Assessment of Advanced Batteries for Energy Storage Applications in Deregulated Electric Utilities

TR-111162

Final Report, November 1998

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This report was prepared by

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Assessment of Advanced Batteries for Energy Storage Applications in Deregulated Electric Utilities, EPRI, Palo Alto, CA: 1998, TR-111162.

REPORT SUMMARY

Energy storage technologies, including advanced batteries, are likely to find new roles in a restructured electric utility environment. This study evaluated the near-term potential of fourteen advanced battery technologies to outperform conventional lead-acid batteries in four key energy storage applications.

Background

EPRI has organized three Think Tanks over the last few years on the potential roles for energy storage in a restructured electric utility environment (EPRI report TR-108894, Volumes 1 and 2). Advanced batteries were among the energy storage technologies that showed promise in a wide range of energy storage roles. These include applications in generation, transmission, and at customer sites. Advanced batteries have potential applications for energy storage systems with power capabilities from a few 100s of kW to 200 MW or more with storage discharge times from a few seconds to 2 to 8 hours. However, a more intensive evaluation of advanced batteries was required before EPRI could confidently propose any extensive development projects to its members. This study was commissioned to help provide the background for EPRI and EPRI-member decision-making on future advanced battery development for utility energy storage.

Objective

To evaluate advanced battery technologies in relation to four model energy storage applications for restructured electric utilities.

Approach

The project team reviewed the literature to determine which of the many battery technologies under development would be available within a five year time-frame for application to utility energy storage applications. Using data from discussions with developers, the team compared the expected capabilities of the selected advanced batteries against the requirements of four specific applications and against a baseline of conventional lead-acid designs. The focus of these detailed assessments was the expected economics of the various advanced batteries, including relative estimates of such cost elements as required converter/power conditioning systems and maintenance and repair.

Results

The report examines the near-term potential of advanced battery technologies for four model energy storage applications: transmission line stabilization, arc furnace area control error regulation, power quality enhancement and peak shaving, and distributed generation. Some advanced battery technologies that are being commercialized or are approaching commercialization for other applications appear to be economically superior to lead-acid batteries in three of these roles on a cost-over-life basis and are expected to have better characteristics such as lighter weight or better cyclability than lead-acid baseline systems. The report provides significant details on the strengths and weaknesses of all the battery technologies reviewed with respect to their potential in the model applications. Other advanced battery technologies are expected to be somewhat more economically attractive than lead-acid batteries or show promise in the future, meaning that there is evidence for their technical superiority but that further information is needed before a determination can be made of their real potential. The economic attractiveness of batteries for the four model applications and the markets for batteries in these applications were not quantified.

EPRI Perspective

This study was one of several commissioned to suggest technical R&D topics and priorities for energy-storage technologies appropriate to the restructured electric utility industry. Technologies addressed in other studies included advanced capacitors, flywheels, and high-temperature superconductors (HTS) for SMES.

Certain advanced battery technologies that are commercialized already or within five years of commercialization appear to be superior to conventional lead-acid batteries for the applications considered in this study. Some of the advanced battery technologies evaluated in this report also have potential advantages in other energy storage applications such as providing backup power at utility substations. While reliable information on advanced batteries is difficult to acquire and the error bands on cost-over-life estimates are broad, it should be noted that the battery technologies that were determined to be economically attractive in this study were better than the lead-acid baseline by a considerable amount. EPRI may consider jointly-funded projects to develop the most promising advanced battery technologies for restructured utility applications.

TR-111162

Interest Categories	Keywords
Power quality	Energy storage
Strategic innovations	Batteries
Energy storage	
Batteries	

ABSTRACT

Fourteen advanced battery technologies, including advanced lead-acid batteries, batteries with nickel oxide positives, flow batteries, high temperature batteries, and ambient temperature lithium batteries, have been critically evaluated. Of these, ten technologies were found to be sufficiently promising to warrant a more detailed assessment. This assessment was performed in relation to four model energy storage applications for restructured electric utilities, by making comparisons with baseline lead-acid batteries that could be usable in the four applications. The economic attractiveness of batteries for the four model applications and the potential markets for batteries in these applications were not quantified.

In the assessment, three battery technologies were found to be more economically attractive on a cost over life basis, and are expected to have better characteristics, such as lighter weight or better cyclability, than the lead-acid baseline systems. A further four technologies are expected to be somewhat more economically attractive, or economically equivalent and better performing than the lead-acid baseline. Four technologies were found to be potential candidates in the future, meaning there is evidence of economic attractiveness and technical superiority, but that further information is needed before a determination can be made as to just how attractive they might be.. A recommendation is made that the possibility of jointly-funded projects to develop the most-promising advanced batteries for restructured utility applications be explored.

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SUMMARY

The objective of the work described in this report was to evaluate and assess advanced battery technologies for energy storage by restructured utilities. Additional objectives were to determine which, if any, of the battery developers should be considered for EPRI **co**-funding to further develop their technologies for utility applications, and which, under the right conditions, might be willing to co-fund such an effort with EPRI.

Advanced batteries were evaluated and assessed in several phases. In the planning and scoping stages, a determination was made as to which battery chemistries, and which battery technologies based on those chemistries, would be evaluated and assessed. The list of the fourteen battery chemistries and technologies included in the study is as follows:

- Advanced valve regulated lead acid (VRLA) batteries:
  - Delphi EV battery with conventional design
  - Electrosource quasi-bipolar battery
  - Optima spiral-wound starter battery
  - Bolder spiral wound sub-C cells

- Nickel-metal oxide batteries:
  - Saft Nickel/cadmium batteries
  - Ergenics Nickel/hydrogen battery with hydride storage
  - Ovonic Nickel/Metal hydride battery
  - Saft Nickel/Metal hydride battery

- Flow batteries:
  - Powercell Zinc Bromide battery
  - Pinnacle Vanadium Redox battery

- High temperature batteries:
  - Sodium/sulfur battery
  - Sodium/nickel chloride (Zebra) battery

- Ambient temperature lithium batteries:
  - Saft Lithium/ion battery
  - Hydro Quebec (with 3M) Li/polymer battery

This list includes technologies that are examples of all the types of battery chemistries that have from time-to-time been considered for utility energy storage applications.

The next step of the study involved delineating four sample energy storage applications which could be of importance to restructured utilities against which advanced battery technologies would be assessed. In delineating the applications, they were first identified, and the requirements for each application were detailed. The final step in this stage of the study was to prepare outlines for a design, and to estimate battery costs, of energy storage systems for these four applications based on available lead-acid batteries. The results of this stage of the work are shown in Table S-1.

Table S-1
Restructured Utility Applications and Baseline Designs for Advanced Battery Assessment

	Transmission Line Stabilization	**Arc Furnace Area Control Error Regulation**	**Power Quality Enhancement + Peak Shaving**	**Distributed Generation**
REQUIREMENTS				
Power	300 MW	80 MW	10 MW, 5 MW	5 MW
Discharge Energy	167 kWh	5 MWh	N/A, 10 MWh	40 MWh
Discharge Time	1 to 10 sec	10 minutes	10 seconds, 2 hours	8 hours
Frequency of Use	1/month	2/hour	1/month, 150/year	100/year
BASELINE DESIGN				
Cycle type	Partial DOD when standing by	Discharge to shallow depth, then recharge	Discharge then full recharge	Discharge then full recharge
Lead-acid type	Maintenance-free truck starting	Flooded enhanced-life UPS	Deep cycle valve regulated (VRLA)	Flooded lift truck
Module voltage	12 V	2 V	2 V	2 V
Number of modules	57600	40000	3000	16000
Expected life	60 cycles 5 years	50k cycles 3 years	1000 cycles 7 years	2000 cycles 8 years
Cost for cells or modules	$25/kW	$24 million total	$200/kWh	$120/kWh
Cost/life	$5/kW per year	$8 million per year	$29/kWh per year	$15/kWh per year

The next stage of the study, which was actually performed in parallel with the previous stage, consisted of the following steps:

1. Data and information on the various advanced battery technologies and on the projects in place to develop them were acquired by reviews of the literature, from discussions with other experts in the field, and by making queries to the battery manufacturers/developers listed above;

2. An evaluation of the literature data and information was made;

3. If the evaluation step indicated that there was some promise that the technology might be applicable to one or more of the four applications summarized in Table S-1, then a detailed assessment of the technology, including analyses of responses received from developers to the pro-forma queries that were made of them, was performed.

During the evaluation and assessment, descriptions of each technology and of the projects to develop them were prepared, and a critical evaluation of each was performed. The critical evaluation included identification of the strengths and weaknesses of each technology and of it's developer. In the assessment step, an outline of a design for the advanced battery technology being assessed was prepared for those applications for which it appeared most suited, and this was compared with the baseline outline design. The advantages and advantages of each advanced battery technology relative to the baseline were also delineated as part of the assessment.

Using the evaluations and the assessments as a basis, recommendations for future actions by EPRI were developed. An important issue in delineating recommendations was the determination as to which of the developers, under the right conditions, might be interested in co-funding work with EPRI on utility battery energy storage. A second issue that was addressed before delineating a recommendation was the determination of the prospects of there being hardware for a sub-scale (multi-kWh) demonstration of the technology for a utility application in 5 years or less.

