National Transportation Safety Board
Washington, D.C. 20594

Hazardous Materials Accident Brief

Accident No.:	DCA04MZ001
Transportation Mode	Air
Location:	Memphis, Tennessee
Date:	August 7, 2004
Time:	3:51 a.m. central daylight time
Carrier:	Federal Express Corporation
Shipper	AC Propulsion, Inc.
Vehicle:	Boeing MD-11
Injuries:	None
Property Damage:	About $20,000
Hazardous Material:	Lithium-ion batteries
Type of Accident:	Cargo fire

The Accident

About 3:51 a.m., central daylight time,[1] on August 7, 2004, a fire destroyed some freight that included lithium-ion batteries; the freight was in a unit load device (ULD) at the Federal Express Corporation (FedEx Express) hub in Memphis, Tennessee. The ULD had been raised on loading equipment and pushed about halfway onto an airplane bound for Charles de Gaulle Airport, Paris, France, when the loading personnel smelled smoke. They returned the smoking ULD to the loading equipment and lowered the ULD to the ground. When Memphis fire department responders opened the ULD, a fire flared up inside. Damage to the ULD and the freight is estimated as $20,000. The airplane was a Boeing MD-11 that FedEx Express operated as flight 0004.

Fire Damage

The packages in the top portion of the ULD were damaged by fire and water. In general, the outsides of the packages were damaged, but their contents were untouched. The battery package was the lowest package in the ULD to be damaged and the only package with fire damage to its contents. Of the two modules it contained, one was destroyed by the fire, and the other sustained minimal damage and sooting.

[1] Unless otherwise noted, all times in this report are central daylight time.

Events Preceding Accident

AC Propulsion (San Dimas, California) had offered the battery package for shipment on August 6, 2004; the package was destined for Courrèges in Neuilly Sur Seine, France. A FedEx Express truck took the package from San Dimas to the Los Angeles International Airport, Los Angeles, California, a distance of about 45 miles. The package left Los Angeles at 8:52 p.m., Pacific daylight time, in a ULD on FedEx Express flight 2308 to Memphis. It arrived at Memphis at 1:30 a.m., on August 7, and went through the hub sorting system. About 3 a.m. it was loaded into ULD AMJ54449FX, the accident ULD.

Shipping Information

According to the shipping documents, the battery package contained "Lithium Batteries, Class 9 [miscellaneous dangerous goods[2]], UN 3090," and was shipped under U.S. Department of Transportation (DOT) approval CA2004050003. The Research and Special Programs Administration (RSPA) had issued the approval on May 21, 2004, to AC Propulsion for the shipment of 20 prototype lithium-ion battery packs.

The DOT approval cited on the shipping documents applied to the transportation of a complete prototype battery pack designed for an electric car. The DOT approval was required because the battery pack, as a prototype or low production model, had not been tested pursuant to the *UN Manual of Tests and Criteria Part III*, as required under the DOT hazardous materials regulations. Consequently, the transportation of the prototype battery packs was subject to the approval of RSPA. RSPA had stipulated in the approval that it was valid only for the transportation of the battery pack and that any change in "the configuration and/or the integral packaging will invalidate the approval." The approval did not apply to modules that were packaged and shipped individually, as was the shipment involved in the fire.

AC Propulsion had stated in its application for the DOT approval that the prototype battery pack would measure approximately 62 inches by 17 inches by 9 inches and weigh about 350 pounds. Each battery pack was to consist of 25 modules that had been individually secured within an insulating fiberglass case. To prevent an inadvertent short circuit of the battery, the fuses were to be removed from the external electrical connections built into the fiberglass case. The battery pack was to be enclosed by a wooden box and bolted to the base of the box; the gross weight of the package was to be 530 pounds. (See figures 1 and 2.)

[2] *Dangerous goods* is an international term for hazardous materials.

Figure 1. Approved battery pack in fiberglass case. The battery pack is without its cover and shows the modules secured in the fiberglass case.

Figure 2. Approved battery pack in covered fiberglass case that is bolted to wooden base. (A wooden box that covers the fiberglass case is then secured to the wooden base.)

In contrast to the packaging requirements for the battery pack, the accident package consisted of a 4G fiberboard[3] box that held two rechargeable lithium-ion battery modules. The accident modules were not secured within a fiberglass case and then mounted in a wooden box. (See figures 3 and 4.)

[3] The Fiber Box Association defines fiberboard as fabricated paperboard utilized in container manufacture. (The common term for this material is *cardboard*.)

