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BATTERIES FOR MARINE AND SUBMARINE APPLICATIONS

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Various types of battery systems, both primary and secondary are in use for different marine applications. Among them, the first and the foremost is the lead-acid battery system. Other systems employed are Ni-Cd, Ag-Zn, Ag-Cd and sea water – activated batteries such as, Mg-AgCl, Mg-Cu_2Cl_2, etc.

In this paper, a detailed account of these battery systems has been dealt with. Information regarding the constructional features and performance characteristics are reviewed with regard to marine applications.

Key Words: Marine batteries, lead acid batteries, alkaline batteries, activated batteries, lithium batteries

INTRODUCTION

A great deal of electrochemical science and technology is being employed in oceanography. Of late, there has been significant expansion in the application of batteries in deep sea explorations, navy and other marine uses.

Various types of batteries are used for marine, navy and oceanography applications. The capacities vary from a few ampere hours to several thousands for various applications such as under-water surveillance, deep sea rescue, tactical deterrance, deep sea exploration, offshore platform devices, sonobuoys, radio sondes, dinghy rescue lights, life raft lights etc. The time of operation of these batteries varies from a few seconds to several hours, depending upon the application. Though various types of batteries are used for such applications, lead-acid, nickel-cadmium, silver -zinc, and sea-water activated batteries play a very prominent role in the above applications. The various battery systems used, their applications, their properties and performance with regard to marine applications are reviewed here.

Lead-acid batteries

Although the lead-acid battery was discovered long ago by Plante [1], it still dominates the field of electrochemical power sources. The first electric boat was demonstrated at Chiswick in 1888 [2]. It used 200 lead-acid cells. Of the 64 submersibles, 48 used lead-acid batteries, 8 used silver-zinc, 4 used shore or ship power via an umbilical chord, one nickel-cadmium, one silver-cadmium, and one fuel cell and one used both lead-acid battery and fuel cell [3]. Batteries on ships were first used in 1883 for lighting purposes. They were also used for starting diesel engines on-board ships. The batteries used on ships supply energy to the various purposes like navigation equipments, navigation lights, cabin lighting, and search lights when the generator is shut down. The capacity of the batteries varies from 200 to 300 Ah, the voltage of the battery being 12 or 24V. The batteries used for engine starting and for auxiliary loads sometimes get discharged to such an extent that the batteries would not be in a position to start the engine. Therefore, it would be better to separate the functions and allot them to two different batteries.

The government regulations stipulate that ships should have an emergency power supply from batteries or generator for a specified time. All ships will therefore have some sort of emergency power supply from batteries. The operational time may vary from 30 minutes to 6 hours, depending upon the type ships, whether it is a commercial passenger ship, cargo ship or a naval vessel. In addition to the above functions, the naval batteries are used for target detection, fusing, safety and arming, deployment, guidance and control, propulsion of weapon and vehicles, which involve a variety of mission profiles and operational environments [4]. Batteries are also used for countering the mines for degaussing or neutralising the permanent magnetism of the steel hull of the ship.

There are a few pleasure-trip ships for which the sole power sources are lead-acid batteries which supply energy to electric motors of 4.5 to 7.5 kw. The capacity of the batteries may vary from 280 Ah to 800 Ah.

The most important application came with the advent of submarines where the batteries are used as the only power source when the vessel is submerged. In the modern nuclear submarines, the batteries simply perform the function of emergency power supply. These nuclear submarines can trvel submerged to more than 1,60,000 km [5]. The inherent characteristic of a submarine requires that ballast be carried to achieve submergence. Though the lead-acid system has a lower energy density commensurate with satisfactory performance for the varying mission time (from 1 h to 100 h), increasing the energy density is not as attractive as increasing the performance of a cell of given weight [6]. Even then, the energy-density has increased from 8.7 Wh/kg (5h rate) in 1901 to 33 Wh/kg in 1978. The present batteries give an energy-density of 21 Wh/kg (1 h rate) to 42 Wh/kg at 60 h rate.

The design problems

The designer of a submarine cell has the ticklish problem of tackling both 1 h and 100 h rate discharge performance and at the same time should ensure that the cell gives a satisfactory life time. After ensuring that there is sufficient amount of active material for the low rate capacity, the high rate performance is achieved by distributing the same amount of active material over more number of thinner plates. The thickness should be sufficient to give a satisfactory life. The latter can be assured by double or triple separation of pasted plates.

