

System Integration of a Safe, High Power, Lithium Ion Main Battery into a Civil Aviation Aircraft

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Vernon W. Chang, Steven B. Waggoner and John W. Gallman
Cessna Aircraft Co.

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ABSTRACT

The Cessna Citation CJ4, certified on March 12, 2010, is believed to be the first civil aircraft with a Lithium Ion main battery. The 26.4VDC, 44Ah Lithium Ion main battery weighs 54 lbs, a 35% weight saving over a Nickel-Cadmium battery. Using phosphate-based Lithium Ion cells, which have no positive feedback thermal runaway failure mode, system integration of the battery and aircraft architecture design is simpler. Electronics and software are needed to optimize life only, not to ensure safety. Emergency discharge with failed electronics is enabled with the selection of a less volatile chemistry, the use of an analog Module Management System for cell balancing and protection, and the use of a microcontroller-based digital Central Monitoring System that reports health. System safety failure hazard assessment is considered Major, and the battery software is certified to the requirements of RTCA DO-178B, Design Assurance Level C. New Battery Fault and Battery Fail annunciations supersede the conventional Battery Overtemperature messages to accommodate other non-temperature related failure modes. Heaters enable performance at cold temperatures while its aircraft-in-the-loop circuit ensures safety. The Lithium Ion battery and the Cessna Citation CJ4 electrical bus and avionics suite designs were integrated to optimize performance, safety, protection, and maintenance frequency.

INTRODUCTION

The selection of a lighter battery and its successful integration into the aircraft system architecture will help improve aircraft performance and minimize aircraft weight, which are constant design goals in aviation. The battery is commonly considered to have the highest weight density of all components in an aircraft. Changing the battery from the conventional Nickel Cadmium (Ni-Cd) or Lead Acid (LA)

chemistries to higher energy density Lithium Ion (Li-Ion) chemistries could result in weight savings as high as 40%. Weight reduction of this single component will yield improvements in an aircraft's payload, range, and center of gravity characteristics. The challenge in realizing these benefits lie in the successful design and certification of the battery into the aircraft's system architecture.

Substantial research has been conducted to document failure modes and safety risks of the various Li-Ion chemistries and standards have been developed to mitigate these risks for space, military, and aviation applications [1, 2, 3, 4, 5, 6]. Despite having a similarly flammable electrolyte, tests show that the phosphate-based cathode chemistry has a significantly less volatile failure response to abusive, destructive, and burn conditions compared to the self-accelerating (positive feedback) thermal runaway response of some oxide-based cathode chemistries, [7, 8, 9, 10]. The more volatile failure mode of the oxide-based Li-Ion chemistry and the potential for the thermal runaway to create a chain reaction increases the challenges of integrating the battery into a certified aircraft because of the increased need for redundant safety devices.

The National Aeronautics and Space Administration (NASA) has deployed Li-Ion batteries for the space shuttle, satellites, and the Mars exploration rovers [2]. The Department of Defense has been flying Li-Ion batteries on the B-2 bomber since 2004 [11], is implementing a 270 VDC battery for the F-35 fighter [12] and is evaluating one for the CH-53K helicopter [13]. The Boeing 787 [14], Airbus A350XWB [15], and Gulfstream G650 [16] civil aviation aircraft intend to certify a large format, Li-Ion battery.

On March 12, 2010, Cessna model 525C, Citation CJ4, received its 14 CFR Part 23 aircraft type certificate, believed to be the first civil aviation aircraft to be certified with a Li-

Ion main battery [17, 18]. The addition of this safe, high power Li-Ion chemistry to existing choices of Ni-Cd and LA batteries results in faster engine starts with higher voltages for battery temperatures [7], higher temperature limits up to +71°C before required servicing, and no thermal runaway failure mode in a lighter 54 lb package [7]. The key specifications for this battery in Table 1 are a result of the nanoscaled phosphate-based cathode chemistry, the addition of battery electronics and heaters, and the aircraft systems integration design.

