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Silver–zinc: status of technology and applications

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Abstract

Michel Yardney and Professor Henri André developed the first practical silver–zinc battery more than 55 years ago. Since then, primary and rechargeable silver–zinc batteries have attracted a variety of applications due to their high specific energy/energy density, proven reliability and safety, and the highest power output per unit weight and volume of all commercially available batteries. Although significant improvements have been achieved on traditional systems such as lead–acid and nickel/cadmium, and in spite of the advent of new electrochemistries such as lithium–ion and nickel/metal hydride, many users still rely on silver–zinc to satisfy their most demanding and critical requirements. Over the past few years, several of the internal components have been subject to many studies which resulted in significant improvements in the battery wet life and cycle life. Specifically, these include new separator materials which offer an alternative to the cellulosic membranes, improvements to the zinc electrode that include additives that help reduce shape-change and dendritic growth, and to a lesser extent, process changes to the silver electrode and additives to the electrolyte. In comparison, the commonly used secondary systems are lead–acid, nickel/cadmium, nickel/metal hydride, and lithium–ion. Each has attributes which make them desirable for certain applications. Where low cost, high voltage, and high rate capability is required, the lead–acid battery is an obvious choice whenever size and weight are not critical. For applications requiring longer wet life, moderate rate capability, and high cycle life, nickel/cadmium or nickel/metal hydride can be used in spite of their poor charge retention and higher costs. Relatively newer systems are also available such as lithium–ion or lithium polymer technology which are preferred for their high voltage and excellent cycle life. Among the disadvantages of these systems are higher costs, limited configurations (usually available in small cylindrical cells) and lack of an established data base. In spite of the advantages noted for the popular secondary systems, the silver–zinc couple still is the system of choice where high specific energy/energy density, coupled with high specific power/power density are important for high-rate, weight or size-sensitive applications. In the 1950s, Yardney developed the first practical rechargeable silver–zinc cell for an underwater application. The U.S. Navy, recognizing the potential of this system for torpedo propulsion, soon adopted it to power the majority of its electric torpedoes—increasing their speed and range, and allowing more room for increasing the performance capability of the torpedo. One of the first programmes which adopted the silver–zinc technology was the MK58 or 'Brush' torpedo which consisted of 44 A h cells. At that time, silver–zinc batteries became the preferred system for many other applications. Some of the unique systems include the largest silver–zinc battery ever made, a 256-ton battery for the Albacore G-5 submarine. This battery consisted of a two-section, two-hundred-and-eighty-cell battery, with each cell rated at 20,000 A h. Each cell was essentially the size of a standard four-drawer filing cabinet. Since that time, many of the silver–zinc applications have considerably scaled down their power requirements. Underwater applications are consistently using the larger sized batteries while the smallest are typically found in missile applications. This paper will describe some of the current activities in addressing the major components of the cell and a summary of the current applications of the silver–zinc system.

Keywords: Silver–zinc battery; Specific energy; Energy density

1. Recent improvements

State-of-the-art silver–zinc cells offer the highest power density among commercial rechargeable batteries (up to 600 W kg^{-1} continuous or 2500 W kg^{-1} for short duration pulses). Other favourable characteristics are very high specific energy (up to 300 W h kg^{-1}) and energy density (up to 750 W h dm^{-3}), low self-discharge rate ($\sim$ 5% per month) and flat voltage during most of the discharge. However, they have two serious limitations: (a) shorter than desired wet life (2–3 years maximum for low-rate cells, 3–18 months for high-rate cells); (b) a moderately rapid degradation in capacity, which reduces the useful cycle life to a maximum of 50–100 cycles, depending on

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the conditions of use (rates of charge and discharge, temperature, etc.).

These shortcomings are due to deficiencies of two of the cell's major components: the zinc electrode and the separators. These have been subjected to many studies and are discussed below:

1.1. The zinc electrode

This component bears the major responsibility for the capacity degradation of the silver–zinc cells. The reasons are shape change or redistribution of the zinc and formation of dendrites.

