Abstract

The latest developments in energy storage devices and power sources are reviewed with regard to their application in electric powered wheelchairs. Chemical storage, electrochemical storage, and mechanical storage devices are considered. The most promising developments appear to be emerging from electric vehicle programs, which have been receiving considerable attention lately in response to zero-emission standards currently mandated in several urban areas. Four improved battery technologies may be available as early as 1995 for field trials, including the Horizon advanced lead-acid battery, the SAFT STM nickel-cadmium battery, the Ovonic nickel-metal hydride battery, and the Westinghouse lithium-iron disulfide battery. The lithium-ion battery technology and the flywheel energy storage technology are also very promising candidates, which have yet to be demonstrated in full-scale prototypes. If successful, any one of these technologies could provide weight and volume savings of over 50% compared to conventional lead-acid wheelchair batteries. The RERC on Improved Wheelchair Mobility, working with Westinghouse Corporation, has contacted selected developers to obtain prototypes for testing when production is started. Reliability, cycle life, and safety will then be determined under actual operating conditions.

INTRODUCTION

The purpose of the present report is to review the status of emerging power sources and energy storage technologies, and to assess the potential applicability of these technologies for wheelchair use. The goal is to evaluate technological developments in all fields, including chemical energy storage, electrochemical energy storage, and mechanical energy storage. However, because a majority of the relevant work is being performed in the electrochemical area by the United States Advanced Battery Consortium (USABC), special emphasis will be given to this field. The USABC is an alliance formed recently by the "Big Three" automakers, government, and industry to develop advanced batteries for electric vehicles (EV's). Their charter is to develop an economical battery for EV use by the year 2000. The first commercial batteries are expected to begin production sometime in the 1995-1996 timeframe, and significant progress is being made towards realizing that goal.

Prior to this most recent EV thrust, virtually all electric vehicles, including the wheelchair, used lead-acid batteries. Lead-acid has historically been one of the most reliable, cost effective, and therefore, the most practical energy storage devices available. Its availability, present performance capabilities, and low cost are the result of decades of work done by the auto industry to improve both the battery and its mass production process. And although these efforts have been focused almost entirely on the Starting/Lighting/Ignition (SLI) requirements for the automobile, the work nonetheless has fostered the development of a number of small electric powered devices (like the wheelchair), that by virtue of their relatively small market size, could not have sustained the costs necessary to bring the improved technologies to market. Today's circumstances are much the same, and the wheelchair and other small electric powered vehicles will again benefit from the renewed industry-wide interest and infusion of funds into the development of advanced energy storage devices for electric vehicles. Funding for USABC and other independent efforts is expected to approach $1 billion through the year 2000. So the focus, the funding, and the economics of scale are all falling into place for the next major advance in power source technology.

A broad range of technologies are under development throughout the industry. Some programs seek to improve upon existing technology, such as advanced versions of the common lead-acid battery. Other programs are devoted to the development of entirely novel concepts, as in the case of lithium-ion battery technology. Yet others are attempting to bring old, but previously impractical concepts to life by applying the most recent advances in materials and physics, as in the case of flywheel systems. Given the diversity of these efforts, the goal of the present overview is to provide some structured basis for comparative evaluations. Specifically, the objective is to accomplish the following:

- to identify the major technologies being developed,
- to summarize and compare present performance levels (e.g. W-hr/kg),
- to establish the utility of the technologies for wheelchair applications based upon performance, cost and scalability,
- to provide detailed discharge data for prototype devices where relevant, and
- to evaluate the commercial availability of production units.

POWER SOURCE DESIGN

Size, weight, reliability, safety, life, availability, maintainability, and cost are some of the primary design issues facing the developer and user. For the purpose of explaining the definitions of each of these terms, some examples are given here. More specifics are given during discussions of the individual technologies in the next section.

Size and weight are functions of the device's performance capabilities versus the power, energy, and usage requirements of the intended application. In the case of batteries, different couples will have inherently different performance capabilities (i.e., energy densities (W-hr/l) and specific energies (W-hr/kg)). In addition, the manner in which these performance capabilities vary with the conditions of use might also be dramatically different. For example, a nickel-iron battery might provide double the energy density and specific energy of a lead-acid battery under low power and room temperature operation. The opposite may be true however at sub-zero temperatures and high power use. Therefore, for batteries , selection of the chemistry itself will have the first impact upon size and weight. Once a chemistry is selected, however, some general rules tend to apply to nearly all batteries. Typically, for any given battery chemistry, a higher drain rate (amperage) requirement, a higher voltage requirement, a longer uninterrupted discharge requirement, or a lower operating temperature requirement will tend to decrease specific energy and energy density and thus increase the size and weight. On the other hand, in electromechanical systems such as compressed air or the flywheel, the size and weight may be less sensitive to the ambient temperature or the length of the uninterrupted discharge, but more dependent upon mechanical design features.

Reliability and life are somewhat inter-related characteristics. Reliability is typically a measure of the device's ability to perform without failure for some number of cycles. For example, in the military establishment, the Mean Time Between Failure (MTBF) is a key measure of reliability. For a battery, "life" is commonly interpreted as cycle life, and therefore the reliability could be defined as the mean number of charge/discharge cycles before failure. "Failure" is typically defined as an inability to maintain voltage, capacity, safety margins, etc. under the designed set of usage conditions. As with specific energy and energy density, the cycle life of a battery can be a function of usage conditions such as drain rate and temperature. Depth-of-discharge (DoD) and the chemical/electrochemical stability of battery materials and components also play important roles. For example, the lead-acid battery can provide many cycles with high reliability when discharged to only 50 % of its rated capacity. At closer to 100% DoD, the cycle life declines dramatically. Frequency and degree of excursions outside of the maintenance and usage profiles for which the device was designed (commonly referred to as abuse) can be another cause of early failure. In good development programs, the reliability is improved through a series of reliability growth cycles (build/test/fault detection/correction) conducted to identify and drive out defects and to make the systems robust, safe, and tolerant to abuse.

Safety is a major consideration in practically all applications. Failure modes should be restricted to gradual degradations in performance, which by definition are not safety concerns. However, any device capable of high energy density and high power density can present serious safety risks if not properly designed. Examples of potential safety issues include violent or unexpected release of stored pressure energy, rotational energy, or electrochemical energy, or the ignition of evolved gases. Issues of safety are the primary reasons for the restrictions placed on the transport of activated batteries on passenger airlines for example. In all cases, safe operation must be ensured even under the most severe conditions of abuse such as puncture, temperature extremes, or accidental misuse.

Availability and maintainability are keys to operating convenience for the user. Availability refers to the time a device is available for use versus the time it must spend undergoing recharge, scheduled maintenance, repair, or reconditioning. Maintainability refers to the frequency, complexity, and cost of keeping the device in operating order. If possible, user involvement in maintenance should be minimized.

Ideally, all of the factors discussed here should be optimized to provide the best design. However, in reality there are many trade-offs that can and must be considered in the selection and configuration of a power source for a given application. In some military applications for example, energy density is critical. Therefore, lower cycle life, increased maintenance requirements, and higher costs are sometimes accepted to maximize energy density. In the wheelchair application the opposite has been true; the size and weight of the lead-acid battery have been accommodated in order to exploit its reliability, safety, availability, maintainability, and cost benefits relative to other existing technologies.

WHEELCHAIR BATTERY NEEDS

The present objective is to reduce the size and weight of the power source, and to extend its cycle life while retaining the otherwise attractive features of the lead-acid battery. Bode [1] reported that the basic size and configuration of the lead-acid battery limits frame design, space for respirators, etc. Reductions in battery weight or volume might also be used to improve portability. In turn, a more portable electric wheelchair might provide significant cost advantages, particularly if specially equipped transport vans and handling equipment could be reduced or eliminated. Therefore, the following discussion seeks to consider all of the issues of design discussed above, but with a focus on size, weight, and life cycle cost reduction.

DEVELOPMENT

Energy storage devices may be broadly classified into three relevant areas: chemical storage devices, electrochemical storage devices, and mechanical energy storage devices. Chemical storage devices are typically those which rely upon combustion of a fuel to provide power. The internal combustion engine is the prime example of a device which converts the stored chemical energy of gasoline to mechanical energy. An electrochemical storage device is one which converts the free energy change of a chemical reaction directly to electrical energy. Batteries are electrochemical devices. Fuel cells are also classified as electrochemical devices by this definition, even though they are used to chemically combust a fuel (typically hydrogen or

Table 1. Relevant USABC battery goals vs average lead-acid wheelchair battery performance.

Performance Characteristic	**USABC Mid-Term**	**USABC Long-Term**	**Conventional Lead-Acid**
Energy Density (W-hr/l)	135	300	70
Specific Energy (W-hr/kg)	80	200	35
Power Density (W/l)	250	600	>200
Specific Power (W/kg)	150	400	>100
Life (years)	5	10	1 to 2
Cycle Life (to 80% DoD)	600	1000	>300
Price ($/kW-hr)	<150	<100	<150
Min. Operating Temp. (^{o}C)	-30	-40	-40
Max. Operating Temp. (^{o}C)	65	85	60
Recharge Time (hr)	<6	3 to 6	6 to 8
Maintenance	none	none	none

(* to 60%DoD)

Table 2. Candidate battery technologies for electric vehicles.

AQUEOUS		**NON-AQUEOUS**	
Acid	**Alkaline**	**Ambient Temp.**	**High Temp**
Lead Acid	Nickel-Iron Nickel-Cadium Nickel-Metal Hydride Nickel-Zinc Zinc-Bromine Zinc-Air	Lithium-Polymer Lithium-Ion	Lithium-Iron Disulfide Sodium-Sulfer Sodium-Nickel Chloride

Table 3. Battery technologies funded by the USABC.

Technology	Company	Funding ($M)	Timing
Nickel-Metal Hydride	Ovonic	19.9	Mid-Term
Nickel-Metal Hydride	SAFT	18.1	Mid-Term
Sodium-Sulfur	Silent Power	12.1	Mid-Term
Lithium-Iron Disulfide	SAFT	17.3	Long-Term
Lithium-Polymer	W.R.Grace	27.4	Long-Term
Lithium-Polymer	Delco-Remy	28.0	Long-Term

methane). Mechanical storage devices are those which store either kinetic or potential energy. Flywheels and pneumatic accumulators (i.e., compressed gas) are the most commonly cited devices in this category.