The technology of lead-acid battery has been described elsewhere in detail [7-11]. It is worthwhile to point out the various bottlenecks encountered in increasing the energy density and life of a lead-acid battery. In the case of tubular positive plate cells, problem arises in casting very thin long spines of grids. A second problem is in filling the long tubes with dry oxides. But modern pressure – die casting techniques have reduced the former problem. The tube filling process is a costly process and poses health problems with the workers. Though new technology for the production of tubular plates is under trial, the problems of filling the tubes is still not satisfactorily solved. Granulating the oxides with sulphuric acid [12], extrusion of a paste into a tube containing thixotropic additives [13] and slurry filling [14] are some of the methods which can reduce the problem to some extent. Encouraging results have been obtained with the last procedure.

In the case of pasted plate, problem arises in casting the complex structure of the grid, particularly when the percentage of antimony is reduced.

The electrolyte stratification

Common problems too both these types of plates are conductivity, heat conduction, and electrolyte stratification. Improved conductivity is obtained by having a negative grid whose components are combined by electrically conductive and mechanically reinforcing lead-coated copper leads [15]. The perforated cross strip is set rivetted and soldered on lead suppressor buttons. The results of tests carried out on the copper plated grids indicate an increase in conductivity by a factor of 4 for positive and 3 for negative plates [16]. The same problem has been attacked from a different angle [17] in what is called a double decker cell. Here, the cell is, so to say, cut into two halves and then superimposed one above the other. They are connected in parallel by pole bridges which have copper cores with thick protective lead coating. Voltage losses are reduced to a minimum. Other advantages are easier tube filling (because of reduced height), improved charge acceptance and lesser heat development. Such cells were introduced in service from 1975, and so far there is no evidence of premature failure because of copper contamination from the lead-coated pole bridges.

The temperature of any lead-acid cell increases during charging and also to some extent during high rate discharges. In a cell of such size as submarine cell, artificial cooling is a must. The 1 h rate discharge or a quick charge necessitates such cooling arrangements, say by simple air pumps [18]. In another type (external cooling), hollow plates are attached to the terminals of the cells and water is circulated through the plates. In a third type, the components (e.g. busbar, connector) of the submarine cell have cooling channels through which water is passed. In the fourth type of cooling [19] the dissipation of heat that is evolved in the cell takes place through cooling elements arranged in the electrolyte above the plates. Recently, the problems of electrolyte stratification have been investigated [20]. During charging, a minimum level of overcharge is needed to produce sufficient gas to take denser acid to the top portion and thus remove the concentration gradient. Simple air pumps are fitted in submarine cells to reduce concentration gradients. By incorporating a light weight electrolyte circulation system [21,22] the overall efficiency of a battery can be improved. A simple low cost pumping device [23] operates on pulsed air without any moving parts to improve the battery performance. A German patent [24] describes elastic bellows with pulsatingly changeable volume submerged in the electrolyte of the battery with liquid electrolyte especially that of a lead-acid battery for removal of gases accumulated in the battery and for extensive **mixing of the acid electrolyte.**

However, tests undertaken [25] on batteries subjected to simulated electric vehicle duty cycling show that the forced stirring of the electrolyte too increases the rate of active material shedding.

To resist damages through depth charges, the cell container and cover are made from high impact strength materials with polyester resin impregnated glassfibre. As a further precaution against leakage of electrolyte, the whole element is contained in a thick walled rubber bag which fits closely into the outer cell container. The groups of plates with the connector bars are suspended from the cover and the latter is screwed to the container and sealed to it with a high strength adhesive. If the cell receives a shock, the latter is transmitted through the container wall to rubber seal between the cover and the container and from there to the plates themselves, thus considerably lessening the intensity of shock. If the cell element is supported in the normal way on the bottom of the container, the intensity of shock is absorbed mostly by the shock absorbing materials between the container bottom and elements. Installing the cells in vessels is also of paramount importance. One technique is to have wooden wedges between cells so that the complete battery is tightly packed in the battery compartment. Another technique is to anchor each cell to the floor of the battery tray. The cell container bottom has a hook shaped metal insert which fits into another such hook in the metal rails at the bottom of the battery tray.