Shape change is a phenomenon by which zinc oxide, formed during the discharge, is partially dissolved in the electrolyte and redeposited during the recharge in a different location from where it originated. The result is a gradual depletion of negative active material at the top and sides of the electrode, with a corresponding reduction in cell capacity. Methods of reducing shape change, which span the entire history of the system, have been only marginally successful. These include:

(a) use of excess zinc over the amount required for stoichiometric equilibrium with the active silver in the positive electrode. This practice is still prevalent.

(b) use of oversized negatives

(c) introduction of special additives and binders into the mass of the electrode, or as a coating on it

(d) use of low concentration KOH, and/or electrolyte additives that lower the concentration of OH^- ions

(e) use of special charging methods

A discussion of all the above methods would be too extensive for inclusion in this paper; however, one variation of method (c), which gave excellent results, will be presented in detail.

A zinc dendrite is a sharp, needle-like, crystalline form of the metal, produced during over-charge. It can perforate the separators causing cell failure by internal shorting. Formation of dendrites can be reduced in several ways:

(a) careful charge control, including the monitoring of individual cell voltages,

(b) use of excess zinc, so that the negatives are not overcharged (however this method is ineffective when the cells age and become zinc-limited on charge),

(c) use of special charge methods, such as pulse charging.

1.2. The separators

Regenerated cellulose, as plain or treated cellophane and clear or fibre-reinforced sausage casing, have been used as the main separators in rechargeable silver–zinc cells since Professor André developed this system in the early 1940s.

It has been reported [1] that there are advantages in using silver-treated cellophane (i.e., C-19 manufactured by Yardney) over plain cellophane, as it gives improved life performance, reduction in rates of silver migration, and promotes a longer performance life.

However, cellophane still has significant disadvantages: poor resistance to attack by the alkaline electrolyte and by the active materials in the electrodes. These limit the wet life of the cells, even when used in multiple layers. Cellophane is also ineffective in preventing shape change, which curtails cycle life.

A variety of other separators have been proposed to replace or complement the cellulosics, including: (a) polyvinyl alcohol (PVA) films, (b) grafted and cross-linked polyethylene film, (c) microporous polypropylene film. This latter separator, very resistant to the electrolyte, is not an adequate barrier to silver or zinc, and therefore it requires a coating of the appropriate material(s) for use in cells. One such coating has been successfully tested at Yardney, but it needs additional development work.

These materials offer some advantages over cellophane but have drawbacks as well, and have not replaced it, except in a few special applications. However, a new material, recently tested at Yardney has shown excellent performance in long-life cells, including high resistance to chemical attack and the capacity to reduce sharply the shape change of the negative electrodes. It will be described later in this paper.

1.3. Improvements to the zinc electrode

The use of bismuth oxide, Bi_2O_3, as an additive to the zinc electrodes has been reported by scientists at the Brookhaven National Laboratory [2]. They investigated the cycling performance of small nickel/zinc cells, which contained Bi_2O_3 as the only metallic additive to the negatives. The beneficial effects of the bismuth (longer cycle life, because of a reduced rate of shape change) were attributed to the following phenomena:

(a) Under-potential deposition of bismuth onto the current collector.

(b) Quantitative reduction of the oxide to bismuth before zinc deposition.

(c) The formation of a needle-like matrix of bismuth in the zinc oxide paste.

Work on the additive started at Yardney in 1991, with the construction of 12 A h cells. Initial results, based on Bi_2O_3 alone, were not successful. However, favourable results were noticed when Bi_2O_3 was used in combination with either mercuric oxide, HgO, or a combination of lead oxide, PbO, and cadmium oxide, CdO.