As mentioned earlier, development programs are being conducted in all areas of chemical, electrochemical, and mechanical energy storage. In general, the most relevant programs are those targeting the EV application. EV programs are relevant because their performance goals are so closely aligned with the improvements needed in a wheelchair power source. Table 1 shows the USABC mid-term (1995) and long term (2000) performance goals compared against present levels of lead-acid wheelchair battery performance. While the long-term goals represent a four-fold improvement over lead-acid in almost every respect, achieving even the more moderate USABC mid-term goals would provide considerable improvements in wheelchair performance.

The most likely battery candidates for EV use are shown in Table 2. The systems are classified by electrolyte type and operating temperature. All aqueous systems operate at ambient temperature. Of the technologies listed in Table 2, USABC has chosen to fund the four shown in Table 3. The remaining technologies are being funded independently at various levels by government and/or private organizations.

In the area of mechanical energy storage for EV use, the primary focus has been on flywheels and compressed air devices. Over 15 companies and government labs are involved in advanced flywheel research. Finally, in the area of chemical energy storage devices, the main focus has been on advanced heat engines such as the stirling engine and gas turbines.

Keys to utility for any of these devices in wheelchairs will be cost and scalability (i.e., the feasibility from both a cost and technical standpoint to retrofit units produced for EV's into wheelchairs).

PERFORMANCE

The first consideration in the quest for a better wheelchair power device is weight. Therefore a general comparison of the specific energy (W-hr/kg) and specific power (W/kg) for the various candidate technologies was used as the first criteria by which to screen the potential candidates. Figure 1 summarizes the performance capabilities of the various devices on this basis. On this basis, devices such as ultracapacitors, superconducting magnetic energy storage (SMES), and accumulators were dropped from further consideration because of low specific energy.

The second criteria used to screen the potential candidates were size and/or scalability. By virtue of their need to carry fuel tanks, systems like the fuel cell and the gas turbine are inherently bulky and complex. Both the energy density (W-hr/l) and the power density (W/l) of these devices are therefore compromised, particularly as they are scaled to smaller and smaller sizes. In large vehicles like vans and buses where these devices are being tested, size can be accommodated to take advantage of the high energy storage capacity. However, retrofitting the large systems developed for EV use into the wheelchair chassis will probably be costly and impractical. Furthermore, the need to re-fuel rather than recharge these devices is a drawback for the wheelchair user, who typically has more frequent and closer access to an electrical outlet.

Given these initial screening criteria, the field of candidates was narrowed to flywheels and electrochemical devices which will be discussed in more detail.

ELECTROMECHANICAL DEVICES

Flywheels: These systems convert the kinetic energy stored in a rotating disc directly to electrical power by coupling the shaft of the flywheel to a motor/generator device. The amount of energy that can be stored in this system can be equated to the moment of inertia of the disc and to the square of the angular velocity. When the properties of materials are factored into this equation, a very simple and useful rule emerges; for any given flywheel shape, the maximum stored energy is directly proportional to the yield strength of the material and inversely proportional to the density of the material. (A good summary of the physics of the system is given by Jensen [2]). The rapid progress that has been made in the last decade on lightweight, high-strength materials has therefore revived interest in flywheel systems.

In a commercial system, the entire disc and motor assembly would be suspended on magnetic bearings in a vacuum container which serves a dual purpose. First, a vacuum is needed to reduce windage and energy losses during open circuit stand. Second, this container serves as a barrier to contain any fragments of the flywheel system if it fails or ruptures (a concern because these systems can operate at near 100,000 rpm). Consequently, the type and weight of the containment vessel can factor heavily into the total system energy density. For this reason, quoted energy densities and specific energies vary dramatically in the literature. Using the latest materials, practical specific energies of the wheels themselves appear to be ranging from 50 to

250 W-hr/kg [3]. When the motor/generator and containment vessel weights are added, the specific energies will be less, but how much less won't be known until more operating prototypes are built. Power in these systems is related more directly to the design of the motor/generator system, which is usually tailored to the given application.

The flywheel system has several attractive features for the wheelchair user. 1) It is a mechanical system, with parts that shouldn't degrade much with time or use, so cycle life should be high. Because there is little degradation, no maintenance should be required of the user, so maintainability is high. If a part (e.g., a bearing or a motor) were to degrade, the part could be repaired rather than replacing the entire unit, thus reducing life cycle costs. 2) The system is electrically rechargeable, because the motor which produces electrical power on discharge also functions as a generator when run in reverse to spin the flywheel back up to speed. The system functions so much like a rechargeable battery that it is often referred to as an electromechanical battery. 3) The system's performance is essentially independent of ambient temperature because there are no rate-dependent chemical reactions to contend with. And 4), scalability looks good. Small 3-kW-hr units are already in the prototype stage at Lawrence Livermore National Laboratories [4].

The major technological challenge cited for these systems is the development of a reliable magnetic bearing system to support the flywheel. Otherwise this system deserves serious consideration for applications such as the wheelchair.

ELECTROCHEMICAL SYSTEMS

A comprehensive overview and comparison of the general performance characteristics of conventional battery technologies is given by Linden [5]. Linden compares discharge characteristics, charge characteristics, cycle life, efficiencies, energy densities, power densities, temperature response, and depth-of-discharge effects for the most common battery types. It is not the intention to reproduce that data here, and therefore only the most relevant comparisons or the most recent developments will be discussed in relation to wheelchair applications.

Lead-Acid Batteries: The next generation power source for wheelchairs may be an extension of the conventional lead-acid technology. The best available conventional technologies are the deep-cycle and the gel-cell batteries. Plots of discharge time, voltage, power, and energy are given in Figure 2 for a gel-cell battery marketed by Johnson Controls. Similar plots for a deep-cycle marine battery are shown in Figure 3. As indicated, the specific energies of these batteries range from 28 to 35 W-hr/kg, very respectable for lead-acid technology. Expected cycle life is a function of depth-of-discharge, with 200 to 300 cycles achievable when run to approximately 60% DoD [6].

Advanced lead-acid development programs are underway to improve further upon these capabilities. Two programs are particularly noteworthy. One is the Horizon battery being developed by Electrosource, Inc. Developers claim that the battery can deliver over 20% more energy than state-of-the-art lead-acid and that it is capable of quick charging in less than 3 hours. A quasi-bipolar design, and a patented extruded grid design have allowed the makers to produce a very low profile module with high power capabilities. The most recent module designs are only 1.69" high (*HxWxL = 1.69" x 9.52" x 15.39" for a 12 volt, 20 A-hr design*) which may provide opportunities for the wheelchair designer. Plots of discharge time, voltage, power, and energy are given for the Horizon battery in Figure 4. Cycle life for this battery has been tested to over 750 cycles at 80% DoD. Westinghouse has been in contact with Electrosource who have indicated that production is about to start and 12 V, 20 A-hr units may be available for test as early as December of 1994.

The second program of interest is the Thin Metal Film™ design being developed by Bolder Battery, Inc. [7]. This battery is still in the small cylindrical cell stage of development, but the technology promises two key advantages; high power and fast recharge rates. Although the quoted specific energy is no greater than conventional lead-acid (between 30 and 35 W-hr/kg), the ability to fully recharge the battery in 5 minutes may make it more useful than competing technologies because its *availability* is so high. The user could completely recharge the battery and be ready for another 6 hour shift in the time it takes to have a cup of coffee. Over 300 deep discharge cycles and over 15,000 shallow discharges have been demonstrated. Scale-up to 30 A-hr cell sizes is underway, and Westinghouse has been in continuing contact with Bolder Battery engineers to monitor scale-up efforts.

Nickel-Iron: Nickel-iron batteries manufactured by Eagle-Picher, Inc. have been used in several Chrysler electric vans. However, the battery is being used primarily to demonstrate other system components (motors, controllers, etc.). Nickel-iron provides specific energies in the 50 - 60 W-hr/kg range, which would provide weight savings compared to present lead-acid systems. Yet this technology suffers from poor charging efficiency which results in frequent water addition requirements, a maintainability issue. The poor charge efficiency also results in the evolution of hydrogen gas, which can become a safety issue if ventilation or watering systems fail or are improperly designed. These safety and maintenance issues have prevented any serious use of the nickel-iron technology.

Nickel-Cadmium: This battery is presently available in production quantities. SAFT, Inc. is supplying nickel-cadmium batteries for electric vehicles in Europe. Marketed under the STM label, the design is a modified version of batteries which they have been producing for aircraft and railroad switching applications for years. Therefore, reliability of the product and production process are somewhat proven. At over 50 W-hr/kg and 90 W-hr/l, these batteries provide almost double the specific energy of conventional lead-acid [8]. Battery life of over 2000 cycles and 7 to 10 years has been demonstrated. Consequently, the long cycle life of this technology will more than compensate for its higher initial cost (estimated at around $300 W-hr/kg by Westinghouse). Availability is also good, with a rapid recharge capability that returns 50 % of the capacity in a 1 hr charge. Plots of discharge time, voltage, power, and energy are given for the STM nickel-cadmium battery in Figure 5. Judging by the data available, this technology appears to be ready for test trials, and Westinghouse has been in contact with SAFT's Valdosta, Ga. manufacturing facility regarding the availability of test prototypes.

Nickel-Metal Hydride: This battery is a relative newcomer, but is making dramatic progress as one of the USABC funded technologies. It originally had been pursued as the environmentally favored replacement for small cylindrical nickel-cadmium cells. Now full size 1.2 kW-hr modules have been built and demonstrated by Ovonic Battery Company of Troy, Michigan. Cells of the 25 A-hr size have achieved over 400 cycles with specific energies above 70 W-hr/kg, twice that of conventional lead-acid [9]. Plots of discharge time, voltage, power, and energy are given for the Ovonic nickel-metal hydride battery in Figure 6. The battery is sealed and therefore maintenance-free, so maintainability is high. Low temperature performance seems to be good, and the battery is somewhat tolerant to overcharge abuse.

Presently, issues being addressed for the EV application include: thermal management, which should be less critical for the smaller wheelchair battery; elevated internal cell pressures, a safety issue which is addressed through vent and case design; capacity loss on stand of up to 30%, which reduces the effective specific energy of the system; and materials cost, which presently make it difficult to approach the $150/kW-hr cost target. This battery is presently at least as expensive as the nickel-cadmium battery, and improvements in cycle life will be needed to bring the life-cycle cost into line with the lead-acid technology. However, this maintenance-free battery would appear to be an encouraging candidate for wheelchair demonstration. Westinghouse has contacted Ovonic for more information on this battery and its availability.