The box used to transport the accident modules had two compartments, one for each module. The box, including the space between the compartments, was lined with a double layer of fiberboard. The equipment to install the modules in the automobile battery was taped to the top of the fiberboard lining over the modules. The equipment consisted of two 2-inch-long metal Allen wrenches, two shrink-wrapped metal combination wrenches, and a bag of nuts and bolts. The total package weighed 30 pounds. (The modules were meant to replace faulty modules in a prototype lithium battery pack. The modules of the prototype lithium battery can be removed and replaced separately.)

Figure 3. Sample modules in a 4G fiberboard box, as were the accident modules.

Figure 4. Tools taped to the top of the fiberboard lining covering the sample battery modules in figure 3, as was done with the accident package.

Lithium-Ion Battery Information

Each module was shipped with a measured voltage of 7.6 volts and consisted of two blocks. The positive terminal grid of one block was bolted to the negative terminal grid of the other block. Each block consisted of 68 lithium-ion cells that were spot-welded to the terminal grids, which were exposed. (See figure 5.)

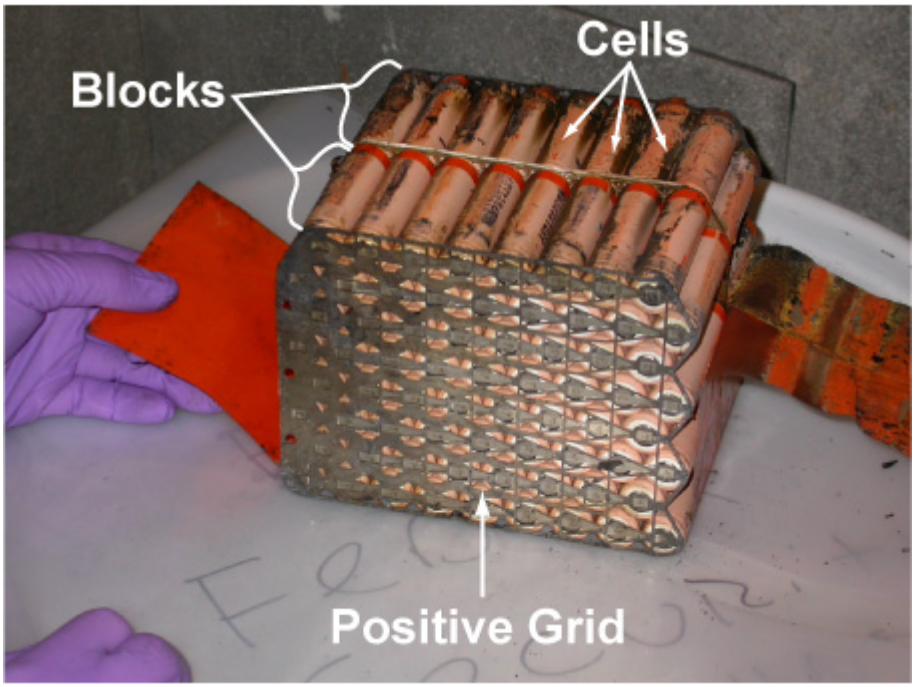

Figure 5. Sooted module after incident. (The handler is wearing gloves.)

The lithium-ion cells[4] that made up the modules had the general appearance of AA batteries but were slightly larger (2 1/2 inches long by 3/4 inch in diameter). Lithium-ion cells do not contain metallic lithium.[5] The lithium in a lithium-ion cell is bonded to chemical compounds used in the cell's electrolyte and cathode. The interior of the cell consists of two thin foils that are separated by a thin polymer sheet. The foils are wrapped together in a spiral and immersed in a liquid electrolyte. The electrolyte has two solvents, one of which, diethyl carbonate, is considered a flammable liquid, with a flash point of 77° F. The other, ethylene carbonate, has a flash point of over 300° F but can be readily ignited by a fire involving the flammable solvent.

[4] There are two types of lithium battery cells: non-rechargeable, called primary cells, or metallic lithium cells, which are constructed using metallic lithium; and rechargeable, called secondary cells, or lithium-ion cells, which are constructed without metallic lithium.

[5] Lithium is a combustible alkali metal that self-ignites in air at 352° Fahrenheit (F). When exposed to water, lithium reacts exothermically and releases hydrogen, creating a dangerous fire risk. Fires involving lithium are extremely difficult to extinguish. Extinguishers using water, gas, or certain dry chemicals cannot control this type of fire. The DOT classifies lithium metal as a division 4.3 material (dangerous when wet). Lithium metal may not be shipped on passenger aircraft but may be shipped on cargo aircraft, provided each package weighs no more than 15 kilograms.