Further work on the additive was done as part of SBIR Phase I and Phase II programs [3,4] sponsored by the U.S. Navy (NSWC, Carderock Division). Although the results on small cells were encouraging, they could not be initially duplicated on large cells, which did only marginally better than the control cells, with no added bismuth. It was found that the addition of sizeable amounts of bismuth to the

Table 1
Performance comparisons of cells with and without bismuth oxide in their negatives

Cell type	Date built	% Depth of discharge[a]	Capacity (A h)		Number of cycles to failure[b]		
			Initial, typical	Minimum	Cells with Bi_2O_3	Cells without Bi_2O_3	% Difference
LR8.5	1994	50.0	11.0	4.25	151	110	+37
LR8.5DC	1994	50.0	11.0	4.25	192	120	+60
LR8.5DC	1998	50.0	11.0	4.25	226	110	+105
MR200DC	1997	62.5[c]	212.5	132[c]	84	40	+110
MR255DC	1998	50.0	307.5	125	220+[d]	100[e]	+120

[a] Based on nominal capacity.
[b] Defined as capacity below indicated minimum.
[c] Except approximately 165 A h or 77% during cycles 1, 11, 21 and 31.
[d] Still on test.
[e] Estimated (no cells without bismuth oxide were tested).

paste created mixing problems, especially during the preparation of large batches. To resolve those problems, Yardney undertook a programme of equipment upgrading and process optimization. As a result, batches of paste of any size can now be mixed with good homogeneity.

Meanwhile, Yardney applied for and was granted a patent [5] on the use of the additive in silver–zinc cells.

Some results obtained with cells containing the additive are shown in Table 1. It is apparent that, after the process improvements, the cycle life of the cells with Bi_2O_3 increased by a factor of two or more.

Additional work with Bi_2O_3 [6,7], sponsored by NSWC, Carderock Division, was done with a dual purpose:

(a) to optimize the concentration of the additive in the zinc oxide mix,

(b) to evaluate binary and ternary additives other than the mixture of Bi, Pb and Cd oxides used for the experiments described so far.

The results of this work show that the original ternary mix is best, although some alternative formulations with lower bismuth concentrations are not far behind and may warrant further investigation. Of special interest are formulations with indium hydroxide, because of its very low toxicity.

1.4. Improvements to the separators

As stated in 2.2., a variety of separators have been tested as possible cellophane substitutes, with mostly disappointing results.

A recently developed separator was tested at Yardney. It is a microporous polyolefin mat, permanently wettable in alkaline solutions, with low electrolytic resistance. It has good chemical resistance to the corrosive silver–zinc cell environment and it is heat-sealable.

The tests completed so far were limited to groups of 12 A h cells, where two layers of the new separator, designated provisionally as PO1, were substituted for five layers of C-19, Yardney's proprietary silver-treated cellophane; all other cell components remained the same. The substitution did not affect the wet thickness of the cell pack.

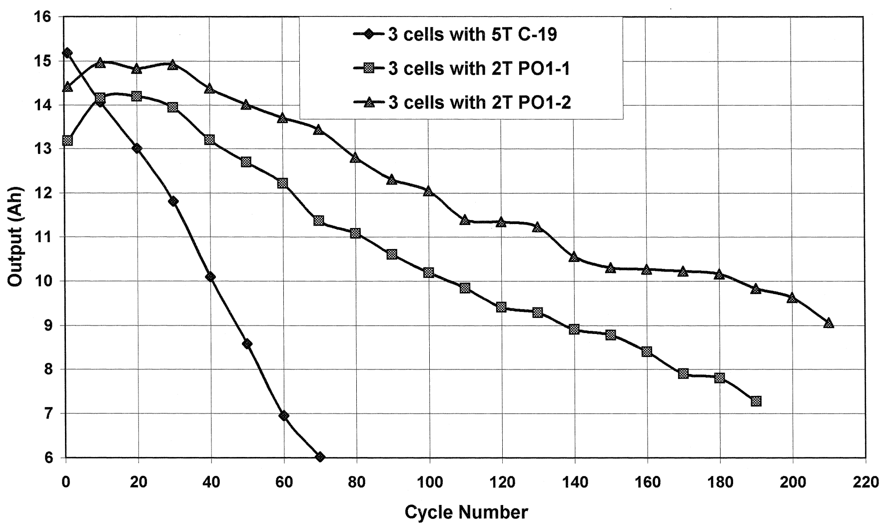

Fig. 1. Comparison of the deep cycling behaviour at 4 A of LR12 cells containing either standard or the new separator types of PO1-1 and 01-2.