Nickel-Zinc: This battery has potentially the highest energy density and lowest cost of the nickel-based couples. Cycle life and reliability are poor, however, due to the solubility of the zinc anode in the alkaline electrolyte. This solubility causes detachment of active zinc material from current collector grids, general shape change of the electrode, and the formation of zinc dendrites which can penetrate separators and cause shorts. Because repeated efforts to solve these problems have failed, this technology is not presently being given any serious consideration for EV application, and is also an unlikely candidate for wheelchair applications.

Zinc-Bromine: This battery was originally developed for stationary applications such as power plant load-leveling. A few demonstrations in electric vehicles have been conducted, but no serious efforts to commercialize this battery are underway. Zinc solubility has detrimental effects on this battery much as with the nickel-zinc technology. Periodic regeneration of the battery is required, and the system is generally intolerant to overcharge abuse. The flow-cell arrangement of this system also adds undesired complexity to the design. Reservoirs, piping, and pumps for the circulation of electrolyte pose reliability issues, and can even be safety concerns because of the toxic nature of bromine gas. All of the complexity of this system will make it difficult to scale to small modular size, therefore, application in wheelchairs is inappropriate.

Zinc-Air: This battery is being actively tested in vans by DEMI, Inc. in the USA, and by Electric Fuel, Ltd. in Europe. Specific energies 4-5 times that of lead-acid are reported [10], and the zinc-air battery probably has the potential for the lowest cost of any of the battery technologies. However, zinc solubility problems create the same maintenance, reliability, and cycle life problems encountered with the other zinc couples. Other issues include poor energy density, poor power density, and reliability concerns surrounding the complex set of auxiliaries needed to pump electrolyte and/or scrub carbon dioxide from the air. Difficulties can be anticipated in trying to scale this system down for wheelchair use.

Lithium-Iron Disulfide: As one of the USABC funded technologies, this battery promises specific energies and specific powers over 6 times that of lead -

acid. Because the system operates at over 400ºC, it is completely sealed in a thermal enclosure, and is therefore maintenance-free. Presently the issues include: cycle life related to ruggedness of the separator system; safety related to the amount and form of the reactive lithium contained; and cost related to the manufacture of cell components. Because it may be most efficient to package an entire EV battery in a single thermal enclosure, batteries developed for EVs may not scale-down easily to modular form for wheelchair use. However, Westinghouse demonstrated a smaller 1.2 kW-hr version of this battery which should fit into the wheelchair chassis. At over 50 W-hr/kg, this battery should provide a weight and volume savings compared to conventional lead-acid. Plots of discharge time, voltage, power, and energy are given for the Westinghouse lithium iron disulfide module in Figure 7. Production of this battery is scheduled for 1995, and prototype units can be available for testing at that time.

Sodium-Sulfur, Sodium-Nickel Chloride: These are sister technologies. Both have been demonstrated to provide 4-5 times the specific energy and power of conventional lead-acid. Reliability and ruggedness of the solid beta-alumina electrolyte are issues, however, and safety has been an issue as cell sizes are scaled up. The sodium-sulfur system also faces a special safety problem associated with the possibility of generating poisonous hydrogen sulfide gas if the battery is ruptured for any reason. Both systems operate at over 300ºC and, therefore, require thermal enclosures which, as mentioned for the lithium disulfide system, present scale-down problems. Because there are no known efforts to produce modular sodium-sulfur or sodium nickel chloride batteries, this system was given no further consideration.

Lithium-Ion: Of all of the room-temperature, rechargeable lithium technologies, the lithium-ion technology has been receiving the most attention in recent months. Unlike the other lithium technologies, this battery employs an "intercalation" anode where active lithium ions are intercalated within a carbon structure. Because the lithium does not exist as metallic lithium, this battery is much safer than the others, and has become the lithium technology of choice. Ultimately, specific energies 6-8 times that of lead-acid are expected. Rayovac and SAFT report the demonstration of small cylindrical cells with specific energies over 100 W-hr/kg and specific powers over 120 W/kg. These cells are sealed and maintenance-free, and the inherent low cost of their materials makes them the most attractive of all the battery technologies. Presently, the main issues are scale-up of the technology to the 30 to 40 A-hr range, and extension of the life which has already been demonstrated to over 400 cycles in D-cells. If successful, this battery could replace all others. Westinghouse is staying abreast of developments and will attempt to incorporate this technology as scaled-up cells become available.

SUMMARY AND CONCLUSIONS

As in the past, improvements in wheelchair battery design and performance will be spin-offs from development programs which target larger markets. The emerging electric vehicle market is presently fueling substantial development efforts which will directly benefit the wheelchair community. Several improved technologies may be available as early as 1995 for field trials, including the Horizon advanced lead-acid battery, the SAFT STM nickel-cadmium battery, the Ovonic nickel-metal hydride battery, and the Westinghouse lithium-iron disulfide battery. If successful, these technologies could provide weight and volume savings of over 50% compared to conventional lead-acid. Reliability, cycle life, and safety are yet to be determined under actual operating conditions. Westinghouse has contacted all of the developers to get access to prototypes for testing when production is started.

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11. Linden, D., op. cit., Figure 14.29.

Figure 1. Comparison of Specific Energy and Specific Power for Various Power Source Technologies

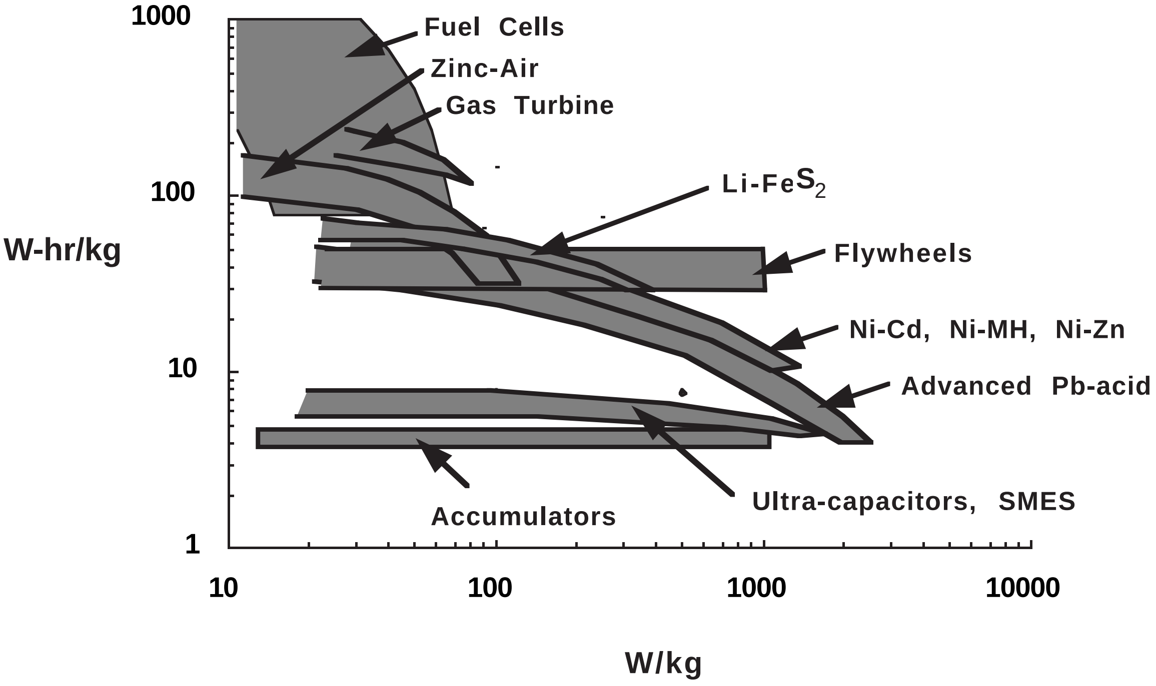
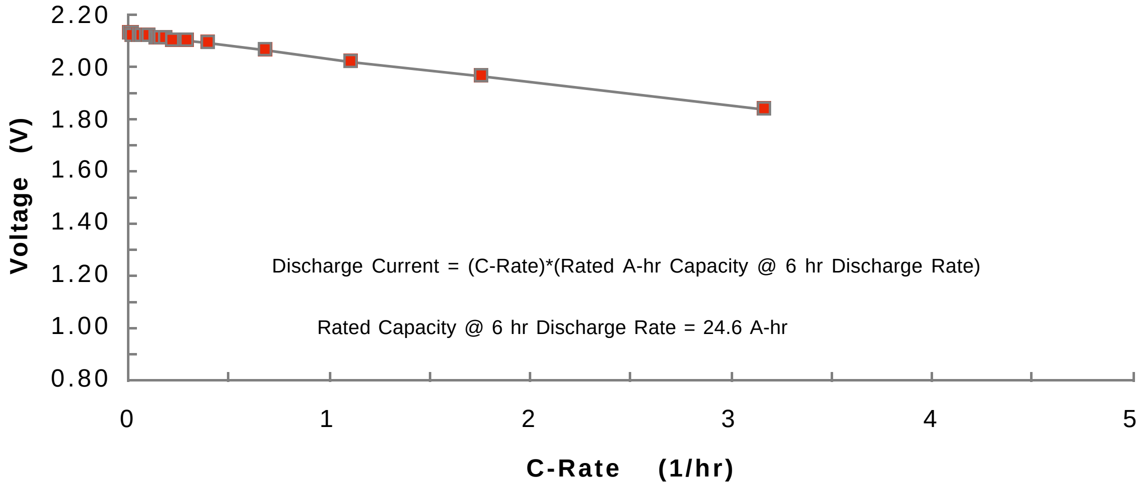


Figure 2. Generalized Performance Characteristics for the Lead-Acid Gel Cell (Based upon the Johnson Controls 12 V, 25 A-hr U1-31 Module)

Figure 2a. Voltage Characteristics for the Lead-Acid Gel-Cell

(Voltage at 50 % Depth of Discharge)

