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Prospects for the Use of Lithium Batteries in Law Enforcement Equipment

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P. Michael Fulcomer

Electricity Division
Center for Electronics and Electrical Engineering
National Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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James K. Stewart, Director

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To describe the subject matter adequately, commercial batteries are identified by the manufacturer's name and type. In no case does such identification imply a recommendation or endorsement by the National Institute of Standards and Technology or the National Institute of Justice, nor does it imply that the material identified is necessarily the best available for the purpose.

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FOREWORD

The Law Enforcement Standards Laboratory (LESL) of the National Institute of Standards and Technology (NIST) furnishes technical support to the National Institute of Justice (NIJ) program to strengthen law enforcement and criminal justice in the United States. LESL's function is to conduct research that will assist law enforcement and criminal justice agencies in the selection and procurement of quality equipment.

LESL is: 1) Subjecting existing equipment to laboratory testing and evaluation and 2) conducting research leading to the development of several series of documents, including national voluntary equipment standards, user guides, and technical reports.

This document covers research on law enforcement equipment conducted by LESL under the sponsorship of NIJ. Additional reports as well as other documents are being issued under the LESL program in the areas of protective equipment, communications equipment, security systems, weapons, emergency equipment, investigative aids, vehicles, and clothing.

Technical comments and suggestions concerning this report are invited from all interested parties. They may be addressed to the Law Enforcement Standards Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899.

Lester D. Shubin, Director
Science and Technology
National Institute of Justice

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COMMONLY USED SYMBOLS AND ABBREVIATIONS

A	ampere	H	henry	nm	nanometer
ac	alternating current	h	hour	No.	number
AM	amplitude modulation	hf	high frequency	o.d.	outside diameter
cd	candela	Hz	hertz (c/s)	Ω	ohm
cm	centimeter	i.d.	inside diameter	p.	page
CP	chemically pure	in	inch	Pa	pascal
c/s	cycle per second	ir	infrared	pe	probable error
d	day	J	joule	pp.	pages
dB	decibel	L	lambert	ppm	part per million
dc	direct current	L	liter	qt	quart
°C	degree Celsius	lb	pound	rad	radian
°F	degree Fahrenheit	lbf	pound-force	rf	radio frequency
diam	diameter	lbf·in	pound-force inch	rh	relative humidity
emf	electromotive force	lm	lumen	s	second
eq	equation	ln	logarithm (natural)	SD	standard deviation
F	farad	log	logarithm (common)	sec.	section
fc	footcandle	*M*	molar	SWR	standing wave radio
fig.	figure	m	meter	uhf	ultrahigh frequency
FM	frequency modulation	min	minute	uv	ultraviolet
ft	foot	mm	millimeter	V	volt
ft/s	foot per second	mph	mile per hour	vhf	very high frequency
g	acceleration	m/s	meter per second	W	watt
g	gram	N	newton	λ	wavelength
gr	grain	N·m	newton meter	wt	weight

area = unit^2 (e.g., ft^2, in^2, etc.); volume = unit^3 (e.g., ft^3, m^3, etc.)

PREFIXES

d	deci (10^{-1})	da	deka (10)
c	centi (10^{-2})	h	hecto (10^2)
m	milli (10^{-3})	k	kilo (10^3)
μ	micro (10^{-6})	M	mega (10^6)
n	nano (10^{-9})	G	giga (10^9)
p	pico (10^{-12})	T	tera (10^{12})

COMMON CONVERSIONS
(See ASTM E380)

ft/s × 0.3048000 = m/s	lb × 0.4535924 = kg
ft × 0.3048 = m	lbf × 4.448222 = N
ft·lbf × 1.355818 = J	lbf/ft × 14.59390 = N/m
gr × 0.06479891 = g	lbf·in × 0.1129848 = N·m
in × 2.54 = cm	lbf/in^2 × 6894.757 = Pa
kWh × 3 600 000 = J	mph × 1.609344 = km/h
	qt × 0.9463529 = L

Temperature: $(T_{°F} - 32) \times 5/9 = T_{°C}$

Temperature: $(T_{°C} \times 9/5) + 32 = T_{°F}$

PROSPECTS FOR THE USE OF LITHIUM BATTERIES IN LAW ENFORCEMENT EQUIPMENT

1. INTRODUCTION

Lithium batteries have been available for a number of years,[1] mainly in primary type (nonrechargeable), low-current drain configurations (i.e., less than 10 mA). Within the past several years, more medium-to-high current drain (50 mA to over 1 A) lithium primary cells have become available, and within the past few years lithium secondary cells (rechargeable) have been introduced. Lithium batteries have some advantages over other battery types. They offer high energy density with respect to volume and weight, a flat discharge characteristic, excellent service over a wide temperature range and a long shelf life. In addition, the secondary cells offer superior charge retention and are not susceptible to a memory effect. The question therefore arises as to their applicability for use in law enforcement equipment. This report addresses that question for both primary and secondary cells.

