells are shown in Figures 3 to 6 and their reported characteristics are in Table 1. Cell sizes selected were those that led to a reasonable number of parallel cell packs in half battery configurations.

In discussions with SAFT over which of their commercial cells would best fit our test program, SAFT personnel indicated some of their developmental VL7P 7 Ah cells could be made available from cosmetic rejects from the developmental program. These cells had increased discharge rate capability over standard commercial cells and might provide some interesting data for the study. These cells were also included in the study but have not been procured at this time.



Figure 2. Two Battery Parallel Test Configuration [2]



Figure 3. Panasonic Cylindrical CGR 18650 E Cell



Figure 4. Representative SAFT Rolled Prismatic Cells



Figure 5. Representative Kokam Li-ion Polymer Cells



Figure 6. SAFT Developmental Cylindrical VL Cells

Half Battery Test Configurations

The half battery test configurations were:

- Panasonic – 8P4S, total capacity: 20.4 Ah
- SAFT MP176065 – 3P4S, total capacity: 19.8 Ah
- SAFT MP174865 – 4P4S, total capacity: 21.3 Ah
- Kokam SLPB 80431226H – 6P4S, total capacity: 19.2 Ah
- Kokam SLPB 11043140H4 – 4P4S, total capacity: 19.2 Ah
- SAFT VL7P – 3P4S, total capacity: 21.0 Ah

There is still internal debate as to whether to string the cells in series first and then in parallel or vice versa. The final decision will depend on which configuration provides the best overcharge and overdischarge protection.

Increased Capacity Effect

To resolve the increased capacity effect question, PRPS decided to use the existing Ni-MH cells shown in Figure 2 to insure there was an apples to apples comparison of the results. By splitting each battery we would have four strings of 10 cells which when combined in parallel would yield 22, 44, 66, or 88 Ah half batteries. The overall capacity would be determined as before, but the 44, 66, and 88 Ah half batteries would be discharged to bring the available capacity down to 19 Ah prior to initiating the low temperature performance test. This would allow comparisons with the Li-ion half battery test results later. However, there are inherent dangers in discharging the higher capacity batteries down to 19 Ah before running the planned test. Specifically, there could be some chemistry changes that affect how a seriously depleted battery behaves versus the fully charged or only marginally depleted battery. Before completing this test some additional literature search on the effect of degree of discharge on the chemistry reactions in a Ni-MH battery must be accomplished. This will verify if this is a valid method to perform the test and to make sure the results produce apples to apples comparison.

DISCUSSION

The parallel design battery test and evaluation project was initiated in late spring after management approval of the funding and project plan. The commercial Panasonic and SAFT test assets were acquired and are in the initial test stages before assembly into half battery configurations. We expect to have most of the testing completed by November 2006 and the results and conclusions will be presented at that time.

ACKNOWLEDGMENTS

Table 1. Li-ion Test Cell Characteristics

Company	Cell Designation	Type	Depth (mm)	Width (mm)	Height (mm)	Dia. (mm)	Capacity (mAh)	Max Rate (C)		Operating Temperature
								Dsch	Chrg	
Panasonic	CGR18650E	Cyl.			65.2	18.6	2,550	1C	CVC C	-20 to + 60 C
SAFT	MP 176065	Rolled Prism.	19.6	60	65		6,800	1.2C	1C	-20(C) to + 60 C -50(D) to + 60 C
SAFT	MP174865	Rolled Prism.	19.0	48	65		5,300	1.2C	1C	-20(C) to + 60 C -50(D) to + 60 C
Kokam	SLPB 80431226H	Prism. Poly	7.6	42.5	127.5		3,200	20C	3C	-30 to +60 C
Kokam	SLPB 11043140H4	Prism. Poly	7.6	42.5	127.5		4,800	20C	3C	-30 to +60 C
SAFT	VL7P	Cyl.			145	41	7,000	15C	C/2	+5(C) to +35 C -30(D) to +60 C

AFRL/PRPS gratefully acknowledges the donation of commercial cells for this program from Panasonic, Inc.

REFERENCES

1. AFRL/PRPS, Unpublished Observations, 2000-2005.
2. Loeber, GJ, Erbacher, JK, and Riepenhoff, CA, "Battery Design/Test Experiments for Advanced Aircraft," **Proceedings of the 9th Electrochemical R&D Symposium, Myrtle Beach, SC: 27-30 June 2005**, Naval Surface Warfare Center, Carderock Division, Bethesda, MD, 20817.

CONTACT

Dr. John K. Erbacher
 AFRL/PRPS
 1950 Fifth St., Bldg. 18G, Rm. 33
 Wright-Patterson AFB, OH 45433-7251
 Tel: (937) 255-2372 or 7770, Fax: (937) 656-7529,
 E-mail: john.erbacher@wpafb.af.mil

DEFINITIONS, ACRONYMS, ABBREVIATIONS

Ah: Ampere-hour, unit of measure of battery capacity

AFRL: Air Force Research Laboratory

Li-ion: Lithium-ion

Ni-Cd: Nickel-Cadmium

Ni-MH: Nickel-Metal Hydride

NRE: Non-Recurring Engineering

PRPS: Electrochemistry and Thermal Sciences Branch

R_n: Circuit Element "n" (Cell Pack) Resistance

R_t: Total Circuit (Battery) Resistance

VDC: Volts Direct Current

VRLA: Valve Regulated Lead-Acid

xPyS: Battery assembly nomenclature - x indicates no. of parallel (P) cells and y the no. of series (S) cells.