

# CHAPTER 37

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## ZINC/BROMINE BATTERIES

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### 37.1 GENERAL CHARACTERISTICS

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The zinc/bromine battery is an attractive technology for both utility-energy storage and electric-vehicle applications. The major advantages and disadvantages of this battery technology are listed in Table 37.1. The concept of a battery based on the zinc/bromine couple was patented over 100 years ago,<sup>1</sup> but development to a commercial battery was blocked by two inherent properties: (1) the tendency of zinc to form dendrites upon deposition and (2) the high solubility of bromine in the aqueous zinc bromide electrolyte. Dendritic zinc deposits could easily short-circuit the cell, and the high solubility of bromine allows diffusion and direct reaction with the zinc electrode, resulting in self-discharge of the cell.

Development programs at Exxon and Gould in the mid-1970s to early 1980s resulted in designs which overcame these problems, however, and allowed development to proceed.<sup>2</sup> The Gould technology was developed further by the Energy Research Corporation but a high level of activity was not maintained.<sup>3-5</sup> In the mid-1980s Exxon licensed its

**TABLE 37.1** Major Advantages and Disadvantages of Zinc/Bromine Battery Technology

Advantages	Disadvantages
Circulating electrolyte allows for ease of thermal management and uniformity of reactant supply to each cell	Auxiliary systems are required for circulation and temperature control
Good specific energy	System design must ensure safety as for all batteries
Good energy efficiency	Initially high self-discharge rate when shut down while being charged
Made of low-cost and readily available materials	Improvements to moderate power capability may be needed
Low-environmental-impact recyclable/reusable components made using conventional manufacturing processes	
Flexibility in total system design	
Ambient-temperature operation	
Adequate power density for most applications	
Capable of rapid charge	
100% depth of discharge does not damage battery but improves it	
Near-term availability	

zinc/bromine technology to Johnson Controls, Inc., JCI (Americas), Studiengesellschaft für Energiespeicher und Antriebssysteme, SEA (Europe), Toyota Motor Corporation and Meidensha Corporation (Japan), and Sherwood Industries (Australia). Several of the Exxon licensees are active in development, leading to a commercial product, and the technology discussed in this chapter is based on the original Exxon design.

### 37.2 DESCRIPTION OF THE ELECTROCHEMICAL SYSTEM

The electrochemical reactions which store and release energy take place in a system whose principal components include bipolar electrodes, separators, aqueous electrolyte, and electrolyte storage reservoirs. Figure 37.1 shows a schematic of a three-cell zinc/bromine battery system that illustrates these components (plus other features which are discussed in Sec. 37.3). The electrolyte is an aqueous solution of zinc bromide, which is circulated with pumps past both electrode surfaces. The electrode surfaces are in turn separated by a microporous plastic film. Thus two electrolyte flow streams are present—one on the positive side and one on the negative side.

The electrochemical reactions can be simply represented as follows:

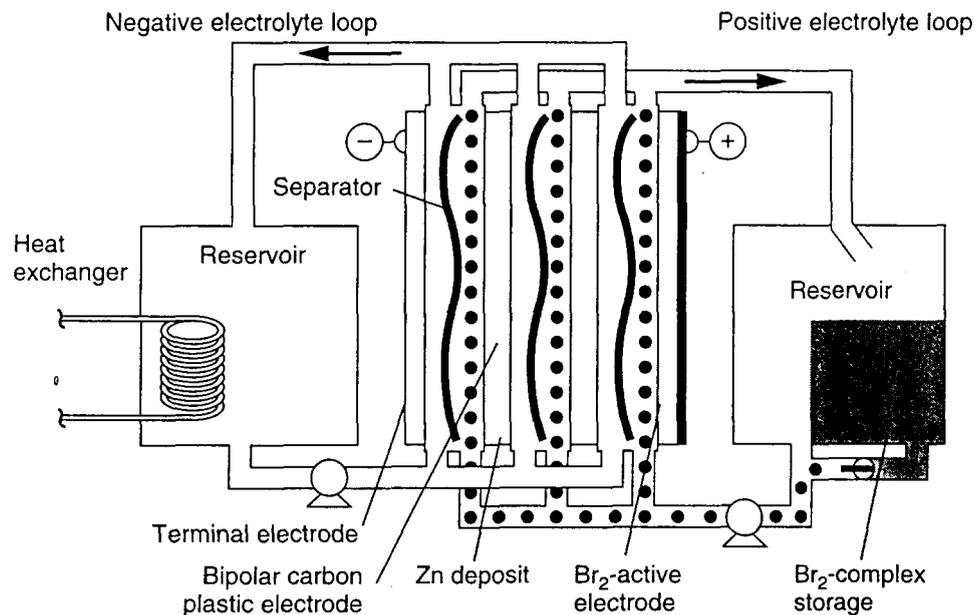
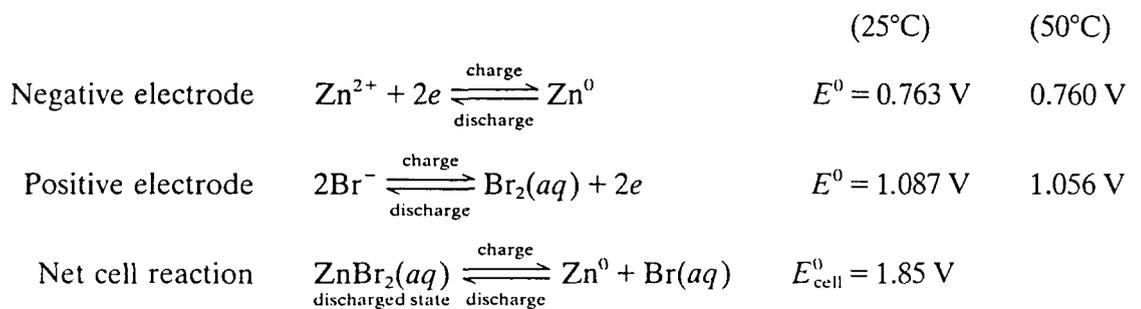


FIGURE 37.1 Schematic of three-cell zinc/bromine module. (Courtesy of Exxon Research and Engineering Co. and Sandia National Laboratories.)

During charge, zinc is deposited at the negative electrode, and bromine is produced at the positive electrode. During discharge, zinc and bromide ions are formed at the respective electrodes. The microporous separator between the electrode surfaces impedes diffusion of bromine to the zinc deposit, which reduces direct chemical reaction and the associated self-discharge of the cell.

The chemical species present in the electrolyte are actually more complex than that described. In solution, elemental bromine exists in equilibrium with bromide ions to form polybromide ions,  $\text{Br}_n^-$ , where  $n = 3, 5, 7$ .<sup>6</sup> Aqueous zinc bromide is ionized, and zinc ions exist as various complex ions and ion pairs. The electrolyte also contains complexing agents which associate with polybromide ions to form a low-solubility second liquid phase. The complex reduces the amount of bromine contained in the aqueous phase 10–100-fold, which, in addition to the separator, also reduces the amount of bromine available in the cell for the self-discharge reaction. The complex also provides a way to store bromine at a site remote from the zinc deposits and is discussed further in the next section. Salts with organic cations such as *N*-methyl-*N*-ethylmorpholinium bromide (MEMBr) are commonly used as the complexing agents. Complexes with these ions are reversible and also have an added safety benefit due to a much reduced bromine vapor pressure (see Sec. 35.6).