The cells were charged at 0.5 A to an end voltage of 2.03 V and discharged at 4.0 A for 90 min (6.00 A h). Every tenth cycle the discharge was continued to an end voltage of 1.20 V. This regime was continued until the cells could no longer deliver the required shallow-cycle capacity. Test results for an early variation of the separator, PO1-1, a newer variation, PO1-2, and for the standard cells with the C-19 are shown in Fig. 1.

The improvements in cycle life and capacity maintenance brought about by the new separator are truly impressive, and can be traced largely to their inhibiting effect on the shape change of the negative electrode. The high-rate and low-temperature performances of the cells (not shown here) were similar, whatever separator was used.

Further work on this separator is needed in order to optimize performance:
(a) Large scale production capability has not yet been developed by the manufacturers.
(b) The initial capacity is low, as shown in Fig. 1, probably due to slow wetting.
(c) It has not yet been tested in large cells.

2. Applications

2.1. Space power

With the inception of the aerospace and NASA programmes, it became apparent that the silver–zinc battery was the logical choice for powering many of the critical systems and equipment due to its characteristics of high energy density and high reliability. Yardney has participated in virtually all manned space programmes to date including Mercury, Gemini, and Apollo. One of the most critical systems that still is powered by silver–zinc batteries is the life support systems for the astronauts. The Portable Life Support System (PLSS) was originally developed for the Apollo mission and supported Lunar exploration. This has evolved to the present life support system known as the Extravehicular Mobility Unit or EMU system. This is used by the astronauts for all EVAs. Other space-related systems include battery power for unmanned rocket or boosters such as the Titan IV, Atlas, Delta. Also Upper Stages that include Boeing's Interim Upper Stage, the Centaur, Payload Assist Module, and the Spinning Stage of the IRIS system, and a number of other applications such as Get-Away Specials (GAS). These are self-contained science experiments, which are located in the Space Shuttle Cargo bay. Tables 2–5 summarize some of the active projects and include some of the electrical and physical characteristics of the batteries. Many power system designers are frequently looking to 'Qualified' battery designs for their power needs. This approach offers 'qualification by similarity' which results in minimal development costs. At times, qualified cells are packaged in custom configurations to offer additional flexibility at a reduced development cost.

The Inertial Upper Stage (IUS), which can be launched from the payload bay of the shuttle or a Titan launch vehicle, is credited with placing into orbit many satellites and spacecraft for both military and NASA missions. Most notable are the TDRS and DSCS satellites and Magellan, Galileo and Ulysses spacecraft. Each IUS is equipped with up to 21 silver–zinc batteries which supply power to the avionics system and spacecraft electrical power bus. The most recent mission was to deploy the AXAF (NASA's advanced X-ray astrophysics facility). The four battery types used in this application are shown in Table 2. Due to the heritage of this system, these batteries were adapted for use in other applications. These are noted in the paper.

The Titan 2 and 4 launch vehicles is a heavy payload, unmanned rocket that is used to place satellite and spacecraft into orbit. This system uses five silver–zinc battery configurations. Titan can be fitted with various upper stages such as the IUS and Centaur, which also uses silver–zinc batteries. The battery types and functions are listed in Table 3.

