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International ATMO Education

Use of Lithium-Ion Batteries in Hyperbaric Chambers

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INTRODUCTION

Rechargeable Li-ion batteries have become the standard for most battery-powered portable devices. Accidents involving rechargeable Li-ion batteries are reported regularly. A personal electronic device (containing a rechargeable Li-ion battery) might be taken into a hyperbaric chamber (either deliberately or accidentally). In multiplace hyperbaric chambers, the types of medical devices we may try to use inside the chamber are likely to have rechargeable Li-ion batteries. In order to properly address the risk of rechargeable Li-ion batteries in the hyperbaric chamber, one must understand the risks of these batteries and follow the recommendations from the battery industry and manufacturer of the equipment containing the battery.

OBJECTIVES

The reader should be able to:

- Explain two aspects of the hyperbaric environment that could present a hazard to rechargeable lithium-ion (Li-ion) batteries.
- Identify three precautions for safe use of rechargeable Li-ion batteries.

QUANTIFYING RISK

In any situation, actual risk is a function of the frequency of exposure to a hazard, the probability of that exposure resulting in a mishap, and the severity of the mishap that might occur. Each of these factors could be rated on a Likert scale (1-5). The overall risk score is calculated by multiplying the rating of each of the three factors. The highest possible risk score is 125 (5x5x5 = 125). The lowest possible score is zero, if one of the three factors is completely eliminated. For example, "exposure avoidance" is one strategy to reduce risk. If a patient or multiplace chamber attendant is experiencing nasal congestion, we may choose not to expose this person to pressure change today. This strategy reduces the Probability of ear or sinus barotrauma in this individual to zero. The assignment of a particular risk rating (1-5) to each of the three factors is somewhat subjective; and one might argue for a higher or lower rating on any given factor. However, the overall risk score is a tool that quantifies our safety decisions and allows us to compare the relative risk of different situations.

Likert Scale for Determining Overall Risk Score

Frequency of Exposure		Probability of Mishap		Severity of Mishap	
1	Annually	1	Unlikely	1	Noticeable (Inconvenience)
2	Monthly	2	Unusual	2	Significant (Minor damage/injury)
3	Weekly	3	Possible	3	Serious (Impaired ability to operate the facility)
4	Daily	4	Expected	4	Severe (Major damage/injury; Facility out of service)
5	Continuous	5	Certain	5	Catastrophic (Destruction; Life-threatening injury; Death)

HOW RISKY ARE RECHARGEABLE LI-ION BATTERIES?

Most of us spend part of every day with a device containing a rechargeable Li-ion battery. Therefore, the frequency of exposure is Daily (4). Because of the large amount of energy contained in Li-ion batteries, they can ignite and/or explode. Therefore, the severity of a potential mishap is Serious (3). Although Li-ion battery fires seem to be reported frequently, there are an estimated five billion people carrying a mobile device with a rechargeable Li-ion battery. Based on this very high number of devices in use compared to the small number of fires, Li-ion battery mishaps are very rare. The probability of this type of mishap occurring is Unlikely (1). The combination of these three factors leads to an overall risk score that is low (4x3x1 = 12).

When a Li-ion battery is being charged, the risk profile changes. The frequency of exposure (i.e., using a device while it is charging) is still a Daily exposure (4). The severity is still Serious (3). The probability of the mishap has increased to Unusual (2). Therefore, the overall risk score is higher (4x3x2 = 24).

If a Li-ion battery is used inside a hyperbaric chamber, the risk profile changes again. The frequency changes to Continuous (5) - the entire time the battery is inside the chamber. The chamber environment contains a higher partial pressure (and possibly a higher percentage) of oxygen. This lowers the ignition temperature of materials, increases the heat of a fire, and increases the flame spread rate. Along with the fact that the chamber is not easily escapable, the severity of a potential mishap has increased to Severe (4). The change in chamber pressure could affect the battery, increasing the probability of a mishap to Possible (3). The overall risk score is higher (5x4x3 = 60). Because of these dynamics, it is important to understand the specific nature of risks when considering a Li-ion battery for use in a hyperbaric chamber.

HYPERBARIC RULES FOR BATTERIES

The National Fire Protection Association (NFPA), has a chapter dedicated to hyperbaric facilities in NFPA 99 Health Care Facilities Code. To the author's knowledge, NFPA 99 is the only standard to specifically address use of battery-operated equipment in hyperbaric chambers. The rules address Class A [multiplace] chambers, and do not address Class B [monoplace] chambers. Although NFPA 99 does not specifically prohibit batteries inside Class B chambers, the intent of the Code is to have power sources outside the chamber.