The electrodes are bipolar and are typically composed of carbon plastic. The presence of bromine precludes the use of metal electrodes—even titanium can corrode in this environment.<sup>7</sup> A high-surface-area carbon layer is added to the positive side of the electrode to increase the area for reaction. On charge, circulation of the electrolyte removes the complexed polybromide as it is formed, and on discharge complexed polybromide is delivered to the electrode surface. Circulation of the electrolyte also reduces the tendency for zinc dendrites to form and simplifies thermal management of the battery. Thermal management will be needed in many applications of present and advanced batteries.

The optimum operating pH range is set by the occurrence of undesirable mossy zinc plating and bromate formation above  $\text{pH} = 3$ , and by an increased zinc corrosion rate at lower pH. Hydrogen evolution due to the reaction of zinc with water has sometimes been observed during operation of zinc/bromine batteries. The hydrogen overpotential on zinc is large, however, and the reaction is slow in the absence of metals with low hydrogen overpotential, such as platinum.<sup>8</sup> During the development program it was found that the amount of hydrogen generated was small in the absence of impurities and had a minimal effect on the capacity of the battery.<sup>9</sup> Because of the circulating electrolytes, it would be easy to add water or acid to the system to compensate for any hydrogen formed, but this has not been necessary.

In a system where the cells are connected electrically in series and hydraulically in parallel, an alternate pathway for the current exists through the common electrolyte channels and manifolds during charge, discharge, and at open circuit. These currents are called shunt currents and cause uneven distribution of zinc between end cells and middle cells. This uneven distribution causes a loss of available capacity because the stack will reach the voltage cutoff upon discharge sooner than if the zinc were evenly distributed. Also shunt currents can lead to uneven plating on individual electrodes, especially the terminal electrodes. This uneven plating can in turn lead to zinc deposits that divert or even block the electrolyte flow.

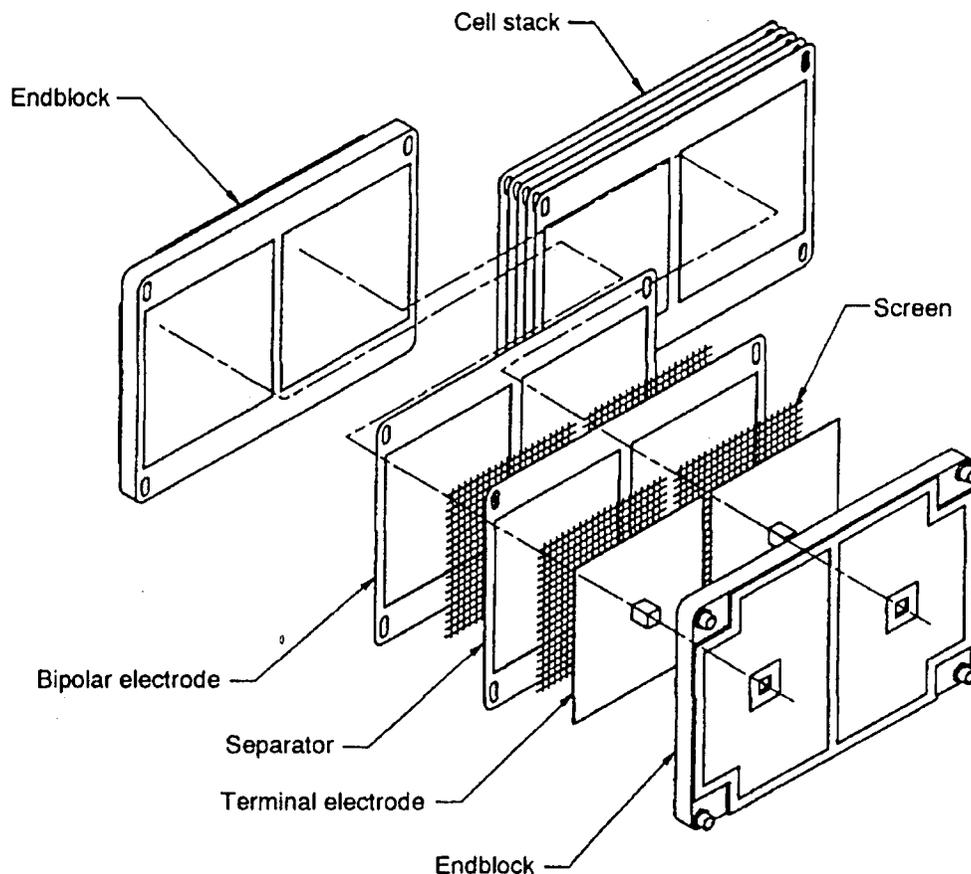
Shunt currents can be minimized by designing the cells to make the conductive path through the electrolyte as resistive as possible. This is done by making the feed channels to each cell long and narrow to increase the electrical resistance. This, however, also increases the hydraulic resistance and thus the pump energy. Good battery design balances these factors. Higher electrolyte resistance reduces shunt currents but also reduces battery power. Since the cell stack voltage is the driving force behind the currents, the number of cells in series can be set low enough that the magnitude of the shunt currents is minimal. In a specific utility battery design with 60 cells or less per cell stack, the capacity lost to shunt currents can be held to 1% or less of the total input energy. When these approaches are not sufficient to control the shunt currents, protection electrodes can be used to generate a

potential gradient in the common electrolyte equal to and in the same direction as that expected from the shunt current.<sup>9</sup> Several modeling approaches to calculate the currents for various applications have been proposed.<sup>10-13</sup>

### 37.3 CONSTRUCTION

In general terms the battery is made up of cell stacks and the electrolyte along with the associated equipment for containment and circulation. The primary construction materials are low-cost readily available thermoplastics. Conventional plastic manufacturing processes such as extrusion and injection molding are used to make most of the battery components. Because terminal electrodes must also collect the current from over the surface and deliver it to a terminal connection, the lateral conductivity must be higher than in bipolar electrodes, where the current only passes perpendicularly through the electrodes. A copper or silver screen is molded into the end block to serve as a current collector. Plastic screens are placed as spacers between the electrodes and separators. The components are assembled into a battery stack either by compression using bolts and gaskets, by using adhesives, or by thermal or vibration welding.<sup>14,15</sup> Figure 37.2 is a schematic showing the components and assembly of a cell stack.