The Delta 2 launch vehicles for medium payloads are equipped with silver–zinc cells with a nominal capacity of 5 A h. Each cell is 2.1 in. wide by 2.9 in. high by 0.815 in. deep and has a maximum weight of 130 g. The cells are configured into a 19- or 20-cell battery by the user, and

Table 2
Silver–zinc batteries used in the inertial upper stage

Battery nomenclature	Nominal capacity (A h)	Voltage requirements	Dimensions (in.)	Maximum weight (lb)
UTILITY-4 (20 × HR13DC-1)	13	26–32 V at 10–40 A and 26 V minimum at 60 A	7.72 long × 9.22 wide × 5.81 high	19
AVIONIC-10 (10 × HR105DC-1)	105	13–16 V at 10–50 A and 13 V minimum at 60 A	8.6 long × 11.14 wide × 6.4 high	31
AVIONIC-11 (10 × HR145DC-1)	145	13–16 V at 10–50 A and 13 V minimum at 60 A	8.6 long × 11.14 wide × 7.47 high	38
AVIONIC-12 (10 × HR170DC-1)	170	13–16 V at 10–50 A and 13 V minimum at 60 A	8.6 long × 11.14 wide × 8.25 high	45

Table 3
Silver–zinc batteries used in Titan

Battery nomenclature	Application	Nominal capacity (A h)	Voltage requirements	Dimensions (in.)	Maximum weight (lb)
FI (19 × HR2DC-5)	flight instrumentation	2	25 V up to 3 A	5.94 long × 7.69 wide × 5.15 high	9.0
TVC (21 × HR58(36)DC-4)	thrust vector control	36	24–32 V at 260–600 A	13.75 long × 10.15 wide × 8.0 high	80
ISDS (16 × HR5DC-7)	inadvertent separation destruct system	5	19–30 V at 12–15 A	11.8 long × 3.50 wide × 3.75 high	12
PYRO-7 (19 × PMV2(4.5)-3)	range safety or telemetry system	4.5	> 21.0 V at 50 A and > 17.0 V at 100 A	8.43 long × 5.12 wide × 3.68 high	7.5
PYRO-8 (19 × PMV2(4.5)-4)	range safety or telemetry system	4.5	> 21.0 V at 50 A and > 17.0 V at 100 A	8.43 long × 5.12 wide × 3.68 high	7.7

used as the prime DC power source in the vehicle. Some of the most recent missions include the Mars Orbiter, Bonum and Deep Space 2 flights.

The Atlas 2 is a heavy payload launch vehicle which is used to place commercial satellites and spacecraft into orbit. This system is equipped with two silver–zinc batteries. The batteries used on this vehicle have been qualified for over 30 years. The Atlas can be fitted with a Centaur Upper Stage, which included silver–zinc batteries manufactured by Yardney. The two battery types and functions are summarized in Table 4.

The space shuttle has been credited with the delivery of many satellites, spacecraft, science experiments as well as astronauts into orbit. Some of the most notable programmes using Yardney silver–zinc batteries are as follows.

(a) Extravehicular Mobility Unit (EMU) which is used in the Life Support System in the astronaut's space suits. YTP has supplied all the battery cells for the astronaut space suits on every EVA (extravehicular activity = spacewalk) to date. Some of the most notable EVAs resulted in the capture and repair of satellites, the Hubble Space Telescope refurbishment and more recently the construction of the Space Station. This battery is unique in that it is recharged on-board the shuttle.

(b) GAS (Get Away Special) experiments such as (NASA) Spartan, cell types LR40-5 and LR350-3 cells (the numeric value in the cell designation relates to nameplate capacity in A h), which was most recently used on the historic 'John Glenn's Return to Space Flight'. These cells were configured as a battery for equipment used to collect solar data during orbit.

(c) The Wake Shield pallet uses the same qualified NASA (LR350-3) cells which are configured in the Spartan. This mission probably used the largest assembly of silver–zinc batteries found in one vehicle. The Wake Shield vehicle carried five batteries comprising nineteen LR350-3 cells. The batteries provided all the power to this vehicle which, when released from the shuttle arm, created an ultra-vacuum environment for the growth of thin-film semiconductors for computer chips.