2. LITHIUM BATTERY BACKGROUND

The term lithium batteries actually refers to a family of battery systems, all of which use lithium as the anode but in which a number of different materials are used for the cathode. The chemistry of a particular system determines the output voltage, but most are in the 2.5 to 3.5 V range. Lithium is attractive as the anode material because it is earth's lightest solid element and has one of the highest electrochemical potentials of any feasible anode material. These characteristics produce a battery of high energy density with respect to volume and weight, theoretically higher than other available battery systems.

Lithium is soluble in aqueous solutions so that nonaqueous solvents must be used as the electrolyte. (This is part of the reason for its excellent low temperature performance.) Organic solvents such as acetonitrile and propylene carbonate, and inorganic solvents such as thionyl chloride are typical. A compatible solute is added to provide the necessary electrolyte conductivity. Lithium is also a very reactive metal, so it is subject to corrosion in many environments. When used with the aprotic[2] organic and inorganic electrolytes, however, it forms an ultrathin film that protects it from corrosion. In fact, this film is responsible for the excellent shelf life of lithium batteries [2].

Lithium primary battery systems are generally classified according to whether the cathode material is liquid or solid and again as to whether the electrolyte used is liquid or solid. Conductivity for the solid electrolytes, of which only a few systems are presently available, is much less than that of the liquids, and discharge currents are generally limited to the microampere range. This report will therefore concentrate on the liquid electrolyte systems. Additional classifications are made according to chemistry (the actual materials used for the cathode and electrolyte) and construction.

Taken together, the cathode, electrolyte and construction determine the lithium battery output qualities. For example, two batteries with the same chemistry but different construction will have the same output voltage but may have different discharge curves. In a bobbin-type construction, the anode and cathode are made thick enough to store a large quantity of energy, but the surface area between the two is relatively small. This combination produces a cell designed to deliver a low current over a long period of time. A spiral wound or jellyroll configuration is typically used for cells that deliver high-pulse currents or medium-to-high steady-state currents. High energy density which translates into a high ampere-hour capacity rating is a characteristic of all lithium battery systems, but not all lithium systems are capable of a high-power output, i.e., high-current drain.

The liquid cathode systems have so far produced both the highest energy densities and the highest output currents of all lithium systems. In these systems, the solvent for the electrolyte also serves as the cathode. This results in an efficient system that can produce high-output currents. The two major chemistries are lithium-thionyl chloride ($Li/SOCl_2$) with an operating voltage of 3.4 V, and lithium-sulfur dioxide (Li/SO_2) at 2.8 V,

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[1] Seventy-five organizations spent $60 million developing lithium cells between 1960 and 1980. Over 400 U.S. patents have been granted for aspects of those cells [1].

[2] A solvent that does not yield or accept a proton.

both developed initially in the United States for military applications. A third liquid cathode system, lithium-sulfuryl chloride (Li/SO_2Cl_2), provides 3.3 V at medium-to-high drain rates. Its low-temperature performance is limited to about −15 °C (5 °F), however. The solid cathode lithium cells have the advantage of not being pressurized but they also have somewhat lower maximum current drains. The majority of these systems have been developed outside the U.S., principally in Japan, for consumer device applications. The cells that are designed for low-rate (low-current drain), long-term applications are generally found in flat or button cell configurations, whereas cells capable of higher rates generally have a spiral wound cylindrical configuration.

The most prevalent of the solid cathode systems is lithium-manganese dioxide (Li/MnO_2) which has a nominal operating voltage of 2.8 V. The other major solid cathode system for medium drain-rate applications is the 2.7-V lithium-carbon monofluoride (Li/CF_x). Lithium-chromic oxide (Li/CrO_x), with an operating voltage of 3 V, has the highest theoretical energy density of the solid-cathode systems but is not, at this time, capable of producing drain rates compatible with typical law enforcement equipment (see sec. 3).