The gassing problem

An overriding criterion for submarine cell design is the limitation of hydrogen evolution during charge an on open circuit stand. Antimony is the main cause of hydrogen evolution during open stand and overcharge, and so antimony is either replaced or its percentage is reduced. The first choice is lead-calcium alloy. Arsenic, which is a common hardener now-a-days used, cannot be used for fear of arsine evolution. The Admiralty – B alloy [26] containing 3% antimony, 0.05% selenium and 1.5% tin has been used for many years. A low antimony-cadmium alloy (for example 2% antimony, 2% cadmium) with or without silver addition also gives good performance [27,28]. The combination of low antimony positive grid and lead-calcium negative grid has reduced the open circuit hydrogen evolution from an 8800Ah cell to 50-80 ml/h. Most of the reseachers consider antimony to be essential because it retards the positive grid corrosion and grid growth [29]. The antimony alloy is said [30] to exhibit great initial resistance to anodic attack and possess the greatest resistance to passivation by lead sulphate. The cycle life of a lead-acid battery is generally limited by the positive plate, the capacity of which gradually falls on cycling. The loss has been attributed to a combination of several mechanisms [31]. The non-antimonial alloy cells fail prematurely. However, with proper treatments (for example, a shallow low-rate discharge from time to time), the non-antimonial alloy cells have been successfully used in nuclear submarines. An increase in the failure rate of the batteries [32] is correlated well with the corrosion rate of the cathode grids. The grid oxidation can be minimised if the cell voltage during the float charge after the battery charging is limited to 2.3V.

Recently, studies have been made [33] on titanium fibre reinforced lead low antimony cadmium (MFX) alloy grids for submarine battery positive grids.

The performance of a submarine cell at various rates of discharge is given below:

Discharge rate h	Current (A)	Actual duration h	Capacity (Ah)	Mean voltage/ cell (V)	Energy-density (Wh/kg)
1	6080	1.07	6506	1.71	21.4
3	2700	3.08	8316	1.86	29.7
5	1760	5.25	9240	1.91	33.9
10	970	10.25	9943	1.96	37.4
20	525	50.25	10631	1.98	40.4
60	191	63.5	12129	2.02	47.1

The maintenance of a battery is of vital importance because the life of the submarine depends mainly on batteries. As with any other lead-acid cells, the level of the electrolyte should be maintained and the cells charged properly. All the conditions applicable to other types of lead-acid cells are also applicable to submarine cells.

Sealed lead-acid cells

Cells with capacities in the range of 1 to 40 Ah are available in semisealed maintenance-free and sealed constructions. There are several characteristics which differentiate the former from the latter: (i) The maintenance-free batteries use some sort of additives (e.g. silica) to gel the electrolyte or an excess amount of electrolyte is absorbed in the separators. In the sealed truly maintenance-free version, the cell operates on a starved electrolyte construction, the electrolyte being absorbed in the special high porous glass fibre separator or similar materials which have the property of allowing oxygen to diffuse from the positive to negative plate. (ii) In the former category, an excess electrolyte is always there to make up for the loss of water due to overcharge. But, in the latter category, only limited amount of electrolyte is used and no loss of water is envisaged since the cell operates on the oxygen cycle basis. The over-sized negative does not get charged fully because the oxygen evolved from the positive goes to the negative and discharges the already charged negative active material. Such types of cell include a pressure release valve operating at 2.8 kg/cm^2 – 4.2 kg/cm^2. Such batteries can be charged by constant current or constant voltage method, but the latter is always preferred. After the basic principle of indirect gas recombination was first stated [34,35] the development of such batteries saw a spurt [36-40].

Applications

Some of the potential applications for maintenance free lead-acid batteries in ships and submarines are for portable floodlights, rationalised tranformer-rectifier units, static-frequency charging equipments, standby use in telemetry monitoring equipments, safety hand lamps, bulkhead lighting, and engine starting. The batteries are also used in fire and security systems, portable alarm and emergency lighting applications.

ALKALINE SYSTEMS

Nickel-cadmium

Except where no ventilation system is available, most of the nickel-cadmium batteries used for marine application are of the pocket type, and the principles are well known [41-43]. The pocket type nickel-cadmium cells are made in ranges from 5 to more than 1000 Ah. Four types of nickel-cadmium pocket plates are used [44]. Nickel-cadmium batteries with pocket type positive plates offer lower internal resistance and therefore superior performance at high discharge rates. Hence, these are used in the marine engine starting application. Nickel-cadmium batteries are used in underwater diving lamps, and underwater sonar and industrial appliances in ocean science (e.g., fish finders, measuring and recording appliances for ships). They are also used for starting of diesel engines in marine vessels; and pocket type batteries are used on board ships for feeding vital equipment in case of power failure.