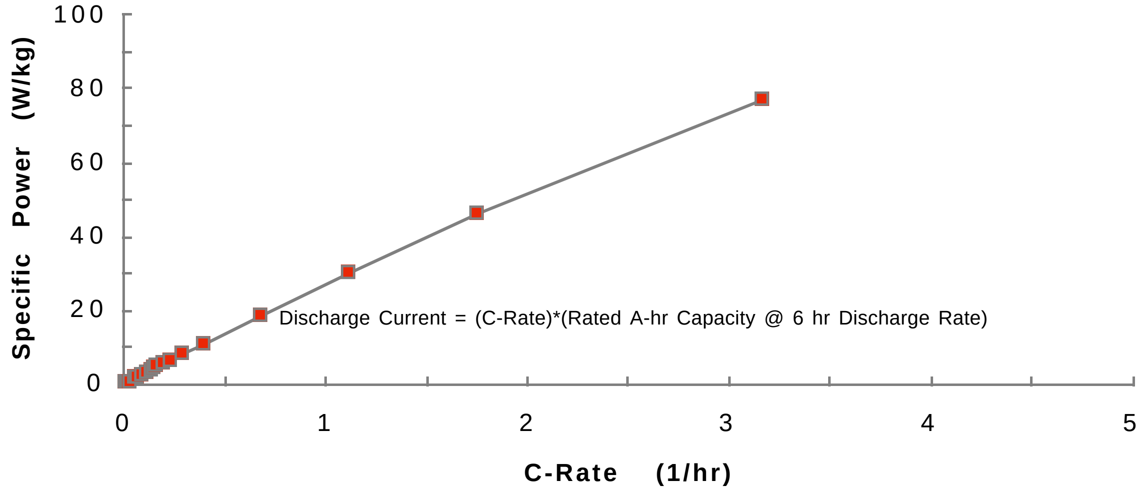


Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Rated Capacity @ 6 hr Discharge Rate = 24.6 A-hr

Figure 2b. Specific Power vs Discharge Rate for the Lead-Acid Gel-Cell

(Power at 50 % Depth of Discharge)



Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Figure 2c. Discharge Duration vs Discharge Rate for the Lead-Acid Gel-Cell

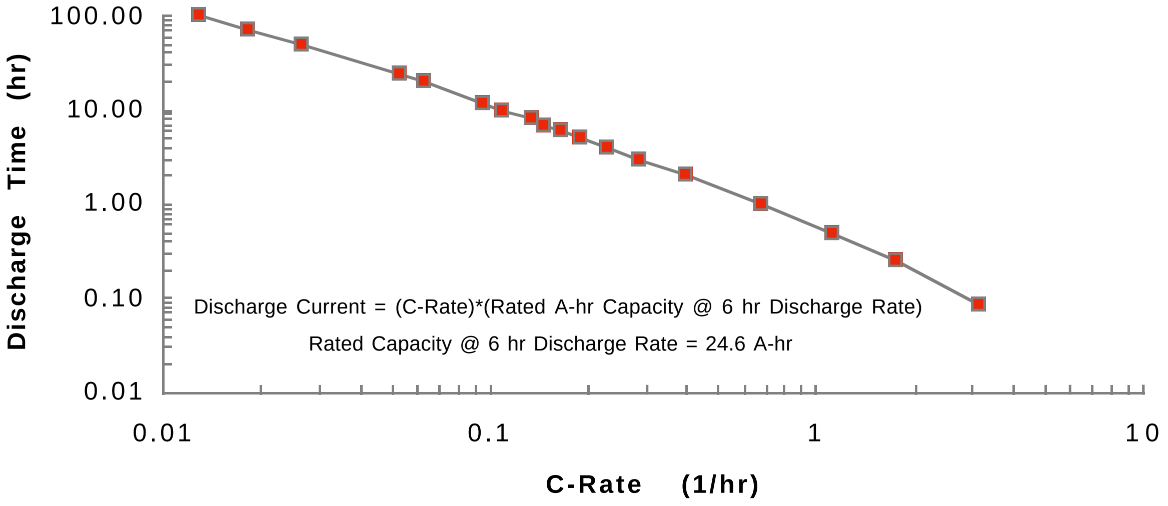


Figure 2d. Specific Energy vs Discharge Rate for the Lead-Acid Gel-Cell

(Energy is Discharge Time* Current* Voltage at 50% DoD)

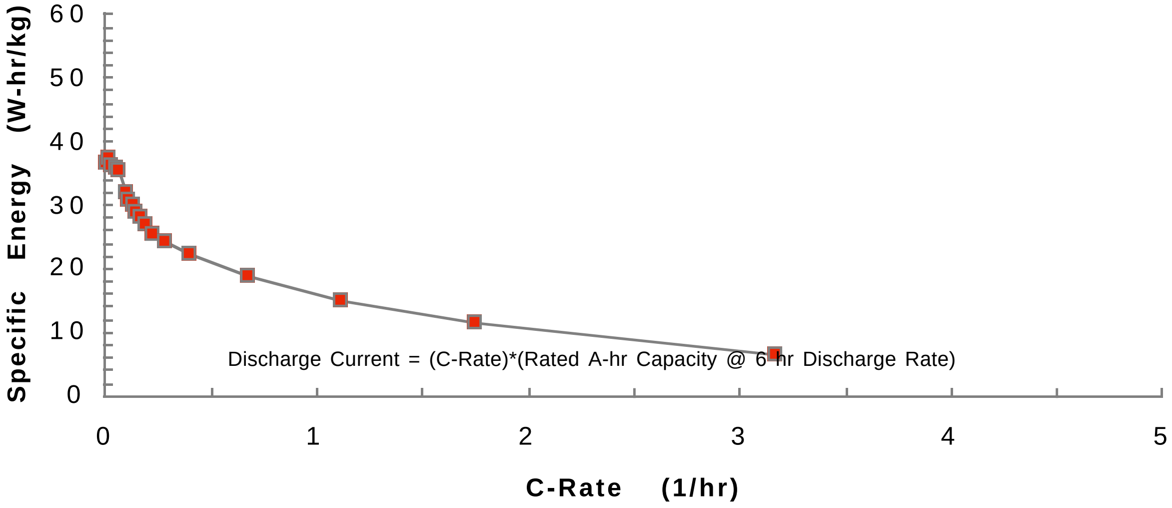
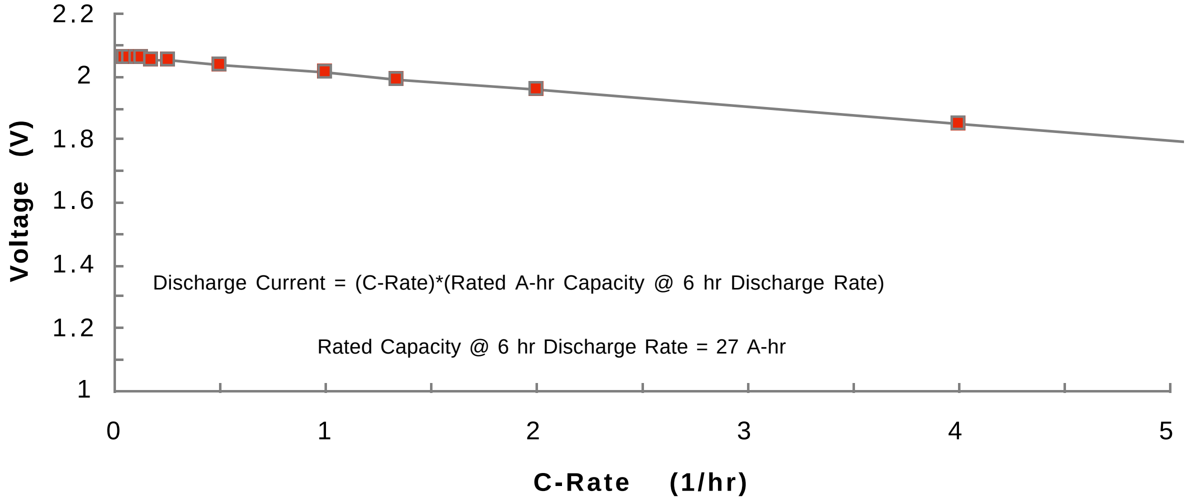


Figure 3. Generalized Performance Characteristics for the Flooded Lead-Acid Deep Cycle Battery
(Based upon the Johnson Controls 12V, 27 A-hr 9601 Model)

Figure 3a. Voltage Characteristics for the Lead-Acid Deep Cycle Cell

(Voltage at 50 % Depth of Discharge estimated from Linden [11])

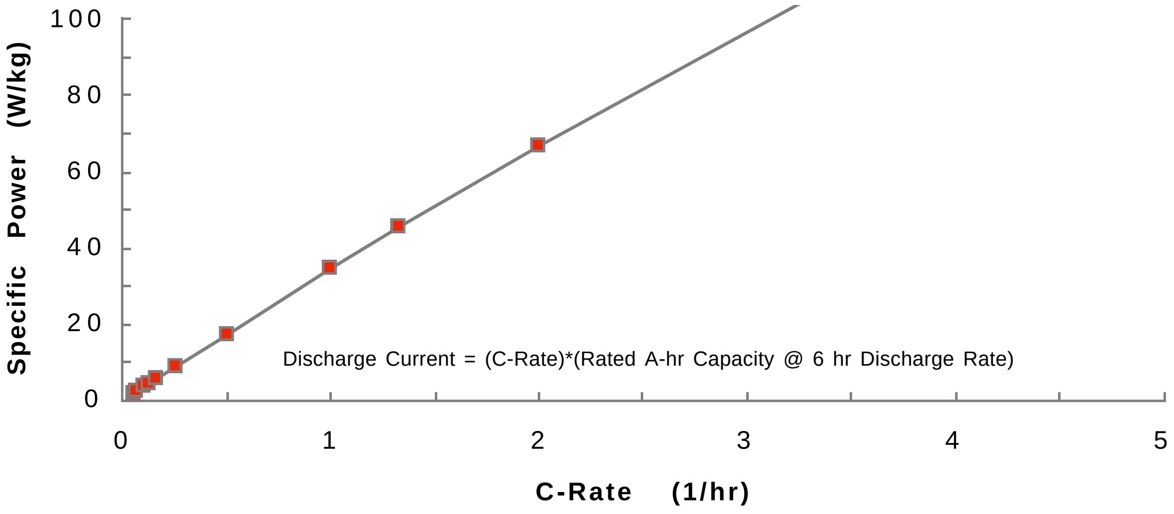


Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Rated Capacity @ 6 hr Discharge Rate = 27 A-hr