Three other solid cathode systems are available from one or two manufacturers of each. Lithium-copper oxide (Li/CuO) and lithium-iron disulfide (Li/FeS_2) are two systems which provide an output voltage close to that of present 1.5-V batteries. The cells now available can only deliver currents in the low end of the medium range, but one manufacturer is planning to introduce an iron disulfide cell in the AA size that will deliver currents in the medium-to-high range (see sec. 6). The copper oxide cells have an open-circuit voltage of about 2.4 V, but this quickly falls to the operating level which is in the 1.2- to 1.5-V range. This phenomenon, referred to as "voltage-up," could damage connected electronics if the circuits are not protected against the temporary overvoltage. A third system, lithium-copper oxiphosphate ($Li/Cu_4O(PO_4)_2$), provides a working voltage of 2.5 V, but its current capabilities are in the low range.

At present, there are only two manufacturers of lithium secondary cells and the cells are available only in the AA size. Other manufacturers have secondary cell systems under development but a viable product from any of them seems to be at least 1-1/2 to 2 years away. Two different chemical systems are available from Moli Energy Ltd., in British Columbia, Canada. These are lithium-manganese dioxide (Li/MnO_2) with a nominal operating voltage of 3 V and lithium-molybdenum disulfide (Li/MoS_2) which has a sloping discharge characteristic and an operating voltage which starts around 2.3 V and ends at 1.3 V. Altus Corporation offers a lithium-copper chloride ($Li/CuCl$) cell at 3.4 V. For each, the chargers are different in design from those used with nickel-cadmium batteries. This will be discussed further in section 5.

3. BATTERY REQUIREMENTS FOR LAW ENFORCEMENT EQUIPMENT

Four specific types of equipment used by law enforcement personnel that require portable power sources are (1) personal transceivers, (2) body-worn transmitters, (3) miniature surveillance recorders, and (4) vehicle tracking devices. At present, items (2), (3), and (4) are often designed for use with easily obtainable batteries, i.e., the standard cylindrical AAA, AA, C, and D batteries, and the standard 9-V snap terminal battery. Item (1) is usually designed for use with a rechargeable nickle-cadmium (Ni/Cd) battery pack. The pack is sometimes composed of an arrangement of C size cells. In an emergency, an equal number of nonrechargeable alkaline C cells can be placed in a structurally similar pack and used to power the transmitter. Occasionally, body-worn transmitters are powered by special flat batteries.

Personal transceivers typically require a battery capacity between 400 and 1300 mAh with 500 to 700 mAh being the most prevalent. Current drains range from 15 to 30 mA at standby up to 750 mA during transmit. The battery must be capable of delivering the higher currents for short periods of time.

Body-worn transmitters typically require a battery capacity between 350 and 550 mAh. The higher power devices provide 1-W output for 1 to 2 h and require that the battery be capable of continuously delivering about 200 mA. Lower power 1/4-W devices operate on currents from 70 to 90 mA continuously for periods of 4 to 8 h.

The batteries for miniature surveillance recorders must provide continuous currents in the range of 50 to 100 mA for periods up to 4 h. This results in battery capacity requirements ranging from 200 to 400 mAh.

Most vehicle tracking devices are only transmitting for periods varying between 3 and 15 percent of their total operating time. The current requirement during transmit varies between 40 and 90 mA, depending on the device, with standby current usually in the 10 mA range. Desired operating time for these devices is at least 30 h which translates into battery capacity requirements of between 300 and 700 mAh.

From the above, it can be seen that steady-state current requirements for battery-operated equipment used by law enforcement personnel fall in the 50- to 200-mA range with pulsed currents (current required for only a small percentage of the time) ranging up to 750 mA. Battery capacity requirements fall in the 200- to 700-mAh range for all but the highest powered personal transceivers. These can require up to 1300 mAh.

4. ADVANTAGES OF LITHIUM BATTERIES

The advantages of lithium batteries include better low-temperature performance, much longer shelf life for primary cells, superior charge retention and lack of a memory effect for secondary cells. Both types of lithium batteries can provide significantly more power-per-volume and per-weight than either alkaline primary or Ni/Cd secondary batteries, but the increased volumetric efficiency of lithium may not be fully realized without redesign of the equipment in which the batteries are used. For example, even though one lithium cell with an output of around 3 V can, in many cases, replace two standard 1.5-V cells, the saving in space cannot be realized without redesign of the equipment. Placing lithium cells in parallel to increase battery capacity for a given space is another option, but this has a disadvantage in that special circuitry is required to prevent a weak cell from being charged by the others. This subject will be discussed in more detail in section 5.

