Lithium Battery Deactivation for Defense Logistics Agency

Lithium cells from a BB2590 being deactivated at OnTo Technology LLC facility in Bend, OR.

John Callaway (Research Intern)
john.callaway@nps.edu

Jason Navarrete (Research Intern)
Jason.navarrete@nps.edu

Ignas Kasulaitis (Research Intern)
ignas.kasulaitis@nps.edu

Eric Hahn (Principal Investigator)
ehahn1@nps.edu

July 2022

Energy Academic Group
Naval Postgraduate School

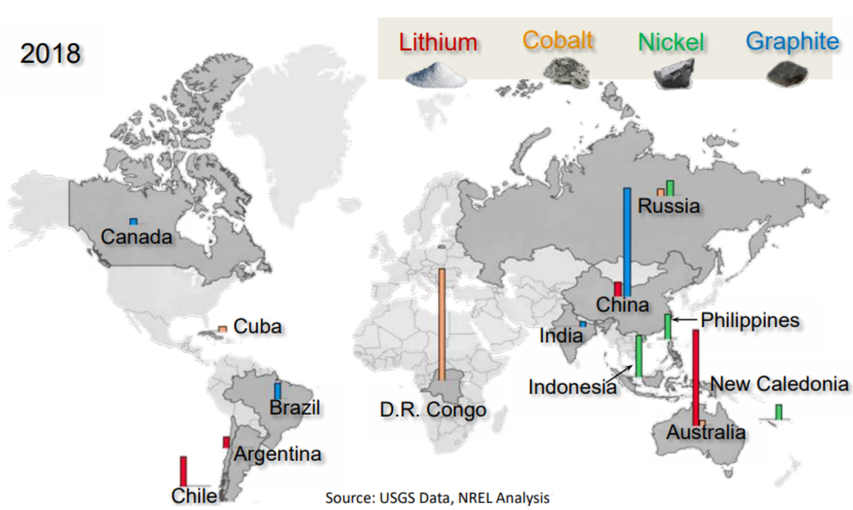
ABSTRACT

This report summarizes stakeholder needs for Li-ion battery (LIB) deactivation system implementation at military installations reporting lithium battery waste and provides a study of a potentially opportune location for a pilot process. This need is driven by increasing demand for LIBs in defense systems. LIBs are increasing in hazardous waste streams generated by defense and industry, representing a safety and cost risk. The top goal for local installation battery deactivation is for immediate safety and to enable dramatically lower subsequent transportation costs. Eventual reclamation of high-value Ni or Co from deactivated batteries supports a national objective. This study found that a large concentration of LIB waste is in the Southern California region. This leads the focus of this study to assess LIB hazardous waste streams and potential opportunities for implementing an emerging LIB deactivation technology at west coast Navy and Marine Corps installations in Southern California.

INTRODUCTION

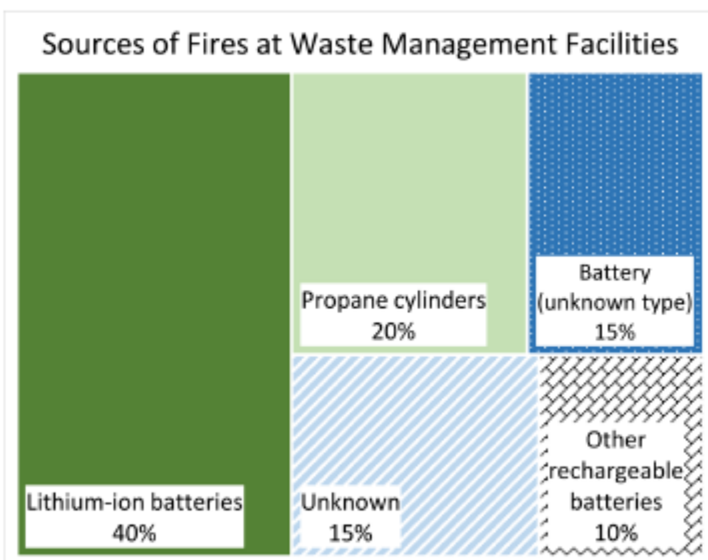
The Defense Logistics Agency (DLA) procures thousands of unique types of batteries, worth over $200 million each year, to meet military requirements.[1] Of that amount,15% is LIB procurement. This procurement only accounts for a portion of overall annual demand from across the department of Defense (DoD), which includes numerous procurements across each of the services, specific to various programs. However, the U.S. currently depends on other countries for LIB raw materials (see Figure 1.) As the DoD prefers domestically sourced, high-density energy storage, DLA has expressed a need for LIB deactivation and recycling technology[2]. DLA's need for deactivation technology comes from the need to mitigate fire risk, reduce waste stream cost, and for the eventual recovery of strategic raw materials from end-of-life batteries, which stem from defense or industrial waste streams. (Small Business Administration [SBA], 2020).

Figure 1: U.S. dependency on other countries for mining and production of LIB materials



There is risk and cost associated with transporting end-of-service life or waste LIBs to recycle them. Lithium and LIBs are always considered dangerous goods when transported. End-of-service life or waste LIBs are no exception. Unless specifically exempted under certain conditions (e.g. small cells or quantities) they must be transported as a fully regulated Class 9 hazardous material, regulated by the Department of Transportation, which adds cost and reduces efficiency at the end of service life. Failure to comply with requirements for Class 9 shipment has resulted in documented fires during transportation.[3] The cost and risk continue as documented in the Environmental Protection Agency (EPA) study of July of 2021 analyzing LIB fires in waste management and recycling[4]. The damage cases collected in EPA's report underscored that LIB-caused fires (see Figure 2) throughout the waste management process are a safety and cost risk. This is projected to become an increasing issue as LIBs are an electrochemical power source present in a wide array of military and commercial applications, and their prevalence is increasing. As devices containing these LIBs reach the end of their useful lives, they will contribute to the LIB waste stream. Likewise, as the world transitions to electric vehicles and more use of intermittent renewable energy that requires significant storage capacity, dealing with large-scale end-of-life LIBs will also become a pressing issue. DLA's need addressed in this study is to identify and compare sites for implementing an already developed deactivation and partial disassembly technology designed for secondary lithium-ion and primary lithium military batteries that utilize supercritical CO_2 removing the flammability hazards from active lithium.