Various materials have been used for the separator. Ideally a material is needed which allows the transport of zinc and bromide ions, but does not allow the transport of aqueous bromine, polybromide ions, or complex phase. Ion-selective membranes are more efficient at blocking transport than nonselective membranes; thus higher coulombic efficiencies can



**FIGURE 37.2** Components and assembly of a cell stack. (Courtesy of Johnson Controls Battery Group, Inc.)

be obtained with ion-selective membranes. These membranes, however, are more expensive, less durable, and more difficult to handle than microporous membranes.<sup>9</sup> In addition use of ion-selective membranes can produce problems with the balance of water between the positive and negative electrolyte flow loops. Thus battery developers have generally used nonselective microporous materials for the separator.<sup>3,4,9,14</sup>

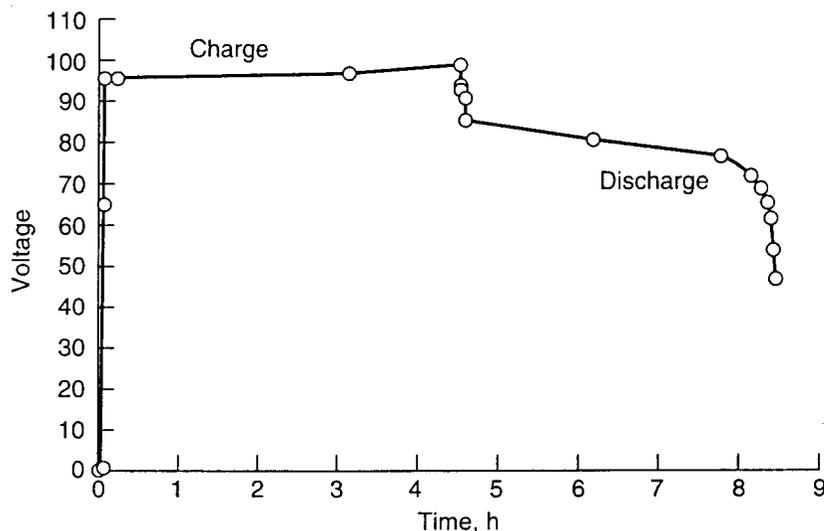
As shown in Fig. 37.1, two electrolyte circulation circuits are needed for the battery and include pumps, reservoirs, and tubing. The positive electrolyte side has an additional provision to store polybromide complex, which settles by gravity into a lower part of the reservoir. In Fig. 37.1 complexed polybromide is being delivered to the electrode surfaces during discharge. During charge, the bulk of the polybromide complex is not recirculated. The polybromide which is formed at the positive electrode associates with the aqueous-phase complexing agent and is collected in the storage area of the reservoir. This limits the potential self-discharge of the battery to only that complex which is in the cell stack at the termination of the charge process. The bromine may be dissolved in the aqueous phase, absorbed on the electrode surface, or complexed as polybromide.

A heat exchanger, located in the negative electrolyte reservoir, as shown in Fig. 37.1, provides for the thermal management of the battery. In general plastic heat exchangers can be used, and even though titanium corrodes when used as electrode material, titanium has been used successfully as the tubing material for the heat exchanger.

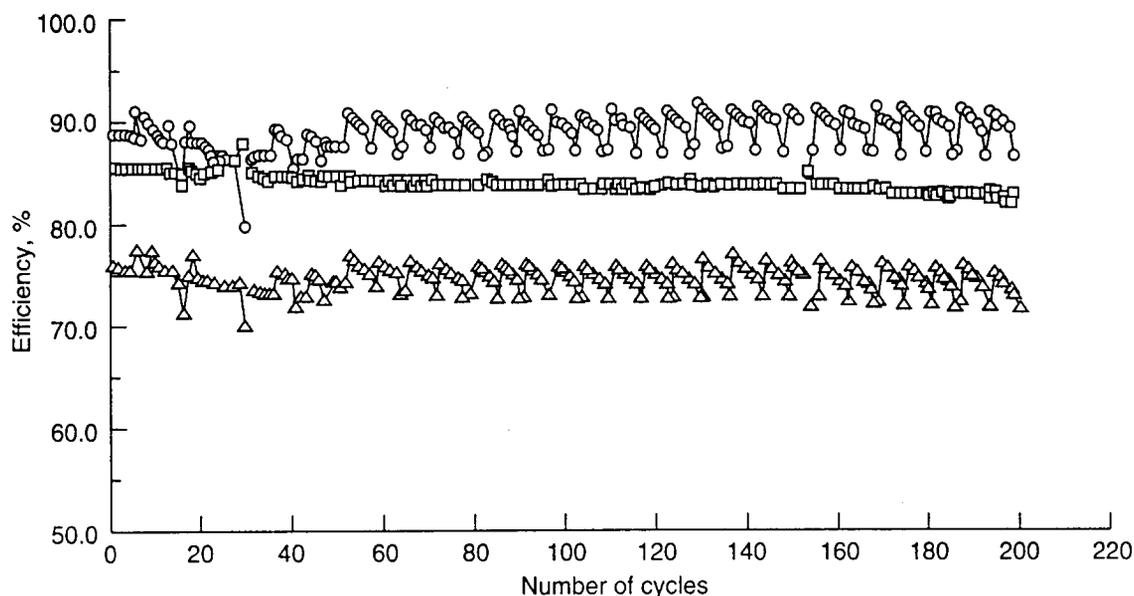
Ultimately the battery parts will be reclaimed or sent for disposal. The most significant parts of the battery in this respect are the cell stacks and electrolyte. The battery stacks are nearly all plastic and can be recycled by conventional processes and new processes that are being developed by the plastics industry. The electrolyte is not consumed in the battery. It will be removed and reused in other batteries.

### 37.4 PERFORMANCE

Zinc/bromine batteries are typically charged and discharged using rates of 15–30 mA/cm<sup>2</sup>. A charge-discharge profile for a 50-cell stack is shown in Fig. 37.3. The amount of charge is set based on the zinc loading that is defined at 100% state of charge. This amount is always less than the total zinc ion dissolved in the electrolyte. Thus rate of charge, time



**FIGURE 37.3** Charge-discharge profile for 50-cell stack. 80% electrolyte utilization; 30°C; 90-mAh/cm<sup>2</sup> zinc loading; 20-mA/cm<sup>2</sup> or C/4.5 charge rate; 20-mA/cm<sup>2</sup> or C/4 discharge rate. (Courtesy of Sandia National Laboratories.)



**FIGURE 37.4** Cycle efficiencies for 15-kWh battery. ○—coulombic; □—voltaic, △—energy. (Courtesy of Sandia National Laboratories.)

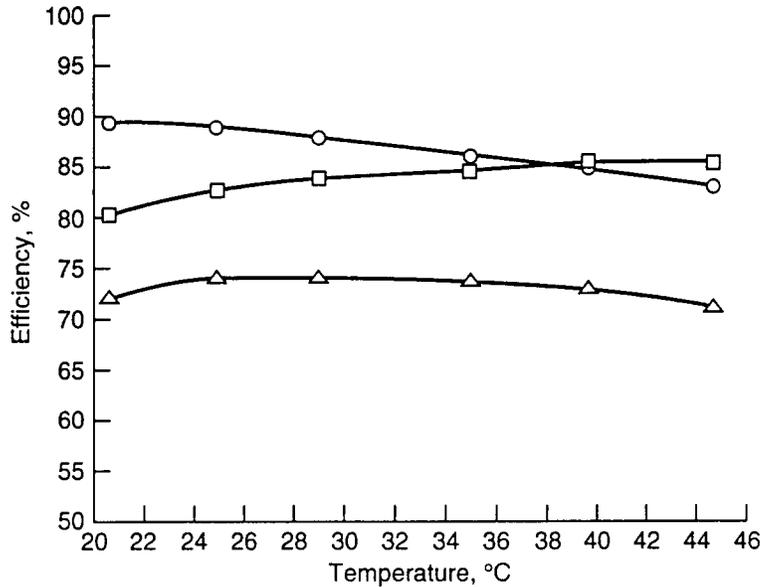
duration of charge, and charge efficiency are used to determine the end of charge. The voltage rises at the end of charge, and severe overcharge will electrolyze water. The discharge is usually terminated at about 1 V per cell since the voltage is falling rapidly at this point.