Many of the lithium primary systems will provide an output at 0 °C (32 °F) which is only slightly reduced from that at room temperature, and at −20 °C (−4 °F) will provide an output roughly equivalent to what alkaline cells will provide at 0 °C. This has distinct advantages for law enforcement equipment, much of which is used out-of-doors. High-temperature performance of both primary and secondary lithium systems is equal to or better than the standard systems now in use. Low-temperature performance of the lithium secondary batteries is roughly equivalent to that of Ni/Cd batteries at −20 °C for two of the three lithium chemical systems now in use, i.e., battery capacity at −20 °C is about 50 percent of its room temperature value. Lithium performance falls off more rapidly than Ni/Cd below −20 °C. One lithium secondary system (Li/CuCl) does not operate efficiently below about −10 °C (14 °F), but it provides a higher percentage of usable capacity at 60 °C (140 °F), the high-temperature end, than the other two lithium or any of the Ni/Cd systems.

The shelf life of lithium primary batteries stored at room temperature is anywhere from 5 to 10 yr, depending on the chemical system. This is a significantly longer period than the nominal 2- to 3-yr life of alkaline cells. The longer shelf life virtually eliminates the chance of buying a weak lithium battery, but how much of this advantage translates to an actual use situation depends upon the logistics of stocking and using batteries. If, for example, an agency buys "fresh" batteries and regularly places them into use soon after purchase, then the increased lithium shelf life may have no special significance. If, however, the batteries are purchased in larger quantities, either to take advantage of a price break or to avoid numerous small purchases, then increased shelf life is an advantage.

In a similar manner, the realization of the advantages that lithium secondary cells have over Ni/Cd batteries with respect to charge retention and memory effect depends somewhat upon the procedures for using and charging the batteries. The self-discharge rate per month for lithium secondary cells is from 1 to 2 percent, depending upon the chemistry used, while for Ni/Cd batteries it is about 30 percent per month. Ni/Cd cells operate most efficiently when completely discharged and recharged each cycle. Repeated shallow cycling reduces the effective capacity of the cell—a phenomenon known as memory effect. Lithium secondary cells are not susceptible to a memory effect and are particularly well suited for partial discharges and recharges over any portion of the voltage range.

If an application requires that the equipment powered by the secondary batteries be ready for maximum effective operation even when the cells have not or cannot be charged within 3 or 4 days of the operation, then lithium secondary batteries provide a distinct advantage. If the application does not completely discharge the batteries prior to recharging, lithium secondary batteries may again provide an advantage. (The latter can occur if the user does not want to chance a battery failure during the next use of the equipment and thus always recharges the batteries after each use.) If however, the equipment is left on charge until used, and each use or series of uses completely discharges the batteries prior to recharging, then lithium secondary batteries might have no particular advantage over Ni/Cd and may have a slight disadvantage since Ni/Cd generally provide more *full* charge/discharge cycles than do lithium secondary batteries for a given temperature and C-rate of discharge.[3] Remember, however, that lithium secondary cells have an advantage in capacity-per-unit volume and per-unit weight. With proper design, this can result in a lower C-rate of discharge for the lithium batteries and a corresponding increase in charge/discharge cycles.

It should also be noted that lithium and Ni/Cd rechargeable batteries differ in the means by which they are recharged and used in equipment. Ni/Cd batteries require an occasional deep discharge to counteract the aforementioned memory effect. This same deep discharge will reduce the cycle life for lithium secondary

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[3] C-rate is a normalized unit of current defined as the ratio of a particular discharge current in amperes to the rated battery capacity in ampere hours. There is an inverse relationship between the number of charge/discharge cycles available at a particular discharge current and the C-rate of that discharge current, i.e., the number of charge/discharge cycles available goes up as the C-rate goes down.

cells, however, and must be prevented by automatically disconnecting a cell from the circuit when its voltage falls below the battery manufacturers' designated cutoff voltage.[4]

The charger for lithium secondary batteries must include provisions for sensing when the voltage of a cell is either below a designated cutoff voltage or above a designated maximum voltage. In the first case, the cell is probably defective and should not be charged. In the second case, the charging should be stopped once the cell has reached its maximum voltage to prevent venting, i.e., the emergency release of internal gas pressures in the cell, or the more serious consequences that may occur if venting does not take place. Venting also occurs with Ni/Cd cells but, because of the nature of the gases released, the process is even less desirable with lithium cells. Lithium secondary batteries should not be recharged with equipment designed for Ni/Cd batteries or even with equipment designed for a different lithium secondary battery chemistry. The latter stipulation results from the difference in both cutoff voltage and maximum voltage during charging between different lithium chemistries.