Figure 2: Sources of Fires at California waste management facilities, according to a 2018 survey by the California Product Stewardship Council (Environmental Protection Agency [EPA], 2021)



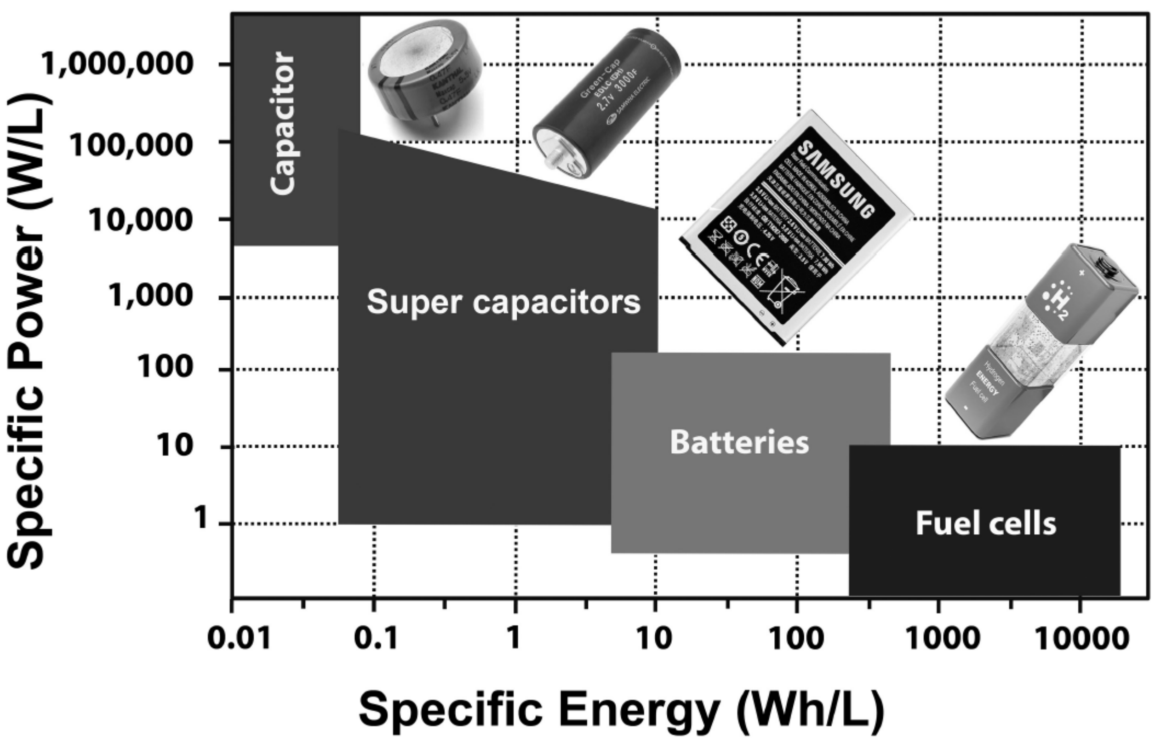
BACKGROUND

Electrically powered technologies have transformed the military and the way in which wars have been fought in recent history. These technologies are associated with directed energy systems; electrified land, air, sea, and space platforms; robotic and autonomous systems; sensors and situational awareness, and other essential military requirements. With electrically powered technologies, comes the need for electrochemical energy storage devices such as batteries, supercapacitors, and fuel cells, which play an important role in storing energy and providing electrical power when and where needed. However, there is a hazardous energy issue that persists at the end of battery service life when it is no longer a satisfactory energy storage device for the system it was powering.

Lithium Batteries

Among the various electrochemical energy storage devices available, batteries are desirable, as they can efficiently store electricity in chemical form and release it responsive to demand. Shown in Figure 3 is a Ragone plot that shows how various electrochemical energy storage systems compare in terms of specific power and specific energy.

Figure 3: Ragone plot showing specific power against specific energy for various electrochemical energy storage systems.[5]

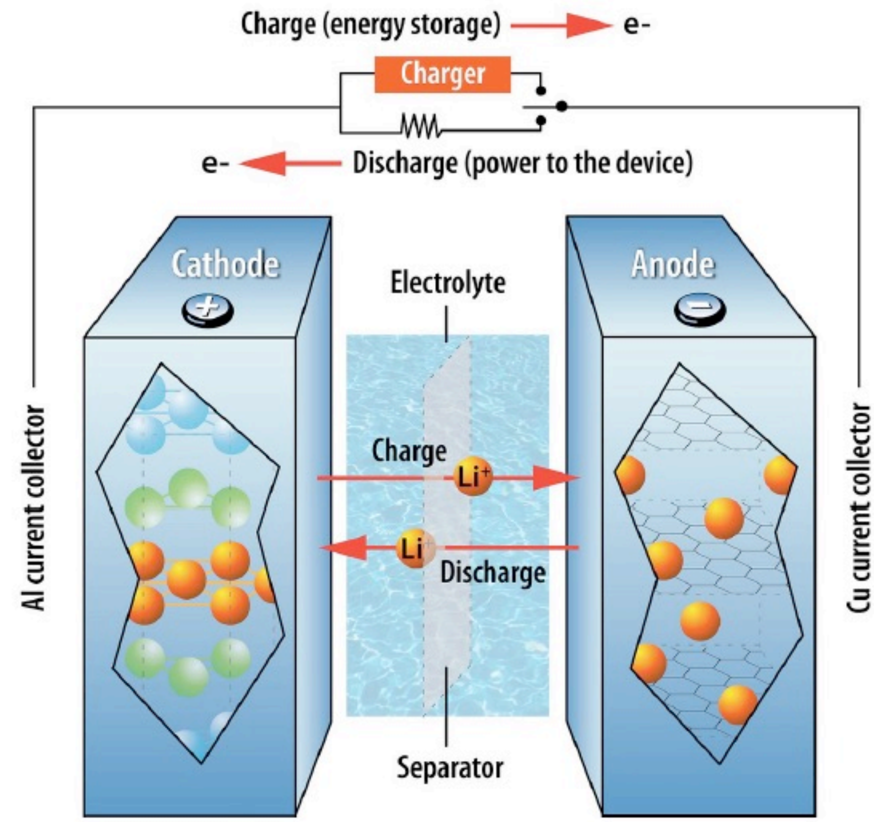


A battery can be defined as an electrochemical power source composed of certain common fundamental components. An electrochemical cell typically comprises an anode, cathode, separator, and electrolyte. A cell can be considered a single-cell lithium battery, but typically a battery contains an arrangement of multiple cells. Electrochemical cells store chemical energy that can be converted into electricity. A battery can be used as a source of power when a load is applied to a charged cell or battery. The stored chemical energy is released when a chemical electron exchange occurs at the electrodes, which results in the flow of electricity.

The two mainstream classifications for modern batteries are primary (non-rechargeable) and secondary (rechargeable). Lithium metal batteries are typically primary and have lithium metal or lithium compounds as an anode. Lithium alloy batteries are a type of lithium metal battery. The amount of lithium in a lithium metal battery is used to determine how or if it is subject to shipping regulations. Cells containing >1 gram and batteries containing >2 grams are subject to more strict levels of regulation depending on the mode of transportation. Secondary lithium batteries do not use pure lithium as the anode, as it is difficult to recharge. Instead, lithium-ions move to and from the cathode and anode. The lithium-ion batteries (LIB) can be safely recharged but have a reduced shelf-life and are less stable when compared to primary lithium batteries. The watt-hour (Wh) rating of a LIB is used to determine how or if it is subject to shipping regulations. A cell with a watt-hour rating of >20 Wh and a battery with a watt-hour rating of >100 Wh are subject to more strict levels of regulation depending on the mode of transportation.[6]

LIBs have gained considerable interest in recent years in terms of their high energy density, cell voltage, their good capacity retention, and their negligibly small self-discharge rates. (Stelbin & Raghavan, 2019) From an environmental health perspective, LIBs are preferable to other rechargeable chemistries like nickel-cadmium (NiCad) batteries because LIBs are not known to contain certain toxic chemicals like lead or cadmium. In a LIB (Figure 4), the anode is usually composed of a graphite matrix embedded with a lithium compound. The anode also contains a current collector (often made of copper). The cathode is often cobalt oxide. Other compounds such as iron phosphate, sulfur, nickel manganese cobalt oxide, nickel cobalt aluminum, etc. can also be used for the cathode. A liquid electrolyte between the anode and cathode, and a thin layer of polyethylene or polypropylene selectively allows lithium ions to pass from one side to another, creating the useful voltage that powers a device. LIBs are composed of one or more of these electrochemical cells.