The overall results of the evaluation and assessment are shown in Table S-2. Of the fourteen battery technologies that were evaluated, ten were sufficiently promising to warrant a more detailed assessment. Of these, an examination of the table shows, there were three battery technologies that were found to be much superior, meaning the technology would be significantly more economically attractive on a cost over life basis, and would have better characteristics, such as lighter weight or better cyclability, than the lead-acid baseline. A further four technologies were found superior, i.e., they would either be more economically attractive, or economically equivalent and better performing than the lead-acid baseline. Four technologies were found to be potential candidates in the future, meaning there is evidence of economic attractiveness and technical superiority, but that further information is needed before a determination can be made as to just how attractive they might be.

Table S-2

Comparison of Advanced Battery Technologies to Baseline Lead Acid Batteries for Energy Storage Applications in Restructured Electric Utilities

	Transmission Line Stabilization	**Arc Furnace ACE Regul'n**	**PQ Enhancement + Peak Shaving**	**Distributed Generation**
Brief Description	300MW cyclic 1/month when transmission close to limits	80MW 5MWh/10 min. 2/hour round the clock	PQ 10MW, 10 sec. round the clock Peak Shave 5MW, 10MWh, 150/yr	5MW, 40 MWh 100/year When favorable economics
Advanced Batteries				
Much superior		Ergenics NiH (1)	Powercell ZnBr	Vanadium redox
Superior (2)		Delphi VRLA (3) Saft NiCad	Zebra (Na/NiCl$_2$) Lithium ion	
Possibly better (4)	Electrosource VRLA Optima spiral-wound		Lithium polymer	Sodium/sulfur (5)
Baseline				
Lead-acid type	Maintenance free truck SLI	Flooded enhanced-life UPS	Deep cycle VRLA	Flooded lift truck
Cost/Life	$5/kW per year	$8 million per year	$29/kWh per year	$15/kWh per year

(1) Developer resource limited; unable to co-fund development for utility applications

(2) Recommend holding discussions with developer about possible co-funded project

(3) Delphi has sold technology to East Penn, discussions should be deferred.

(3) Recommend reviewing again in a year or so.

(5) TEPCO and NGK Insulators have 6MW/40MWh battery operating. Unable to assess adequately. EPRI might try to follow up with CRIEPI to get more information

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No attempt was made in this study to quantify economic attractiveness of batteries in an absolute sense for the four model applications, or to quantify the potential markets for batteries in these applications. Rather, estimates of the OEM prices for cells or modules of advanced batteries were made, and the impact of the battery technology on the costs of the balance-of-battery-plant and on the costs of the power conversion unit were semi-quantitatively evaluated. Estimates for the life that could be expected for each of the advanced batteries were also obtained, as were characteristics that could lead to higher operating costs. On the basis of all these steps, as Table S-1 shows, it is recommended that EPRI consider holding discussions with seven advanced battery developers to investigate the possibility of a joint development project on utility applications. A further recommendation is that only one or two projects for which there is the greatest corporate commitment to developing products for restructured electric utilities applications be funded, assuming of course that funds are available to do so.

It became clear during the study that none of the advanced battery technologies assessed were really suitable for the transmission line stabilization application. Although not part of the study, it also became apparent that none of the batteries in the study offered any great advantage for the largest use of batteries by electric utilities, which is for standby power at distribution and transmission sub-stations and at generating plants. These are therefore issues that require further study. It is also recommended, since continued great advances are expected to be made on batteries because of market forces resulting from the growth of portable electronics and hybrid electric vehicles, that advanced battery technologies for restructured utility applications be assessed on an ongoing basis in the coming years.

As far as the applications that have been addressed in the current study are concerned, however, it is clear that there are a number of advanced-battery technologies that are being commercialized or approaching commercialization for other applications that appear could be economically much superior to the lead-acid baselines. There are other advanced battery technologies that are further away from commercialization and for which there is less information available, which we think could be economically competitive for utility applications in the longer term. Moreover, most of these advanced battery technologies would require a lot less space than the baseline designs of lead-acid batteries for these utility applications. These advanced battery technologies are sufficiently attractive to warrant direct discussions between EPRI and developer personnel with a goal of establishing co-funded development projects to expedite the availability of these lower cost energy storage options for restructured electric utilities.

1

INTRODUCTION

1.1 Background to Assessment

For several years, EPRI and some of it's utility members have been considering the potential roles for energy storage in a restructured electric utility environment. Towards this end, the Exploratory Research and Power Delivery Divisions of EPRI organized three "Think Tanks" on this topic during 1996 and 1997. (1, 2) At these Think Tanks utility and EPRI personnel, together with various experts in deregulation and in energy storage, conceptualized the emerging roles and applications for energy storage technologies. The research and development needs for the various storage technologies were also discussed at the Think Tanks. It became increasingly clear in the course of these Think Tanks that the applications for which energy storage might find greatly expanded use in the deregulated environment could possibly be served by a number of advanced storage technologies, providing such are developed with technically- and economically-competitive characteristics.

Advanced batteries were among the energy storage technologies that it appeared might find such expanded use. Advanced batteries have been under intensive development for defense, aerospace, electric vehicle, utility energy storage, portable electronic, and for existing applications (such as starting automobiles) for more than twenty years. During this period, a broad spectrum of chemistries have been considered for advanced batteries, and some of these chemistries have been developed into battery technologies. The amount of information and data on these battery technologies that could be brought before the Think Tank participants was relatively small, however, and as a result, the conclusions that could be reached were only tentative. It was clear that a more intensive evaluation of potentially applicable energy storage technologies, particularly advanced batteries, would be required before EPRI could confidently propose any extensive development projects to it's members. In this report, the results of such an intensive evaluation of advanced batteries that was performed during late 1997 and early 1998 by Electrochemical Engineering Consultants, Inc. are described and discussed. This report should help provide the background for EPRI and EPRI-member decision-making on future advanced battery development for utility energy storage.

There are a number of applications for which energy storage systems with advanced batteries might be useful in the restructured (i.e., deregulated/reregulated) utility environment. These include applications in generation, e.g., load-following using distributed resources; in transmission, e.g., line stabilization; in distribution, e.g., to allow deferral of asset acquisition; and at customers' sites, e.g., to enhance power quality and reliability. This range of applications that are potentially of interest for advanced batteries require energy storage systems with power capabilities from a few 100s of kW, for some customer applications; to 10 or 20 MW, for distributed applications; to perhaps 200 MW or more, for transmission applications; and with storage discharge times from a few seconds, for customer power quality and transmission and distribution (T&D) stabilization applications; to 30 minutes, for short-term spinning reserve and power reliability; and from 2 to 8 hours or more, for peak shaving and distribution system (including distributed generation) duty. In fact, EPRI already has a project underway to investigate incorporating conventional battery storage into the Flexible AC Transmission System (FACTS) and the Distribution Static Condenser (DSTATCON) technologies, so as to enhance the capabilities of these devices for transmission and distribution applications, respectively.

As indicated earlier and discussed in more detail later in this report, there are a large number of advanced battery technologies that could conceivable be used for energy storage in restructured electric utilities. This, coupled with the large number of possible applications, means that a structured assessment methodology had to be used to conduct the study. This is now outlined.

1.2 Assessment Methodology

According to the methodology employed in preparing this report, generic battery types are referred to as "batteries" or "battery chemistries", while embodiments of the various chemistries that are specific to particular developers are referred to as "battery technologies". Not all possible combinations of advanced batteries and conceivable utility energy storage applications were evaluated in the study reported on herein. Rather, the capabilities of a selected group of advanced battery technologies expected within a five year time-frame were critically evaluated in relation to the requirements for particular applications.

The specific applications against which the advanced batteries were assessed were selected in a collaborative process between the EPRI Project Manager and the Contractor. These specific applications are described in Section 2 of the report. It is thought that these applications might become commercially viable within the same five year time-frame for which the battery assessment was made. In Section 2, outline baseline designs of battery systems for the specific applications using more-or-less conventional lead-acid batteries are described. During the evaluation process, the expected capabilities of the selected advanced batteries were compared against the requirements of the specific applications and against the baseline lead-acid designs. The requirements for the specific applications themselves were not evaluated or analyzed as part of the work, however, nor yet were potential markets for the specific applications projected.

The battery technologies considered for assessment are listed in section 1.3 of the report. The technologies which were assessed in detail were selected in a two-step process. First, during the planning and scoping stages of the project, the Contractor reviewed the literature to determine which of the many battery technologies under development might be suitable for inclusion in the assessment. A first down-selection to the most suitable technologies was then made by the Contractor, in collaboration with the EPRI Project Manager. The number of technologies to be subjected to detailed assessment was further reduced during the scoping stage of the project when several developers indicated they were unable or unwilling to share data and information with the Contractor, i.e., a few developers (see Section 1.3) indicated they were not interested in participating in the project.

It was assumed for the detailed stage of the study that no major changes would be made in the technologies assessed in the five years time-frame of the assessment. In particular, it was assumed that any work to make the assessed technologies more attractive for utility applications would involve only refinement of current designs, not completely new designs developed specifically for this market. This assumption was made because we think it unlikely that any significant funds beyond those presently being expended will be available to develop utility-specific advanced battery designs in the five year time-frame of the study. During the detailed stage of the assessment, a further down-selection was made according one of more of the following criteria:

- The availability of data and information on each technology in the open literature;
- Technology status, including critical evaluation of the technology;
- The Contractor's evaluation of the technology development program underway, including the expected availability, within the five-year assessment time-frame, of sub-scale demonstration quantities of components, such as plates or individual cells, that appear appropriately-sized for electric utility applications;
- Show stoppers, if any;
- Business and commercialization aspects, e.g., capabilities and resources of developers, interest of developer in co-funding work for utility applications with EPRI, use of developments for other applications such as EVs;
- Possible safety and environmental issues.