Few disadvantages of lithium cells have been noted in the previous discussions, unless one considers the "voltage-up" characteristic of lithium-copper oxide cells (see sec. 2). One disadvantage, at least initially, is cost, but this difference in cost is not as great as it may first appear. Lithium cells may be 2 to 10 times more expensive than an equivalent size nonlithium cell, but the lithium cell may deliver 1.5 to 4 times more energy during its lifetime. For equal size and per unit of energy delivered, the lithium cells could, at present, be calculated at about 1.5 to 3 times more expensive than the best equivalent nonlithium cells. Included with the lithium, however, is a savings in weight and better low-temperature performance.

Although not a disadvantage when handled properly, it should be noted that lithium is a highly reactive alkali metal that reacts vigorously with water, alcohol, acids and other oxidants. Adequate safeguards must be used in the handling, storage and use of both primary and secondary lithium cells. This accounts, in part, for the special Department of Transportation regulations for shipping lithium batteries, for the more complicated nature of the chargers used with lithium secondary cells, and for the safeguards that must be built into both batteries, and, in some cases, the circuits with which they are used. These safeguards and shipping rules are discussed in the next section. Once applied there should be no cause of concern.

When requested, Underwriters Laboratory (UL) component recognition has been granted for various lithium battery systems, both primary and secondary. Component recognition is applicable to products evaluated for use as components of end-product equipment. The component is not necessarily sold directly to consumers.[5] To receive this recognition, the individual cells are subjected to an extensive series of tests by UL which may include short circuit, vibration, drop, reversed voltage, charging (for a primary cell which is normally not designed for it), crushing, high-temperature storage with and without humidity, and thermal cycling.

5. SAFETY PRECAUTIONS

Many of the safety precautions for lithium batteries are designed to prevent the buildup of heat within the cell. Lithium melts at the relatively low temperature of 180 °C (356 °F) and if this happens, pressure inside the cell can increase to dangerous levels. Heat buildup is a hazard with almost any battery system, but the internal temperature at which it can occur is lower and the possible resulting pressure is higher with lithium. Many lithium cells are constructed with an internal fusing device that is designed to open and stop current flow (thus preventing excessive heat buildup in the cell) should the current increase significantly above that for which the cell was designed. An external fuse or current-limiting resistor should be used in the absence of protection internal to the cell. As with all battery systems, a second line of defense is to build into the cell a mechanical venting system which is designed to open at pressures above a predetermined level.

Cells with approximately equal capacity should be used together whether in series or parallel configurations. This lessens the chance of a weak cell becoming reverse polarized in a series string, or of being charged by the other cells in a parallel arrangement—neither condition being desirable. An external diode should be added in series with each primary cell in a parallel arrangement to prevent such charging, i.e., current cannot flow into a cell, only out of it. A shunt diode may be used with each primary[6] cell in a series string to prevent a weak cell from becoming reverse polarized by more than the forward drop across the diode. When the batteries are functioning normally, the diodes are reverse biased and out of the circuit.

Lithium batteries must remain sealed against the entrance of water or even moist air. Should water somehow enter a cell, the lithium anode will react with it to produce hydrogen. Large quantities of water

[4] For a battery with several cells in series, this is done by adding the cell cutoff voltages and automatically disconnecting the battery from the circuit when the battery voltage falls below this voltage.

[5] At the present time, the higher rate lithium batteries are generally not available directly to consumers.

[6] A minimum voltage sensor is recommended for secondary batteries (see sec. 4) which would eliminate the need for individual-cell shunt diodes.

can produce enough hydrogen to cause an explosion if not dispersed. Lithium can also burn in moist air. Some of the chemicals used as cathode material in the high-discharge-rate liquid cathode systems also produce noxious fumes when exposed to moist air. Each manufacturer notes the safety precautions required when using its cells and these precautions should be strictly observed.