Figure 4: Diagram of an LIB. "How a lithium-ion battery works" by Argonne National Laboratory licensed with CC BY-NC-SA 2.0. To view a copy of this license, visit https://creativecommons.org/licenses/by-nc-sa/2.0/



The energy density of lithium-ion cells (~150 Wh/kg) is less than common fuels. However, in most lithium-ion cell designs reactive materials are combined in a tight space and are very close to volatile and flammable electrolytes. When the barriers separating these very reactive materials are damaged (see next section on risks), a chain of reactions creates a thermal event that increases the temperature, up to 700-800 ºC.[7]

Primary lithium and secondary LIBs are widely used in Naval equipment and systems (see Table 1). LIBs have gained increased use in non-military Electric Vehicles (EV) and are now also an important technology in the scope of electrical energy storage systems on military land vehicles.[8] Rechargeable (secondary) LIBs are desirable for these systems due to being capable of delivering high rates of high-power discharge capability with a high energy density and specific energy. They have a long shelf life, long cycle life, and lack of a memory effect which make them attractive for propulsion power applications for unmanned systems (terrestrial, underwater, and aerial) and other defense systems. Although there is no published formal estimate, the DoD anticipates demand for these batteries (including advanced LIBs for combat applications) will grow beyond traditional uses (e.g., combat platforms, weapons, sensors, and individual warfighter equipment) to include the introduction of tactical microgrids (EPA, 2021).

Table 1: Naval Equipment and Systems Requiring Electrochemical Power Sources[9]

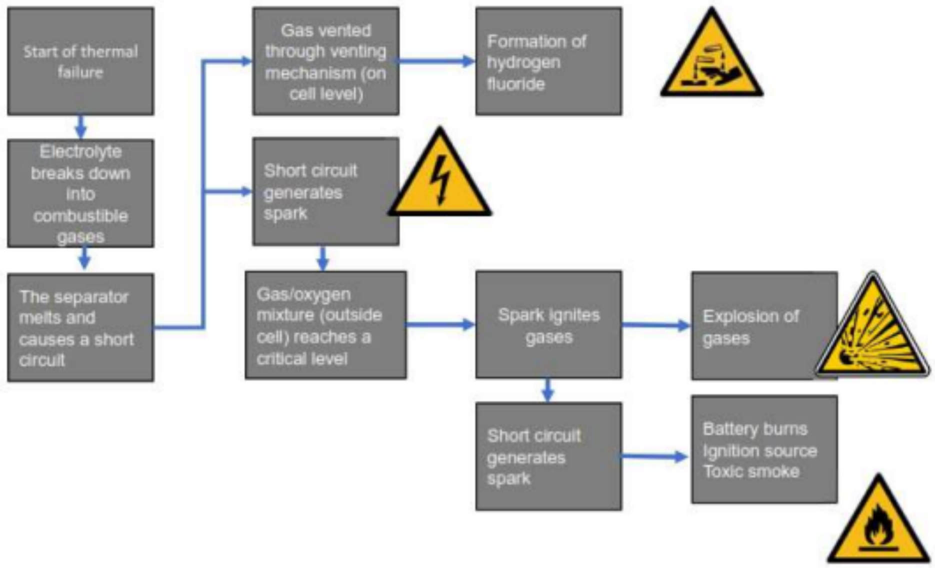
Guided missiles	Memory backup
Bombs	Depth charges
Mines	Aircraft
Fuzes	Telemetry
Guided projectiles	Surveillance buoys
Torpedoes	Sonobuoys
Underwater targets	Sound sources
Submarines	Acoustic transponders
Swimmer delivery vehicles	Field communications
Unmanned Underwater Vehicles	Laser designators
Unmanned Aerial Vehicles	Countermeasures
Explosive Ordnance Disposal Robots	Night vision
Medical equipment	Weapons handling equipment

Risks Associated with Lithium Batteries

Primary and secondary lithium batteries have high energy densities, which are significant drawbacks. When crushed or otherwise damaged they can undergo thermal runaway (a reaction in which the battery unexpectedly releases its energy and begins self-heating in a runaway reaction). Thermal runaway can also result from overcharging, over depletion, or shorting. The result can be the venting of toxic, flammable gases, and a large energetic reaction (fire and explosion). Thermal runaway can also quickly produce enough heat to ignite materials near the battery, even if the battery itself does not ignite. LIBs are particularly prone to combustion as they contain combustible materials. This high energy density and combustible material are what creates the high risk of fire. A LIB's electrolyte is also combustible, though there is ongoing research to find non-ignitable electrolyte substitutes.

During a thermal event as introduced in the previous section, lithium batteries may release combustible gasses. The smoke from a fire of LIBs contains combustible, carcinogenic, toxic, and corrosive substances. A thermal event starts with an increase in the temperature of the battery (thermal failure, see Figure 5). This can propagate through the battery as the heat may extend to other parts of the battery. Once a certain temperature has been reached, gases are generated from the electrolyte and the material that separates the anode and cathode (or separator) melts causing a short-circuit. This may initiate a cascading reaction leading to additional generation and release of gases, sparks, or the release of oxygen outside the cell.[10]

Figure 5:What happens when a lithium-ion battery fails? (Source: SENS Foundation | WEEE Forum Operations Committee, 3 December 2020) courtesy Herreras-Martínez and Bountis (2021)

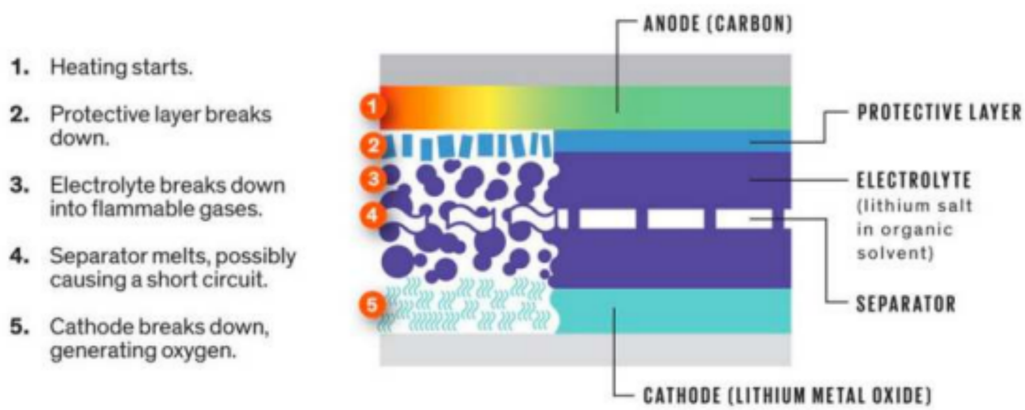


Thermal runaway occurs when the temperature in a cell continues to increase as oxygen is released which facilitates combustion as follows[11] (see Figure 6):

- Once the temperature of the cell reaches ~80 °C, decomposition of the layer protecting the anode (or solid electrolyte interphase, SEI) begins generating heat in a reaction of lithium with the solvents in the electrolyte.
- Between 100 °C–120 °C the electrolyte begins to break down in another reaction liberating heat and generating gases within the cell.
- Between 120°C–130 °C, the separator (layer separating anode and cathode) eventually melts, allowing the anode and cathode electrodes to internally short-circuit and generate more heat.
- Between 130 °C–150 °C, the cathode breaks down in another chemical reaction that liberates heat with the electrolyte, which also generates oxygen.
    - The release of oxygen along with carbonate-blend $LiPF_6$ electrolytes used in commercial LIBs allows the cell to burn and catch fire.
    - Decomposition of the cathode active material is an exothermic reaction that continues to drive cell combustion.