For the final group of battery technologies that remained after the two down-selection steps, an assessment was made of the expected characteristics of each technology in comparison to the requirements of the specific application or applications for which it appeared most suited. The most important part of this detailed assessment was the expected economics of the various advanced batteries. The economic evaluations were made by estimating the costs for outline conceptual designs, i.e., system configurations, for full systems for each of the battery technologies selected for detailed analysis. The outline conceptual designs were "developed" as part of the study and took into account the critical evaluations of the technologies that were made. The economic evaluations also included an assessment of the cost impact of any special requirements for the converter/power conditioning system. We also made relative estimates of the elements of operating costs (including the impact of energy efficiency), and the components of the costs for maintenance and repair, including cell- or module-replacement costs. The last of these items involved an assessment of the possible life of the advanced batteries under study.

Data and information for the assessment came from telephone and/or face-to-face discussions with developers, this being backed up with documentation if possible. In many cases, information was solicited from battery developers using a “form”, shown in Appendix A, that was developed by the Contractor for this purpose. In addition, published and privately-obtained documents (e.g., papers, presentation graphics) on each of the advanced batteries were reviewed, and relevant information and data was abstracted from these as required. No proprietary developer data or information is included in this report, although such information was shared with the Contractor by a few of the participating developers, this having been only used to support the conclusions discussed below.

1.3 Battery Technologies Assessed

Many advanced battery technologies were initially considered for inclusion in the study. These technologies include examples of most of the battery chemistries that have from time to time been suggested for utility energy storage. The battery chemistries that were included in the detailed assessment phase (see Section 1.2), together with a shorthand description of some of the specific technologies and/or developers for each chemistry, are as follows:

- Advanced valve regulated lead acid (VRLA) batteries:
  - Delphi EV battery with conventional design
  - Optima spiral-wound starter battery
  - Bolder spiral wound sub-C cells
  - Electrosource quasi-bipolar battery

- Nickel-metal oxide batteries:
  - Saft Nickel/cadmium batteries
  - Ergenics Nickel/hydrogen battery with hydride storage
  - Ovonic Nickel/Metal hydride battery
  - Saft Nickel/Metal hydride battery

- Flow batteries:
  - Powercell Zinc Bromide battery
  - Pinnacle Vanadium Redox battery

- High temperature batteries:
  - Sodium/sulfur battery
  - Sodium/nickel chloride (Zebra) battery

- Ambient temperature lithium batteries:
  - Saft Lithium/ion battery
  - Hydro Quebec (with 3M) Li/polymer battery

The results of our detailed assessment of these battery technologies are described in Sections 3 to 7 of the report. The overall conclusions from the assessment, together with some general comments, can be found in Section 8.

Some of the technologies initially considered for inclusion were eliminated from the detailed assessment either in the planning stage or as the study proceeded, according to the methodology described in Section 1.2. Those eliminated, together with the reason for elimination, were as follows:

- Arias bipolar VRLA battery: Eliminated during analyses at request of developer.

- Nickel/iron oxide and nickel/zinc oxide batteries: Eliminated during planning phase because no relevant projects in hand.

- Nickel/hydrogen batteries with pressurized hydrogen storage: Aerospace technologies of Eagle Picher and Russian developers eliminated during analyses because chemistry better addressed with Ergenics technology.

- Japanese nickel/metal hydride battery technologies: Eliminated during analyses because better addressed with Saft and Ovonic technologies.

- ZBB zinc/bromine flow battery: Eliminated during analyses at request of developer.

- Meidensha zinc/bromine flow battery: Eliminated during analyses because adequately addressed with Powercell technology.

- Vanadium/chromium and zinc/ferri-ferrocyanide redox (flow) batteries: Eliminated during planning phase because no relevant projects in hand.
- Saft lithium/iron sulfide battery: Eliminated during planning phase because no relevant projects in hand.
- Sony lithium/ion: Eliminated during analyses because chemistry more easily addressed with Saft technology.
- Other ambient temperature lithium batteries,: Eliminated during planning phase because no relevant projects in hand.

1.4 References

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2

ELECTRIC UTILITY ENERGY STORAGE APPLICATIONS FOR BATTERY ASSESSMENT

2.1 Overview

The underlying purpose of the study reported on here is the determination as to which, if any, of the advanced battery technologies are possibly worthy of accelerated R&D funding (from EPRI, or others) to move forward their commercialization for energy storage in restructured electric utilities. In order to be able to meet this objective, it was decided during the planning stage for this work that the projected capabilities of various advanced battery technologies would be assessed against the requirements for specific restructured utility applications. In this section, we first define, for the purposes of the study, what restructuring is assumed to be. Then, in the terms of this definition, five specific applications for energy storage that might be important for restructured utilities are described. A baseline design for a conventional lead-acid battery that could meet the needs of each of these applications, albeit perhaps not economically, is then shown. For each baseline design, we indicate what characteristics must be exhibited by an advanced battery technology so that it could be considered better than the baseline, i.e., meet the needs of the application more economically. In this way, the basis for the assessment of advanced battery technologies that is given in Sections 3 to 7 will be set.

What first was described as deregulation of the electric utilities has come to be known, as the process proceeded, as reregulation or, more recently as restructuring. During the three “Think Tanks” arranged by EPRI during 1996 and 1997 (see Section 1.1), the restructuring of electric utilities that is presently underway in the United States was described in terms of the following processes:

- Reorganization from vertically-integrated, regulated monopolies to reregulated horizontally-integrated businesses.
- Deregulation of the generation portions of old-style electric utilities so that existing and new suppliers can compete on an open market basis.

- Continuing operation of the transmission and distribution assets of utilities as regulated monopolies, but with these parts of the electricity supply system in the restructured situation as separate (horizontally-integrated) business entities.

- Open access to the transmission and distribution systems from generation assets **and** to load centers, with charges for use of these assets on some kind of "per-use" basis.

- Transition to a market where end-use customers have the opportunity to contract to purchase their electricity from the supplier of their choice, **and** the opportunity for any properly-qualified "supplier" to purchase electricity in an open market and to offer electricity for sale to end-users.

The reorganization processes that are underway are spawning a new set of companies and organizations, as inferred by the above. Some of the more important of these companies or organizations from the energy storage perspective are:

- Generation companies, particularly those involved in distributed generation.

- Independent system operators (ISOs) and the like, which will be charged with operating regional or statewide transmission systems and with coordinating dispatch of generating equipment within their purview, and for which acquisition of ancillary services will probably become increasingly important.

- The power pool or what in California is known as the "Power Exchange", i.e., the trading "floor" for bulk electricity sales that are not the subject of bilateral contracts.

- Distribution companies.

- Energy service companies, that purchase electricity from generators or the power pool, and then sell it and electricity services to end-use customers.

For these companies, it is thought that customer service, where the customer is the party to which the company is providing the electricity or the service, not necessarily the electricity end-user, will become the guiding business principle. Although customer service is important to vertically-integrated utilities, it was previously thought of within the limits of regulated monopolies, and with end-users (as opposed to other entities in the electricity supply chain) as the only customers.

In the Think Tanks, in the course of the study reported here, and in parallel work by EPRI and elsewhere, the following, not necessarily in order of market potential, have been determined as the most promising areas for the application of energy storage in restructured utilities:

- To allow trading to and from the power pool.

- To allow generators to operate their plant(s) more profitably, particularly distributed generation plants, and most particularly those utilizing renewable resources.
- To provide ancillary services such as spinning reserve and load following to ISOs.
- To stabilize and otherwise allow cost-effective operation and expansion of transmission systems.
- To maximize the utilization of distribution assets, and to thereby defer additions to this portion of the electricity supply system.
- To enhance the reliability and the quality of power provided to end-use customers.

Based on these general areas of opportunity, specific applications for energy storage have been defined as part of the present work and by others. These applications are used in the study to assess advanced battery technologies and are shown in Table 2-1.

Table 2-1
Restructured Utility Applications for Assessment of Advanced Batteries

	Transmission Line Stabilization	Arc Furnace ACE[a] Regulation	PQ[b] Enhancement + Peak Shaving	Distributed Generation
<u>REQUIREMENTS</u>				
Time of use	When transmission facilities close to limits	Round the clock	PQ round the clock Peak Shave when RTP ratio high	Whenever favorable economics
Power	300 MW	80 MW	10 MW, 5 MW	5 MW
Discharge Energy	167 kWh	5 MWh	N/A[c], 10 MWh	40 MWh
Type of Use	Oscillatory discharge/charge	Variable rate discharge	Block load discharge	Block load discharge
Discharge Time	1 to 10 sec	10 minutes	10 seconds, 2 hours	8 hours
Frequency of Use	1/month	2/hour	1/month, 150/year	100/year
DC Bus Voltage	10 kV	10 kV	2 kV	2 kV

(a) Area Control Error

(b) Power Quality

(c) Not applicable

In the next five sub-sections of the report, we discuss the deign criteria shown in Table 2-1 and describe baseline (lead-acid based) battery systems for these specific energy storage applications. Throughout the following, it will be assumed, for the sake of simplicity, that all the power requirements are for the DC side. Implicit in this is the further assumption that differences in the efficiencies of AC-to-DC-to-AC power conversion units (PCUs) for different battery technologies are negligible within the margins of error on the data for the batteries that have been assessed.