Transportation of lithium batteries within the United States is regulated by the Department of Transportation (DOT) in the Code of Federal Regulations, CFR49, "Transportation." The DOT makes a distinction between cells containing 0.5 gm or less of lithium and those cells containing more than 0.5 gm of lithium. Cells with 0.5 gm or less of lithium must be separated in the package so as to prevent short circuits, and must be packed in strong outside containers. There are no regulations concerning the number of cells per package, marking, or modes of transportation. Cells with more than 0.5 gm of lithium must be shipped in compliance with a DOT exemption. These regulations require the battery manufacturer to certify that safety and packing requirements have been satisfied. These requirements state that each cell must:

(1) be capable of venting,

(2) be equipped with a means to prevent external short circuits,

(3) pass altitude testing at 50,000 ft,

(4) pass thermal stability at 75 °C (167 °F) for 48 h,

(5) pass shock and vibration testing.

6. APPLICABILITY OF LITHIUM BATTERIES FOR LAW ENFORCEMENT USE

The use of lithium batteries would be beneficial to the operation of most battery-operated equipment used by law enforcement personnel. As previously discussed, lithium batteries have several advantages over the best available nonlithium cells. These advantages include better low-temperature performance and longer shelf life for primary cells, superior charge retention and lack of a memory effect for secondary cells, and a higher energy-to-volume and energy-to-weight ratio for both types of cells. Designers of new equipment should certainly consider the use of lithium batteries. The disadvantages, which include higher initial cost and the possibility of some additional circuitry to address the special characteristics of lithium batteries, are minimized when the batteries are designed into new equipment. New design can take advantage of the higher energy-to-volume and energy-to-weight ratios for lithium and can use the economics of volume production to reduce the cost of any additional circuitry needed. Some or all of the reduced volume and/or weight requirements could, of course, be traded for extended operating time per charge or per set of batteries, an additional advantage for law enforcement personnel using such equipment.

Retrofitting lithium rechargeable cells into personal transceivers which use a battery pack may be possible, as long as the output voltage and current from the lithium pack is equivalent to that produced by the original pack. Lithium *primary* cells could also be retrofitted into these same transceivers under the above conditions but the use of lithium primary cells is not comparable to *rechargeable* Ni/Cd cells. The use of the primary cells would be limited to emergency situations where the transceiver is in the field for an extended period of time with no means to recharge the battery pack.

Retrofitting lithium cells into present law enforcement equipment which uses standard size cells (i.e., AA, C, D, etc.) is possible but, with the exception of (1) the 9-V snap-terminal primary battery available from Kodak and (2) a 1.5-V AA size primary battery soon to be available from Eveready, retrofitting also presents some problems. A partial list of manufacturers that produce lithium cells in standard sizes[7] is given in table 1. Retrofitting could take advantage of the better low temperature performance of lithium primary cells and the better charge retention and lack of memory effect of the secondary cells, although the latter advantage depends somewhat upon the logistics of charge/discharge used with the present equipment as discussed in section 4. Retrofitting may even take partial advantage of the higher energy density of the lithium cells. However, as noted in section 2, most lithium systems have an output voltage per cell which is 1-1/2 to 2-1/2 times that of the battery system which it would replace. Direct substitution of a higher voltage lithium cell into a holder designed for a 1.2- to 1.5-V cell would cause overvoltage and possible damage to the electronics which receive power from the batteries.

[7] The actual dimensions should be noted because in some cases the manufacturer has intentionally made the lithium cell sufficiently larger or smaller than the standard size so that either it cannot be inserted or it will not remain inserted in the holder designed for the nonlithium cell.