(d) The Spas/IBSS space pallet was launched, and later retrieved by the Shuttle for various experiments. This system used Yardney's LR500 and LR140(190) cells.

(e) TSS (Tethered Satellite System) used an 'as is' qualified battery design from the IUS programme for this application. This mission, which was a joint effort between NASA and ESA, had four batteries providing all of the vehicle's power requirements.

(f) The Hubble Space Telescope refurbishment effort used silver–zinc cells for both the EMU and the Power Ratchet Tool.

In addition to the above, many more cells and batteries have been used to provide power for experiments on-board the shuttle. These experiments were developed by many organizations, primarily universities and research laboratories. Table 5 highlights the characteristics of the battery types mentioned above.

2.2. Missile power

As it became apparent that long life and instant activation were required for tactical missiles and warshot torpedoes, Yardney became one of the pioneers in the develop-

Table 4
Silver–zinc batteries in Atlas

Battery nomenclature	Application	Nominal capacity (A h)	Voltage requirements	Dimensions (in.)	maximum weight (lb)
PYRO-6 (19 × PMV2(4.5)-2)	range safety or telemetry system	4.5	> 21.0 V at 50 A and > 17.0 V at 100 A	8.43 long × 5.12 wide × 3.68 high	7.5
MAIN (19 × PM30-1)	main power	30	26.5–30 V at 40–115 A	12.97 long × 8.45 wide × 7.50 high	37

Table 5
Silver–zinc batteries for space shuttle applications

Battery/cell	Application	Nominal capacity (A h)	Voltage or power requirements	Dimensions (in.)	Weight (lb)
EMU (11 × HR25-4)	life support system	25	1.45 V at 3.80 A	9.09 long × 2.64 wide × 4.30 high	7.84
SPARTAN (LR40-5)	experiments	40 (initially 60)	1.37 V at 5 A	3.27 long × 1.09 wide × 7.09 high	1.6/cell
(LR350-3)		350 (initially 550)	1.37 V at 10 A	4.24 long × 4.24 wide × 8.76 high	12.2/cell
WAKE SHIELD (19 × LR350-3)	computer chip manufacture	350 (initially 550)	28 V at 7–38 A	34 long × 14 wide × 11 high	325
PRT HR1.5DC-3 (20 CELLS)	power ratchet tool	1.5	1.20 V at 2–15 A	1.09 long × 0.57 wide × 2.32 high	0.9/cell
TSS (10 × PML140-1)	tethered satellite system	140	34 h at 43 W 0.6 h at 77 W 3.9 h at 192 W	8.6 long × 11.14 wide × 7.47 high	37

ment of highly complex automatically and remotely activated silver–zinc batteries. These batteries are inert prior to activation, nonrechargeable, and intended for one-shot applications. Even though this battery type may be the most complex in terms of construction, it seems that the power system designer forgets about the battery until the rest of the vehicle is already designed. This produces creative form factors for many of these applications.

This assembly of components can be characterized as a pneumatic/hydraulic electrochemical device that provides instantaneous electric power for relatively short periods of time (usually measured in hours or minutes). In a reserve system, the electrolyte is isolated from the cells. The electrolyte is stored in a container, which is typically stainless steel, whose exit port is sealed with frangible diaphragms. Activation is accomplished by application of an electrical pulse to fire a gas generator. This results in the generation of a high pressure, which breaks the frangible seal, and forces the electrolyte into the battery cells. Activation time (i.e., from firing the gas generator to the time it takes to reach the minimum required battery voltage) is typically 1 s or less. This principle produces a system with a very long shelf life (usually over 10 years), which make it ideal for reserve or stand-by applications. There is a slight weight and volume penalty associated with this design, depending on the size of the battery. When the battery is small, the physical constraints of the activation system make this design less efficient. On the average, the volume penalty is usually about 1.2 and the weight penalty about 1.5 times the basic battery/cell configuration. Although wet life is normally limited, enhancements had resulted in designs that can reliably achieve over eight hours of wet life. The trade-off with wet life is activation time. Primary reserve batteries are also noted for their high-rate/specific power capabilities, in addition to the excellent voltage responses. It is not uncommon to have many voltage taps within a battery, which are used to provide power for different parts of the vehicle. Since electrolyte storage and delivery is a critical feature of the battery, there are three type of activation systems available. This can be characterized as the tank, coil, or piston system. Each has advantages over the other depending on various factors such as battery envelope, weight, pressure characteristics and orientation. Most battery designs use an externally powered electric heater for cold-temperature operation (i.e., at -40°C).

