

Development and Test of Safe, High Power Lithium Ion Main Batteries for General Aviation Aircraft

Vernon W. Chang, John W. Gallman Michael E. Richardson and Bryce D. Fenton
Cessna Aircraft Company

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ABSTRACT

Advanced chemistry batteries may help reduce weight and increase aircraft performance. Lithium Ion chemistries' high energy density enables 40% weight savings over existing baseline, Lead Acid and Nickel-Cadmium (Ni-Cd) batteries. Baseline requirements for Lithium Ion batteries were developed by studying Cessna's aircraft product line. Nanoscale phosphate-based Lithium Ion cathodes improve safety through inert failure modes, while delivering higher power over conventional oxide-based Lithium Ion and baseline chemistries. Cells and batteries were tested under selected load, environmental, and temperature conditions using procedures adapted from RTCA DO-293 and DO-160. On-board aircraft testing verified performance compatibility. Safety tests verified inert failure mode and flight environment compatibility. Test results showed nanoscale phosphate Lithium Ion batteries are promising as a safe, high power Lithium Ion main battery in general aviation aircraft.

INTRODUCTION

Improving aircraft performance and minimizing weight are constant goals in aviation. One method is to adopt new systems technologies that expand today's performance envelope while reducing component weight and volume. A main battery is commonly considered to have the highest weight density of all components in an aircraft. Weight reduction of this single component may yield improvements in an aircraft's payload, range, or center of gravity characteristics.

Advanced battery chemistries such as Nickel Metal Hydride (NiMH) and Lithium Ion (Li-Ion) have greater energy densities (Wh/kg) than the Lead Acid and Nickel-Cadmium (Ni-Cd) baseline chemistries currently used in general aviation aircraft. However, only some cells have a power density (W/kg) matching or exceeding that of baseline chemistries.

These advanced battery chemistries are now being developed and deployed in large capacity format for space, military, and air transport applications. The National Aeronautics and Space Administration (NASA) [1, 2, 3, 4] and Department of Defense (DOD) have evaluated many advanced chemistry cells. Of these, several have been demonstrated, selected, or deployed for existing and future space and military vehicles [5, 6]. In aviation, Li-Ion batteries have flown on the B-2 stealth bombers since 2004 [7, 8]. Recently, air transport manufacturers, Boeing and Airbus, have selected Li-Ion main batteries, for their respective B-787 [9] and A350XWB [10] programs.

To better meet military mission requirements, the United States Air Force (USAF) tested cold-soaked Li-Ion batteries [11] and NiMH batteries [12] for the F-16. However, battery requirements for some military aircraft like the F-16 may not be applicable in general aviation because of differences in two areas:

- Cold soaked batteries (-40°C) in some military aircraft must be capable of -40°C dispatch from remote air bases [12]. Many general aviation flight manuals recommend battery removal to prevent cooling below -10 to -20°C [13, 14].
- Some military aircraft use batteries to indirectly start the main engine [15, 16, 17]. Most general aviation aircraft rely on batteries to directly start engines, resulting in higher loads.

For fielded battery technologies, NASA, DOD, and the Federal Aviation Administration (FAA) managed battery safety risks with monitoring and safety devices [18, 19]. Lead Acid batteries use sump jars and pressure relief vents to mitigate ignition of emitted gases [20, 21]. Nickel-Cadmium batteries rely on temperature monitoring and disconnect relays to mitigate thermal runaway risks [22, 23]. Recent attention on laptop fires and aircraft cargo fires caused by oxide-based Li-Ion batteries have led the FAA to new Li-Ion carry-on limits

and guidance for airline passengers [24], Li-Ion fire safety studies [25, 26], and increased scrutiny of Li-Ion battery certification requirements [27, 28, 29, 30]. With general aviation's focus on costs and flexibility for less demanding performance requirements compared to space and military missions, a safer failure mode battery chemistry was preferred to mitigate monitoring and safety device design complexities.

Baseline requirements were developed for general aviation. Lithium Ion has higher energy density over NiMH and provides 40% weight savings over baseline chemistries (**Figure 1**). A Li-Ion cell technology, using nanoscale phosphates, with inert failure modes, was selected for compatibility and verification testing against the baseline general aviation requirements.