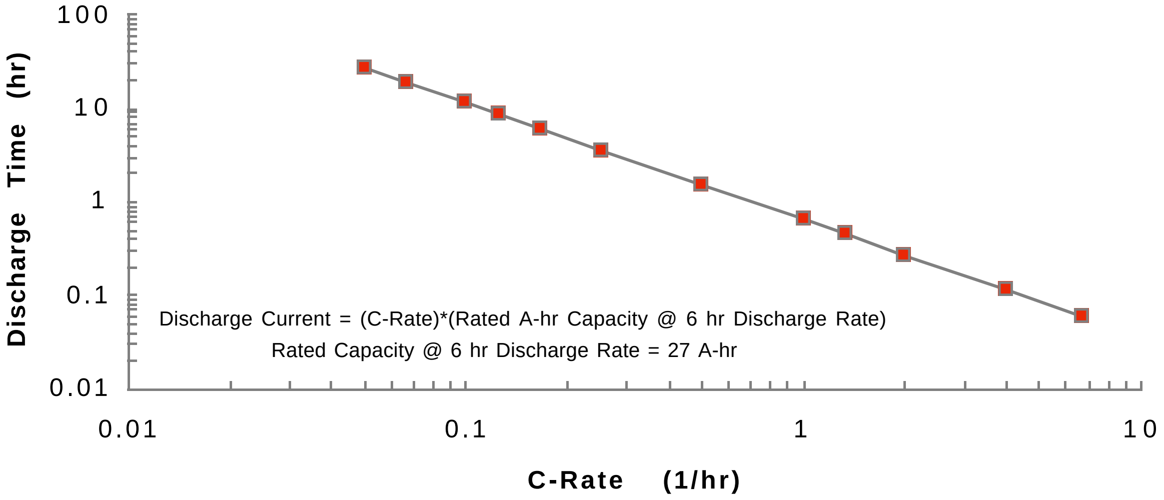
Figure 3b. Specific Power vs Discharge Rate for the Lead-Acid Deep Cycle Cell

(Power at 50 % Depth of Discharge)



Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Figure 3c. Discharge Duration vs Discharge Rate for the Lead-Acid Deep Cycle Cell

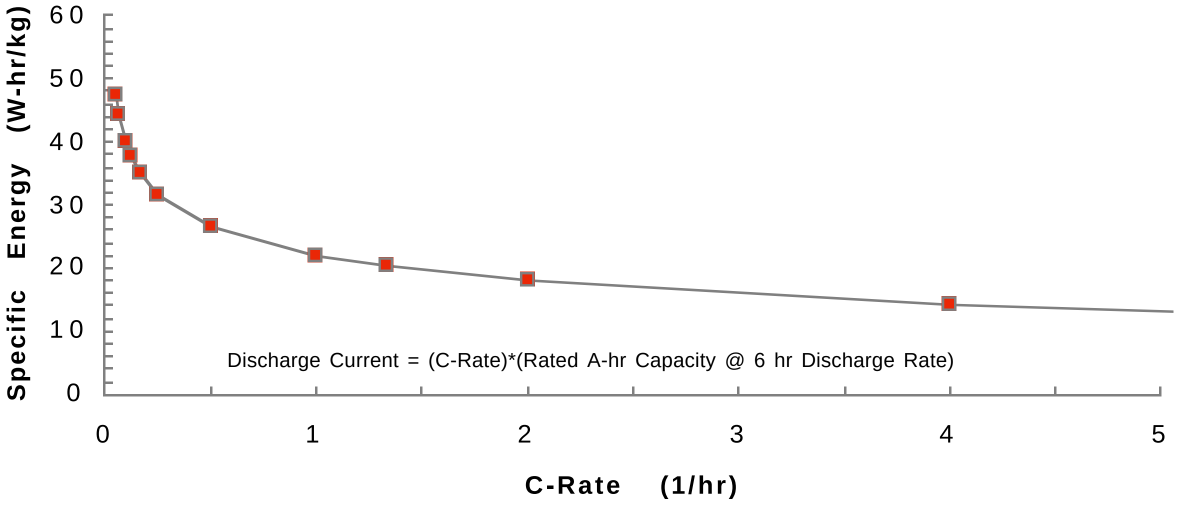


Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Rated Capacity @ 6 hr Discharge Rate = 27 A-hr

Figure 3d. Specific Energy vs Discharge Rate for the Lead-Acid Deep Cycle Cell

(Energy is Discharge Time* Current* Voltage at 50% DoD)



Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Figure 4. Generalized Perofrmance Characteristics for the Electrosource Lead-Acid Battery (Based on the Horizon 12V, 20 A-hr Module)

Figure 4a. Voltage Characteristics for the Horizon Lead-Acid Cell

(Voltage at 50 % Depth of Discharge)

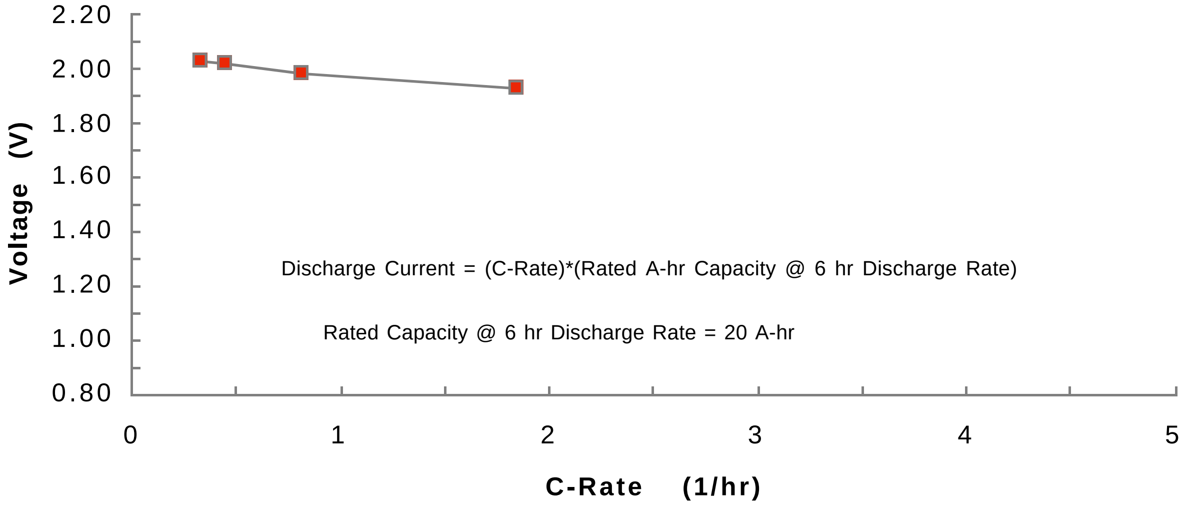


Figure 4b. Specific Power vs Discharge Rate for the Horizon Lead-Acid Cell

(Power at 50 % Depth of Discharge)

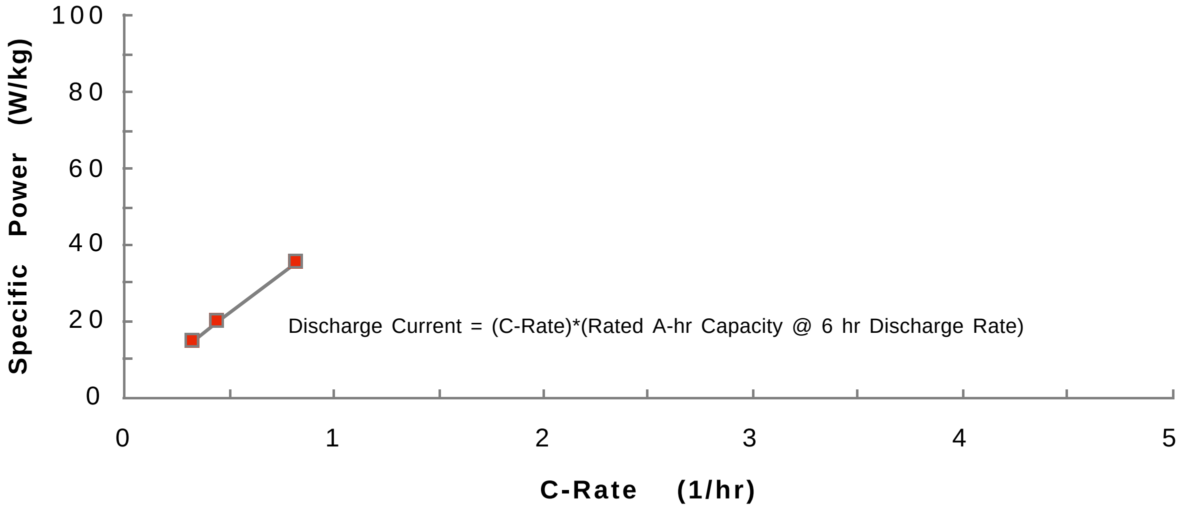
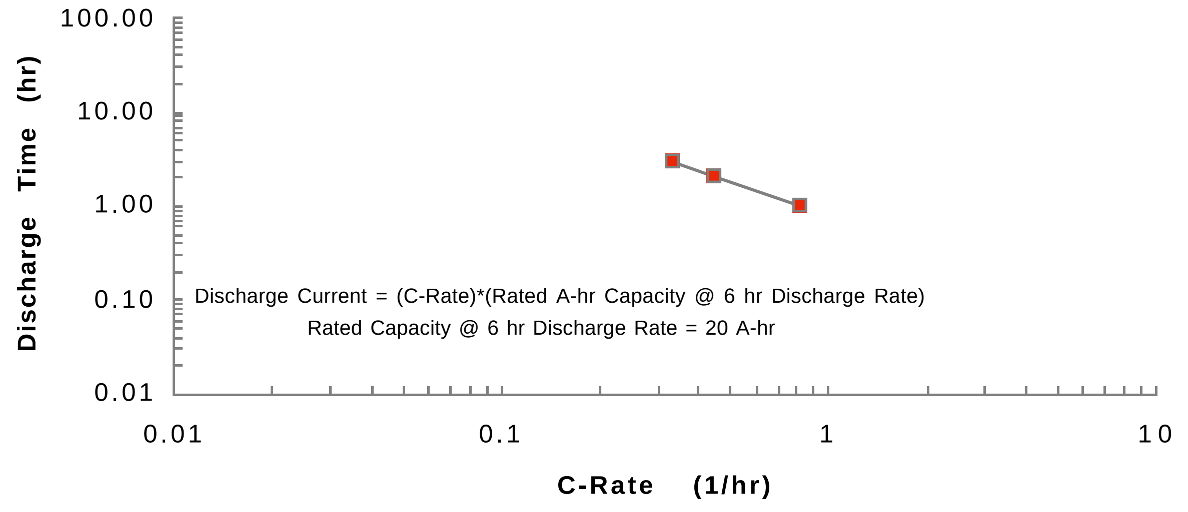