Table 1. Battery Specifications [19]

Description	Specification		
Nominal Voltage	26.4 Volts (V)		
Nominal Capacity	44 Ampere hours (Ah)		
Maximum Voltage	30.2V		
Minimum Voltage	20.0V		
Recommended Standard Charge	28.4V to 28.8V		
Recommended Float Charge	27.6V		
Recommended Charge Current	60 Amperes (A)		
Maximum Charge Current* (max. duration of 5 minutes)	400A		
Operating Temperature Range	-20°C to 63°C		
Storage Temperature Range	-20°C to 30°C		
Maximum Weight	54.0 lbs (24.5 kg)		
Shelf Life (from 100% to 80%)	63 days		
Shelf Life (from 100% to 20%)	253 days		
Constant Voltage Discharge Current	23°C (74°F)	-18°C (0°F)	-30°C (-22°F)
Ipp (0.3 sec)	1500 A	848	397
Ipr (15 sec)	1500 A	419	240

Optimization of the battery and aircraft systems architecture design for flight and maintenance has continued since this Li-Ion main battery's first flight at Cessna on August 16, 2007. This 44Ah Li-Ion main battery design consists of 28.5 VDC modules, a built-in digital Central Monitoring System (CMS) with an operating system (OS) and application software (AS). The Cessna Citation CJ4 electrical bus and avionics suite have been designed to integrate and maximize the benefits of the Li-Ion main battery while ensuring compatibility for Ni-Cd and LA batteries. A phosphate-based chemistry enabled certification of a Li-Ion battery for the CJ4 with relatively simple battery electronics and minimal changes to the aircraft architecture.

BATTERY DESIGN

The Li-Ion main battery, certified on the Cessna Citation CJ4, was designed to integrate with the aircraft optimally to ensure overall performance, safety, protection, and reduced maintenance, while minimizing the quantity and complexity of changes to the aircraft architecture.

This Li-Ion battery consists of 160 ANR26650M1 cells from A123Systems of Watertown, Massachusetts, USA. These cells are configured in single 8-cell series (8S1P) modules for a nominal voltage of 26.4VDC. Twenty modules are paralleled using bus bars for an 8S20P configuration to achieve a 44 Ah rated capacity. Components within the battery include the modules, bus bars, a Central Monitoring System (CMS), two resistive thermal detectors (RTDs), and two heaters (Fig. 1). The battery has 3 connectors (Fig. 2): Connector 1 is for power transmission and Connector 2 is an 18-pin communications/service port connector that provides analog and digital outputs. Connector 3 has 4-pins with direct analog output of the 2 RTDs, isolated from the CMS and modules to give an independent temperature output to the aircraft. The 12 lb steel, battery case does not have vent ports.

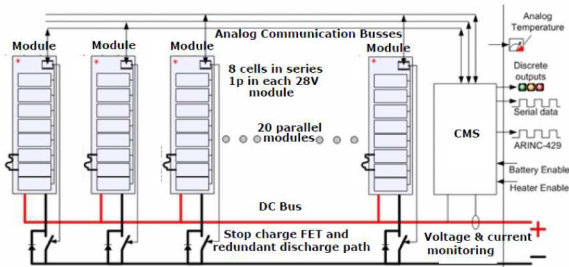


Figure 1. Battery Pack Architecture [19]



Figure 2. 44Ah Aircraft Battery [19]

MODULES

The battery module consists of 8 cells and a Module Management System (MMS); the MMS balances cell state of charge (SOC), protects, detects faults without inhibiting safe discharge, and reports module health to the battery's Central Monitoring System (CMS). The cells are connected in series by welded nickel straps and a fusible link, and are then sandwiched by two printed circuit boards (PCBs) with analog circuitry that collectively form the MMS. When a voltage disparity between cells indicating cell imbalance is detected,

a Stop Charge Field Effect Transistor (FET) circuit is triggered to open, preventing the module from receiving additional external charge current. The MMS then discharges higher voltage cells until all voltages are equal, indicating the same SOC. The MMS' FETs also open to protect against cell over-voltage, excessive charge current, and over-temperature if a preset limit of the voltage sensor or the embedded digital temperature detector is exceeded. Each module has no active discharge protection devices, but relies on the passive fusible link which melts when an excessive discharge (short circuit) condition occurs. The MMS health report can be monitored via a connector on the PCB. When a module fault is detected, a RED light emitting diode (LED) located on the top corner of each module will also flash; When the battery container lid is removed, faulted modules can be identified without diagnostic equipment. The MMS does not contain nor rely on any software [20] or complex airborne electronic hardware (AEH) [21].