The anode, or negative foil, is made of copper that has a layer of baked-on graphite and carbon. The cathode, or positive foil, is made of aluminum that has a layer of deposited lithium cobaltite.

When the battery is charged, lithium ions are generated at the cathode and transferred within the electrolyte to the anode. The ions are attracted to and collect on the graphite matrix of the anode as lithium atoms, resulting in electric potential. (The lithium atoms are alloyed to the graphite, producing a "lithium-carbon" matrix[6] on the anode surface when exposed to a current.)

The lithium-ion cells involved in the incident had been constructed with four safety features designed to prevent short circuits and violent ruptures. (See figure 6.) The features were meant to satisfy Federal regulations (49 *Code of Federal Regulations* [CFR] 173.185[e]).

1. Each cell had a polymer disc under its cap, or positive connection. (The polymer conducts electricity but increases its electrical resistance as the temperature within the cell increases in response to current flow. Therefore, any significant increase of temperature within a battery, as occurs during an uncontrolled reaction or from a high-current flow, such as a short circuit, increases the electrical resistance of the polymer and slows the reaction and discharge.)

2. A current interrupter device (CID) was between the polymer disc and the cap. (The CID has an inward-facing dimple that electrically connects the cathode foil to the top cap. Excess gas generated during an uncontrolled reaction within the cell causes the dimple to pop outward, breaking the connection between the cathode foil and the cap and stopping the reaction.)

3. The CID was responsive to excessive pressure. (If the pressure within the cell is great enough, the CID fractures, releasing the gas into vent holes in the top cap and preventing a burst of the cell.)

4. A porous polymer sheet was between the anode and cathode foils. (The sheet allows a controlled ion flow as the battery is charged or discharged, basically allowing it to act as a rechargeable battery. At an internal temperature of 248° F, the sheet deforms and collapses, sealing its pores and stopping the ion flow.)

[6] According to the U.S. Navy's research analyst on lithium batteries, the "lithium-carbon" matrix, if immersed in water, can react exothermically, like lithium metal, and release hydrogen, a flammable gas.

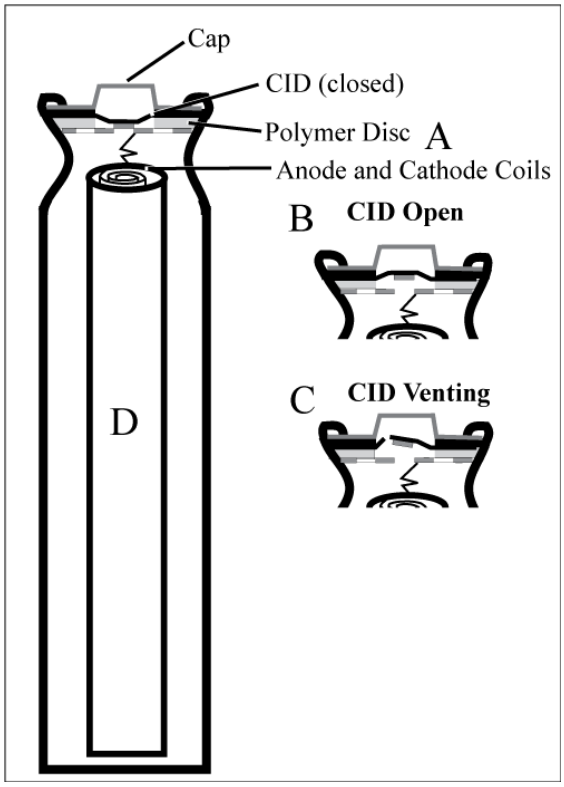

Figure 6. Lithium-ion cell with safety devices. (**A**: The disc is a temperature-sensitive polymer that resists electron flow as the temperature increases. **B**: The CID opens with internal pressure breaking the cell circuit. **C**: Increased pressure causes the CID to vent to the cap. **D**: A polymer sheet between the anodic and cathodic foils melts at a given temperature, stopping the electron flow.)