2.1 Line Stabilization Using STATCON Augmented with Energy Storage

2.1.1 Description of Application

On a national (U.S.) basis, there appears to be adequate generation capability in place or planned to meet expected peak load demands for the next few years. Moreover, it appears that the reregulation of the utility industry is proceeding such that it is likely that market forces will ensure the availability of adequate generation capability in the longer term. The same cannot be said of the transmission network, however. Constraints exist or are expected to develop within transmission systems so that it may not be possible for generated power to pass to the loads during periods of peak demand. Some of these constraints exist because of the potential for instabilities in some of the longer transmission lines. These instabilities, when they occur, are exhibited as relatively low (~ 1 Hz) oscillations between the generation and load nodes of the transmission line.

Static condenser (STATCON) devices are one of a class of equipment for Flexible AC Transmission Systems, or FACTS. FACTS devices can modify power flows in a transmission network by injecting or absorbing reactive power at the load end of transmission facilities. STATCON devices could help quench instabilities in transmission lines if energy storage was incorporated into them so that they could deliver and absorb real power, on a cyclic basis, when instabilities start to develop. (1, 2, 3)

2.1.2 Design Criteria

The general requirements for energy storage to be incorporated into STATCON devices to quench transmission line instabilities are:

- Power delivered and absorbed: 250 to 1000 MW;
- Net energy delivered during instability event: 600 to 2000 MJ;
- Frequency of occurrence: 12 events/year.

The specific design points for STATCON energy storage that will be used for the present study are:

- Power delivered/absorbed in maximum instability: 300 MW
- Net energy delivered during instability event: 600 MJ, equivalent to 167 kWh
- Frequency of instability: < 1 Hz
- Energy discharged (or charged) in one half-cycle: ~150 MJ or 41.67 kWh
- Number of cycles in each instability event: < 10
- Frequency of occurrence: 12 events/year
- DC bus voltage in STATCON: 10,000 volts (nominal)
- Peak DC current to DC bus at nominal voltage: 30,000 amps

It is these design points that will be used, in later sections, to develop outline designs for those advanced batteries that appear possibly suited to this application. The baseline battery design based on these design points is discussed in the Section 2.1.3.

It should be noted that the battery requirements for equipment to be used to provide PQ enhancement in the distribution systems of utilities, say at distribution sub-stations, are very similar to those cited in this section for transmission line stabilization, except that the power level will be of the order of 10-20 MW. This "pure PQ" application, which should be distinguished from the PQ enhancement + peak shaving application discussed in section 2.3, was therefore not addressed separately in the study. (See also Section 8.)

2.1.3 Baseline Battery Design

The battery must be almost equally capable of discharge and charge when the transmission instability event occurs, although the first deviation from normal will probably require a discharge from energy storage. Thus, it will be necessary for the battery to be at a partial state of charge whenever the transmission system is operating close to the constraints. While this is not 100% of the time, this is still not a situation that is optimal for long life of lead-acid batteries. Thus, the baseline design with lead-acid batteries in this case, although technically viable, could possibly lead to a battery life that is less than satisfactory.

On the other hand, the discharge or charge time in any one instability cycle is very short. Compared to the way that many batteries are used, the power that is being delivered or adsorbed in the entire instability event is very high while the net energy delivered or absorbed is rather small. For batteries, this is a situation where the design is driven by the power that must be delivered or absorbed, as opposed to being determined by the energy that must be delivered. In fact, for lead-acid batteries, the obvious choice for the baseline design in this case is a high-quality, maintenance-free, starter battery.

In fact, the power and energy requirements for transmission line stabilization would appear to be met rather well with the same type of battery as that used in Omnion's PQ2000 backup power supply. The PQ2000 is intended to provide up to 15 seconds of uninterruptible power at a customer service entrance. The batteries in this equipment will deliver more than 2000 kW and the replacement cost for these batteries is said to be approximately $50,000. Thus the cost of these maintenance-free, 12 volt truck starter batteries is ~$25/kW. Even with regular STATCON costs of ~$100/kVA, battery costs are likely to be a relatively small fraction of the STATCON with storage system costs.

It would take 57,600 of these 12 volt starter batteries to provide the 300 MW specified in the design points for transmission line stabilization if the batteries were to be used in the same way as in the PQ2000. In fact, since the discharge time is much shorter for transmission line stabilization than specified for the PQ2000, it is possible that significantly fewer batteries than this could be used. However, for our study we will assume the more conservative, PQ2000 power levels. This should help ensure that the batteries will last for the five years that can normally be expected for these batteries in starter service in moderate climates. The physical size of this number of batteries is, of course, a considerable design constraint that would have to be addressed when a design was prepared.

In order to meet the DC bus voltage requirement for the specific design points, it would be necessary to arrange the 12 volt batteries in strings with, say, 960 batteries in series. Although the nominal no-load voltage of such an array would be rather high, 11,520 volts versus the estimated nominal discharge voltage of 10,000 volts, this is still regarded as desirable so as to minimize the DC current flowing during an event. With 960 batteries in series, there would be 60 parallel strings making up the 300 MW battery system.

Although the cost for the lead acid batteries in the baseline transmission line stabilization design are expected to be relatively low, $6 million for the 300 MW system, there are other costs for the battery system, and other factors and issues for lead-acid batteries, that may make some advanced batteries appear more attractive for this application. The most important of these are:

- Although they are a very low cost option, the truck starter batteries of the baseline design are not really appropriately-sized for utility applications so a very large number of modules would be needed to provide the required power.
- Operation for long periods of time in the partial depth of discharge mode could be problematical, as mentioned above. However, the large number of parallel strings

required in the battery system, plus the fact that the system may not have to be totally available for 100% of the time but only during periods when transmission constraints are important, means that it should be possible to always arrange for strings to be periodically taken out of service to be fully charged.

- There will be a need for thermal management to ensure the batteries operate properly and have the expected life-time.
- There will be a need for hydrogen gas management, with attendant, but probably relatively low, additional costs.
- There are unknown, but almost certainly costly requirements to ensure that all the batteries in the array are charged, brought to the necessary state of discharge, and that they can in general operate properly.
- There are unknown, and perhaps costly requirements to ensure the battery system operates reliably, particularly with so many batteries in series and parallel.
- There need to be many sectionalizing switches in each string, with added cost, to ensure the battery system can be assembled and maintained in a safe fashion.
- With such a high battery voltage, there is a high likelihood that ground faults will cause problems when the system is first assembled, so that there will probably be high start-up costs. Ground faults could be a continuing problem with such a design.

2.1 Arc Furnace Peak Clipping/Instantaneous Spinning Reserve

2.2.1 Description of Application

Electric-arc furnaces constitute a significant fraction of the load in some areas of the United States. The companies operating these furnaces are transmission line customers of the local utilities. When the arc “strikes” in one of these furnaces, a very large, generally phase-unbalanced, load is drawn from the transmission facilities, which can cause problems with voltage flicker for the arc furnace customer and other customers which are electrically close on the transmission lines. In addition, the variability of the arc furnace loads are such that these cause problems with “area regulation” for the supplying utility.

Area regulation relates to deviations from contracted transfers between electrical regions or “areas” of the generation and transmission network. According to NERC rules, unscheduled transfers between areas, i.e., those deviating from the agreed amount, should net to zero in each 15-minute period. An unscheduled transfer in a

15-minute period that does not net to zero is called the area control error, or ACE. The net unscheduled transfers of electrical energy must be made up by the utility not meeting it's area regulation agreements, and can be costly to the utility with the area regulation problems.

Of course, in the era of deregulation, utilities will want to do everything possible to retain their valuable arc furnace customers without having complaints from other customers, but they will want to do this in as economical fashion as possible. Solving the voltage flicker problem does not require real power flow, but including battery energy storage systems (or other energy storage devices) in the power electronics systems used for control of voltage flicker could help alleviate ACE regulation problems associated with are furnace operations. (1) Of course, it should not be assumed that an ACE problem solved with a battery discharge in one 15-minute period will be immediately followed by a 15-minute period when battery charge can be permitted without adding to ACE regulation problems. However, over a period of an hour or so, the ACE regulation energy flows for individual 15-minute periods must net to zero through changes in generation. The number of energy storage discharges and charges will each average to two per hour. In other words, there will be on average two charge-discharge cycles per hour.

It should be noted that an energy storage system for ACE regulation service, if designed and sized appropriately, could also provide instantaneous short term spinning reserve, with additional potential economic benefit. In this instantaneous reserve service, the battery energy storage system could replace generators actually spinning with generators that could instead be started in the event of an generation or transmission emergency.

2.2.2 Design Criteria

The battery energy storage system for alleviating the real power problems associated with arc furnaces (and that also **might** provide instantaneous reserve) will of course include not only the energy storage component, but also power electronics and switchgear to allow connection to the arc furnace loads, the arc furnace customer service entrance, or to the utility on the supply side of the meter. Control of voltage flicker will not require real energy flow from the battery, so it is the regulation of ACE that is the determining requirement for sizing the battery. The requirements for the "arc furnace" energy storage component are:

- Round the clock operation
- Power to be delivered: Up to 80 MW;

- Energy to be delivered to reduce ACE: Up to 5 MWh over a ten minute period, which is equivalent to an average discharge rate of 5 MWh/(1/6 hours) or 30 MW;

- Frequency of ACE regulation occurrence: 2 discharge-charge cycles per hour;

- Charge/discharge cycles for ACE regulation: 17,520 per year;

- DC bus voltage in power electronics: 10,000 volts (nominal);
- Peak DC current to DC bus at nominal voltage: 8,000 amps;
- Average DC current to DC bus at nominal voltage, for discharge of 5 MWh over 10 minute period: 3,000 amps.