- Between 150 °C–180 °C if the cell fails to rapidly dissipate, the heat being generated may become self-sustaining.
    - Gases may continue to build up inside the cell, causing rupture or venting through a safety valve, expelling flammable gases and electrolytes that could be ignited by the introduction of a spark causing flame, fire, and potentially an explosion.
    - Pressure increase can also burst open the cell ejecting the "jellyroll" from the housing.
    - At this point, thermal runaway is self-sustaining, oxygen generation sustains the fire until all the fuel has been consumed.

Figure 6: Illustration of thermal runaway process in lithium-ion battery cells courtesy Herreras-Martínez and Bountis (2021)



Safe and cost-effective waste management is essential to minimize immediate risks to operations and installations from thermal runaway hazards of end-of-life lithium-ion batteries and enable safe recycling. However, damage cases collected by EPA between 2013 and 2020 found 245 fires at 64 waste facilities were caused by, or likely caused by Lithium primary or LIB secondary batteries. LIB-caused fires throughout the waste management process pose a current risk to the safety of workers, bystanders, and emergency responders, and are resulting in increased costs to the industry.[4] This is also a risk and cost for defense operations and installations that will increase as more lithium-ion batteries are procured to meet requirements.

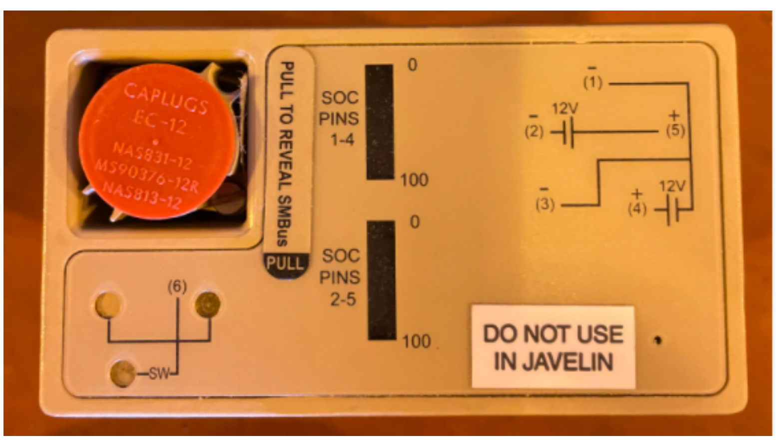
Focus of Study

The DLA Research & Development Program recognizes that lithium-ion battery recycling is costly and hazardous for transportation. DLA has a need for study and analysis into what the requirements are to facilitate a deactivation process that reduces the disposal cost and to create localized deactivation that lowers the cost of transportation. This allows, at the point of LIB generation, to reduce the risk of fire, opens the availability of safely storing the deactivated LIB's waste for an extended period, and lower costs associated with transporting hazardous waste.

The greater Southern California Naval Concentration area in San Diego consists of 3 major Navy Installations; Naval Base San Diego, Naval Base Coronado, and Naval Base Point Loma, and 3 major Marine Corps Installations; Marine Corps Base Camp Pendleton, Marine Corps Air Station Miramar, and Marine Corps Recruit Depot San Diego. Current hazardous waste guidance and standard operating procedures at these installations identify that Lithium-ion batteries fall under Department of Transportation Hazard Class 9 (which is miscellaneous, as defined in the code of federal regulations).

There are about 300 sites and activities aboard these installations and their associated outlying training areas that are generating and reporting a combined average of about 28 thousand pounds of waste lithium-ion batteries each year. These waste streams are reported by weight at the turn by the individual units and sites, in accordance with California Environmental Protection Agency Hazardous Waste reporting requirements. However, data on specific types of batteries are not reported. This means lithium-ion battery waste streams at these installations include both military batteries like the BB-2590 battery (see Figure 7), as well as commonly used non-military lithium-ion batteries. Hence there is an effective need for achieving deactivation as close as practicable to specific units generating specific military lithium-ion battery waste streams to mitigate logistics costs and risks to these units' mission both in homeport and on deployment.

Figure 7: BB-2590 Top View



Marine Corps Base Camp Pendleton accounts for just under 50% of the total amount by weight. It is collected by a DLA contractor from the 47 permitted accumulation sites on the base and currently delivered to permitted Treatment Storage and Disposal Facilities (or TSDFs). There are 74 currently operating, permitted TSDF's in California (see Figure 8). However, the DLA contractor for Pendleton currently uses one TSDF located in Mesa Arizona, and another in Anaheim California. The remainder of the Southern California Naval sites and activities turn in batteries to two TSDF's, one located aboard Naval Base San Diego (see Figure 9) and one on Naval Base Coronado.

Figure 8: Operating, permitted Treatment Storage and Disposal Facilities in California

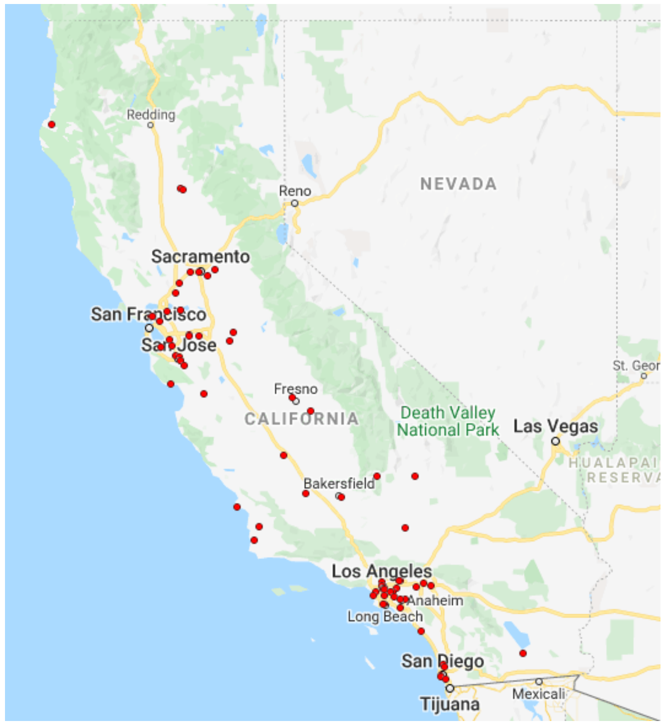


Figure 9: Treatment Storage and Disposal Facility Aboard Naval Base San Diego

Suitable alternatives for Southern California Naval installation lithium-ion battery deactivation pilot sites are identified and assessed assuming the implementation of an emerging deactivation technology that uses supercritical carbon dioxide (CO_2) to remove flammability hazards from active lithium (see Appendix A). These sites will have higher densities of known military lithium-ion batteries entering the waste stream and will be closer to the source of generation. This, in turn, will foster lower cost and storage risks and will result in safer shipping to an end recycler. Best practices from a successful demonstration in the Southern California Naval concentration area can then inform further implementation studies and efforts at other locations.