The capacity of a battery is directly related to the amount of zinc that can be deposited on the negative electrodes, and zinc loadings can range from 60 to 150 mAh/cm<sup>2</sup>. One hundred percent state of charge is defined as a specific zinc loading and can vary depending on the battery. Considerable effort has been expended to ensure good-quality dense zinc plating. It is important to control the pH to avoid undesirable mossy zinc deposits. Circulation of the electrolyte reduces the occurrence of dendritic deposits. Studies have shown that current density, zinc bromide concentration, electrolyte additives, and operating temperature also affect the quality of the zinc deposit.<sup>4,14</sup> With these studies and improvements, the problems are being managed or have been eliminated.

Zinc deposited onto a clean carbon plastic surface is smoother than when deposited on top of zinc; but zinc can be completely removed by total discharge to renew the surface. This is, in effect, a 100% depth of discharge and does not damage the battery but improves it. In practical applications the battery should complete many cycles before a strip cycle is run. A plot of the cycling efficiencies of a 15-kWh battery is shown in Fig. 37.4. The periodic nature of cycles 60–200 is a result of multiple tests in which five cycles were followed by a strip cycle and also occasionally a baseline cycle. The first new cycle is only slightly lower in efficiency because the base coat of zinc is being replated.

The amount of ZnBr<sub>2</sub> electrolyte that can be reacted at the electrodes is called the utilization and varies depending on the application. For utility applications battery efficiency is a primary concern, and percent utilization is about 50–70% to maximize efficiency. For electric-vehicle applications battery size and weight are more important, and the percent utilization can be as high as 80–90%. High utilization results in solutions of lower conductivity at the end of charge, which lowers voltaic and energy efficiencies. Attempts to charge to very high utilization result in electrolysis of water as a competing reaction, and high utilization cycles are also opposed because some of the reactant material is isolated in the opposing electrolyte chamber.<sup>16</sup>

In a battery system a portion of the energy will be diverted to auxiliary systems such as thermal management, pumps, valves, controls, and shunt current protection as required. The energy needed for auxiliaries depends on a number of factors, including the efficiency



**FIGURE 37.5** Efficiencies vs. operating temperature for battery with load-leveling electrolyte. ○—coulombic; □—voltaic; △—energy. (Courtesy of Johnson Controls Battery Group, Inc.)

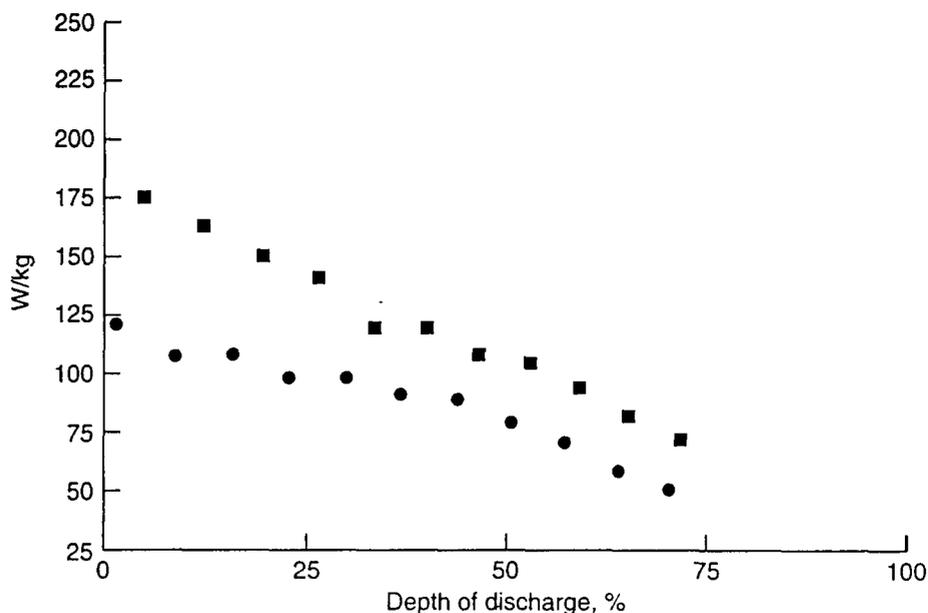
of pumps and motors, pump run time, and system design. Few publicly available data exist on energy requirements of auxiliary systems since development has focused on electrochemical performance, materials, and manufacturability. Management of auxiliary system energy requirements is continually improving, and the energy devoted to auxiliaries is projected to be less than a few percent of the total battery energy. It should be noted that other systems have auxiliaries and balancing inefficiencies as well.

Energy will also be lost during stand time. This was measured in one zinc/bromine battery system to be about 1%/h (watt-hour capacity lost) over an 8-h period.<sup>15</sup> During the test, electrolyte, which did not contain the complexed bromine phase, was circulated periodically to remove heat. The self-discharge reaction ceases once bromine in the stacks has been depleted.

Zinc/bromine batteries normally operate between 20 and 50°C. Typically the operating temperature has little effect on energy efficiency, as shown in Fig. 37.5. At low temperature the electrolyte resistivity increases, resulting in lower voltaic efficiency. This is offset by slowed bromine transport, which results in higher coulombic efficiency. At high temperature the resistance decreases and the bromine transport increases, again partially compensating for each other. Temperature control is accomplished with a heat exchanger and the circulating electrolyte. The optimum temperature will vary depending on the individual battery design and electrolyte used.

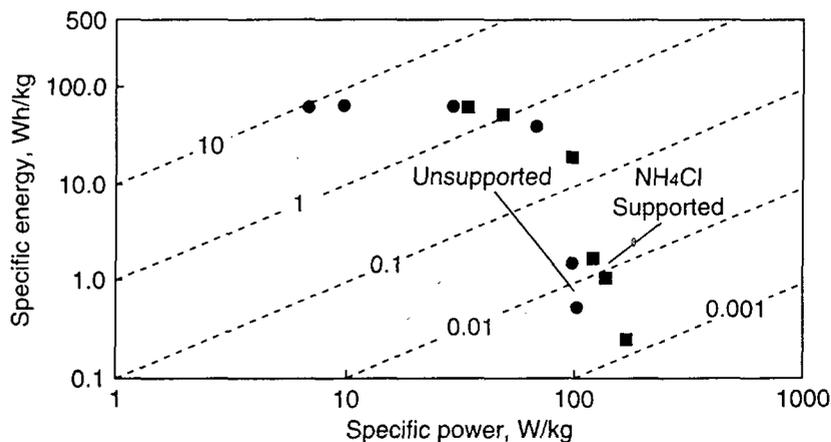
For applications which require high-power discharges, such as electric vehicles, the conductivity of the electrolyte can be enhanced by using additives such as KCl or NH<sub>4</sub>Cl. In this way internal ohmic energy losses are decreased. A test using NH<sub>4</sub>Cl supported electrolyte showed more peak power capability than unsupported electrolyte over a range of depths of discharge, as shown in Fig. 37.6. A Ragone plot of data from sustained power tests is shown in Fig. 37.7. Batteries with supported electrolyte, however, do have disadvantages. Overall efficiencies are about 2% lower than with unsupported electrolyte. Also plating additives are needed to counteract the tendency of supported electrolytes to produce rougher zinc deposits.<sup>14</sup> Since the supporting salts increase the weight and cost of the battery without increasing the energy content, they would not be added unless the extra power was necessary. Multicycle and long-term testing is needed to determine the specifications for optimum operation.