These are the design points to be used, here and in later sections respectively, to develop and outline baseline (lead-acid) design and outline designs for advanced batteries that might be suited to the "arc furnace" application.

2.2.3 Baseline Battery Design

Although the total discharge time of the battery system for the area control error (ACE) correction portion of the arc furnace application is the rather short, for most battery systems, including lead-acid, it is the frequency and number of battery cycles that will be the driving factor in design. This is because of the following set of reasons.

For most battery systems, it is the ampere-hour throughput rather than the number of cycles *per se* that determines the cycle life at any particular state of discharge. Thus, a battery that can sustain 1000 cycles at 80% depth of discharge (DOD) will likely to able sustain 2000 cycles at 40% DOD. (There are a few battery systems for which calendar time rather than ampere-hour throughput is the most important life-determining factor, the high-temperature batteries to be discussed in Section 6 being most notable in this regard.) Lead-acid batteries are peculiar with regard to cycle life and ampere-hour throughput insofar that more cycles can be sustained with cycles at low DODs than expected from cycle testing performed at high DODs. For example, a lead-acid battery that can sustain 1000 cycles at 80% DOD may be able to sustain 3000 cycles at 40% DOD and 8000 cycles at 20% DOD. This is clearly a factor that must be taken into account in the arc furnace application, where tens of thousands of cycles have be sustained by the battery energy storage system over a period of just a few years. Since the cycle life of most batteries is measured in 1000-2000 deep cycles at most, batteries in the arc furnace application will have to be cycled at shallow DODs so that a life of several years can be attained before battery modules must be replaced.

Thus, the lead-acid battery baseline design for this application will be driven mostly by the cycling requirement, but some consideration must be given to the relatively short discharge time involved. Note that the average power requirement over the ten minute ACE period in which real energy is delivered is 30 MW, significantly less that the peak of 80 MW (measured on AC side) that the battery system must provide. This further emphasizes that the peak power delivery requirement is also important for the baseline design.

An appropriate but not a unique choice for the lead-acid battery cell type for the baseline design for the arc-furnace application seems to be one similar to that used in the Puerto Rico frequency regulation and spinning reserve battery system. (Obviously, if designed for an appropriate DOD for arc furnace ACE regulation, this type of battery would be suitable for the instantaneous reserve service that is also included as a requirement.) For an island like Puerto Rico, it is frequency regulation rather than ACE regulation that must be handled. The 20 MW, 14 MWh Puerto Rico battery is based on 2 volt cells that are essentially of a large, flooded, UPS-type, with some added features (wrapped positives) to ensure a 8+ year life under the shallow cycling conditions required by the frequency regulation service. There are 6,000 cells each with a nominal capacity of 2000Ah (4 hour rate) in the Puerto Rico plant, these being arranged in 6 strings of 1000 cells each; the estimated present day cost for these is approximately \$600/cell or ~\$150/kWh of rated capacity at the 4-hour rate.

For the arc furnace baseline design, with the 17,520 cycles per year of ACE regulation service, we calculate (see below) that 40,000 of the above cells will be needed to give 3 years of service. It appears most appropriate to arrange the cells in 8 strings of 5,000 cells each, in order to minimize the costs of the interface between the battery and the power conversion equipment. The life calculation is based on testing performed by C&D (the manufacturer of the cells for the Puerto Rico battery) that indicated that in shallow cycling, the equivalent (in ampere-hour) of 1600 100% DOD cycles could be sustained before failure. With 8 strings in the plant, the average current in each string during ACE regulation discharge will be 375A, and the capacity withdrawn will be 62.5 Ah, so the DOD will be ~3% at a C/5.33 discharge rate. Thus, a life of ~51,200 cycles, or 2.9 years of ACE regulation can be expected. In fact, at the low rates of charge and discharge that are going to be used with this number of cells, it could well be significantly more than 3 years before the strings are unable to deliver the power required for ACE regulation. However, the cells will have to be thermally managed and charged properly if they are to sustain an acceptably long life.

The 40,000 cells chosen for the baseline design should be easily capable of delivering the peak requirement of 80 MW, since this represents a peak DC current of only 1000A per string, or the C/2 rate. In addition, the DOD is such that many ACE discharges could be sustained before the battery would have to be recharged, again without any great impact on cell life, which would simplify the control of the ACE regulation system. An occasional instantaneous spinning reserve cycle to much greater depth than an ACE regulation cycle would be unlikely to greatly diminish life. The cost for the cells for the arc furnace application is estimated to be very approximately \$24 million, or \$300 per peak kW. From the present state of knowledge, it is estimated that these cells would have to be replaced every three years, but the replacement period could turn out to be significantly longer than this.

Of course, there are many problems that would have to be solved and many other cost issues that would have to be addressed before this baseline lead-acid battery design could be considered viable for the arc furnace ACE regulation application. Some of the most important of these problems and issues, and thereby the areas in which advanced battery technologies may be more attractive for the arc furnace application than conventional lead-acid batteries, are as follows:

- Even with the low DODs used in the baseline design, the life of the cells is still only projected to be 3 years, albeit conservatively. This estimated three-year replacement period for the cells is rather short, so there may be unacceptably high maintenance costs.

- Higher voltage cells (or modules of cells in series) would allow reduction of the number of potentially-troublesome electrical connections.

- Means will have to be arranged for the cells to be charged between ACE regulation discharges, and for them to be fully charged and equalized fairly frequently in order to attain the desired life. (The use of 8 parallel strings should allow some relief in this regard.)

- Thermal management will be needed to ensure the cells operate properly and have the expected life-time.

- Auxiliary systems for electrolyte agitation, cell watering, and hydrogen gas management will be required, with some additional costs.

- There will need to be a sub-system to ensure that all the cells in the array are charged, equalized, and discharged properly.

- There are some perhaps costly requirements to ensure the battery system operates reliably, particularly with many cells in series and the eight parallel strings.

- Many sectionalizing switches in each string will be needed, with added cost, to ensure the battery system can be assembled and maintained in a safe fashion.

- As with the transmission line stabilization system, there is a high likelihood that ground faults will cause problems, particularly when the system is first assembled. This implies some high start-up costs, and perhaps continuing costs because of ground faults.

2.3 Power Quality Enhancement and Peak-Shaving on Supply-Side

2.3.1 Description of Application

Enhancement of the quality of the power being sold to businesses with "high-tech" manufacturing is becoming of increasing interest to electricity suppliers. As restructuring proceeds, it is beginning to appear that the responsibility for power quality (PQ) is beginning to change. Moreover, the end-use electricity market is becoming increasing competitive, so that electricity providers have to find ever more economic ways to purchase electricity and to ensure that the quality of the service is at a level that the customer finds acceptable. An appropriately-sized energy storage system between the distribution company and the company selling the electrical energy to the end-user could enhance PQ and simultaneously allow the owner of the energy storage system to purchase and then resell electricity at those times that are favorable with respect to real time prices. (Alternatively, if the energy storage system is owned by the end-user, then that company could take advantage of real time prices (RTPs), or in the nearer term could minimize peak demand charges by using peak shaving.) For the PQ enhancement mode, the power electronics will have to either operate continuously, as in a full-time or series UPS, or they will have to be switched into the circuit very rapidly, as with a standby-type UPS.

2.3.2 Design Criteria

The PQ enhancement and peak-shaving system for supply side use will consist of power electronics, switchgear and energy storage batteries sized as necessary to provide the peak power for PQ enhancement and the energy and power for peak shaving, respectively. The requirements for the energy storage component are:

- Round the clock operation for PQ enhancement;
- PQ enhancement power: 10 MW for 30 seconds;
- Assumed frequency of PQ enhancement event: One per month
- Peak shaving at 5 MW for 2 hours (10 MWh, block-loaded) when RTP high;
- Charge for no more than 2 hours at 5 MW when RTP low;
- Frequency of peak shaving operation: Up to 5 times/week, but probably not more than 150 times per year, when difference between high and low RTPs is sufficiently great;
- DC bus voltage in power electronics: 2,000 volts (nominal discharge);
- Peak DC current to DC bus at nominal voltage: 2,500 amps.

In this and later sections, these design points will be used to develop and outline baseline (lead-acid) design and outline designs for advanced batteries that are possibly suited to the PQ-enhancement/peak-shaving application.

2.3.3 Baseline Battery Design

A lead-acid battery for the PQ-enhancement/peak-shaving application would have to be designed mainly on the basis of the required energy delivery, with due cognizance being given to the discharge period and the peak power that must be delivered.

There is already one battery energy storage system installed with operating characteristics that are not too dissimilar from those listed above for the PQ-enhancement/peak-shaving application, the GNB Vernon facility. This plant is used to provide backup power for air extraction equipment at a lead recycling smelter, and can also be used for peak shaving by the owner. Another similarly-designed plant, the Metlakatla facility in Alaska, is used for peak clipping, generation cost minimization, and system control for a small island utility.