LITERATURE AND DATA REVIEW

A literature and data review are presented in this section to build up independent knowledge in the subject matter area of LIB disposal needs, starting with law, regulations, standards, and official guidance for military activities. Federal universal waste rules are found in Title 40 Code of Federal Regulations (CFR), Part 273. LIBs are considered universal waste, as it is well documented by DNV (the world's preeminent classification society) that LIBs "pose significant hazards with regard to fire".[12] In accordance with Defense Materiel Disposition: Disposal Guidance and Procedures Department of Defense Manual 4160.21, Volume 1, LIBS may be managed as universal waste under DLA Disposition Services, which is defined as an organization that "provides DoD with worldwide reuse, recycling and disposal solutions that focus on efficiency, cost avoidance, and compliance."

Given DLA Disposition Services' global view of disposal solutions, data on LIB disposal amounts requested by pounds was obtained from DLA Disposition Services. The data was reviewed for FY 2019 and 2020 to identify any locales that contributed significantly to the total, by weight, of all LIB disposal requests. This data captured LIB disposal requested by individual Department of Defense Activity Address Codes (DODAAC) at Department of Defense Installations across the Continental US (CONUS) and Hawaii. A review of this data showed that California installations accounted for more than a quarter of the total amount of LIB disposal requested by weight.

In California, batteries that exhibit a characteristic of hazardous waste (e.g., fire hazard) are considered universal waste and can be handled, transported, and recycled following requirements outlined in the universal waste regulations (UWR) (California Code Regulations, title 22, division 4.5, chapter 23). At Southern California Naval installations, LIB disposal is managed in accordance with Marine Corps Installations West and Marine Corps Base Camp Pendleton (MICWEST-MCB Camp Pendleton) Order 5090.7A aboard Marine Installations; and in accordance with Commander Navy Region Southwest Waste Management Plan San Diego Metro Area 5090 aboard Navy Installations.

Some Navy activities are not using DLA Disposition Services contracts for universal waste management of LIB waste (but instead use alternate Navy hazardous waste contracts). Therefore, LIB turn-in data was also requested from Naval Facilities Engineering Systems Command (NAVFAC) Southwest Environmental Department as well as the Hazardous Waste Section of Environmental Security for MCIWEST-MCB Camp Pendleton. This data revealed about 300 sites and activities in the Southern

California Naval Concentration Area between Camp Pendleton and the San Diego metropolitan area, and their associated outlying training areas are generating and reporting a combined average of about 28 thousand pounds (12,700 kg) of waste stream containing lithium-ion batteries each year.

To assess the risk of fire currently posed by the LIB waste stream (without deactivation), literature on fire damage attributable to LIBs in the waste stream was reviewed. This includes *An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling* by the United States Environmental Protection Agency; *Cutting Lithium-ion Battery Fires in the Waste Industry* published by the Independent Consultancy called Eunomia and the resource and waste management trade body known as the Environmental Services Association, of the United Kingdom, along with a news article from an independent recycling and waste management industry publisher in the UK called "letsrecycle.com". Both the US EPA and UK references contained qualitative and quantitative descriptions of the consequences of LIB fires in the waste stream. The news article from letsrcycle.com contained data on the total amount of battery waste streams that contain LIBs in the UK. In addition to a quantitative assessment of the fire risk, the cost of disposal was estimated using online data DLA Disposition Services Hazardous Waste Contract Line pricing.

To assess the growth of the LIB waste stream, both recently enacted US law and research prepared for the Australian Department of Environment (Australian DoE) were considered. Although the DoD has not released official predictions on the future needs of lithium-ion batteries, growth is considered likely due to 10U.S.C.2922g that came into effect on the 13th of January 2021. The law mandates that the "Military department or Defense Agency, the Secretary of the military department or the head of the Defense Agency shall provide a preference for the lease or procurement of motor vehicles using electric or hybrid propulsion systems." This would reasonably result in growth in the LIB waste stream as these Electric Vehicle (EV) batteries reach the end of their service life. Quantitative research performed for the Australian DoE quantitatively predicted the growth of the Australian LIB waste stream (in terms of an average annual growth rate percentage through 2036) due to EV, handheld devices, and photovoltaic systems. (Randall, 2016)

METHODOLOGY

LIB disposal amounts requested of DLA Disposition Services by DODAAC at Department of Defense Installations across the Continental US (CONUS) and Hawaii for FY19 and FY20 were evaluated. The overall LIB amounts (in pounds) requested are assumed to be under the actual amounts of LIB entering the waste stream because not all activities use DLA Disposition Services Hazardous Waste contracts. However, percentages relative to the total are used to compare among the activities requesting LIB disposal to identify where there are larger relative quantities of LIBs entering the waste stream. Relative percentages of the total LIB disposal amounts requested by the state were compared first. Within the state that had the highest relative percentage, the relative percentages among the installations in the state were compared next. Comparing the relative percentages of the activity addresses within the installation with the highest relative percentage of LIB disposal amounts requested, we identified activities that were most frequently requesting LIB disposal amounts. Overall, quantities of waste LIBs reported by installation activities were also requested from installation environmental services staff at the installations identified highest with relative percentages of disposal amounts reported to DLA disposition services. These quantities of waste LIBs were used to assess fire risks at these installations and rank potential deactivation locales.

A quantitative measure of risk can be expressed as the product of the probability that an event will occur and the consequence of that event happening.[13] The fire risk of non-deactivated waste LIBs is quantified using a probability that a given amount of non-deactivated LIBs in a waste stream will result in a fire, times the total costs of fire damage attributable to non-deactivated LIB batteries in a waste stream. This study assumes that a consequence (C_{UK}) of £158 million in fire costs is attributable to non-deactivated waste LIBs (Brown et al., 2021) present in a reference amount equal to 5,723 metric tons of waste batteries (containing non-deactivated LIBs) that were collected in the United Kingdom in 2020.[14] The probability (p_{1t}) in this study is assumed to be equal to the ratio of the amount of non-deactivated waste LIBs under consideration to the reference amount. This corresponds ($R_{1t} = p_{1t}C_{UK}$) to a risk of £28k (or $36K in 2022) for a metric ton (1000kg, t) of non-deactivated waste LIBs.

$$R_{1t} = p_{1t}C_{UK} = \frac{1t}{5{,}723t}£158(10^6) = £28(10^3) = \$36(10^3)$$

Potential deactivation locales are ranked based on their respective quantities reported with consideration to fire hazard risk at the location. The valuation of risk from a fire attributable to LIB is calculated as well as hazardous waste contract costs. Base fire protection, environmental, and planning experts at selected sites were interviewed for feedback regarding the fire risk and deactivation process to gain feedback on the potential implementation of a deactivation technology (described in Appendix A) aboard their installation.