The NFPA rules first made specific allowance for battery-operated equipment inside a Class A hyperbaric chamber in 1993, long before Li-ion batteries were an issue. After Li-ion batteries became prevalent in the marketplace, the 2012 edition of NFPA 99 made specific mention of Li-ion batteries, "Lithium and lithium ion batteries shall be prohibited in the chamber during chamber operations, unless the product has been accepted or listed for use in hyperbaric conditions by the manufacturer or a nationally recognized testing agency." In the 2018 edition of NFPA 99, this sentence was removed. The 2018 edition of NPFA 99 contains the following rules in section 14.2.8.3 Wiring and Equipment Inside Class A Chambers:

14.2.8.3.17.5 Battery-Operated Devices. Battery-operated devices shall meet the following requirements:

(1) Batteries shall be fully enclosed and secured within the equipment enclosure.

(2) Batteries shall not be damaged by the maximum chamber pressure to which they are exposed.

(3) Batteries shall be of a sealed type that does not off-gas during normal use.

(4) Batteries or battery-operated equipment shall not undergo charging while located in the chamber.

(5) Batteries shall not be changed on in-chamber equipment while the chamber is in use.

(6) The equipment electrical rating shall not exceed 12 V and 48 W.

Current NFPA rules on batteries in hyperbaric chambers are not specific to Li-ion batteries; and do not address all potential issues one might have with Li-ion batteries. One of these issues is exposing a battery-powered device to an oxygen-enriched environment. The use of any powered device in an oxygen-enriched operating environment (i.e., where oxygen is likely to be above 23.5%), should only be considered where batteries are secured and contained in fully enclosed housings.

SUMMARY OF RISKS

The period of highest risk occurs during re-charging. It is essential that batteries are not re-charged during hyperbaric operations. Non-rechargeable (i.e., disposable) Li-ion batteries, such as a coin battery, are thus safer and more suitable for use. Some rechargeable Li-ion batteries have a disposable counterpart (e.g., AA, AAA, 9V), and some do not (e.g., those shaped like a rectangular box). Therefore, replacing the rechargeable battery with a disposable one may or may not be an option.

The following is a list of concerns associated with the use of rechargeable Li-ion battery powered devices (some of which apply to use inside a hyperbaric chamber):

1. Li-ion batteries can rupture, ignite or explode when exposed to temperatures above 60°C (140°F) or prolonged exposure to direct sunlight. Heat combined with humidity may stress the battery and cause permanent damage.
2. Degradation and irreversible damage to the battery may occur when charged at temperatures below -18°C (0°F). This can also lead to thermal runaway, causing the battery to ignite or explode when in use.
3. Short-circuiting a Li-ion battery can cause it to ignite or explode. A short-circuit may be caused by loss of conductor insulation, incorrect storage, incorrect installation, moisture ingress, submersion in water, contamination during manufacture, or through equipment failure. To mitigate the risk of short-circuit, equipment manufacturers may include safety features in their products, including vents to release gas built-up inside the battery compartment, power-flow regulators, temperature monitors, and fuses. If vents are present, activation of a multiplace chamber fire suppression system can cause ingress of water into a device. If the interior of a multiplace chamber is humid, decompression of the chamber may cause condensation to form, which may be a source of water ingress.
4. Rupture of the battery inner separator can cause an internal short-circuit. The rupture could occur with mechanical damage from dropping the device (or other impact), rough handling when installing or removing batteries. The pressure increase inside a hyperbaric chamber could potentially affect the inner separator.
5. Any attempt to open or modify a Li-ion battery casing (to vent or allow it to vent safely in the hyperbaric chamber) is dangerous. This could negate the safety features that protect the internal cells from damage, which can cause the battery to ignite or explode.
6. Liquid-based electrolytes in a Li-ion battery contain some form of lithium salt in an organic solvent, which is classified as flammable. Ignition will occur if there is enough heat. The hyperbaric environment tends to lower the ignition temperature of materials.
7. Over-charging a Li-ion battery can damage the battery and lead to thermal runaway. For this reason, device manufacturers frequently design their equipment to prevent overcharging. This involves carefully determining the optimum voltage and then preventing further charging. These systems can fail, and batteries can be damaged during this vulnerable stage.
8. A flaw in manufacturing could introduce contaminants in the battery cells. Contaminants can cause a short-circuit.

EXAMPLES OF SOME LI-ION BATTERY TYPES

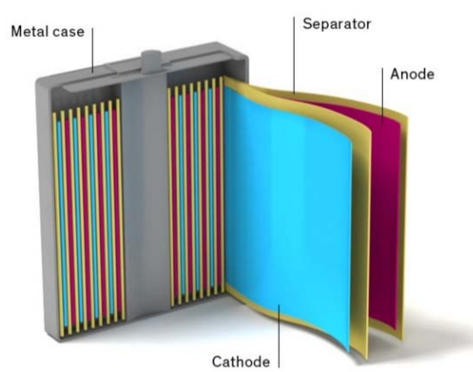
Disposable (Coin Shape)

Disposable (Unique Shape)

Rechargeable (AA Size)

Rechargeable (Unique Shape)