The largest factor influencing the lifetime of zinc/bromine batteries is most likely the long-term compatibility of the components with bromine. Improvements have been made



**FIGURE 37.6** Zinc/bromine battery peak power for  $\text{NH}_4\text{Cl}$  supported (■) and unsupported (●) electrolyte. Peak power—maximum power that can be achieved for 20 s. 80% electrolyte utilization; 30°C; 90-mAh/cm<sup>2</sup> zinc loading. (Courtesy of Johnson Controls Battery Group, Inc.)

in dealing with degraded seals, corrosion of the terminal current collectors, and warpage of the electrodes (which can interfere with the flow of the electrolytes), and in many cases problems have been solved. Studies have been done on a variety of plastic compositions.<sup>3,4,14,17,18</sup> Additives which may affect battery performance can be leached out of polyvinylchloride. Fluorinated polyolefins are generally chemically stable, but they are expensive, and carbon-loaded materials are not dimensionally stable in the presence of bromine. High-density polyethylene with glass fibers appears to be a good choice of materials for battery components from the viewpoint of chemical and dimensional stability and has displaced polypropylene. With control of warpage, a battery lifetime of more than 2000 cycles is possible. Studies have also been done on the stability of the quaternary ammonium salts used as bromine complexing agents, and decomposition was not found.<sup>9,19</sup>



**FIGURE 37.7** Zinc/bromine sustained power discharge. 80% electrolyte utilization; 30°C; 90-mAh/cm<sup>2</sup> zinc loading. Diagonal lines denote hours. (Courtesy of Johnson Controls Battery Group, Inc.)

Another study showed that a carbon-plastic bipolar electrode could tolerate 3000 cycles of zinc deposition and removal without degradation.<sup>3</sup>

### **37.5 TRADEOFF CONSIDERATIONS**

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The zinc/bromine battery, as do all battery systems, offers a tradeoff between high-rate discharges and lower-rate discharges; i.e., power and energy. Other additional design tradeoffs can be made. The two most important are increasing the ratio of electrolyte volume to electrode area to favor energy storage over power, and adding a conductivity salt to the electrolyte to favor power over energy. There is no clear evidence that operating a zinc/bromine battery at high power necessarily reduces life. If, however, the battery is allowed to operate at higher temperatures, plastic material degradation has been observed which does lead to reduced life. Therefore thermal management is a key issue that has to be addressed in high-power applications. To be assured of adequate cooling in a high-power application, larger cooling systems may be needed, which would also increase the battery weight.

The specific energy of the battery may decrease depending on the degree of safety required. Containment can be enhanced by incorporating multiple barriers to minimize electrolyte loss through a breach. Impact and leak sensors with shut-down controls can be incorporated to further ensure that electrolyte circulation ceases in the event of an accident. All of these additions, however, add weight which contributes to lower specific energy.

### **37.6 SAFETY AND HAZARDS**

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Very little free bromine exists in the battery. Bromine is present as polybromide ions dissolved in the aqueous portion of the electrolyte or bound with complexing agents in a second phase. Any remaining bromine is dissolved in the aqueous electrolyte. Liquid or gaseous bromine is hazardous; it injures through physical contact, especially inhalation.<sup>20</sup> In the complexed condition, however, the chemical reactivity and the evaporation rate are greatly reduced from those of pure bromine. For example, at 20°C the vapor pressure of bromine over the complex with MEMBr is more than 20 times lower than for elemental bromine.<sup>21</sup> If spilled, the charged electrolyte will slowly release bromine from the complex, which in turn will form vapor downwind from the spill site. Bromine has a strong odor, and it is readily detected at low levels. Spilled electrolyte can be treated using methods recommended by qualified industrial hygienists or methods listed in material safety data sheets. The EPA DOT reportable quantity for zinc bromide spills is 1000 lb.<sup>22</sup>

Runaway chemical reactions are unlikely because the polybromide complexes are stored away from the zinc. Even if the zinc electroplate were somehow flooded with polybromide complex, the reaction rate of the complex would be relatively slow because of the low zinc surface area available for reaction.

### **37.7 APPLICATIONS AND SYSTEM DESIGNS**

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A great deal of flexibility is available when designing zinc/bromine battery systems. Batteries can be custom built for a particular application, where multiple modules share a single set of electrolyte reservoirs or where each module contains a complete system of cell stacks, reservoirs, and controls. Modules can be stacked to conserve footprint in energy storage applications, and reservoirs can be made to match the space available in electric vehicles.

**TABLE 37.2** System Properties for SEA Designed Zinc/Bromine Batteries

Cell voltage, theoretical	1.82 V
Cell voltage, nominal	1.5 V
Coulombic efficiency	88–95%
Voltaic efficiency	80–86%
Energy efficiency	68–73%
Gravimetric energy density	65–75 Wh/kg
Volumetric energy density	60–70 Wh/L
Specific power	90–110 W/kg
Operating temperature	Ambient

SOURCE: From Tomazic.<sup>23</sup>

### 37.7.1 Electric-Vehicle Applications

The Studiengesellschaft für Energiespeicher und Antriebssysteme (SEA) in Mürzzuschlag, Austria, has been developing zinc/bromine batteries for electric vehicles since 1983 and has produced batteries with capacities ranging between 5 and 45 kWh.<sup>23</sup> SEA replaced the original Exxon molding of electrolyte channels into the flow frames with an external tubing manifold system. This allowed a flexible tubing connection of the stack to the reservoirs and ease of assembly and disassembly. The stacks are in horizontal layers, allowing low-profile construction. Programmable microprocessor controllers have been developed to allow thorough, safe, and reliable operation of the systems under various loads. Systems designed by SEA demonstrate a range of characteristics, as listed in Table 37.2.

SEA has installed a 45-kWh 216-V battery in a Volkswagen bus which the Austrian Postal Service has been using to deliver packages in the mountains around Mürzzuschlag (Fig. 37.8). The battery weighs about 700 kg, and the maximum speed achieved by the bus is 100 km/h. The maximum range at 50 km/h is 220 km.

Hotzenblitz, a German company, has designed an electric vehicle to be powered specifically by a zinc/bromine battery (Fig. 37.9). The battery is 15 kWh 114 V and is located in a compartment under the passenger area, as shown in Fig. 37.10. It is sealed from the passenger area and is located between side impact barriers for safety. Specifications and performance data are given in Table 37.3.