RESULTS

The relative LIB disposal amounts requested of DLA by State, determined by DODAAC are shown in Figure 10. Two states, California, and North Carolina were found to report most of the total amount requested, contributing to nearly 50% of the entire DLA LIB waste. The amounts of reported LIB waste are attributed to major Marine Corps installations located in these states. Overall, the Army was the largest

LIB waste reporting agency (see Figure 11.) However, the waste LIB amount reported from Marine Corps installations facilities is concentrated in key regions. The largest concentration of all LIB waste in California is in San Diego County (see Figure 12) and correlates with the large Marine Corps installation of Camp Pendleton.

Figure 10 Total DLA LIB Waste by State

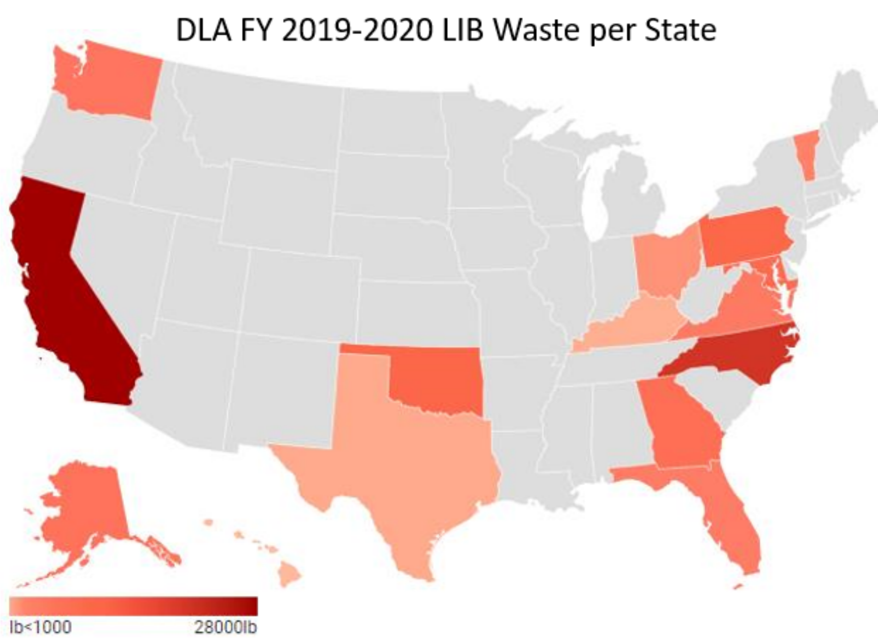


Figure 11: Total DLA LIB Waste by Agency

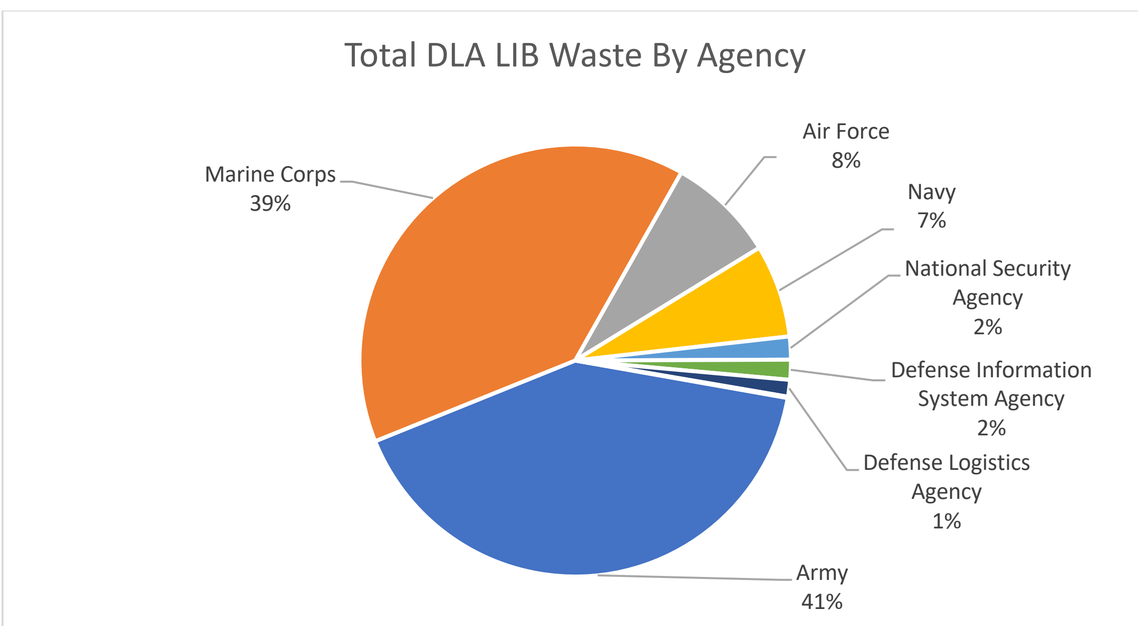
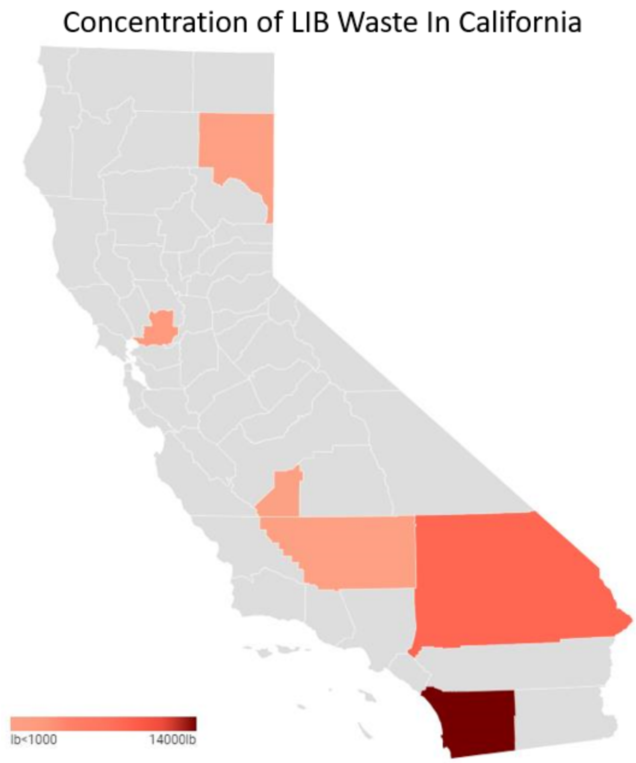