Figure 1 – Weight comparison, Li-Ion vs. Ni-Cd [31]

BASELINE REQUIREMENTS

Before advanced chemistry batteries can be evaluated for potential application as aircraft main batteries in general aviation, baseline requirements had to be established. A study of Cessna's existing propeller and Citation business jet aircraft product line was performed to identify:

- Critical battery load scenarios;
- The most demanding load profile for a baseline battery; and
- Ground and flight environments.

CRITICAL BATTERY LOAD SCENARIOS – The primary utilization of aircraft main batteries on general aviation aircraft is for on-the-ground, battery-only starts of main engines and auxiliary power units (APUs). In the air, the main battery is an essential power source for an in-flight emergency.

One in-flight emergency scenario that relies on main battery power is the dual generator inoperative condition [32, 33]. One example of this condition is when one engine has had a precautionary shut down resulting in the loss of its generator output and the remaining engine continues operating to provide thrust with a failed generator. In single battery, 14 CFR Part 23 and some older Part 25 aircraft, the FAA requires the battery to

provide emergency power for 30 minutes [34, 35]. In newer Part 25, dual battery, parallel bus architecture aircraft, the European Aviation Safety Agency (EASA) requires each battery to provide half the emergency power for 60 minutes (30 minutes in instrument meteorological conditions (IMC) and 30 minutes in visual meteorological conditions (VMC)) [36]. Engine start load profiles drive the discharge rate and power density requirements of the advanced chemistry battery, while the emergency profiles drive the energy density/capacity requirements of the battery.

Quantification of baseline battery performance was based on an end of life (EOL) battery energy state equal to 72% rated capacity. This 72% rated capacity was based on an assumption that a battery had degraded to retain only 80% rated capacity [18] and had been charged only to 90% state of charge (SOC) before an emergency occurred. Ni-Cd batteries were deep cycled and discharged to 72% rated capacity prior to baseline testing.

The rated capacity is the amount of energy at start of life (SOL), in terms of Ah, which can be discharged at 1C rate. The 1C rate is the constant current discharged from a battery of capacity 'C' in 1 hour before reaching its end point voltage (EPV). A 10C rate corresponds to the constant current discharged from a battery of capacity 'C' in 1/10th of an hour before reaching its EPV.

Although most aircraft equipment can operate down to 18.0V, the battery's useful voltage cut-off was set at 20.0V to account for additional voltage drop that may occur over the long wire run in an aircraft. For engine starts, the lowest voltage threshold was 12.5-13.0V. For discharge rates less than 2C (equivalent to 30 minute emergency discharge), the end point voltage (EPV) of 20.0V was used. For higher C rate discharges such as APU and engine starts, an EPV of 12.5V was used.

MOST DEMANDING LOAD PROFILE FOR A BASELINE BATTERY – The advanced chemistry battery should be capable of matching the same performance as the baseline battery chemistry for the operating environment and applications defined.

Engine starts were identified as the most demanding load profile for power performance. Two key power performance metrics were: (1) peak power (in terms of current in C rate) and (2) voltage under the most demanding, engine start discharge profile. The advanced chemistry battery should deliver power and voltages matching or exceeding the baseline.

Of all Cessna aircraft, the Citation Bravo has the most demanding, engine start profile for a single battery. Engine start tests were performed on the Citation Bravo to define the baseline load profile.

Since Ni-Cd batteries, in the 43 to 44 Ah size, are used in most currently produced Citation aircraft and the Citation Bravo, this battery's performance was used as a

baseline. After discharging to 72% rated capacity, the Ni-Cd batteries were soaked overnight at temperatures between -30°C through $+70^{\circ}\text{C}$. The Ni-Cd battery was removed from the environmental chamber and installed into an ambient temperature Citation Bravo aircraft. Engine starts were initiated while battery temperature was recorded.