Over many years, Yardney has supported a large number of programmes for remotely activated, reserve batteries. These include missiles programmes such as the Polaris, Patriot, Pershing, and Poseidon. In addition, Yardney has provided batteries for many torpedo programmes. These include the MK 37, Brush, and MK 5. Table 6 is a summary of Yardney's current applications, and their battery characteristics.

Table 6
Current reserve primary silver–zinc applications

Battery nomenclature	Nominal energy output (W h)	Weight (kg)	Volume (dm^3)	Application
SST4	236,000	408	467	torpedo
SPARROW (P-315)	5.8	1.0	0.4	missile
TRIDENT II (D-5)	650	34	31.2	missile
Mk46 mod 2 (SLMM)	8,100	120	96.6	torpedo
TRIDENT I (C-4)	325	5	1.1	missile
HARPOON (P-435)	559	8.6	3.5	missile
STANDARD MISSILE (P-192)	392	10.9	6.5	missile

Table 7
History of underwater applications

Application	Designation	Type	Configuration
MK37 Torpedo	MK46 MOD1	Primary	18 × 22AHP/56 × 79AHP
	MK46 MOD2	Primary	18 × 22AHP/56 × 79AHP
	MK53 MOD0	Secondary	18 × HR18/60 × HR140
	MK53 MOD1	Secondary	18 × HR35/60 × HR140
MK42 Torpedo		Secondary	33 × HR40
MK41 Torpedo		Secondary	20 × HR20
MK44 Torpedo	MK61 MOD1	Primary magnesium/ silver chloride, water-activated	234 cell, bipolar stack
MK66 Torpedo (Astor)	MK65 MOD0	Secondary	18 × PA20
	MK78 MOD0	Secondary	18 × PA45
MK58 Torpedo (Brush)		Secondary	20 × HR44
MK45 Torpedo	MK67 MOD1	Primary	461 cell, bipolar stack
	MK66 MOD0	Secondary	188 × HR115
MK48 Torpedo (ADCAP)		Secondary	2 × 19 × HR1.5-2 (silver–zinc) 26 × YS5 (silver–cadmium)
SST-4 Torpedo		Primary	150 × 110AHP/20 × 29AHP
MK27 Target	MK104 MOD1	Secondary	2 × 66 × HR140
MK30 Target	MK126 MOD0	Secondary	156 × HR190
	MK139 MOD0	Secondary	168 × LR190
	MK128 MOD0	Secondary	158 × HR190
Mast Target		Secondary	56 × LR427/17 × LR90
ADMATT/AMASS	Med. Performance	Secondary	60 × HR300/58 × HR300
	High Performance	Secondary	120 × PML110/116 × PML110
MK5 MOD0/ADC		Primary	22 × 5.8AHP/28 × 5.8AHP
USS Albacore G-5	Submarine	Secondary	2 × 280 × LR20,000
USS Barracuda G-2	Submarine	Secondary	165 × LR16,000
USS Dolphin G-7	AGSS-555	Secondary	2 × 165 × LR4000

2.3. Underwater power

Since the U.S. Navy's initial interest in 100 A h, rechargeable silver–zinc batteries in 1949, Yardney has been involved on a wide range of programmes for torpedoes, targets, buoys, UUVs, AUVs, submarines, submersibles, and other unique applications such as the Swimmer Delivery Vehicle (SDV) and diver heating system used by U.S. Navy SEALS.