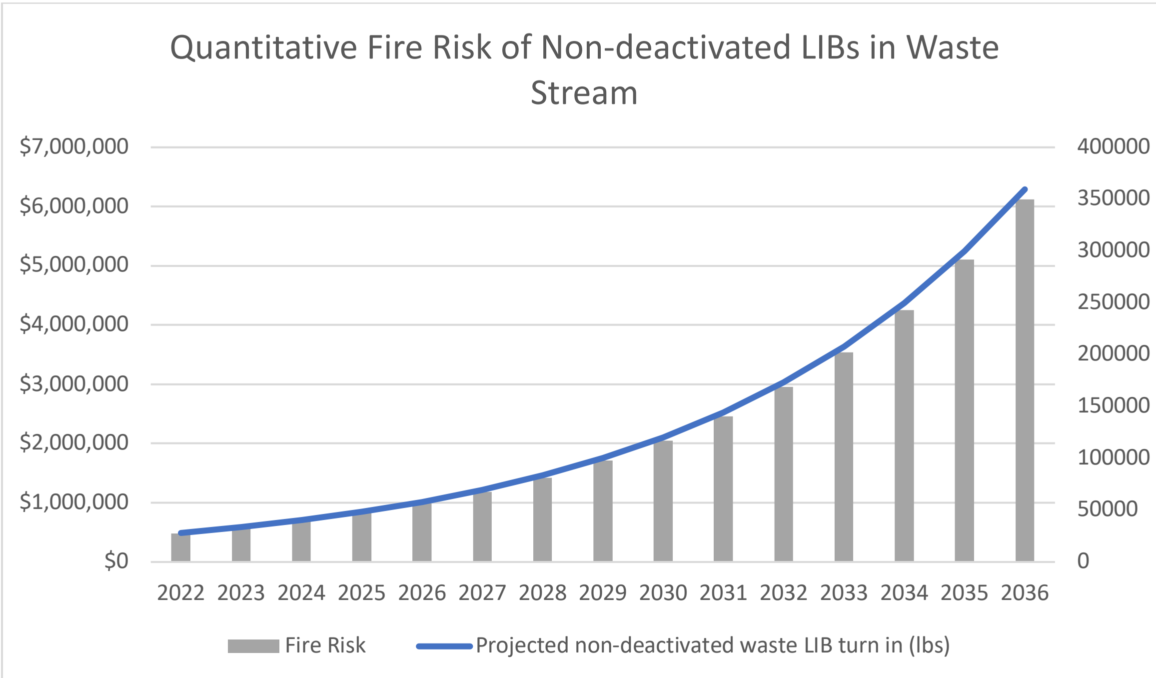
Figure 12: Concentration of DLA LIB waste in California per county



The yearly waste stream containing LIBs in the Southern California Concentration Area is currently estimated to be 28,000 pounds, according to available DLA data shown in Appendix E, and is projected to grow with an average annual growth rate of 20% through 2036 to 360,000 pounds. 28,000 lbs x $(1+0.20)^{14}$ = 360,000 lbs. This corresponds to a fire risk (expressed quantitatively) of $467,000 in 2022, growing to $6,122,000 by 2036 (see Figure 13). An average unit price of $0.93/lb for hazardous waste contracts from DLA Disposition Services to manage LIBs as universal waste in California corresponds to a 2022 average cost of $26,000 that is also projected to grow at the same rate and have an average cost of $334,000 in 2036.

Another factor that could greatly increase the cost due to a LIB fire in the Southern California region is that the region is highly susceptible to wildfires, due to the dry climate and prevalent winds. This risk is elevated at Camp Pendleton due to the nature of operations occurring at the facility. On average, 185 fires annually are caused directly by base operations. Due to the constant threat of fire, the facility maintains 11 fire stations that house 175 personnel and over 150 miles of fire breaks.[15] This still does not eliminate the fire threat. In 2019, over one hundred of these fires turned into active wildfires and burned 4,533 acres.[16] These wildfires impact operations in the area, as mandatory evacuation zones are put in place until the blaze is contained. This reduces the combat effectiveness of units that rely on the impacted areas to conduct training.

Figure 13: Quantitative Fire Risk associated With Waste Containing Non-deactivated LIBs at Southern California Naval Installations



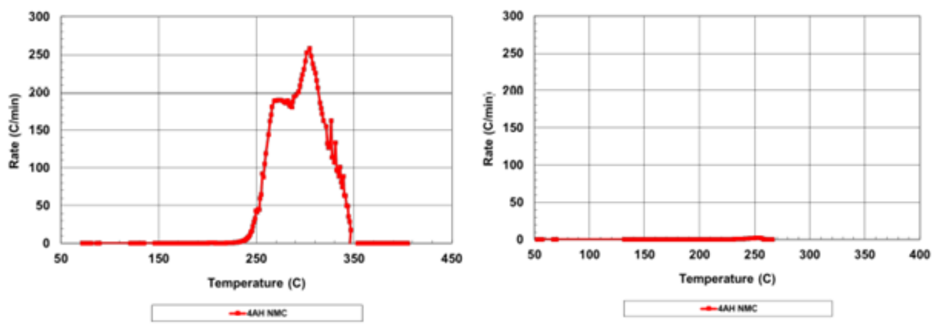
DISCUSSION

The Southern California area is shown to have a significant amount of DLA total reported LIB waste stream. As shown in section 3.3, this region generates 28,000 lbs per year. This makes this region a suitable candidate for a pilot deactivation site for three key factors:

1. This region is the largest contributor to reported LIB waste in the area (data in Appendix E.) This large volume of reported LIB waste concentrated in the area reduces transportation requirements for deactivation.
2. The diversity of the lithium and lithium-ion batteries in the military and commercial waste stream in the Southern California region would allow a broad variety of LIBs that the DOD and commercial sector utilizes to be tested for deactivation.
3. The availability of qualified contractors that work with hazardous materials and have familiarity with DoD installations and regulations.

A Small Business Innovation Research (SBIR) developer under contract with DLA R&D (OnTo Technology LLC) has developed a deactivation process, as shown in appendix A, that has shown promising results for deactivating LIB and has been independently verified at Sandia National Laboratory on three different LIBs', as shown in Appendix D. From that study, it was shown how treated cells rate of heating was significantly reduced compared to non-treated cells, as shown in Figure 14 below.

Figure 14: Sandia National Laboratory Results



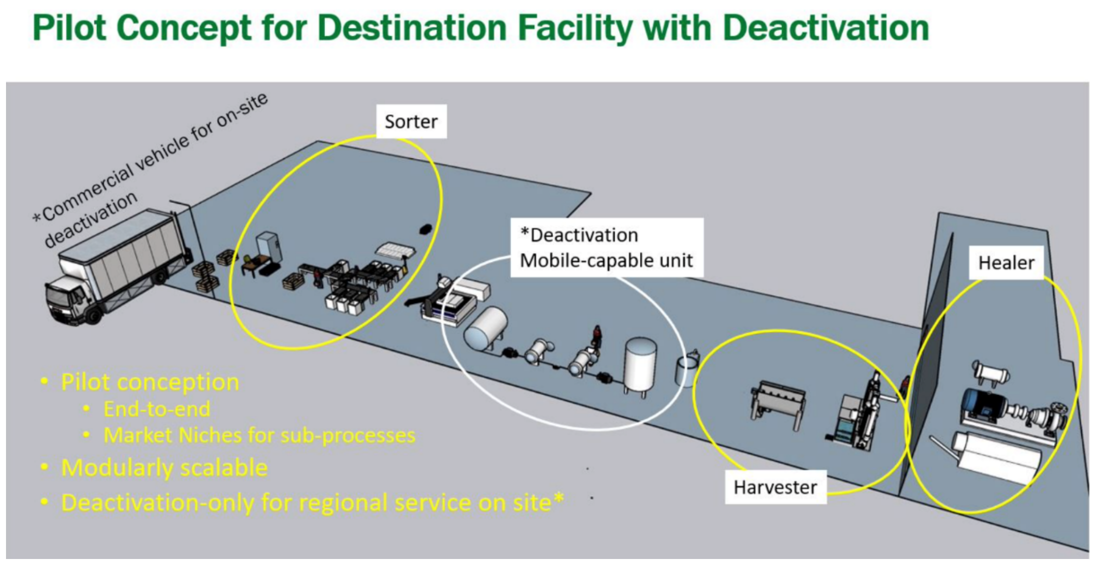
DLA seeks projects to implement this deactivation technology (mobile, expeditionary systems are preferred) at key Continental U.S. (CONUS) and Outside the Continental U.S. (OCONUS) locations.[17] Currently, LIB recycling facilities, such as the Redwood Material processing plant in Nevada have a 550,000 sq ft footprint. Mobile expeditionary capability is needed to allow for the deactivation of LIBs to take place near where the LIB is taken out of service to reduce or eliminate the fire risk associated with LIB's during transport from CONUS and OCONUS military activity locations and at the recycling facilities.