Figure 2 shows the highest load profiles within each temperature range that were used as the baseline engine start profile for testing advanced chemistry batteries in that temperature range:

- -18°C Ni-Cd profile for -30 to 0°C tests
- $+23^{\circ}\text{C}$ Ni-Cd profile for 0 to $+55^{\circ}\text{C}$ tests
- $+56^{\circ}\text{C}$ Ni-Cd profile for $+55$ to $+85^{\circ}\text{C}$ tests

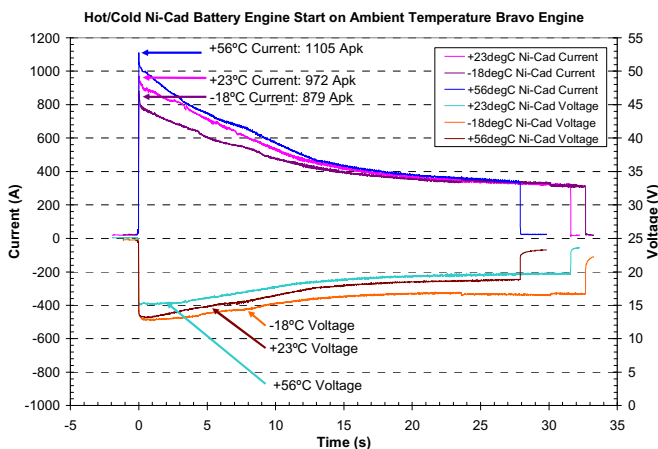


Figure 2—Ni-Cd Engine Start Profile vs. Temperature on Ambient Temperature Citation Bravo Engine

The peak current demand for -18 , $+23$, and $+56^{\circ}\text{C}$ Ni-Cd batteries were 879, 972, and 1105 A peak, respectively. Based on a rated capacity of 44 Ah (at 1C rate), the peak power required would be $(879 \text{ A}/44 \text{ Ah}) = 20\text{C}$ rate at -18°C , 22C rate at $+23^{\circ}\text{C}$, and 25C rate at $+56^{\circ}\text{C}$. The minimum voltage that must be delivered during the peak current is 12.5V.

GROUND AND FLIGHT ENVIRONMENT – The temperature and pressure environment to which aircraft and battery are exposed is defined. This environment exposure requirement was developed by reviewing test data, reports, and aircraft operating and flight manuals [13, 14].

Pressure altitude – Exposure to ground and in-flight pressures may affect the battery's performance. For ground operations, the battery's operating boundaries are defined as $-1,000$ ft to $14,000$ ft pressure altitude. The $-1,000$ ft lower limit represents high pressure conditions above the nominal standard day. The $14,000$ ft pressure altitude represents the highest elevation airport in the world, in La Paz, Bolivia [37]. In flight, the highest altitude certified for a Cessna aircraft is $51,000$ ft [38]. Since no significant difference in battery

configuration or operating profile exists between ground and flight, the battery is expected to operate at pressure altitudes of $-1,000$ ft to $51,000$ ft.

Ground temperature – Aircraft may be exposed to ground temperatures below -40°C in polar regions and above $+55^{\circ}\text{C}$ in equatorial regions [39]. Cold weather presents a greater challenge for aircraft to start because of battery electrolyte freezing that may inhibit power to aircraft equipment and increased engine oil viscosity that requires higher torque to start engines. Since some aircraft engines can start after overnight exposure to -40°C [12, 13, 14], other aircraft components needed for dispatch in this climate are subjected to the -40°C requirement as well. Many test standards, including DO-293 [18] and DO-160 [40], have used -40°C as the lower temperature limit for ground, cold weather exposure tests.

The USAF wants a -40°C battery to enable engine starts in remote air bases. USAF aircraft utilize batteries [41, 42] in three different engine start architectures: (1) high current battery discharge to directly start engines [43]; (2) high current battery discharge to indirectly start engines by starting an auxiliary power unit (APU) [44, 45]; (3) low current battery discharge to indirectly start engines by operating hydraulic or pneumatic stored energy systems controllers. Batteries for direct start of engines and APUs have similarly high load demand as general aviation aircraft. In the near term, development of -40°C batteries appears focused on aircraft with low engine start load demand. On aircraft like the F-15 and F-16, the battery energizes controllers that trigger hydraulic pressure release from an accumulator to spin up a jet fuel starter (JFS), which then uses its hydraulic starter motor to spin up the main engine [15, 16, 17].