Silver-zinc batteries

Right from 1940s, these batteries have been manufactured commercially [45]. They are very much noted for their exceptionally high energy-density and power-density. Among all the available rechargeable systems today, this system has the highest attainable energy density. Its high-rate discharge capacity is very high coupled with a very flat voltage discharge characteristic and good shelf life. Because it can generate the same amount of electrical energy as any other systems in volume as little as $^1/_5$th of their size and $^1/_6$th of their weight, the system provides the long awaited answer to the design engineer. Today, it happens to be an integral part of every major torpedo programme. One important point to be noted is the very constant voltage during the greater part of discharge. The flat portion of the discharge curve is related to the fact that as silver oxide is reduced to metallic silver, the conductivity of the electrode increases, thus counteracting the polarization effects.

The applications of these batteries include submarine and torpedo propulsion applications. More recently, their applications have expanded to underwater test vehicles, underwater search lights, and to submersible vessels such as rescue vessels and various exploratory submarines. Apart from these, these batteries are used in underwater sleds, for external pipeline and drilling rig base examination, underwater sea-bed surface mining devices and underwater lighting portable cameras.

Yardney silver-zinc battery system designed to replace the lead-acid battery in a particular navy vessel has the same weight and volume as the lead-acid battery, but has an endurance of 31 hours at 1.5 knots and 6 hours at 2.5 knots as compared to 10 hours and 1.9 hours for the two speeds respectively, for lead acid battery. The critical parameter in operating the submergibles is the cost per hour while submerged operators concerned with the cost effectiveness want an answer to the question of which battery is best. The answer depends on the mission and crew. If t is a low budget programme, the lead acid battery is the best. On the other hand, when adequate funding is available and a need for the maximum attainable submerged operating time is required then the choice is silver-zinc battery. A life span of 400-500 cycles is claimed by a few manufacturers.

Silver – cadmium

W. Jungner, in 1899, first built the silver-cadmium batteries. An exceptionally high energy-density is an important feature of these batteries. The silver-cadmium battery has better cycle life and low temperature performance than silver-zinc batteries ,but inferior in these characteristics compared with nickel-cadmium batteries. Its energy-density too is in between those of the nickel-cadmium and silver-zinc batteries. These batteries came into use in the late 1950s.

These batteries are currently used in missiles, rockets, torpedoes, and moon/space applications. They are also used as power sources for submarine simulator-target drones. For this purpose, high current drains are required coupled with greater recyclability compared to silver-zinc counterparts used in torpedo propulsion. Such batteries are of vented design made from high temperature plastic containers and thinner plates.

Activated batteries

These are primary reserve type and were developed during 1940s. They are constructed and stored in dry condition. When the requirement arises these batteries are activated by the addition of water or an aqueous electrolyte. They possess a very long shelf life. Magnesium or aluminium is used as the anode material and several cathode materials like silver chloride, cuprous chloride, lead chloride are used. There are three main types of water-activated batteries: immersion type, forced flow type and dunk type. They can also be grouped depending upon the type of activation: (i) Water-activated cells (either fresh water or sea water); (ii) Cells activated by special electrolytes; and (iii) Cells activated by addition of a reactive gas.

Of the three major mechanical activation systems in use in modern primary batteries (coil, piston, tank), each has its set of characteristics making it preferable under certain conditions. Normally, the coil or tubular electrolyte reservoir type is used in batteries that must activate in any position, while the pressure-over-liquid or tank types are most efficient of volume utilization, and are also better adapted to the larger batteries. Piston and inversion types are really positive displacement devices, and are used in specialised applications.

Remotely activated primary silver-zinc batteries

This system consists of mehanical, pyrotechnic, hydraulic and electrochemical components. This has a very long storage life, (more than 12 years) and very high reliability. Such batteries supply propulsion power for torpedoes. They can be discharged at very high rates with good gravimetric and volumetric energy-densities (83.6 Wh/kg, 122 Wh/dm^3 [46]. The MK-37 electric torpedo uses a silver-zinc battery of 35 kw propulsion power weighing 118 kg.