The DLA data used in this research shows that the average disposal contract per pound for LIBs in the Southern California region is \$0.93/lb. Alkaline batteries for the same region are \$0.05/lb. Assuming deactivated LIB's, because of their reduced fire risk, could cost the same as alkaline batteries for disposal This would generate an \$0.88/lb savings for deactivated LIBs compared to non-deactivated LIBs. Also, assuming that localized deactivation was utilized, this would significantly reduce transportation cost and reduce the fire risk of storing active LIBs. A cost analysis was done based on these assumptions. That analysis found that a localized deactivation site would need to process 90lbs/day to break even for the operating cost. The average generation, between 2019 and 2022, in the southern California region is 115lb/working-day. This indicates that the Southern California region has the potential to become net positive if localized deactivation is utilized.

CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH AND TRANSITION

The accumulation of over 25,000 lbs of LIB waste, within the Southern California area, poses a significant fire risk to facilities and personnel, as explained in section 6. Marine Corps Base Camp Pendleton is the recommended location for a pilot process (e.g. Figure 15) in Southern California due to the concentration of reported LIB waste and the elevated wildfire risk that could result from a LIB fire. These fires are especially dangerous at storage and processing facilities. LIB attributed fires in transportation and at recycling facilities see the greatest destruction of equipment and risk to personnel. The ability to deactivate a LIB where it is taken out of service, would all but eliminate the risk of fire and allow the downstream waste system to reduce the risks of handling LIB waste.

Figure 15: Pilot Concept



Additional research needs to be conducted to accurately determine and certify a suitable deactivation for risk-free transport. Currently, the state of a LIB cell after a deactivation process can be verified by inducing a condition for thermal runaway and observing the reaction of the cell. This is a time-intensive process that is counterproductive to the goal of limiting fire hazards. Other methods have been purposed, such as using the pH of the cell to determine deactivation and checking the level of residual charge of the cell. These methods would require follow on study to determine their feasibility.

Further study should be conducted on the rate of deactivation to improve the efficiency of the process. This will aid in the calculation of where and how many deactivation platforms will be needed to accomplish not only the current production of LIB waste but to effectively plan for the growth of future LIB waste. This study could also create an initial scheduling of deactivation in the region by predicting the amount of time a deactivation site would need to spend at each LIB waste generator's location.

Figure 16:A Battery Energy Storage System at the Microgrid Testbed at NAVFAC EXWC

This study has preliminarily assessed the rate and projected growth of waste LIB generation in the Southern California region. An extension to this study should be conducted to understand the rate of LIB waste production at individual DOD commands. At the facility scale LIB Energy Storage Systems (ESS), like the one shown in Figure 16, is expected to be present in future DOD installations the LIB waste generation will increase. Facility scale LIB ESS is relatively new and can have a service life of at least ten years with active cooling, and about half that life expectancy without cooling.[18] Further study of LIB ESS and other LIB generators would allow the planners of military operations to take into consideration the risk that will come from the LIB waste produced in these operations both locally and abroad. This risk assessment will allow planners to make informed decisions regarding the cost to deploy a deactivation platform in conjunction with these operations compared to its benefits. This study would also lay the grounds for a cost analysis to be performed that could determine if it is cost-effective to use LIBs or an alternative energy storage system over system life cycles.

Note: appendices available upon request.

[1]FCAB, Executive Summary National Blueprint for Lithium Batteries 2021-2030 https://www.energy.gov/sites/default/files/2021-06/FCAB%20National%20Blueprint%20Lithium%20Batteries%200621_0.pdf

[2] Small Business Administration. (2020, May 6). Optimizing Lithium-Ion (Li-Ion) Battery Recycling Technology to Recover Cobalt and Nickel from Industrial and Defense Waste Streams. https://www.sbir.gov/node/1696695

[3] United States Coast Guard Safety Alert 01-22 https://www.dco.uscg.mil/Portals/9/DCO%20Documents/5p/CG-5PC/INV/Alerts/USCGSA_0122.pdf?ver=rc2OiSsMMTKGn-vIDvy4_w%3d%3d

[4] Environmental Protection Agency, Office of Resource Conservation and Recovery. (2021). *An analysis of lithium-ion battery fires in waste management and recycling.* https://www.epa.gov/system/files/documents/2021-08/lithium-ion-battery-report-update-7.01_508.pdf

[5] Stelbin Peter, F., & Raghavan, P. (2019). Lithium Ion Batteries History, Basics and Challenges. In Graphene and Carbon Nanotubes for Advanced Lithium Ion Batteries (1st ed., pp. 1–18). CRC Press. https://doi.org/10.1201/9780429434389-1

[6] https://danielstraining.com/classification-of-lithium-batteries-for-transportation-in-commerce/

[7] Herreras-Martínez, L., Anta, M., Bountis, R. (2021) et al. Recommendations for tackling fires caused by lithium batteries in WEEE- A report of the Batteries Roundtable. https://weee-forum.org/wp-content/uploads/2021/07/Tackling-fires-caused-by-batteries-in-e-waste.pdf

[8] Sims, & Crase, S. (2017). Review of Battery Technologies for Military Land Vehicles.

[9] Dow, & Batchelor, C. (2010). Navy Lithium Battery Safety.

[10] Herreras-Martínez, L., Anta, M., Bountis, R. (2021) et al. Recommendations for tackling fires caused by lithium batteries in WEEE- A report of the Batteries Roundtable. https://weee-forum.org/wp-content/uploads/2021/07/Tackling-fires-caused-by-batteries-in-e-waste.pdf

[11] Ibid. pp. 16-17

[12] https://www.dnv.com/Publications/technical-reference-for-li-ion-battery-explosion-risk-and-fire-suppression-165062

[13] Varde, & Pecht, M. (2018). Risk-based engineering : an integrated approach to complex systems : special reference to nuclear plants. Springer. p16

[14] https://www.letsrecycle.com/news/uk-narrowly-misses-2020-battery-target/

[15] Marine Corps Base Camp Pendleton > Main Menu > Staff & Agencies > Environmental Security > Wildland Fires (marines.mil)

[16] Videos - The National Guard

[17] Defense Logistics Agency. (2021, November 18.) Amendment 3 to Broad Agency Announcement BAA0002-20 for Emergent III Research & Development Program https://sam.gov/opp/e814c9a7aea248b6a2b4ee26129ab898/view

[18] National Reneable Energy Laboratory. Life prodition model for grid-connected Li-ion battery energy storage system, Life Prediction Model for Grid-Connected Li-ion Battery Energy Storage System: Preprint (nrel.gov)