NiMH and Li-Ion batteries were tested to discharge the 34A for 30s needed for a F-16 engine start: ElectroEnergy Inc.'s 38.9Ah bipolar NiMH battery discharged the profile and maintained a 19.0V minimum while at -40°C and maintained 20.0V minimum at -29°C [12, 46]. Saft's 22.8Ah NiMH battery performance was extrapolated to provide 20.0V minimum at -25°C [12]. Yardney/Lithion's Li-Ion 9 Ah cell discharged 28C at -20°C [47]. Saft's 19 Ah (rated 16 Ah) Li-Ion battery nearly passed the profile at -30°C [11]. However, the USAF observed: "Recent experiments on advanced battery chemistries have shown poor performance at ultra low temperatures below -20°C [48]."

A battery's required operating temperature in general aviation is less severe than in military aviation. Cessna airplane flight manuals (AFM) provide guidance that reflects common practice in general aviation: If the temperature is expected to drop overnight, the AFM recommends removing the battery from the aircraft to keep it warm indoors. **Table 1** shows the temperature at which the Caravan and Citation aircraft AFM recommend battery removal [13]. These operating procedures imply that batteries colder than these temperatures should not be used to perform engine or APU starts:

**Table 1 – Recommended Battery Removal Temps
[13, 14]**

Coldest Battery Temp for	Model 750	Model 208	Model 525 525A 525B	Model 550 (s/n 001-733)	Model 550 (s/n 801 & on)	Model 560XL 680
Main Engine Start		-18°C	-18°C	-12°C	-18°C	-10°C
APU Start	-20°C					

(The respective model numbers correspond with the marketing model names: 750 is Citation X; 208 is Caravan; 525, 525A, and 525B are CJ1+, CJ2+, CJ3; 550, s/n 1-733 is Citation II; 550, s/n 801 and on is Bravo; 560XL is Excel/XLS+; and 680 is Sovereign [49].)

These AFM operating procedures enable direct engine or APU start at cold temperatures with current baseline batteries. Neither advanced chemistry or current baseline batteries can perform direct engine or APU start when soaked to -40°C.

Cessna conducted tests to determine the coldest Ni-Cd battery temperature that would start an ambient temperature Bravo aircraft engine (oil temperature ~ +23°C). A -25°C Ni-Cd battery successfully started the warmer, lower torque, +23°C engine [50].

The warmer cold battery temperature limits currently used in these general aviation aircraft (-10 to -20°C) makes the use of advanced chemistry batteries more feasible in general aviation.

Flight temperature – Outside air temperature (OAT), airspeed, and the heat of adjacent components establish the temperature of an unpressurized battery compartment.

Battery Environment – The location of the battery compartment relative to other aircraft systems can also have a significant impact on temperature. The tail cone compartment for the Citation Bravo, **Figure 3**, receives some heat transfer from: (1) nearby engine bleed tubes that supply the aircraft's environmental control system; (2) air exhausted from the cabin's outflow valves; (3) heat exchange from a vapor cycle cooling system or air cycle machine. For the Citation Sovereign, **Figure 4**, the battery is installed in the fairing battery compartment and does not benefit from these heat sources.



Figure 3–Citation Bravo–Battery installed in Tailcone



Figure 4–Citation Sovereign–Battery installed in Fairing

Airspeed and OAT – At pressure altitudes of 35,000 ft to 70,000 ft, an OAT of -55°C or colder may exist. Test standards such as DO-293 [51] and DO-160 [52] have used -55°C as the lower temperature limit for in-flight, cold weather exposure tests.

The total or ram air temperature (RAT) established the temperature environment of the aircraft surface and thereby the aircraft structure and boundary of the battery compartment. The relationship for RAT is defined as:

$$\frac{T_{total}}{T_0} = 1 + \frac{\gamma - 1}{2} \cdot M_a^2 \quad [53, 54]$$

T_0 = Static Air Temp (K or °R) = Outside Air Temp (OAT)

T_{total} = Total Air Temp (K or °R) = Ram Air Temp (RAT)

M_a = Mach Number

γ = Ratio of Specific Heats = ~ 1.4 for air

This equation shows that for a constant OAT, as aircraft speed (Mach number) increases, the RAT increases. Therefore, the aircraft skin is exposed to a warmer temperature than OAT during flight. (The RAT is measured by the aircraft instruments and OAT is calculated.)