Magnesium-silver chloride water activated batteries

These serve as the prime power source for electric torpedoes. These sea-water activated batteries find extensive use in oceanographic science and navy (buoys, flashing beacons, submarine escape-hatch lighting, life rafts, life jackets, sonobuoys, flares, mines, distress beacons for ships and oceanographic equipments). Information regarding the manufacturers, and specifications for these batteries have recently been compiled [47]. Higher energy density was achieved by making three major change [48]: the conventional alloy was replaced by more active MTA 75 alloy, the diameter of the file was increased, and the principle of the electrolyte recirculation was employed. Batteries with detachable unit cells have also been described [49].

When the magnesium anodes have a coating of methyl cellulose or its derivatives which are water soluble, such batteries show faster voltage recovery compared with batteries without such coated anodes [50]. In another sea-water battery [51] the anode and the cathodes have a PVC spacer along with a piece of paper impregnated in an aqueous $CaCl_2$suspension and dried to form a separator. Such batteries give faster voltage recovery.

Magnesium-cuprous chloride and magnesium-lead chloride systems

Since the silver chloride battery is a costly one, attempts have been made to employ inexpensive cathode materials like cuprous chloride and lead chloride [55-57]. Cathodes have been fabricated with cast-in current collection screen by fusion casting [58]. Other non-silver water activated batteries have been developed recently, primarily as power source for anti-submarine warfare (ASW) equipment. The systems developed and successfully used are magnesium-lead chloride, magnesium-cuprous iodide-sulphur, magnesium-cuprous thiocyanate-sulphur and magnesium-manganese dioxide, utilising an aqueous magnesium perchlorate electrolyte [59]. These batteries, though less costly, have lower energy-density and are inferior in every aspect when compared with magnesium silver chloride battery.

Magnesium-cupric formate sea water battery

It has a high discharge voltage (1.0 – 1.4V) with higher efficiency

[60]. The battery can replace the magnesium-silver chloride batteries for marine use.

Pressure compensated batteries for deep sea application

In the past few decades, power requirements for propulsion, instrumentation and life support of oceanographic submersibles have grown very fast. The reason is the fast developing field of oceanography, particularly a renewed interest in coastal areas [61].

In the course of time, the space within the pressure hull became so limited that some other locations for batteries became a must. This was achieved by pressure compensated systems [62,63]. Here the battery is contained in a tray; the battery module is fitted with a dome-shaped cover which is connected hudraulically to a flexible compensating bladder. The volume of the module including the space under the cell cover immediately above the electrolyte is flooded with pressure-transmitting fluid (e.g., Exxon, Mariol oil 70, Primol 207) which also fills the bladder. As the module is submerged and is subjected to an increase in pressure, the fluid filled bladder is compressed and more fluid is forced into the battery module, thus causing an equal increase in the internal pressure of the module. This movement of the fluid causes zero or negligible pressure differential between the exterior and interior portion of the module. On ascent, the decrease in pressure forces fluid from the module to the bladder.

Another pressure compensating system for underwater battery utilises the sea-water itself for controlling the hydrostatic pressure difference [64]. A vent cap having a valve which seals immediately under the influence of a relatively low external fluid pressure and which retains its sealing effectively has been described [65]. The lead-acid battery and silver-zinc battery have been studied with respect to cycling characteristics, material compatibility and hardware development [63]. Normal capacity reduction is encountered with the low temperature operation. The increased pressure has a positive effect on lead-acid battery. The special features of the battery design are: (i) the common vent cap is replaced by an "electrolyte scrubber" which effectively prevents the loss of the electrolyte during gassing by having a highly tortuous path for the gas escape; (ii) the exposed terminals are encapsulated in polyurethane foam especially developed for this purpose; the material is resistant to electrolyte, the pressure - compensating fluid and salt water. This prevents the ground voltage problem; (iii) pressure release valve which takes care of a presssure build-up inside the cell which, during a hurried ascent of the vessel, may cause a violent release of previously evolved compressed gas; and (iv) the sealing is done with an epoxy resin [62].