Table 7 is a summary of past programmes supported by silver–zinc batteries. Some of these programmes are resurrected, based on the customers' needs and funding.

A summary of the major programmes that are presently funded are given in Table 8. Some of the older research submarines have recently been decommissioned and usually placed on permanent loan for display in maritime museums. The most notable undersea applications are as follows.

(a) DSRV (Deep Submergence Rescue Vehicle). This requires two batteries (76 × LR700(DS)-6) for all power

Table 8
Silver–zinc batteries for underwater applications

Number of cells per battery/cell type	Application	Nominal capacity (A h)	Voltage requirements	Dimensions (in.)	Weight (lb)
DSRV 76 × LR700(DS)-6 (pressure compensated)	deep submergence rescue vehicle	700	100 V at 100–300 A	45 long × 37 wide × 23.6 high	2564
DSV 57 × LR750(DS)-5 (pressure compensated)	deep submergence vehicle	750	1.40 V at 240 A 1.45 V at 150 A 1.50 V at 100 A	5.52 long × 3.75 wide × 19.5 high	30.9
NR-1 150 × LR850-21	nuclear research submarine	850	210 V at 170–275 A 213 V at 45–87.5 A	4.76 long × 4.56 wide × 18.9 high	32.2
MK89 (SDV) 128 × LR360DC-4, -5	SEAL delivery unit	360	1.20 V at 60 A	5.8 long × 2.75 wide × 6.4 high	9.7
MK30 MOD 1 168 × LR190DC-1	torpedo target	190	1.28 V at 32–185 A	6.01 long × 1.55 wide × 6.405 high	4.56
LR875DC-1	various UUVs/AUVs	875 (initially 1100)	1.50 at 30 A 1.42 V at 90 A	3.14 long × 6.4 wide × 7.22 high	14.48

requirements. The cells are housed in a fibreglass case. The unique feature of this battery is that it is pressure compensated, so all internal battery components must be completely filled with mineral oil to prevent an implosion during descent.

This Navy vehicle has become quite well known for its application since having been filmed in two well known movies, ‘The Hunt for Red October’ and ‘Gray Lady Down.’

(b) DSV (Deep Submergence Vehicle). This uses LR750(DS)-5 silver–zinc cells for most of it’s power requirements. The two Navy vehicles ‘Sea Cliff’ and ‘Turtle’, have been recently decommissioned. Both vehicles were used by the Navy for research, military operations, and training. This has a depth capability of 20,000 ft and therefore, uses a pressure-compensated design. Most recently, the ‘Turtle’ was delivered to Mystic, CT, for Mystic Aquarium’s new ‘Institute for Exploration’ exhibit headed by Dr. Robert Ballard.

(c) NR-1 (Nuclear Research Submarine). This requires 150 LR850-21 silver–zinc cells enclosed in the submarine battery compartment. The battery is used as emergency back-up power for the submarine. The submarine’s most notable missions have included search and recovery of the ill-fated Space Shuttle ‘Challenger’ and most recently, under the direction of Dr. Robert Ballard, the discovery of historic sunken ships in the Mediterranean. This mission was documented in ‘National Geographic Magazine.’

(d) SDV (Swimmer Delivery Vehicle). The MK89, used by the U.S. Navy SEALS, uses silver–zinc cells which are housed within the vehicle.

There are other programmes which use silver–zinc batteries that are considered classified. Typically these include UUVs, AUVs, and buoy applications.

3. Conclusion

The silver–zinc system already has a well-documented history (over 55 years) of safe and reliable service for a broad variety of applications. Many power system designers still look to silver–zinc to fulfil many critical applications where low weight and/or volume and high specific energy are required. Although other energy systems have replaced silver–zinc on certain applications, new applications, especially for underwater vehicles and launch vehicles, will make this a viable couple for at least the next twenty years. Current and future R & D efforts still result in significant performance improvements and further enhance their enhance their usefulness to the end users.

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