Toyota Motor Corporation has also been developing zinc/bromine batteries for electric vehicles.<sup>24,25</sup> A concept urban transportation vehicle, called the EV-30, has been designed for use with Toyota's zinc/bromine battery and has been displayed at motor shows in Japan. This two-seater vehicle would transport people in buildings, shopping centers, small communities, and to and from train stations—a “horizontal elevator” concept. The front-wheel-drive system uses an ac induction motor built by Toyota Motor Corporation. The battery system is modular zinc/bromine at 106 V and 7 kWh.

### 37.7.2 Energy Storage Applications

The use of zinc/bromine batteries in energy storage applications is also being demonstrated. In the United States the Department of Energy and Sandia National Laboratories are supporting the development of zinc/bromine technology for utility applications through a cost-sharing contract with Johnson Controls Battery Group, Inc.<sup>15</sup> Leak-free battery stacks, steady long-term operation, and energy efficiencies greater than 75% have been demonstrated on systems up to 15 kWh. The goal of this project is to design and build a 100-kWh low-cost, long-life system. Figure 37.11 shows a schematic of a prototype 50-kWh module which will be used as a submodule in the 100-kWh system. It is envisioned that the 100-kWh system can be further used as a submodule of a larger system.



FIGURE 37.8 Volkswagen bus powered by SEA zinc/bromine battery. (Courtesy of SEA.)

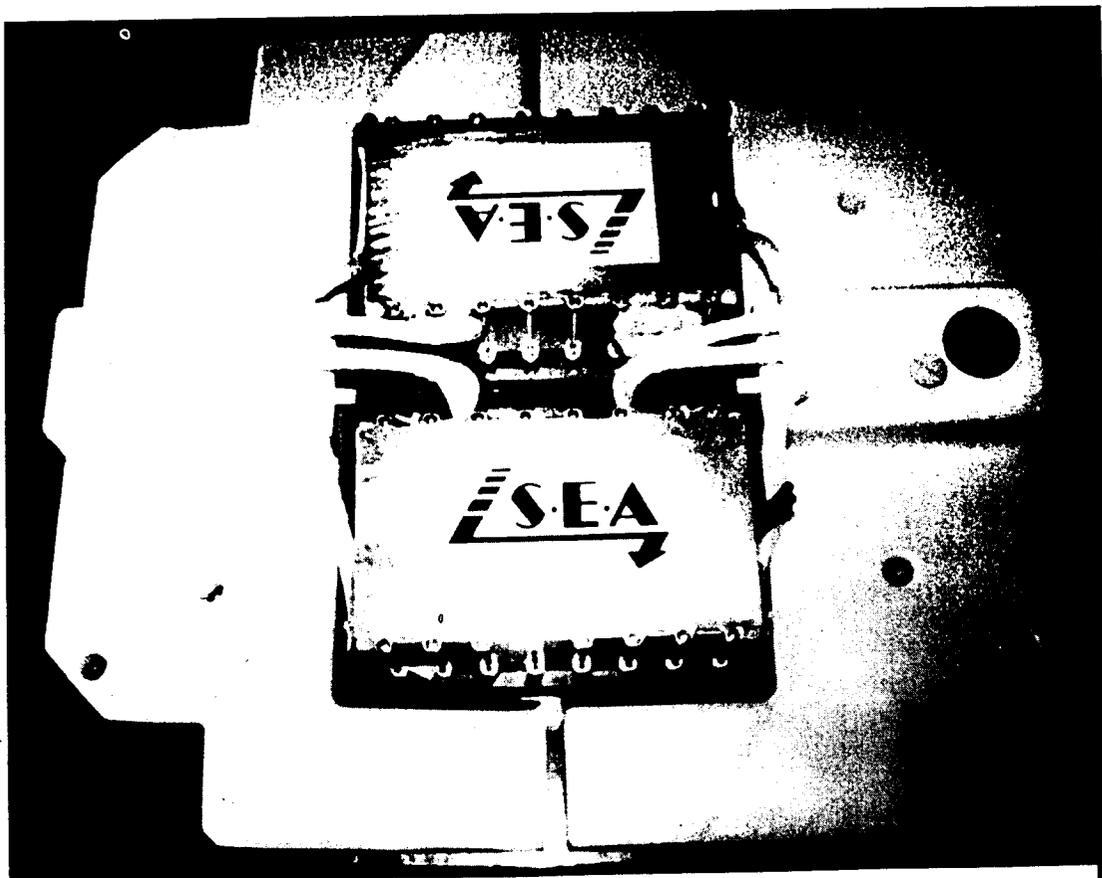
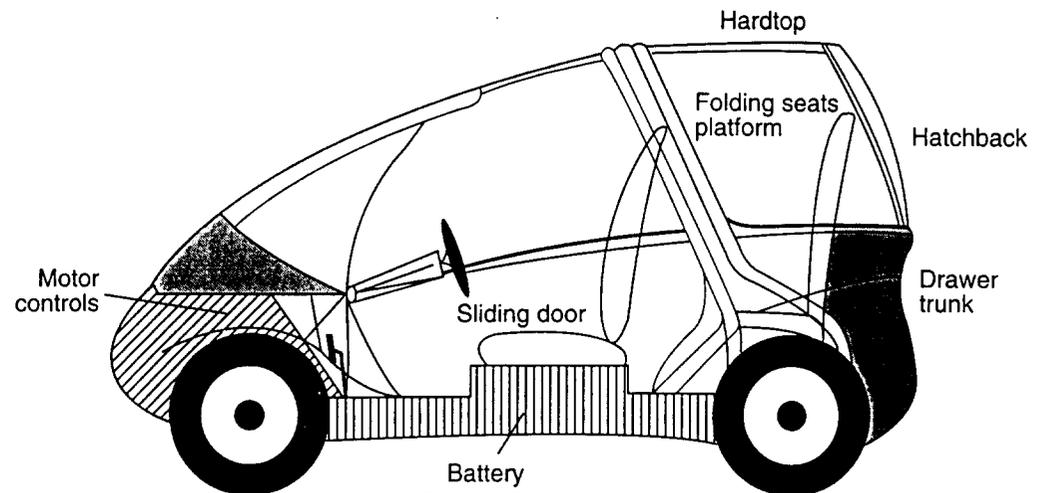


FIGURE 37.9 SEA 15-kWh 114-V zinc/bromine battery used to power Hotzenblitz EL SPORT. (Courtesy of SEA.)