TABLE 1. *Lithium primary cells produced in standard sizes (listed in table) vs. cell chemistry and manufacturer*

				Manufacturers							
Cell type	*Cell chemistry*	*Open cir. volts*	*Nom. oper. volts*	*Battery Engrg. Inc.*	*Electro-chem. Indust.*	*Eveready Battery Co., Inc.*	*Eastman Kodak Co.*	*Panasonic Indust. Co.*	*Power Converison Inc.*	*Saft Advanced Batt. Sys.*	*Tadiran Electronic Industries*
Liquid cathodes	Sulfur Dioxide Li/SO_2	3.1 V	2.8 V						AA C D	C D	
	Thionyl Chloride $Li/SOCl_2$	3.6 V	3.4 V	AA C D	AA C D					AA C D	D
	Sulfuryl Chloride Li/SO_2Cl_2	3.9 V	3.3 V		AA C D						
Solid cathodes	Manganese Dioxide Li/MnO_2	3.0 V	2.8 V				9-V Snap-Term.				
3.0-V systems	Carbon Mono-fluoride Li/CF_x	3.0 V	2.7 V					C			
	Copper Oxiphos-phate $Li/CU_4O(PO_4)_2$	2.8 V	2.5 V							AA C	
1.5-V systems	Copper Oxide Li/CuO	2.4 V	1.5 V							AA	
	Iron Disulfide Li/FeS_2	1.6 V	1.5 V			AA (soon)					

Some alternatives are available. For example, if a present piece of battery-operated equipment uses four standard size 1.5-V batteries in series to provide 6.0 V for operation, then two lithium 3-V cells (of the same size so they would fit into the present holders) could provide the necessary voltage. However, the two empty battery compartments would have to be shorted to provide a completed circuit, and, as discussed in section 5, (1) some type of fusing would be necessary to prevent excessive heat buildup in the lithium cells in the event of a short circuit, (2) a shunt diode may be necessary across each series-connected lithium cell and, (3) in the case of secondary cells, circuitry would need to be added to automatically disconnect the lithium cells from the circuit, once the total voltage decreased below the battery manufacturer's designated cutoff voltage. The above procedures are possible but may not be practical as a retrofit.

The potential problem caused by higher voltage lithium cells in packages common to 1.2- to 1.5-V battery systems may be addressed indirectly by a new American National Standards Institute (ANSI) standard on lithium primary cells and batteries under preparation by an accredited standards committee. The proposed standard is designated C18.3 and should be available some time in 1990. Information received at the time this report was written indicated (1) that the standard will be concerned only with two major solid cathode systems, lithium-manganese dioxide at 2.8 V and lithium-carbon monofluoride at 2.7 V and (2) that the standard will *not* specify higher voltage lithium cells in cylindrical sizes which are standard to the 1.2- to 1.5-V battery systems.

Lithium batteries are also presently available in nonstandard sizes that are not intended for retrofit into existing equipment. For example, redesigned law enforcement equipment could possibly use the thin flat pack lithium-manganese dioxide primary batteries manufactured by Gould Electronics. They have voltage outputs of 3, 6, and 9 V and continuous current capabilities up to 125 mA. Their size increases as voltage and current capability increase. For example, a 3-V, 1400-mAh battery designed for 65-mA maximum continuous current is approximately 3.6 × 45.7 × 76.2 mm (0.14 × 1.8 × 3 in), whereas a 6-V, 1400-mAh battery designed for 125-mA maximum continuous current is approximately 4.5 × 76.2 × 94 mm (0.18 × 3 × 3.7 in). In addition, a number of nonstandard size cylindrical lithium primary cells are manufactured by various companies in the spiral wound or high current capability configuration. These also could be designed into new equipment.

Lithium primary batteries are available now for law enforcement equipment that use the standard 9-V snap terminal battery in medium and low rate applications, i.e., less than 150-mA continuous current drain. The lithium-manganese dioxide battery is manufactured by Kodak and provides a service life up to twice as long as that of the alkaline 9-V battery. It also provides better low-temperature performance and when purchased in quantity is only slightly more expensive than the alkaline battery. The lithium cell includes a safety shutdown mechanism to prevent overheating and venting in case it is short-circuited. One disadvantage compared to the alkaline cell is that the maximum continuous current drain for the lithium cell is limited to about 150 mA, but this would still satisfy many of the requirements of present law enforcement equipment (see sec. 3).

On the horizon, if not already available by the time this report is published, is a lithium-iron disulfide (Li/FeS_2) 1.5-V AA size cell from Eveready Battery Company which will be directly interchangeable with all present AA size 1.5-V batteries. The lithium cell is expected to provide superior low-temperature performance, a flatter discharge curve, a shelf life of 10 years or more and a service life up to double that of the alkaline AA cell. The greatest advantage in service life is expected to occur at current levels of 300 mA or more. The advantage in low-temperature performance should extend to all current levels. Since the new lithium battery is expected to cost about 2-1/2 times that of an equivalent alkaline cell, it may not be cost effective at the lowest current levels (where its lifetime advantage decreases) unless low-temperature performance is very important. The latter is the case for many law enforcement applications. The lithium battery weight will be 30 percent less than the alkaline equivalent.