CENTRAL MONITORING SYSTEM (CMS)

The CMS monitors module and battery pack health, collects and logs parameters related to utilization, over-limits, faults, and events, and then reports the battery's condition to the aircraft or off-aircraft service equipment. The CMS consists of a PCB with a microcontroller, relays, and connectors. The microcontroller is loaded with an operating system (OS) and an application software (AS) that can be customized for varying aircraft system interfaces. The CMS receives module health and temperature inputs from each of the 20 modules' MMS. The OS will monitor and determine battery condition, while the AS will control discrete communication output to the aircraft. The CMS reports the battery's condition externally via digital ARINC 429 and serial buses and via 28V/ground discretes through the communications/service port connector. The CMS facilitates the operation of the battery's internal heaters. Although the CMS contains software under the guidelines of RTCA DO-178B [20], its hardware is not considered AEH and does not fall under the guidelines of RTCA DO-254 [21].

Operating System and Application Software

The OS monitors input to the CMS, compares the values against predefined limits, and reports the appropriate battery pack condition. The OS uses several labels in ARINC 429 to report utilization, over-limit, fault, and event logs to the aircraft and/or battery servicing equipment. The parameters include: a count of the number of failed modules; battery status word; battery pack voltage; maximum battery pack voltage; battery pack current; highest battery pack charge current; highest battery pack discharge current; CMS temperature; highest battery pack temperature being measured; highest battery pack temperature that was measured; battery temperature of module banks 1, 2, and 3;

battery pack state of charge; battery pack state of charge based on current; battery pack state of charge based on voltage; remaining charge in battery pack; capacity of battery pack; total awake time; total sleep time; total time temperature was above 60°C; total time that the SOC was below 10%; total time charge current was over 200A; the count of the number of engine starts; existing battery impedance; and battery impedance growth.

Based on the OS-monitored battery parameters, the OS will determine if the Battery Normal (OK), Battery Failure, Battery Maintenance, and Battery Discharging conditions are true. The AS will set the value of 4 digital outputs corresponding to each of these battery conditions, which will then command the open/close positions of relays. When the relay is closed, a discrete signal to the aircraft will indicate that the battery condition corresponding to the closed relay is true. These relay positions are also reported as high/low values in the first 4 bits of a 19-bit status word that the OS uses to report crucial battery conditions. The battery status word and other key monitored parameters are reported via ARINC 429 on the communications/service port.

Either method of reporting key battery conditions to the aircraft may be used. For the Citation CJ4, an aircraft with an Electronic Flight Instrument System (EFIS) based on the Rockwell Collins Pro Line 21 avionics suite with an Engine Indication and Crew Alert System (EICAS), key battery conditions is determined from the OS's battery status word. The status word is communicated via Label 276 of ARINC 429 to the EICAS' Data Concentrator Unit (DCU) and the appropriate values and annunciations are displayed on the EICAS screen. Discrete output will be required for non-EFIS/non-EICAS aircraft to trigger annunciator lamps, but may also be used for EFIS aircraft to trigger digital EICAS annunciations. For off-aircraft battery servicing, the Status Word and other monitored battery parameters are communicated through the serial interface.

Awake and Sleep Modes

Awake and Sleep modes are used to conserve battery energy. When no active aircraft operations are occurring or when the battery is removed from the aircraft, the battery will switch to a Sleep mode and power down most of the MMS/CMS electronics and discrete output relays. Awake mode is triggered by the CMS's OS whenever an external ground discrete 'Battery Enable' signal is received. An Awake mode can also be triggered by a change in battery current or receipt of a serial port character. After 5 minutes in the Sleep mode, Awake mode is activated momentarily for the CMS to check battery status. Sleep mode is restored whenever the hardware enable signal is inactive, battery voltage is below 27.5 VDC, the battery current is less than 10 A, and no serial characters have been received for 32 seconds.