**FIGURE 37.10** Schematic of Hotzenblitz EL SPORT showing location of zinc/bromine battery. (From Tomazic.<sup>23</sup>)

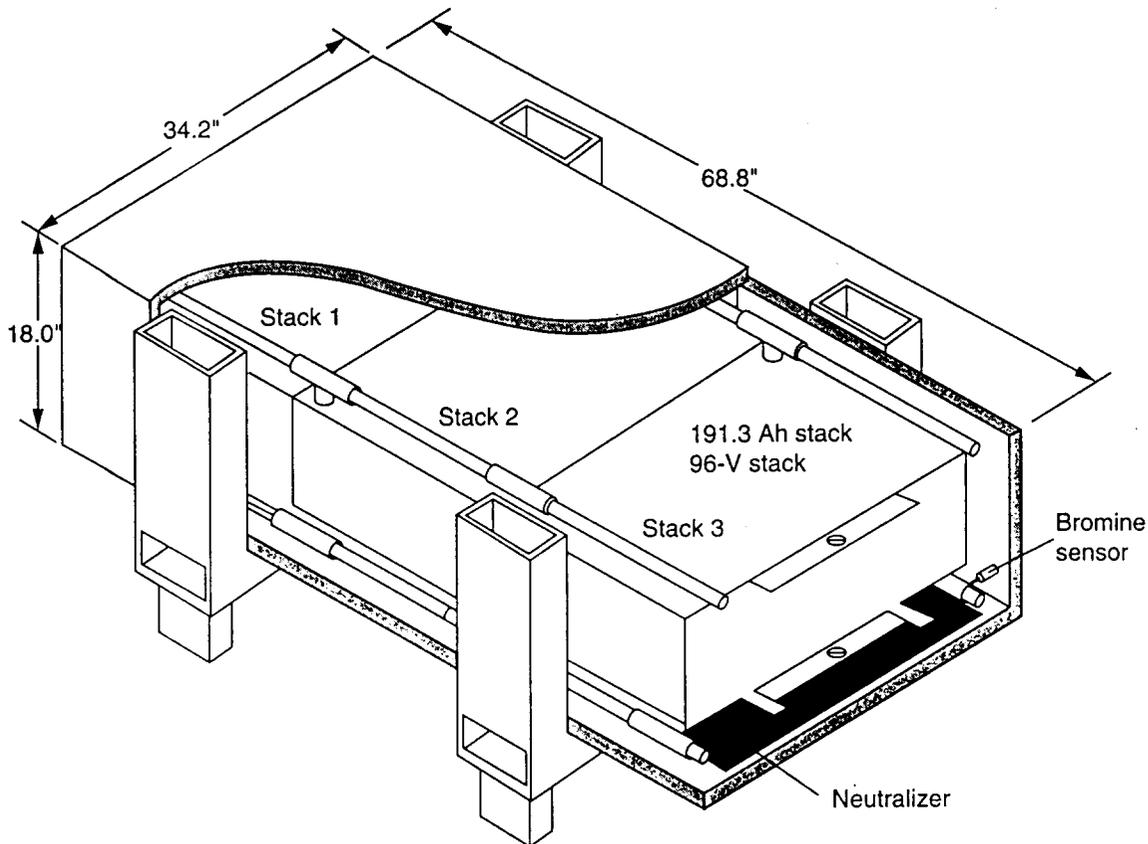
In Japan a long-term project to develop zinc/bromine battery technology for electric-utility applications has been part of the Moonlight Project under the sponsorship of the Ministry of International Trade and Industry.<sup>26,27</sup> During the 1980s research and development resulted first in 1-kW batteries, then 10-kW batteries, and finally 60-kW battery modules. The modules were used as components of a larger system, and in 1990 a 1-MW 4-MWh battery was installed at the Imajuku substation of the Kyushu Electric Power Company in Fukuoka City by the New Energy and Industrial Technology Development Organization, the Kyushu Electric Power Company, and the Meidensha Corporation (Fig. 37.12). The battery room of the Imajuku energy storage test plant is shown in Fig. 37.13. The system is composed of 24 25-kW submodules connected in series and is presently the largest zinc/bromine battery in the world. Design specifications are given in Table 37.4.<sup>28</sup>

Operation testing began in 1991, and the battery had an energy efficiency of 65.9% after 158 cycles.<sup>29</sup> A typical charging voltage (dc) nominally is about 1400 V with a current of 520 A, while the discharge starts at 1186 V at an average current of about 900 A.<sup>27,30</sup> Discharge is terminated when the voltage drops to 720 V. Discharge can be carried out for 8 h at 500 kW or for 4 h at 1000 kW. The 1100-V dc battery output is supplied to a self-commutated inverter of 1000 kVA, and the output transformer is a self-cooled 1200-kVA type. The ac output is fed to the Kyushu utility grid in times of peak demand. In periods of low demand the batteries are recharged from the grid.

**TABLE 37.3** Specifications and Performance Data for Hotzenblitz EL SPORT

Vehicle	Battery
Length, 2700 mm	Type, zinc-bromine battery
Width, 1480 mm	Charging time, approx. 5–6 h
Height, 1500 mm	Onboard charger, 3 kW
Gross vehicle weight; approx. 650 kg	Battery weight, approx. 240 kg
Payload capacity, 300 kg	Speed max, >100 km/h
Range, 150–180 km	Gradability, approx. 25%
Motor, 12 kW/144 V	