Figure 4c. Discharge Duration vs Discharge Rate for the Horizon Lead-Acid Cell

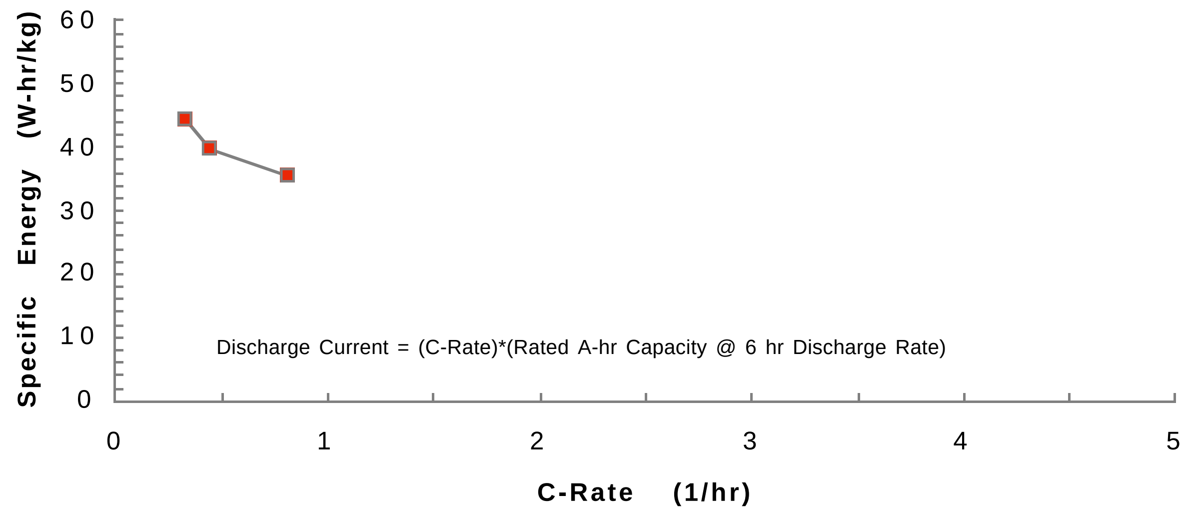


Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Rated Capacity @ 6 hr Discharge Rate = 20 A-hr

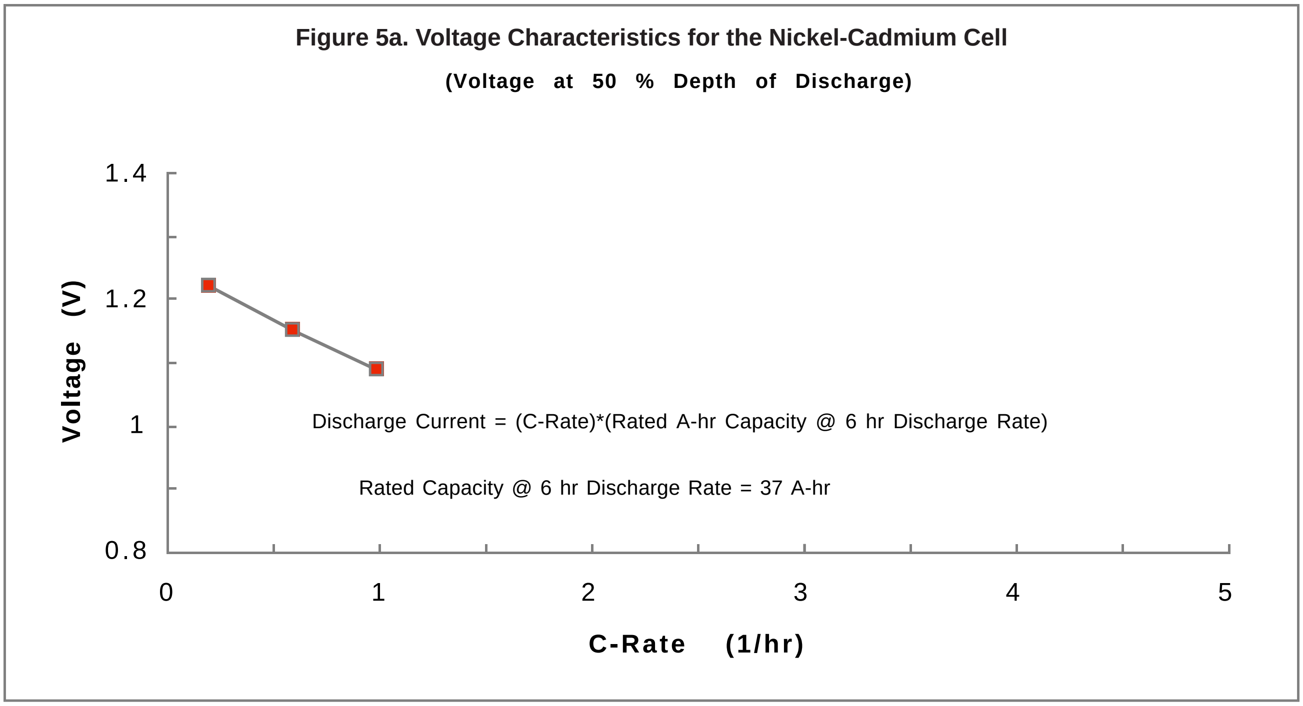
Figure 4d. Specific Energy vs Discharge Rate for the Horizon Lead-Acid Cell

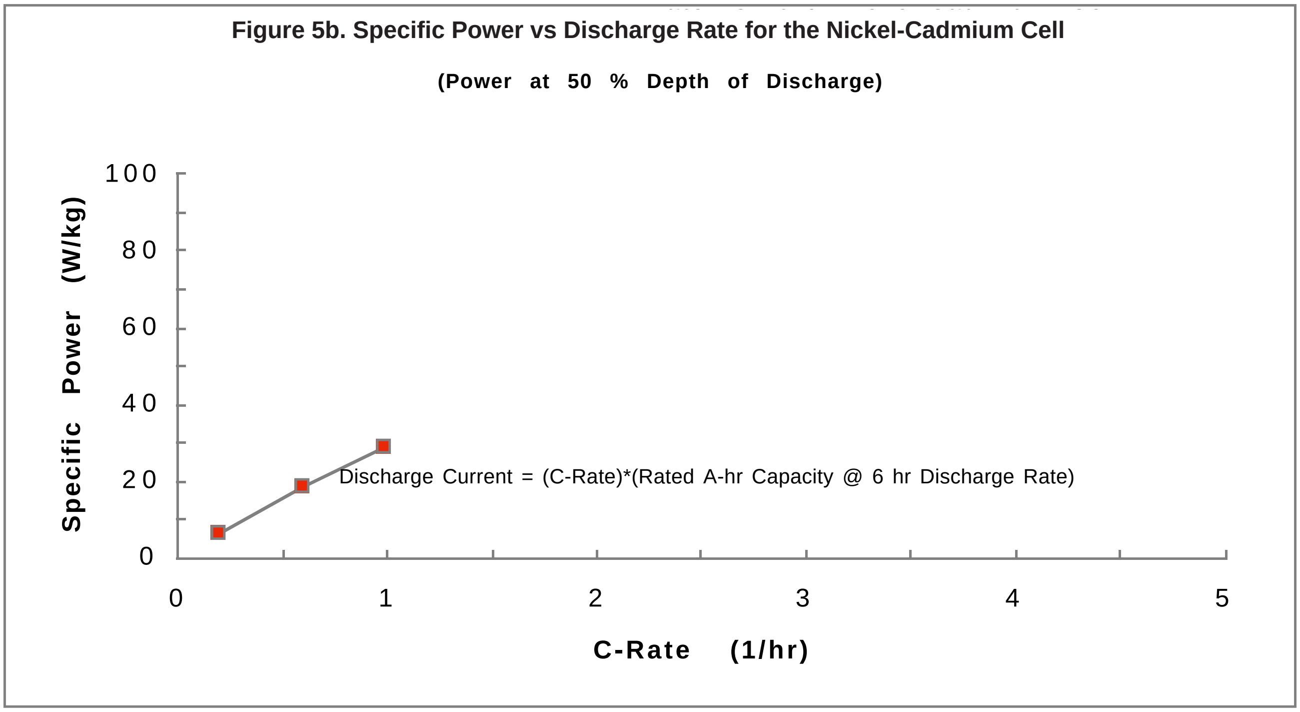
(Energy is Discharge Time* Current* Voltage at 50% DoD)



Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Figure 5. Generalized performance Characteristics for the Nickel-Cadmium Battery (Based upon the SAFT 1.2V, 37 A-hr STM 1.40B Cell)





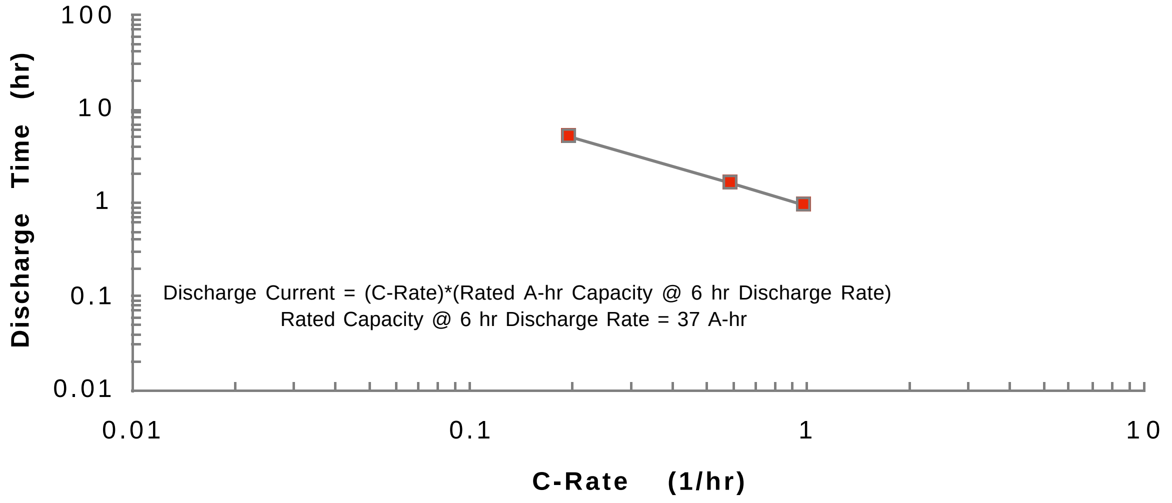


Figure 5c. Discharge Duration vs Discharge Rate for the Nicklel-Cadmium Cell

Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)
Rated Capacity @ 6 hr Discharge Rate = 37 A-hr