Postaccident Testing and Examination

With the help of personnel from the Navy's Carderock Facility, National Transportation Safety Board investigators visually examined the burned modules in order to assess their condition and to identify any damage or failures that were present before the fire. The shrink-wrap on the outside of the cells in the damaged module had either melted or been consumed by fire, and the majority of those cells had uniform sooting. The walls and caps of most of the cells showed no evidence of punctures, tears, breaches, or any other type of damage. Three cells had rounded bottoms, indicating overpressure, and copper or aluminum foil exuded from the top vent holes, indicating exposure to heat. However, one cell with no evidence of overpressurization had a longitudinal opening in its sidewall, and some of its internal material had exuded through the opening. An adjacent cell had a longitudinal scrape on its sidewall that closely matched the opening on the first.

Chemical and radiological testing of the cells did not reveal any evidence of contamination or other internal defects.

The Navy's Carderock Facility replicated internal cell failures caused by electrically induced overheating of exemplar blocks and cells and found that the cell temperatures increased during testing but not enough to ignite a fire in packaging materials. However, tests showed that a localized external short can provide enough energy that lasts long enough to ignite packaging materials. (A localized external short of this type can occur if the exterior jacket of one or more cells is penetrated by a foreign conductive object, if a conductive object bridges the positive and negative terminal grids, or if a conductive object bridges the positive terminal grid and an exposed section of the negative sidewall of a cell. The tools included with the modules were conductive, and several were long enough to bridge the positive terminal grid and the cell sidewall. No tool was long enough by itself to bridge the positive and negative terminal grids.)

According to the Navy's summation of the battery fires in its test report,[7]

> Based on the materials at hand, and the testing conducted, no clear mechanism is seen as the cause of the fire event. However, the preponderance of the observations supports the probable onset of external short circuits during handling at the Memphis FedEx facility. This short circuit is most likely to have been through an external circuit and produced sufficient local overheating to initiate thermal abuse events of the cell adjacent to the short.

Other Incidents Involving Lithium Batteries

On April 28, 1999, a fire destroyed freight, including primary lithium batteries, on two cargo pallets at the Northwest Airlines cargo facility at Los Angeles International Airport. The pallets had been taken off a passenger flight from Osaka, Japan. (The airplane was a Boeing 747, which Northwest Airlines had operated as flight 0026.) The Safety Board investigated the accident and issued safety recommendations to both RSPA and the Federal Aviation Administration (FAA). The recommendations asked them to evaluate the fire hazards posed by lithium batteries in an air transportation environment and require that appropriate safety measures be taken to protect aircraft and occupants (Safety Recommendations A-99-80 and -85, respectively).

According to RSPA, from January 1, 1989, through May 31, 2005, six other incidents in air transportation involving lithium batteries have been reported.[8] In one incident, the batteries were damaged, but there was no evidence of fire or charring. In the other five incidents, there was some evidence that the batteries had caused fire or charring of the packaging.

- On May 24, 1989, a box of 25 lithium-ion batteries that had been transported on a FedEx Express airplane caught fire in the FedEx Express freight sorting facility in Memphis. The fire burned a hole "completely though the inner and through the outer box."

[7] For more information, see "Memphis Event," *Federal Express Battery Fire Evaluation Report*, Winchester, Clinton, and DeJarnette; Hampton; Naval Surface Warfare Center, Carderock Division, West Bethesda, MD; August 1, 2005.

[8] These are incidents reported to RSPA under 49 CFR 171.16. There may be other unreported incidents.

- On September 26, 1996, wires connected to eight lithium batteries (type unknown) apparently shorted and burned a hole in their package, which was in the Airborne Express sorting area in Wilmington, Ohio. The batteries were connected in series inside a plastic express envelope.

- On November 3, 2000, a package of primary lithium batteries in a FedEx Express truck near Portland, Oregon, showed evidence of internal leakage and charring around one battery.

- On April 12, 2002, a fiberboard box started smoking while it was inside a FedEx Express ULD in Indianapolis, Indiana. The box contained lithium batteries (type unknown) that had short-circuited, starting a fire and damaging the interior of the box.

- On August 9, 2002, a lithium-ion battery in a Samsung minicomputer/Palm Pilot wrapped in bubble wrap inside a fiberboard box short-circuited, causing the bubble wrap to catch fire and start to melt. The box was discovered by a sorter at the FedEx Express hub in Los Angeles, California.

During the same period, six incidents or accidents involving lithium batteries in other modes of transportation were reported, but only one included a fire that was directly related to the transport of lithium batteries. On March 5, 2002, near Houston, Texas, a fiberboard box of lithium batteries (type unknown) inside an American Freightways truck was crushed when other freight fell on top of it. The batteries and box caught on fire.