SOURCE: From Tomazic.<sup>23</sup>

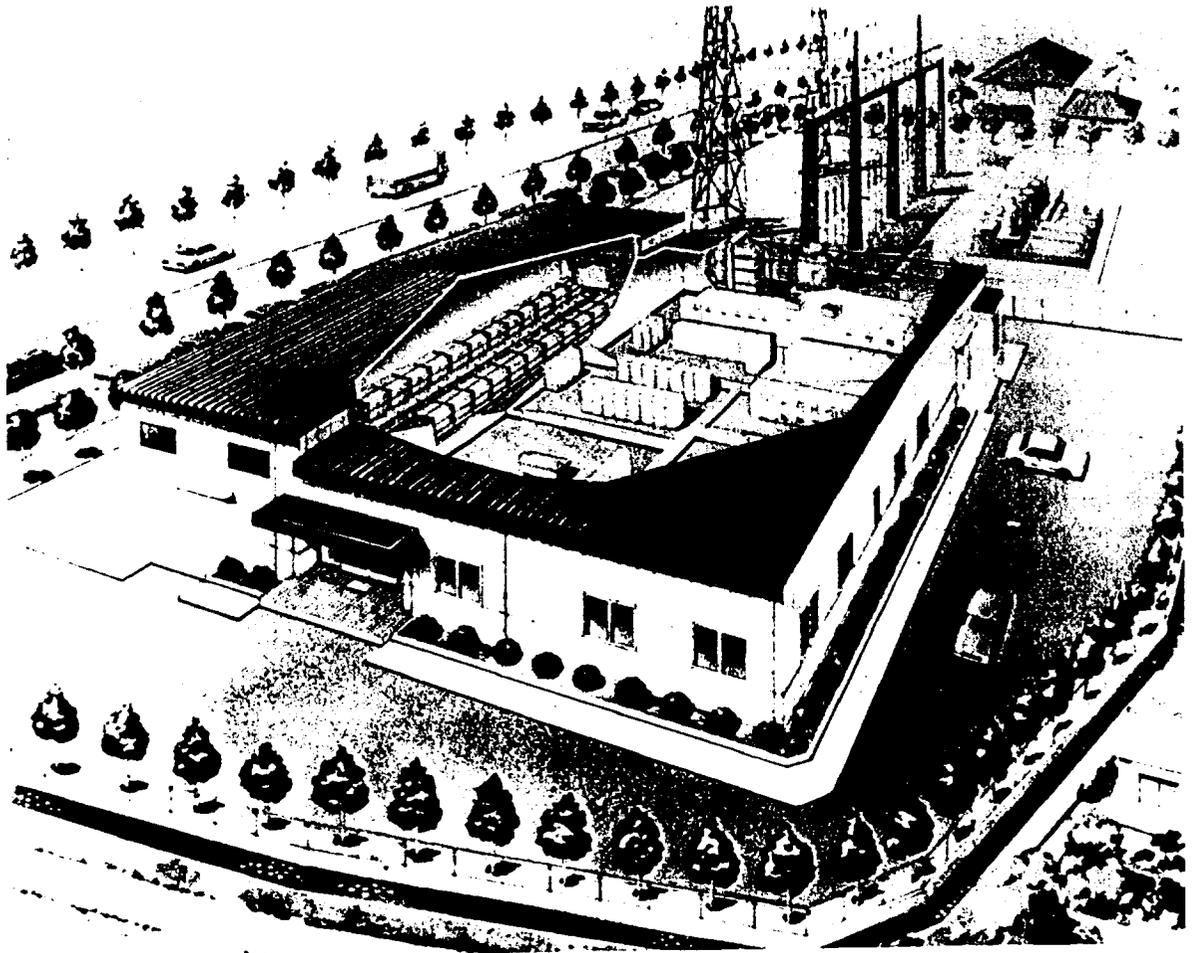


**FIGURE 37.11** Schematic of prototype 50-kWh module for energy storage (573.9 Ah, 96 V). Open-circuit voltage—108 V; nominal voltage—96 V; low-voltage cutoff—60 V. (Courtesy of Johnson Controls Battery Group, Inc.)

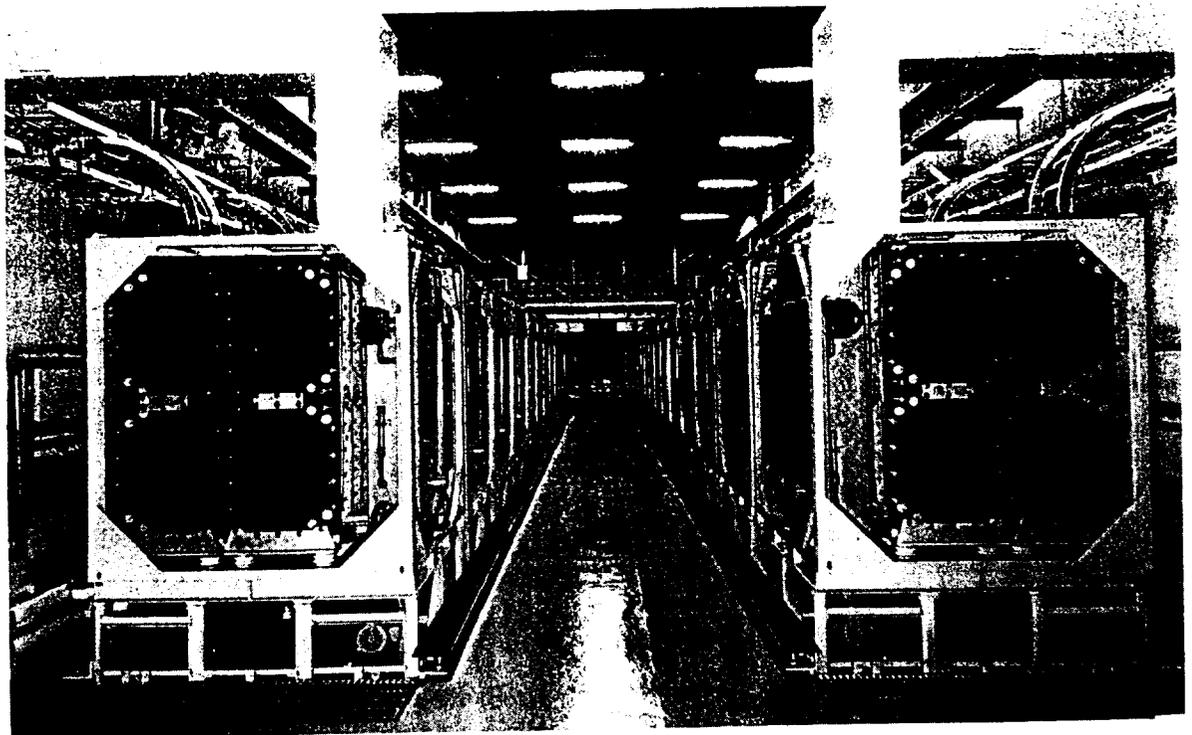
### 37.8 DEVELOPMENTS AND PROJECTIONS

In the United States and Japan the most likely near-term market for zinc/bromine batteries is electric-utility applications. Sales of millions of kilowatthours of capacity per year may be possible at an estimated cost of \$150/kWh or less. Application of zinc/bromine technology to electric vehicles in the United States is a longer-term market possibility, and the USABC (United States Advanced Battery Consortium) has presently chosen not to fund development of zinc/bromine technology. In Europe, however, interest in electric-vehicle applications for zinc/bromine technology is stronger and represents the near-term market. SEA has a yearly production capacity of 4000 kWh.<sup>23</sup>

Research and development issues are being addressed and will result in further improvements to the performance of the zinc/bromine battery system. For example, materials for separators which would allow improved transport selectivity while maintaining low resistivity would result in higher efficiencies. Development of a high-surface-area carbon layer with enhanced stability will lead to improved electrodes and longer lifetimes. Rigid plastics for frames and electrodes will minimize warpage and allow even flow of electrolyte. With any materials development, tradeoffs between performance, cost, and manufacturability need to be considered. Development of more efficient auxiliary systems is needed. System design is also important and includes factors such as footprint, structural integrity, number of cells per stack, number of stacks, and number of stacks per electrolyte reservoir.



**FIGURE 37.12** Artist's conception of Imajuku energy storage test plant. (Courtesy of NEDO, Kyushu Electric Power Co., and Meidensha Corp.)



**FIGURE 37.13** Battery room of Imajuku energy storage test plant. (Courtesy of NEDO, Kyushu Electric Power Co., and Meidensha Corp.)

**TABLE 37.4** Design Specifications for Imajuku Energy Storage Test Plant

Power	1 MW ac
Capacity	4 MWh ac (1000 V ac, 4 h)
Cell electrode area	1600 cm <sup>2</sup>
Current density	13 mA/cm <sup>2</sup> (nominal)
Stack	30 cells bipolar
Submodule	25 kW (30 cells in series, 24 stacks in parallel)
Dimensions (height × width × length)	3.1 × 1.67 × 1.6 m
Weight	6380 kg
Module	50 kW (25-kW Submodule, 2 series)
Pilot plant system	50 kW, 12 series
Total weight	153 tons

SOURCE: From Fujii et al.<sup>28</sup>

The following are the goals for the next 10 years:

- Specific energy of up to 100 Wh/kg or higher
- Specific power of up to 150 W/kg
- Power capability that is nearly independent of the state of charge
- Energy density of up to 100 Wh/L
- Energy efficiency of 80%
- Full charge time of 2 h or less possible, partial charge shorter
- Efficiencies of greater than 75% with a 4-h charge and 3-h discharge
- Stand loss of 1% the first day and less than 0.1% per day thereafter
- Lifetime of 3000 cycles
- Capability of 100 or more cycles without stripping

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