In the case of silver-zinc cells, an additional problem with regard to electrolyte level arises. Normally the cells have a 5% extension of the separator envelope (with respect to the plate height). The electrolyte level is always below the top of the separator wrap. But the level frequently drops below the plate height during which time the plates are likely to be made inactive by the pressure compensating fluid. Hence after careful study, the separator envelope was increased to 25% of the plate height.

At increased pressure, the lead acid cell gives increased output and as is well known, gives less capacity at lower temperature. In a specific case of increased pressure, 700 kg/cm^2 and lower temperature (273K) the net effect is a 3% decrease in ampere-hour capacity, although the former parameter increases the ampere-hour capacity by 15% and the latter decreases the capacity by 10-30%. During charge, the high pressure has a detrimental effect on capacity, the loss being 25-35% for all types of charging examined. This is aggravated by the decreased temperature encountered in deep ocean.

In the case of silver-zinc batteries, there is no increase in capacity at elevated pressure as this system is inherently much more efficient than the other. The effect of temperature is not very much significant. Though the cold temperature affects the charge acceptance seriously, the increased pressure has not been found to have any effect on charge acceptance.

Zinc-air or oxygen batteries

The primary zinc-oxygen electrochemical system can provide energy densities far greater than lead-acid cells at high rates of discharge and is competitive with power sources such as fuel cells for periods of operation approaching several hundred hours. The total energy system called the ZENO energy system consists of the onboard energy system together with the necessary mothership installations like lift-out and replacement arrangement of the spent battery, replenishment of oxygen supply and battery overhaul and renewal [66]. The system can be electrically recharged, but its life cycle is limited due to the usual disadvantages of the zinc electrodes such as dendritic growth, active material shedding, shape change etc. The system is also mechanically rechargeable. An energy density of 100 Wh/kg can be easily obtained. These batteries are proposed as power sources for propulsion of submersibles [67].

FUEL CELLS

From the very beginning of the modern deep-ocean exploration, fuel cells appeared very attractive since they can provide 5-30 times the energy density of any battery [68-74]. The extensive and expensive work carried out for the space programmes can be taken advantage of. However, at the present time, the deep ocean vessels are constrained to battery power only because of the costs and unpredictable operating life of the fuel cells.

LITHIUM CELLS

Though the electrochemical potential of lithium-based cell has been known for a long time, it was only in 1960s that practical cell hardware and the benefits that were theoretically possible were demonstrated. This was possible because of the advances in non-aqueous electrolyte, material handling and material processing. The achievement of safe, reliable and high energy lithium batteries with sizes and electrical performance characteristics adaptable to various marine uses has made it the most important battery.

Three principal types are considered most relevant for marine use, namely lithium-sulphur dioxide, lithium-thionyl chloride and lithium-silver oxide. However, the first system is the most advanced and is being used in various marine applications such as underwater mines, sonobuoys, databuoys/stations and weather sondes. A significant application for the large 10,000 ampere-hour cells is as the standby power source in missile silos in the event of loss of commercial or other power [75]. Lithium-thionyl chloride cells are employed for offshore oil rig equipments. A 120V, 5000 ampere-hour lithium/sulphur battery having an energy- density of 150 Wh/kg has been designed for submarine application [76]. The battery delivered 600 kWh with a power output of 50 kW.

The investigations on lithium-thionyl chloride battery for navy applications lead to improved, low discharge hermetically sealed cells and batteries in several ocean oriented applications [77]. Further developmental programmes envisage cells of capacities up to 10,000 Ah for many military applications that require large amounts of energy.

A lithium-water marine battery with lithium anode/steel cathode stack assembly has been assembled and tested [78]. The battery delivers 160 Wh/kg with an energy-density of 4000 Wh/kg based on lithium alone. The average voltage of the cells is 1.25 V.

Charging systems

In marine applications, the electric energy is normally obtained from an on-board generator or alternator driven from the prime engine. The D.C. necessary for charging is usually obtained by rectifying A.C. The chargers may be wall-hung or mobile units or floor mounting type. Modern chargers have microprocessor controls and can sense battery condition, temperature, voltage, charge current etc., and are capable of multi-step charging.

CONCLUSION

Some of the batteries described above are available commercially while others are still in the research and investigation stage. Although a large number of battery systems appear very promising, the capital cost of these replacement batteries will be a few times more than the present price of the lead-acid batteries. A great deal of effort is required on the part of the scientists and engineers engaged in the research and development of batteries to reduce the cost of the future batteries.

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