Both these plants are based on GNB's Absolyte IIP VRLA cells, the 100A75 version of which is rated at 2 volts and 3.35 kWh at the one-hour rate. These cells can be safely discharged at the half-hour rate, and will then give twice the normal discharge power, for short periods such as 30 seconds. These cells can thus be expected to be used to deliver the peak power required for the PQ-enhancement/peak-shaving application. Rather conservatively, the 100A75 cells can be expected to give 3.3 kWh over two hours (utilizing ~ 80% depth of discharge) for approximately 1000 cycles.

The baseline design for the PQ-enhancement/peak-shaving application would require a total of 3,000 of the GNB 100A75 cells. These cells would have to be arranged in 3 parallel strings of 1,000 cells each. The estimated cost for the baseline design is $200 per delivered kWh, or a total of approximately $2 million for the cells for the 10 MWh, 10 peak MW, PQ-enhancement plus peak-shaving battery.

Batteries based on VRLA cells cannot be maintained in the way that flooded cells must be, so the capital and operating costs for this type of battery system are lower than for flooded types. However, there are other issues and problems for the baseline design just outlined that might be alleviated with one or more of the advanced battery technologies assessed in later sections of the report, as follows:

- Even though the costs for battery auxiliaries are included, the estimated costs, over the expected life of the VRLA cells of the baseline design, are significantly higher than is thought to be competitive for this application.

- The size and weight of the cells are such that the energy storage plant could not be accommodated at most utility sites.
- There will be a need for ventilation in the vicinity of the cells to handle occasional hydrogen gas emissions, with attendant, but probably relatively low, additional costs.
- There will probably be fairly costly requirements to ensure that all the batteries in the array are charged, and occasionally, equalized properly.
- There are unknown, and perhaps costly requirements to ensure the battery system operates reliably, particularly with many batteries in series.
- There need to be several sectionalizing switches in each string, with added cost, to ensure the battery system can be assembled and maintained in a safe fashion.

2.4 Energy Storage for Distributed Generation

2.4.1 Description of Application

Distributed generation has for some time been promoted as an asset addition option for electric utilities. Distributed generation can be a relatively low cost method for adding generation, particularly for peaking, can allow deferral of costly transmission and distribution facilities, and can increase the reliability of the electricity service provided to customers. Distributed generation can also be a supplier of other generation requirements such as spinning reserve and load following. In restructured utilities, distributed generation is expected to take on an even more important role, as generators, wirecos and other electricity providers each try to maximize their marketing position and minimize their operating costs. In particular, it is thought that entities such as ISOs are going to be seeking to contract for the ancillary services (e.g., emergency generation, transmission support) that were formerly provided by the generation operations of vertically-integrated utilities.

In the restructured marketplace, energy storage systems as an asset addition might be regarded as a special sort of “stand-alone” distributed generation with zero local emissions, or it may be looked upon as support for “true” distributed generation such as diesels, micro-turbines, fuel cells, or distributed renewable resources such as solar PV or wind generation. As support to true generation, storage could provide load following, reserve capacity, firming of renewable generation, and so on. In either case, storage can be a source of ancillary services or as a peaking generator, can allow deferral of T&D asset acquisition, can improve the local reliability of service, and could be used by it’s owner for trading in the wholesale electricity market.

2.4.2 Design Criteria

In order to function in the multiple roles just outlined, the energy storage distributed generation system, which will have to of course include the energy storage battery and the power electronics sub-systems, will have to be capable of a variety of functions. As far as the battery sub-system is concerned, the following will be assumed as the design criteria for the comparison of battery technology characteristics with the distributed generation application:

- Discharge power capability: 5 MW continuous;
- Must be available full-time for ancillary services, reliability, etc.;
- Full power discharge period: 8 hours;
- Discharge energy capacity: 40 MWh;
- Assumed frequency of full-energy discharges: 40 per year, with a larger number of discharges to less depth;
- Complete charge from full discharge in 10 hours;
- DC bus voltage in power electronics: 2,000 volts (nominal);
- Peak DC current to DC bus at nominal voltage: 2,500 amps.

This set of design points for a distributed generation energy storage system is intended to represent the requirements for one module of what could be a single- or multi-module system at any given site. These assumed requirements (design points) are those that will be used in the next sub-section, and in later sections of the report, to prepare an outline baseline (lead-acid) design and outline designs for advanced batteries, respectively.

2.4.3 Baseline Battery Design

As far as we are aware, there is no lead-acid battery technology presently on the market that could economically meet the requirements for distributed generation energy storage; only an advanced battery technology of a type to be determined in later sections could conceivably do this. However, of the lead-acid types that are sold, lift truck batteries appear to most closely meet the needs of this application if economics are included. (Although VRLA cells would offer advantages with regard to maintenance, they are at least one-third more expensive and exhibit about half the life of flooded cells offered for the same service.) Flooded lift truck batteries, which are already sold in relatively large numbers, might best meet the technical and economic requirements for the distributed generation application, so one variety of this type of battery will be used for the baseline design against which advanced battery technologies will be later compared.

The largest standard size lift truck battery cell produced in quantity has a capacity of 1,540 Ah at the 6 hour rate; this is the type of cell that will be specified for the baseline distributed generation design. When operated at a temperature of 25 to 30 C, it is estimated that this type of cell can be discharged at 156 amps, and an average of 2 volts, for a period of more than 10 hours. The conceptual design for a lead-acid based distributed generation plant chosen, however, would limit discharges to 80% depth, i.e., cells would be discharged at 156 amps for 8 hours. The usable capacity of the lift truck cells in this application is therefore 2.5 kWh, versus it's nameplate rating of 3 kWh. If all discharges were to the 80% depth, a life of approximately 2,000 cycles can probably be attained, providing the cells are recharged within a few hours after discharge and the cells are not allowed to get above 30 C. A greater number of discharges for shorter periods is thought to be possible. The wholesale price of these cells is in the range of $100-120 per nameplate kWh (to 100% depth) when purchased in relatively large quantities.

When discharged to a depth of 80%, a total of 16,000 cells with a 6-hour rated capacity of 1,540 Ah would be needed to provide one 5 MW/8 hour module of distributed generation. These cells might be arranged in 16 parallel strings each with 1000 cells per string to provide the DC bus voltage and current capability required for this application. The total cost for the cells in the distributed generation plant is estimated to be $5 to 6 million, or $1000-1200/kW.

Even though it is possible to define the baseline (lead-acid based) distributed generation energy storage plant in the way just outlined, there are many issues and problems that would have to be resolved before such a plant could be considered viable. It is these issues and problems, the most important of which are given in the following list, that might make one or more of the advanced battery technologies that are being assessed a better and more economic option:

- Even with low-cost lift truck cells, the battery costs are probably too high for this to be an economically competitive design.
- The size and weight of the cells are such that the energy storage plant could not be accommodated at most utility sites.
- The cells chosen for the baseline design are relatively low in cost and their cycle life may be satisfactory with the use as presently envisaged, but their calendar life may be less than desirable.
- Thermal management will be needed to ensure the cells operate properly and have the expected life-time.

- Auxiliary systems for electrolyte agitation, cell watering, and hydrogen gas management will be required, with some additional costs.
- There will need to be a sub-system to ensure that all the cells in the array are charged, equalized, and discharged properly.
- There are some perhaps costly requirements to ensure the battery system operates reliably, particularly with many cells in series and the four parallel strings.
- There will probably be fairly costly requirements to ensure that all the batteries in the array are charged, and occasionally equalized, properly.
- There are unknown, and perhaps costly requirements to ensure the battery system operates reliably, particularly with many cells in series.
- There need to be potentially-costly sectionalizing switches in the strings so the battery system can be first assembled and later maintained without the possibility of harming workers.

2.5 Summary of Applications and Baseline Designs

In table 2-2, the requirements for the four applications against which advanced batteries will be assessed are summarized. Additionally, Table 2-2 shows the baseline lead-acid battery systems that were delineated for each of these applications. This table will be referred to extensively in the advanced battery assessments that are described in Sections 3 to 7 of the report, and in the Discussion in Section 8.

2.6 References

(1) Hackworth, D. T, et al, "FACTS with Energy Storage -- Conceptual Design Study," prepared by Westinghouse Electric Corp., EPRI TR-111093 (Not yet published)

(2) De Steese, J. G., et al, "Utility Benefits of SMES in the Pacific Northwest," prepared by Battelle Northwest, EPRI TR-104802, September 1996.

(3) De Steese, J. G., et al, "West Coast Utility Transmission Benefits of Superconducting Magnetic Energy Storage," prepared by Battelle Northwest, EPRI TR-104803, January 1996.