Larger Citation aircraft have maximum cruise speeds from Mach 0.77 (Citation Sovereign) up to Mach 0.92 (Citation X). The RAT could range from -20°C (at Mach 0.92 in -55°C OAT) to -30°C (at Mach 0.77 in -55°C OAT) during these flights. Slow flying, high endurance, high altitude aircraft such as surveillance UAVs may experience colder RAT due to their low Mach numbers.

Flight Test Data – Measurements of battery compartment temperature during flight tests of both the Citation Bravo and the Citation Sovereign confirm the warming effects of both RAT and heat transfer from other system components.

Figure 5 shows the smaller Citation Bravo aircraft flew in an average OAT of -55°C for 60 minutes during flight 1727, from Dallas-Fort Worth (DFW) to Wichita (ICT). The data recording was turned on once the aircraft had flown into -55°C air. Timestamp 59:34 of **Figure 6** shows the Bravo's RAT at -39.5°C for an OAT of -54.7°C and Mach = 0.589. With the OAT at around -55°C, the battery zone temperature measurements

thermocouple located in the tail cone within 6 inches of the battery, stabilized at -20°C after about 60 minutes.

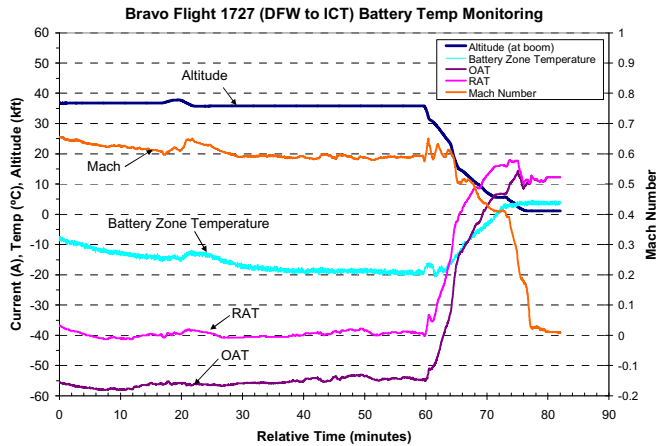


Figure 5—Citation Bravo—Battery Zone Cooling

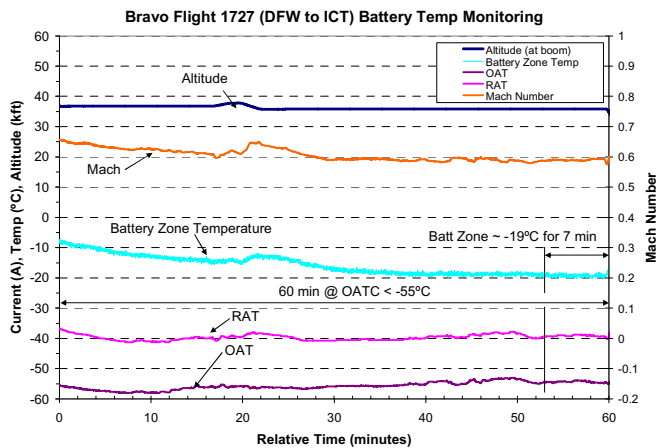


Figure 6—Citation Bravo—Battery Zone Cooling

Figure 7 shows the Citation Sovereign flew in an average OAT colder than -55°C for 101 minutes during flight 1152, from Wichita (ICT) up towards the Canadian border before returning to ICT. Timestamp 48:40 of **Figure 8** shows the Sovereign's RAT at -29.9°C for an OAT of -55.7°C and Mach = 0.773. In an OAT that ranged from -55°C to -65°C , the battery compartment temperature stabilized at -20°C after 101 minutes.