RSPA mentioned another incident involving metallic lithium batteries in a 1999 advisory:[9] (Because the incident did not happen in this country, it is not listed in the RSPA database.)

> In May 1994, while being delivered to a handling agent by road, a shipment of small [primary] lithium batteries destined for Gatwick Airport in London, England, was found emitting smoke from a Unit Loading Device. The shipment consisted of batteries, approximately the size of a dime and about 5 millimeters high, which had been tossed loosely in a box. The batteries apparently short-circuited when exposed battery terminal tabs came into contact with other batteries, and subsequently started a fire that significantly damaged the shipment.

The Canadian Transportation Safety Board also is investigating an incident involving lithium batteries. In April 2004, a flashlight began smoking in a seatback pocket on a Canadian airplane. The flashlight became so hot that the flight attendants could not handle it without oven mitts. The flashlight had a primary lithium battery and had been manufactured and bought in Beijing, China.

[9] *Advisory Guidance; Transportation of Batteries and Devices that Contain Batteries,* Docket No. RSPA-99-5143, *Federal Register,* Vol. 64, Number 129, p. 36744. July 7, 1999.

On November 3, 1999, the FAA Associate Administrator for Civil Aviation Security sent a memo to several agencies, including RSPA's Associate Administrator for the Office of Hazardous Materials, identifying four incidents that had happened that year that were not on aircraft but did involve the overheating and bursting of lithium-ion batteries in automatic external defibrillators. Additionally, the FAA has a record of 30 other incidents involving a variety of other types of batteries that shorted and caused damage ranging from smoke to fire and explosion.

Since the August 2004 accident in Memphis, the FAA has begun investigating at least two other fires involving lithium-ion batteries. On October 29, 2004, a fire and small explosion involving a 9-volt lithium-ion battery occurred on a chartered flight from the Raleigh-Durham airport in Morrisville, North Carolina, to Parkersburg, West Virginia. No one was injured, but an aircraft seat sustained minor damage. On June 30, 2005, a package containing lithium-ion batteries was discovered at the United Parcel Service (UPS) airfreight terminal in Ontario, California. One of four battery packs within a package had caught fire and been completely destroyed during transportation. The fire was out and the package cold when it was discovered. The package containing the battery packs had flown on UPS aircraft from Shanghai, China, to Anchorage, Alaska, and on to Ontario.

In August 2004, the Consumer Product Safety Commission recalled about 28,000 lithium-ion battery packs that LG Chem Ltd. of South Korea had manufactured for Apple PowerBook computers. The problem was identified as an internal short, which can pose a fire hazard. The recall was the response to four incidents: in two, the computers had caught fire; in one, the computer had merely smoked; and in one, the odor of burning had come from the ventilation grille. All of the batteries were lithium-ion.

Postaccident Actions

On December 15, 2004, RSPA issued an interim final rule[10] that prohibits the transportation of primary (non-rechargeable) lithium batteries and cells aboard passenger aircraft. The rule addresses Safety Recommendations A-99-80 and -85, the safety recommendations that the Safety Board issued as a result of its investigation of the 1999 fire at the Northwest Airlines cargo facility at Los Angeles International Airport and the testing of lithium batteries at the FAA laboratory.[11] The rule does not prohibit the transportation of lithium-ion batteries, but it notes the FAA and RSPA concerns about lithium-ion batteries and cells. As of August 3, 2005, the FAA and the Pipeline and Hazardous Materials Safety Administration (PHMSA)[12] are testing lithium-ion batteries using similar methods to evaluate primary batteries and cells.

[10] Interim Final Rule, Docket RSPA-04-19886 (HM-224E), *Hazardous Materials; Prohibition on the Transportation of Primary Lithium Batteries and Cells Aboard Passenger Aircraft*, December 15, 2004.

[11] For more information, see FAA Report DOT/FAA/AR-04/26, *Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft*, National Technical Information Service (NTIS), Springfield, Virginia, June 2004.

[12] As part of a DOT reorganization, RSPA ceased operations on February 20, 2005. RSPA's hazardous materials program moved to a new DOT agency, PHMSA.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the fire in a unit load device at the Federal Express Corporation hub in Memphis, Tennessee, on August 7, 2004, was the failure of the unapproved packaging used by AC Propulsion, Inc., which was inadequate to protect the lithium-ion battery modules from short circuits during transportation.

Adopted: September 26, 2005