INTERNAL DESIGN OF RECHARGEABLE LI-ION BATTERY



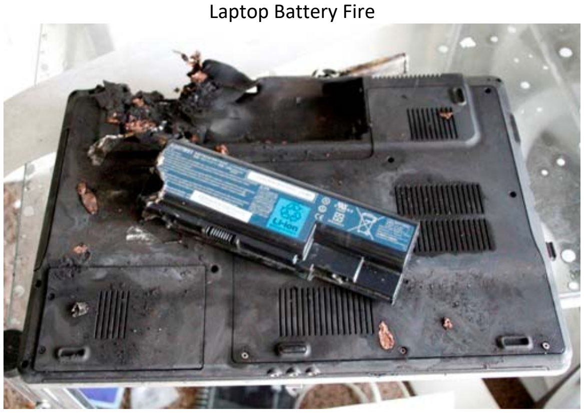
LI-ION BATTERY RECALLS

Sony (2006) recalled several million batteries used in Dell, Sony, Apple, IBM, Toshiba, Fujitsu and other laptops. The reported reason was internal contamination with metal particles. Under some circumstances, these can pierce the separator, causing the cell to short, rapidly converting all of the energy in the cell to heat resulting in an exothermic "oxidizing" reaction, increasing the temperature to hundreds of degrees in a fraction of a second. This causes the neighboring cells to heat up rapidly, causing a thermal chain reaction. Quality control is thus essential during the production of all Li-ion batteries.

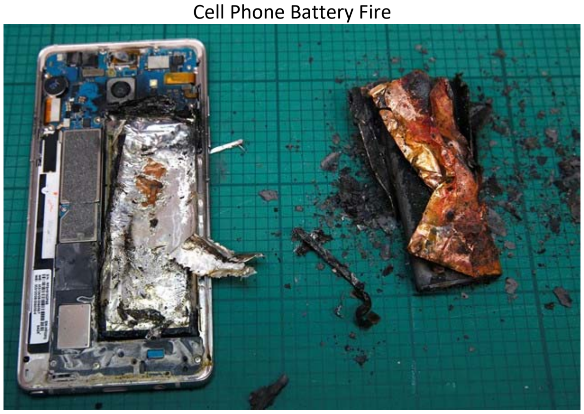
Although probably the largest recall to date, Sony was not the only manufacturer to recall batteries. There have been several recalls of Li-ion batteries in cell phones and laptops owing to overheating problems during periods of intense working of the devices.

- Kyocera (2004) recalled cell phone batteries
- Dell (2006) had recall of laptop batteries from the U.S. market
- IBM (2007) recalled laptop batteries due to an explosion risk
- Nokia (2007) recalled millions of batteries due to overheating and possible explosion

Laptop Battery Fire



Cell Phone Battery Fire



What about the battery in an implanted medical device?

Implanted pacemakers, defibrillators, and most likely all implanted devices use a disposable lithium-ion battery. The biggest concern for most implanted devices is pressure tolerance, not the power source. Any gas spaces in the device will be affected by chamber pressure. This might cause a malfunction or failure of the device but would not likely affect the disposable battery.

RECOMMENDATIONS FOR SAFER USE

1. Adhere to the OEM specified operating conditions. This is especially important in terms of temperatures and humidity. Any damage caused by external pressure should be evaluated during testing and assessed with regular visual inspection (prior to each use).
2. Use only OEM chargers. The manufacturer may locate the cut-out device to prevent over-charging in either the device or the charger; and this detail is often not known. The necessary cut-out device may be absent from an after-market charger.
3. Use only OEM-specified replacement batteries.
4. Keep Li-ion batteries charged to the optimum level. These batteries typically operate best and with the least amount of stress if charged between 65% - 75%. The device manufacturer should indicate the preferred storage level (usually not less than 40%) and minimum level at which they should be recharged (these batteries typically shut down when the charge level approaches 25%).
5. Do not charge under hyperbaric conditions or at temperatures below freezing.
6. Do not leave a device unattended when it is charging (i.e., overnight).
7. Disconnect the charger when charging is complete.
8. Inspect Li-ion batteries regularly for signs of deformation or leakage. A failing Li-ion battery will show signs of bulging, hissing and/or leaking electrolyte. Also verify the battery is secured in the housing (i.e., it cannot move), and the power leads and contacts are secure.
9. Do not tamper with any part of the battery, including the casing, wrapping or connections to internal parts.
10. Develop, implement and practice an emergency action plan for any form of Li-ion battery failure during operations. This should include locking the device out of the chamber and managing a Li-ion fire. Foam, carbon dioxide and dry chemical extinguishers are suitable extinguishing mediums for fires occurring outside the chamber. Water from the fire extinguishing system inside a chamber is not suitable and may exacerbate a Li-ion battery fire. The device containing the battery should be removed from the chamber immediately, using either the medical or transfer lock.

THE FUTURE OF LI-ION BATTERIES

Li-ion battery technology continues to develop. Current new battery technology includes features such as non-flammable, solid ceramic electrolytes. The future should bring higher capacities (i.e., more power), and hopefully more robust and better internally protected products. Combined with appropriate caution, these products may become more suitable for use in hyperbaric chambers.

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