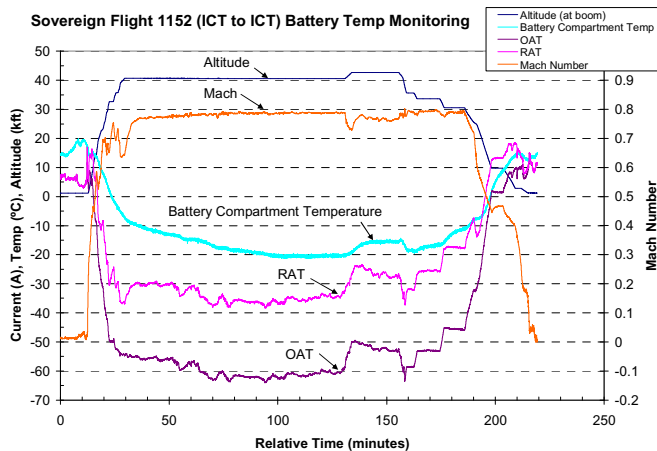


Figure 7—Citation Sovereign—Battery Zone Cooling

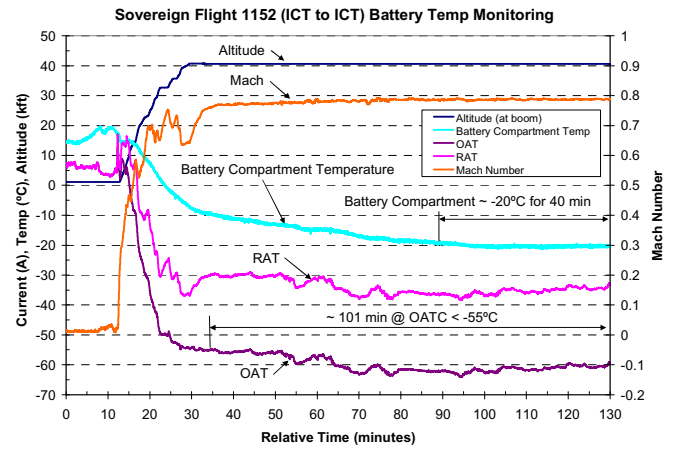


Figure 8—Citation Sovereign—Battery Zone Cooling

Long duration, high speed missions up to 7 hours may be achieved on aircraft like the Citation X and Citation Sovereign, although these missions may not be typical. However, the battery's cool down rate over this maximum mission duration should be characterized.

The coldest recommended dispatch temperature for a battery (-20°C for Model 750, through -10°C for Models 560XL/680) and flight test data (zone temperatures stabilized at -20°C) helped establish Cessna's baseline requirement that the battery be capable of providing emergency discharge when soaked to -20°C .

LITHIUM ION TECHNOLOGY

The high-current demands of direct engine start and desire for low cost safety protection systems are challenges for the application of Lithium Ion batteries in general aviation aircraft. Battery temperature monitoring, safety vents, and sump jar are some low cost methods used in general aviation to mitigate hazards in baseline lead acid and Ni-Cd batteries [20, 21, 22, 23]. Within Li-Ion technology, varying chemistries of anodes, cathodes, and electrolytes have been developed for high power or high energy density applications. Large format batteries using many of these chemistries require protection against thermal runaway by using costly, complex, redundant, charge/discharge management electronics.

The phosphate-based Lithium Ion battery [55] was selected for this study because of its inherent resistance to a thermal runaway, its high current discharge, and the potential for a 40% weight savings relative to current aircraft batteries.

SAFE, HIGH POWER CHEMISTRY – Traditionally, conventional chemistries of Li-Ion batteries using oxide-based cathodes (LiCoO_2 , LiMn_2O_4) have not been made into high current, large format batteries because of thermal runaway concerns. In some chemistries, the cathode can decompose at temperatures as low as 150°C [55], releasing lithium ions and oxides. The lithium ions form pure lithium metal which can auto-ignite at $+180^{\circ}\text{C}$ [56] and the oxides form oxygen, which feeds the lithium metal fire. This decomposition can occur

whenever heat is generated within the cells during over-charge or high rate, long duration discharge. Battery management electronics are employed in large format batteries to ensure safety and to mitigate risk by controlling charge and discharge voltages and currents.

New phosphate-based chemistries ($\text{Li}_2\text{V}_2(\text{PO}_4)_3$, LiFePO_4) of Lithium Ion batteries have been introduced which claim an inert failure mode. The cathode does not decompose until 800-1000°C [57]. The decomposition releases phosphates, not oxygen. Therefore, even if auto-ignition of lithium metal occurs during the high temperature decomposition, there is no oxygen to fuel a fire and no thermal runaway can occur. Phosphate-based chemistries do not require battery electronics for controlling charge and discharge to ensure safety. Battery electronics are employed for cell balancing to optimize operating life.