Table 2-2
Restructured Utility Applications and Baseline Designs for Advanced Battery Assessment

	Transmission Line Stabilization	Arc Furnace ACE Regulation	PQ Enhancement + Peak Shaving	Distributed Generation
REQUIREMENTS				
Power	300 MW	80 MW	10 MW, 5 MW	5 MW
Discharge Energy	167 kWh	5 MWh	N/A, 10 MWh	40 MWh
Discharge Time	1 to 10 sec	10 minutes	10 seconds, 2 hours	8 hours
Frequency of Use	1/month	2/hour	1/month, 150/year	100/year
BASELINE DESIGN				
Cycle type	Partial DOD when standing by	Discharge to shallow depth, then recharge	Discharge then full recharge	Discharge then full recharge
Lead-acid type	Maintenance-free truck starting	Flooded enhanced-life UPS	Deep cycle VRLA	Lift truck
Module voltage	12 V	2 V	2 V	2 V
Number of modules	57600	40000	3000	16000
Arrangement	960 in series 60 in parallel	5000 in series 8 in parallel	1000 in series 3 in parallel	1000 in series 16 in parallel
Module rating	5.2 kW Very shallow DOD	4 kWh Used at 3% DOD	3.3 kWh	2.5 kWh
Expected life	60 cycles 5 years	50k cycles 3 years	1000 cycles 7 years	2000 cycles 8 years
Cost for cells or modules	$25/kW	$150/kWh at 100% DOD $24 million total	$200/kWh	$120/kWh
Cost/life	$5/kW per year	$8 million per year	$29/kWh per year	$15/kWh per year

3

ADVANCED LEAD-ACID BATTERIES

3.1 Overview

Lead-acid batteries have been articles of commerce since the latter part of the last century. In the last fifty years, the major uses for batteries based on this chemistry have been for starting, lighting, and ignition in automobiles (SLI batteries) and for providing standby power for telephone and other industries (stationary batteries). Since the beginning of the lead-acid battery industry, manufacturers have conducted R&D that has allowed them to make steady improvements in their offerings to their largest groups of customers. In addition, new entrants to the industry have been developing products that they believe will allow entry into both traditional lead-acid markets, and markets served by other battery technologies

In addition to these efforts on commercial products, there were during the 1950-1975 time frame, sporadic but intensive DOD-funded efforts to develop better lead-acid batteries for submarines and for electric fork lift trucks. Also, there have been, during the past three decades, recurring surges of government and other institutionally co-funded R&D efforts to try to develop lead-acid battery technologies for new commercial applications. In the 1970s, there were significant levels of DOE-funded efforts at various lead-acid battery companies to develop new technologies for electric cars, and during the 1980s, EPRI and DOE helped to fund efforts to develop improved lead-acid batteries for utility load leveling.

The most recent development efforts on advanced lead-acid battery technologies have been spurred by two factors:

- The explosion in markets for battery-powered portable electrical and electronic equipment. This market was first satisfied by small nickel-cadmium batteries, and subsequently by more advanced nickel/metal hydride and lithium batteries. This led current lead-acid battery manufacturers and technical entrepreneurs to try to develop lead-acid based technologies that, because of their inherently lower cost, might compete for selected portions of the portable equipment market.

- The resurgence of interest in electric vehicles in the early 1990s that was spawned by the California Air Resources Board regulations of that time. This in turn led to several efforts to develop advanced lead acid battery technologies, the most notable of which were:
    - A GM Delphi Division program to develop a high-performance VRLA battery for GM EV1 vehicle
    - A set of projects co-funded by the members of the International Lead-Zinc Research Organization (ILZRO) and lead-acid battery developers, called the Advanced Lead Acid Battery Consortium (ALABC) program.
    - A project co-funded by EPRI and Electrosource to further develop the latter's advanced lead-acid battery technology

As a result of these recent development efforts, a number of advanced lead-acid battery technologies have recently been, or are in the process of being, commercialized. In the planning stages of our study, three of these technologies, those of Electrosource, Optima and Bolder, were selected for assessment in restructured utility applications. A fourth, the Delphi EV technology, was added during the scoping stages of project, because the developer was indicating <u>at that time</u> that they might be interested in having their system considered for energy storage. (1)

All these advanced lead-acid battery technologies, as well as the conventional ones discussed in the last section of the report, as based on the same chemistry, with the overall electrochemical reaction during discharge being as follows:

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

The recharge reactions are the reverse of the discharge reactions, of course.

Note that as the discharge proceeds, the concentration of the sulfuric acid electrolyte falls, since H_2SO_4 is consumed and water is produced. As a result, the no-load (open circuit) voltage of a lead acid cell varies during a cycle from ~2.1 volts at the top of charge to ~2 volts at the bottom of useful discharge. In addition, the decreasing concentration of electrolyte, together with other factors, leads to an increasing internal resistance. All these factors mean that for a given current, the terminal voltage of the lead acid cell is lower at the end of discharge than at the beginning.

Two side reactions can occur in lead-acid cells, primarily at the top of charge: hydrogen evolution from the lead negative plates and oxygen evolution from the lead dioxide positives. In flooded cells, these side reactions lead to a loss of water that must be made up in some way from time to time. (See Section 2.) The loss of water is particularly high during overcharge and equalization of batteries of cells, which must be performed each full charge and once every ten or twenty cycles, respectively.

Overcharge and equalization both involve charging the lead-acid cells somewhat beyond the ampere-hour capacity that has been discharged, so as to ensure that all the electrodes of all the cells of the battery are fully and equally recharged.

Beginning in the early 1980s, lead-acid battery manufacturers introduced a new type of technology to the market, valve regulated lead acid or VRLA batteries. There are several variants of this technology, depending on manufacturer or developer. However, they all employ the same basic principles of a starved, immobilized electrolyte and positive-limited cells that are sealed with a pressure relief. This means that oxygen begins to be evolved before any significant amounts of hydrogen, that the pressure can be allowed to safely build up, and that the oxygen can migrate to the negatives and react there. This allows long periods of overcharge at relatively low currents without water loss. The variants in this technology involve the methods of immobilizing the electrolyte, utilizing silica gel or absorbent glass mat, and in the alloys used for making the positive and negative substrates (grids) of the electrodes. All the advanced lead-acid battery technologies assessed in the study on which we are reporting here are absorbent glass mat VRLA technologies.

VRLA batteries are inherently more expensive and shorter lived than corresponding flooded batteries, but they never require watering, and thus need much less maintenance than flooded cells. VRLA cells are lighter in weight and smaller in volume, by 10 to 25%, than flooded cells designed for the same service. On the other hand, VRLA batteries suffer most of the same limitations as flooded cells, the most important of which for utility applications, as may be clear from the discussions in Section 2, are:

- Lead-acid batteries are heavy (low Wh/kg) and have only a moderately-good energy density (medium Wh/l). This combination means that significant area is needed for a lead-acid battery energy storage plant.

- The ampere-hour capacity that can be delivered by a lead-acid battery at high discharge rates (relative to it’s specification) is significantly less than at low rates. Thus, if a lead-acid battery is used in an application that requires a large fraction of the discharge at a high rate, the energy delivered will be less than the specification indicates, and the cost of it’s energy storage capability will be higher than the nominal ratings indicate.

- If their life is not to be compromised, lead-acid batteries must be recharged immediately after discharge, and cannot be cycled extensively at a partial state-of-charge. This means that they are not well-suited for applications that require both discharge and charge at high power levels. It should be noted that some recent data from the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia indicates that certain types of gel VRLA cells seem to cycle better at partial states-of-charge than other VRLA and flooded lead-acid types. (2) No gel lead-acid batteries were included in our assessment, since there are, to our knowledge, no advanced types under development.

- The reliability and reproducibility of lead-acid cells are not as high as desirable to easily construct long (high voltage) strings. As a result, special controls, at added cost, must be used to ensure that high voltage strings have an acceptable reliability.
- Overdischarge of lead-acid cells seriously shortens their cycle life. This means that the capacity of a string of cells is set by the weakest cell in the string, and that controls are required to identify weaker cells so that they are not overdischarged.
- Overcharge of lead-acid cells shortens their life, yet overcharge is required to ensure that all the cells in a string are fully charged. Thus, controls, with additional cost, are required to make sure a string of cells is charged properly without unduly compromising cycle life.

Our critical evaluation and assessment of the advanced lead-acid batteries identified above will now be discussed. The critical evaluations in this section are different from those for batteries utilizing advanced chemistries, insofar that lead-acid batteries are already articles of commerce for a variety of applications, and thus there are no "show stoppers" for the technology in general. There could be resource limitations with regard to lead if a very large, world-wide, market for utility batteries developed, but this is considered to be a remote possibility and even then to be far enough in the future as to be beyond the scope of this study.

3.1 GM Delphi VRLA Technology

3.1.1 Characteristics

Delphi's VRLA battery technology was specifically designed and developed as a power source for the GM EV1 electric car. (3) It is one of the many variants on the basic VRLA technology that have been developed since the immobilized and starved electrolyte concept was commercialized around 1980. The Delphi EV version employs a glass mat to absorb the electrolyte, specially-formulated alloys for the grids, newly-developed active material compositions, and a plate loading that is designed to mutually maximize the energy and power densities.

Although first developed for the EV1, Delphi has produced limited quantities of a few variations on module design for different electric vehicles. The pre-production versions of these modules all utilized the same cell design, however, with a capacity of ~55 Ah. The EV1 module has six of these cells, for 12 volts, and will deliver energy to 100% depth of discharge (DOD) at the 3 hour rate which corresponds to a specific energy of 35 Wh/kg and an energy density of 84 Wh/liter. The specific power capability of the EV1 module, sustained for least 30 seconds at two-thirds of the open circuit voltage, corresponds to a specific power of ~250 W/kg at 100% state-of-charge (SOC) and ~150 W/kg at 80% DOD. The demonstrated cycle life of EV1 modules in EVs is 350 cycles to ~80% DOD, and an operating life of 2 to 3 years is said to have been demonstrated. In single module tests, Delphi has indicated that the life has been shown to be up to 1000 cycles (perhaps 4 years) at 80% DOD at C/3. The higher and more optimistic values will be assumed to be attainable in the five-year time-frame of our study, and thus 1000 cycles and 4 years will be used in the assessment.