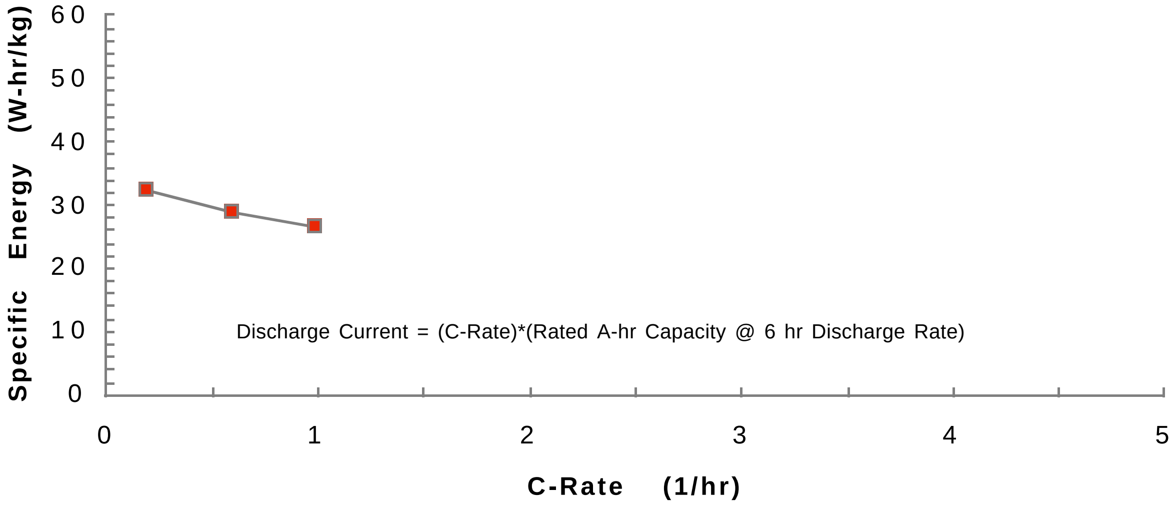


Figure 5d. Specific Energy vs Discharge Rate for the Nickel-Cadmium Cell

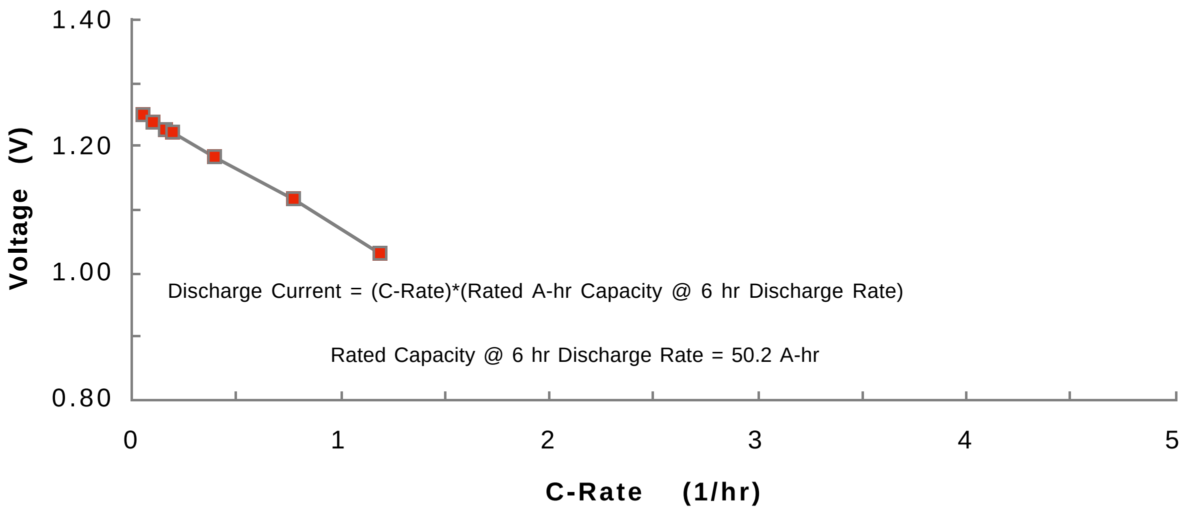
(Energy is Discharge Time* Current* Voltage at 50% DoD)

Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Figure 6. Generalized Performance Characteristics for the Nickel-Matel Hydride Battery (Based uopn the Ovonic 1.2V, 250 A-hr Cell)

Figure 6a. Voltage Characteristics for the Nickel-Metal Hydride Cell

(Voltage at 50 % Depth of Discharge)

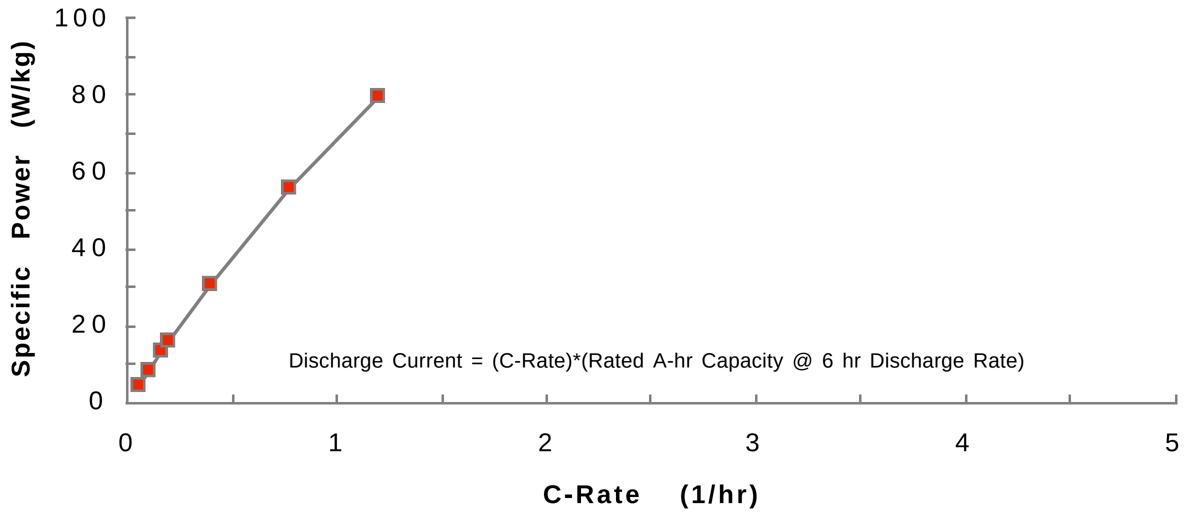


Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Rated Capacity @ 6 hr Discharge Rate = 50.2 A-hr

Figure 6b. Specific Power vs Discharge Rate for the Nickel-Metal Hydride Cell

(Power at 50 % Depth of Discharge)



Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Figure 6c. Discharge Duration vs Discharge Rate for the Nickel-Metal Hydride Cell

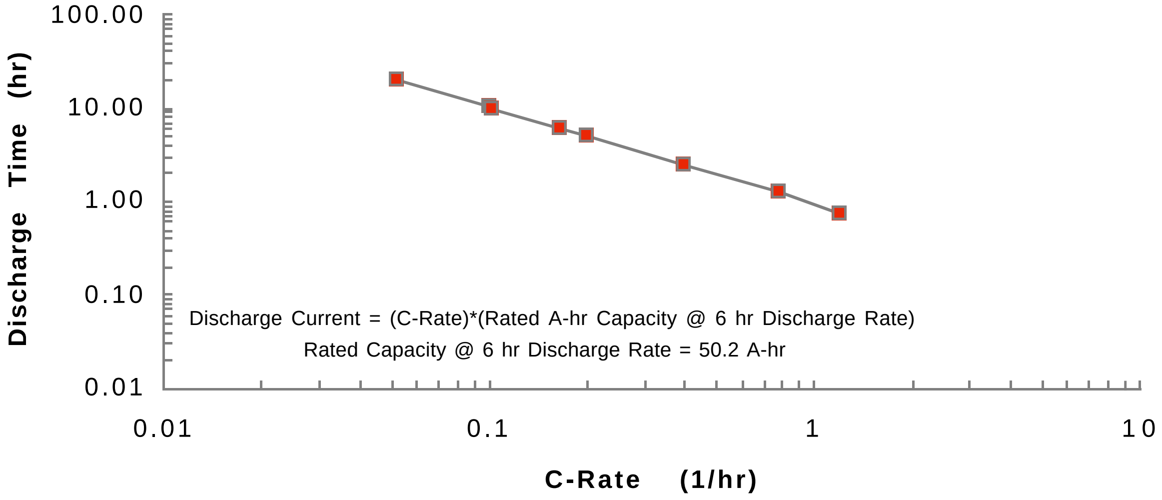
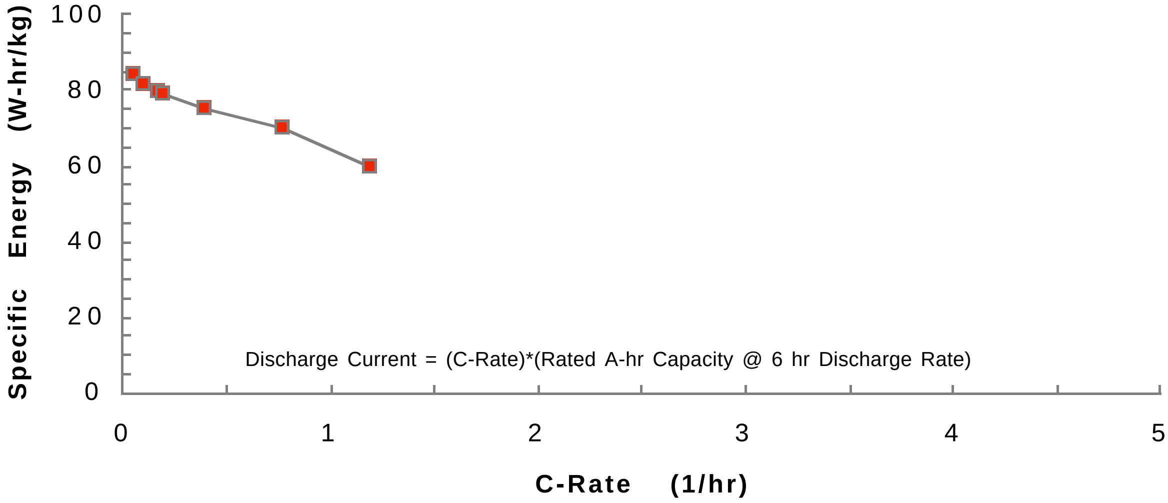
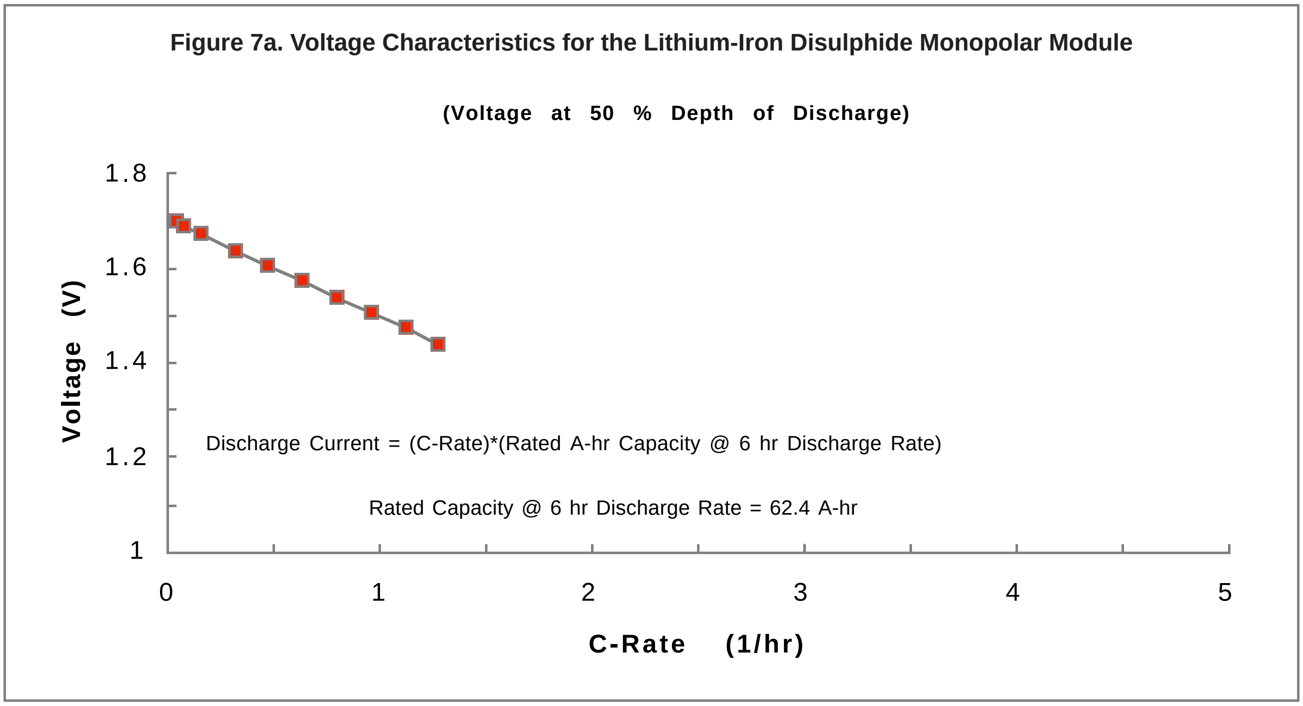