One developer of the phosphate-based Lithium Ion chemistry is A123Systems of Watertown, Massachusetts, USA. With an energy density of 110 Wh/kg, it has achieved peak discharge rates in excess of 80C (3300 W/kg) for 5 s or 2914 W/kg for 30s [55], an advantage claimed over other oxide-based and phosphate-based cathode chemistries [58]. This high discharge rate is enabled by nanophosphates doped in the cathode. While typical oxide-based Li-Ion cathode particle diameters range from 5, 10, to 20 microns (**Figure 9**) [59], doped nanophosphates can have nominal cathode particle diameter less than 100 nm (0.1 micron) or 100 times smaller (**Figure 10**) [60].

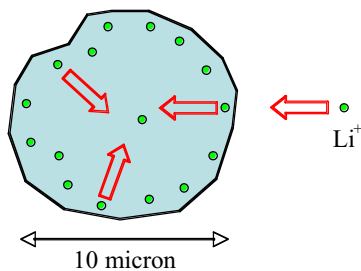


Figure 9 – Oxide-based Li-Ion cathode particle [60]

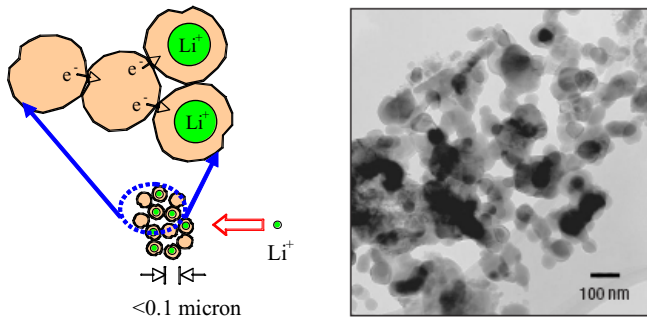


Figure 10 – A123Systems' doped nanophosphate-based Li-Ion cathode particles [60, 61]

The smaller nominal particle size increases the cathode surface area by several orders of magnitude and opens more paths for the physical movement of lithium ions from the cathode to the anode. This reduced impedance to ion flow enables the doped nanophosphate cell to be

more conductive over conventional oxide-based and phosphate-based cells, achieving higher charge/discharge rates. The charge and discharge rate limitations placed on oxide-based cathodes to prevent thermal runaway negate any benefits that may be realized in developing a high rate, nanoscale oxide-based cathodes.

Doped nanophosphate-based Li-Ion cells have a safe failure mode and can achieve the high power performance needed for aviation main batteries.

AIRCRAFT BATTERY CONCEPT – Cells and a developed 44Ah Li-Ion battery were tested, compared against baseline Ni-Cad performance, and evaluated for compliance with the baseline requirements.

A123Systems' basic cell is the ANR26650M1, which is 26mm in diameter and 65mm long. This cell's nominal voltage is 3.3 to 3.35V. Its recommended charge voltage is 3.6V and the maximum allowable voltage is 4.2V [62]. Placing 8 of these cells in series into a battery module would provide 26.4V nominal voltage, 28.8V recommended charge voltage, and 33.6V maximum allowable charge voltage. These 8-cell modules comply with the baseline requirements of 28.5V nominal voltage on the aircraft electrical bus and 33.5V over-voltage protection limit. These same baseline requirements define 12.5-13.0V as the lowest threshold voltage for high rate discharges such as APU and engine starts, equaling 1.56-1.63V at the cell level. For low rate emergency profile discharges, the EPV is 20.0V or 2.5V per cell. Based on 2.5V EPV for a cell, the cell's rated capacity is 2.2 Ah. To configure a 44Ah battery, twenty (20) 8-cell modules were placed in parallel. The modules were connected with bus bars and installed inside a 12 lb steel case. The total prototype battery weighed 52 lbs.

INITIAL CELL FEASIBILITY TESTS

The ANR26650M1 Lithium Ion cells were tested to characterize initial feasibility against baseline aircraft main battery requirements. The tests were adapted from RTCA DO-293 Minimum Operational Performance Standards for Nickel-Cadmium and Lead Acid Batteries and DO-160E Environmental Conditions and Test Procedures for Airborne Equipment. The discharge performance of the cells across temperature ranges is reported.

Figure 11 shows that groups of five (5) cells were used for each feasibility test. Each cell was tested individually. The average results are presented.