As indicated above, the new battery will use iron disulfide for the cathode. Iron disulfide is relatively inexpensive and produces a 1.5-V output, both of these attributes being advantageous for a lithium battery that is designed to be interchangeable with present nonlithium batteries. Lithium-copper oxide batteries, which also generate 1.5 V when connected to a circuit,[8] are available in the AA size from Saft Advanced Battery Systems. Although their capacity in ampere hours is relatively high, their bobbin-type construction limits maximum continuous current drain to about 40 mA. There were no plans at the time this report was prepared to introduce a spiral wound, higher-current version.

The same lithium-iron disulfide chemistry used by Eveready could also be used to manufacture standard 1.5-V C and D size cells, but the manufacturer had not revealed any plans to do so at the time this report was prepared. The AA size that is going to be produced comprises approximately 50 percent of all batteries sold today, however, and, because of its wide availability, it is utilized in much of the equipment presently used by law enforcement personnel.

7. SUMMARY AND CONCLUSIONS

The use of lithium batteries would be beneficial to the operation of most battery-operated equipment used by law enforcement personnel. The advantages of lithium include better low-temperature performance and much longer shelf life for primary cells, and superior charge retention and lack of a memory effect for secondary cells. Both types can provide significantly more power-per-volume and per-weight than equivalent nonlithium batteries. To fully realize the above advantages however, and to minimize the effect of their higher initial cost, lithium batteries should, with three exceptions, be designed into new equipment. The three exceptions are (1) a 9-V snap-terminal lithium primary battery available for direct substitution into law enforcement equipment that use nonlithium batteries of that size in low-to-medium drain rate applications, i.e., less than 150-mA continuous current drain, and (2) a 1.5-V AA size lithium primary battery that should be available in late 1989 or 1990 and is designed to have all the advantages of lithium and yet be interchangeable with present AA size nonlithium batteries, and (3) the possible use of rechargeable lithium cells instead of Ni/Cd cells in replaceable battery packs used in many personal transceivers.

Lithium primary batteries with capacities and current ratings commensurate with present law enforcement equipment are available now from a number of different manufacturers in the standard sizes most often used in law enforcement equipment. The problem is that, with the exception of the two batteries mentioned above, the voltage of the lithium cells is between 1-1/2 and 2-1/2 times that of the batteries which they would replace. Direct substitution is therefore not feasible. The lithium batteries, with the same two exceptions listed above, are also not generally available except by purchase directly from a manufacturer or distributor. This situation results partly from the difference in voltage and partly from the special safety precautions required

[8] The open circuit voltage is approximately 2.4 V. If the battery is to be substituted for a conventional alkaline cell, it must first be determined that this initial 2.4 V will not damage the electronics to which it is connected.

with lithium batteries. There are various ways around these problems (see sec. 6) but the result is that retrofitting higher voltage lithium batteries into present equipment may not be practical at this time.

Lithium primary batteries are also presently available in nonstandard sizes that are not intended for retrofit into existing equipment. Of particular interest to law enforcement are flat pack batteries with voltage outputs of 3, 6, and 9 V and continuous current capabilities up to 125 mA, and cylindrical cells with voltage outputs from 2.5 to 3.5 V and continuous current capabilities up to 200 mA.

Lithium secondary cells with capacities and current ratings commensurate with present law enforcement equipment are available now in the AA size from two manufacturers. Special precautions needed when using lithium cells may require that additional circuitry be added to the equipment in which they will be used, however. Each lithium secondary cell system also requires its own charger—they cannot be charged with Ni/Cd battery chargers or chargers used by a different type of lithium secondary cell. Again, retrofitting lithium secondary cells into present law enforcement equipment may not be practical at this time.

The issue of requirements for lithium batteries used in law enforcement equipment, i.e., the revision of certain National Institute of Justice standards such as NIJ Standard-0211.01 [3], to include specifications for lithium cells, has not been mentioned previously in this report. The author believes that this issue could be addressed better after lithium batteries have been time-tested in actual use situations. To revise standards prior to actual incorporation of the batteries into equipment could result in specifications that are either too loose or unrealistically stringent.

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