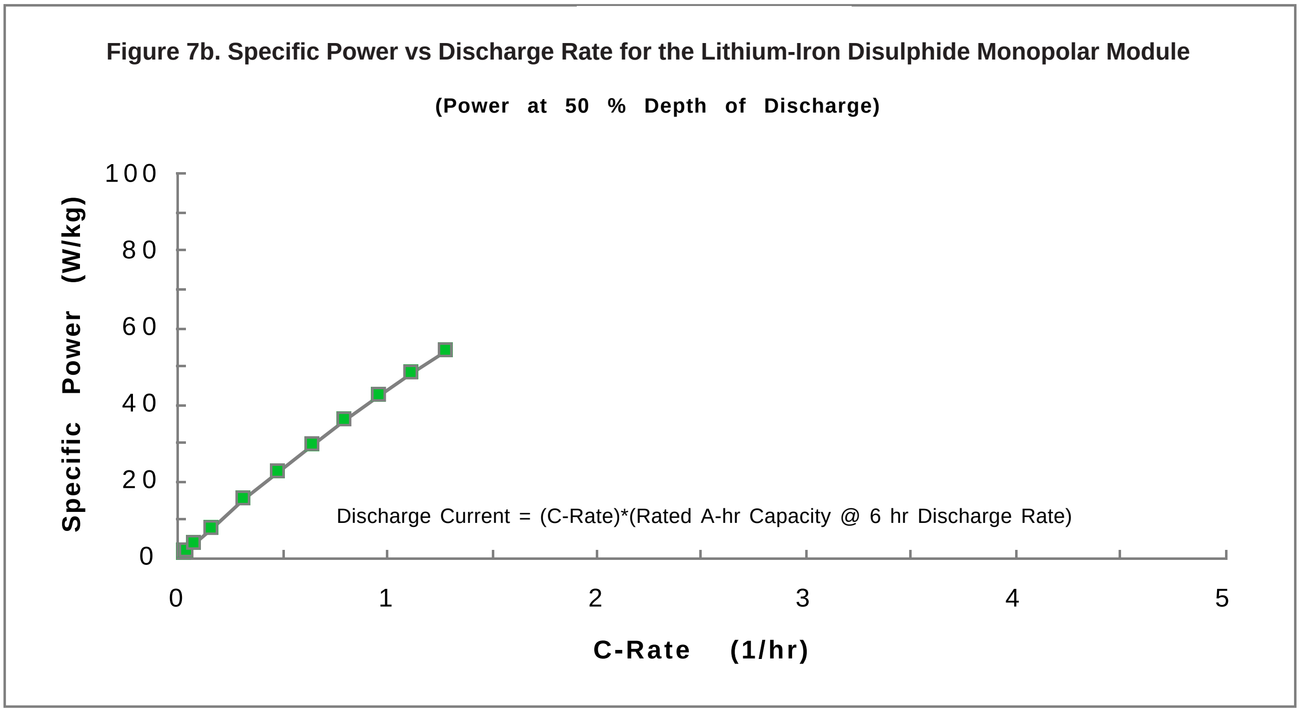
Figure 6d. Specific Energy vs Discharge Rate for the Nickel-Metal Hydride Cell

(Energy is Discharge Time* Current* Voltage at 50% DoD)

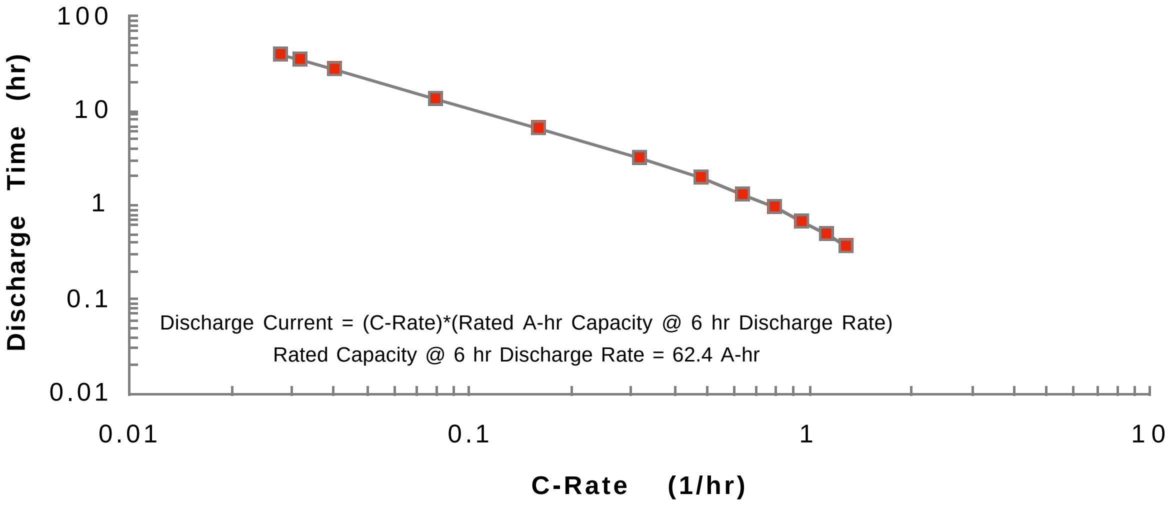


F 7. Generalized Performance Characteristics for the Lithium-Iron Disulphide Battery (Based uopn the Westinghouse 12V, 63 A-hr Monopolar Module)





Fgure 7c. Discharge Duration vs Discharge Rate for Lithium-Iron Disulphide Monopolar Module

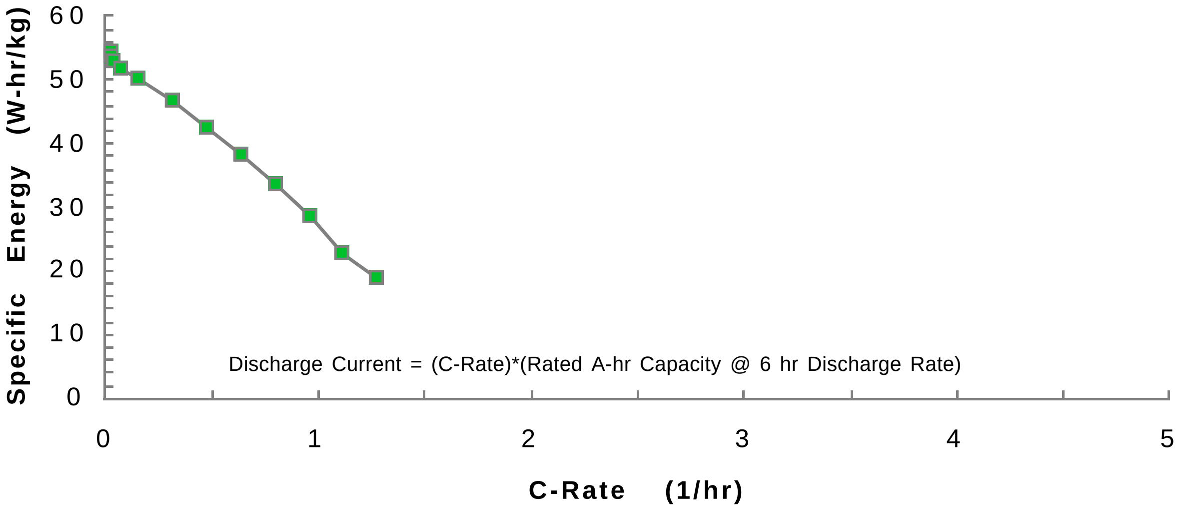


Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)

Rated Capacity @ 6 hr Discharge Rate = 62.4 A-hr

Figure 7d. Specific Energy vs Discharge Rate for Lithium-Iron Disulphide Monopolar Module

(Energy is Discharge Time* Current* Voltage at 50% DoD)



Discharge Current = (C-Rate)*(Rated A-hr Capacity @ 6 hr Discharge Rate)