Although GM Delphi has not yet released details of their pricing, the OEM price of EV1 modules, in production quantities of few MWh per year, is thought to be in the range of $150 to $200/kWh. This estimate was inferred in the course of our assessment from published information on electric vehicle costs. This corresponds to OEM price of $21 to $28/kW for discharges sustained for up to 30 seconds. However, the values for peak power cited above are those attainable for at the beginning of life, and they can be expected to decline slowly through the life of the battery. As a result, the higher of these costs will be used for our assessment.

3.1.2 Critical Evaluation/Assessment

From the above information, the EV1 module characteristics can be calculated to be as follows:

- Nominal voltage: 12 volts
- Energy capacity at 3 hour rate: 0.672 kWh
- Module weight: 19.2 kg
- Module volume: 8 liters
- Power capability, 30 seconds sustained at 100% SOC, beginning of life: 4.8 kW
- OEM price of $200/kWh, equivalent to $28 per peak kW

The technical performance listed above appears incontrovertible. The life and cost that are estimated for Delphi EV modules are:

- Operating life: 4 years, 1000 cycles at 80% DOD
- Cost/life: $50/kWh per year, $7/(peak kW) per year

There is some question as to whether the life will be sustained in large arrays of this technology and whether the cost listed will be realizable. The life of Delphi VRLAs, from the little that has been published, seems to be less than had been originally projected, so there is a good possibility that the 4 years listed for this technology is, if anything, optimistic for utility applications. Moreover, there is some reason to believe, because of the lower plate capacities and the higher levels of quality control required, that Dephi VRLAs will be somewhat more costly than commercially available batteries of this type, such as the GNB VRLA used for the PQ enhancement baseline design. Thus, although Delphi VRLA modules appear to show a significant improvement in performance over other VRLAs, they are likely to be less long-lived and more expensive than commercially available products.

In comparison with the requirements and the baseline battery for restructured utility applications, as defined in Section 2 and summarized in Table 2-2, the Delphi VRLA appears **possibly** suited for the transmission line stabilization, arc furnace ACE regulation, and the PQ enhancement + peak shaving applications. In a more detailed comparison with the baseline batteries for these applications, the following observations can be made:

- For transmission line stabilization: The cost, weight and volume are comparable with the baseline, but the cost/life parameter is higher, i.e., \$7/kW per year versus \$5/kW per year. There appears to us to be no particular incentive to develop the Delphi VRLA technology for this application

- For arc furnace ACE regulation: For a given capacity, the weight and volume appear less than the baseline by about one-third. In addition, the cycle life at 80% DOD (1000 cycles) indicates that the cycle life at shallow DODs could be comparable to that of the baseline. However, it should be noted that the no data to support the 1000 80% DOD cycle capability has been published to data. The cost of Dephi VRLA cells is one-third more than that estimated for the baseline, \$200/kWh versus \$150/kWh. On the other hand, Delphi VRLAs do not require maintenance (cannot be maintained) so there should be lower costs for auxiliaries and ongoing maintenance. Given the confidence with which cost estimates can be made, we think Dephi VRLAs should be comparable to the baseline. Given their smaller size and lower maintenance requirements, Delphi VRLAs appear a moderately good candidate for development for the arc furnace ACE application.

- For PQ enhancement + peak shaving: The weight and volume could be less than the baseline by about 20% in this application. Conversely, the first cost over the life of the cells is projected to be higher than the baseline by almost a factor of two. As a result, this does not appear to be an appropriate application for which to develop Delphi VRLAs.

Our overall assessment of the Delphi VRLA technology is, therefore, that this is a technology that appears to offer some advantages with respect weight and volume, and that in the arc furnace ACE regulation application, there appears to be some probability that lifetime costs could be competitive. Moreover, battery watering would not be required, nor would there be an electrolyte agitation system that could break down. Beyond this, preparation of an outline design, i.e., a more detailed assessment, does not appear to be warranted at this time. Despite this, we were ready, as the analysis was being prepared, to make a recommendation to EPRI that the possibility of co-funded development program with Delphi be investigated. Since the analysis was completed, however, it has been learned that Delphi has sold the technology to another battery company, East Penn Manufacturing. Therefore, it is recommend that EPRI wait until the sale is closed and the technology has been transferred to East Penn before giving consideration to the possibility of a co-funded development program.

3.2 Electrosource Technology

3.2.1 Characteristics

Electrosource is a company that was formed in the early 1980s, as a spin off from Tracor, specifically to develop it's version of an advanced VRLA battery. The Electrosource Quasi-bipolar Horizon™ technology is based on the use of fiber-glass thread that is coated with pure lead using a proprietary process, together with proprietary active materials. (4) Otherwise, the Electrosource technology is a VRLA battery with absorbent glass mat (AGM) used to immobilize the electrolyte. The thread is woven into cloth that is then cut so as to form the grids of "bi-plates". In these, slightly less than half of each bi-plate becomes the positive of one-cell of a module (stack) while the other half forms the negative of the next cell in the stack. The active materials are pasted onto the positive and negative parts of bi-plates, while the conducting cloth remaining between the positive and negative parts of each bi-plate is coated with hydrophobic material. After interleaving the bi-plates with glass mat and stacking them into a module, the portion of the bi-plate between the areas coated with positive and negative active material becomes the intercell connector. This is the reason the Electrosource technology is called a quasi-bipolar battery. The stack of cells is then placed, together with end terminals, into a reinforced plastic box, and acid is added and absorbed in the glass mats to form electrolyte layers between the plates. The module is completed with a cover for the box and a pressure regulating valve. As can be seen from this explanation, there is a mechanical and manufacturability limit of about six or so to the number of cells in a module by virtue of the amount of interleaving and the length of the stack of cells.

Most of the emphasis of the work at Electrosource for more than the last decade has been batteries for electric vehicles. In about 1994, Electrosource had a small manufacturing facility constructed, which like their Horizon battery design, involves proprietary processes. The manufacturing facility is designed to make EV batteries, with the only product of interest for the present study being an 85 Ah, 12 V (~1 kWh) battery module. (A few "sample" aircraft starting batteries are also being made for military customers.) At the 3 hour rate to 100% DOD, the Electrosource module will deliver energy corresponding to a specific energy of 45 Wh/kg and an energy density of 86 Wh/liter. The published specific power capability of the Electrosource module, sustained for at least 30 seconds at two-thirds of the open circuit voltage, corresponds to a specific power of 153 W/kg at 80% DOD. Our estimate of the 30 second specific power is 250 W/kg at 100% SOC. Electrosource have demonstrated a life for their module of 310 cycles to 80% DOD with 3 hour rate discharges. Improvements are said to be in hand, and have been demonstrated in 4V R&D modules, to give a cycle life of 1100 cycles to 80% DOD C/3 rate. The operating life is understood to be about 3 years. Given the 5-year time frame of our assessment, the more optimistic of these values, 1100 cycles and 4 years will be taken for the analyses here.

According to June and July 1998 press releases from Electrosource, a purchase order for 5800 modules has been placed with the company at a price of slightly over $1 million, or ~$170/kWh. This was said to represent the production capacity of Electrosource's production facility for several months. However, coincident with these announcements, Electrosource stated that it was restructuring it's debt with an infusion of $1.5 million in cash from Kamkorp Limited, which owns a minority interest in the Malaysian customer for the 5800 modules. As a result, we think the for-profit OEM price for Electrosource modules in higher than that derived from the 6/98 and 7/98 press releases. It is estimated that the OEM price of Electrosource modules, in production quantities of few MWh per year, will be ~ $200/kWh. This estimate is based on a cursory comparison of the production processes for these modules in comparison with those for commercialized VRLA batteries. This corresponds to OEM price of ~$36/kW for discharges sustained for up to 30 seconds at close to 100% SOC. As for other lead-acid batteries, these are values for peak power at the beginning of life, and they can be expected to decline slowly through the life of the battery.

Electrosource has for a year or so had a contract from DARPA to develop the Horizon battery for an hybrid electric vehicle (HEV). The module capability specified for the HEV battery is 50V, 5Ah, and 750-1000W/kg. The short discharge time of an HEV battery is thus more like that required for transmission line stabilization and arc furnace ACE regulation applications discussed in Section 2. Electrosource has defined a modified version of their design approach for the HEV battery. However, as of this writing, no performance information is available for an HEV module, so it will probably not be available in the pre-production quantities required for a sub-scale utility energy storage demonstration within the five year time frame of the present study. Thus, despite it's potential applicability for restructured utility applications, the HEV version of the Electrosource technology will not be considered in detail in this assessment.

3.2.2 Critical Evaluation/Assessment

The Electrosource module characteristics can summarized, as follows:

- Nominal voltage: 12 volts
- Energy capacity at 3 hour rate: 1.02 kWh
- Module weight: 24.9 kg
- Module volume: 11.7 liters
- Power capability, 30 seconds sustained at 100% SOC, beginning of life: 6.2 kW
- Operating life: 1100 cycles to 80% DOD, 4 years
- OEM price of $200/kWh or $36 per peak kW
- Cost/life: $50/kWh per year, $9/(peak kW) per year

The Electrosource EV module shows the highest specific energy of any of the lead-acid technologies assessed. However, this module is optimized for an all-electric vehicle so the design discharge time is not quite as short as for other advanced lead-acid technologies, and the projected cost per kW for an Electrosource module is approximately 50% higher than for these other batteries. Moreover, Electrosource refers to the need for a "charge management system" for it's modules when they are used in larger batteries. This leads us to believe that the total $/kWh costs for this battery plus battery auxiliaries may be even higher than for commercially available batteries of this type, such as the GNB VRLA used for the PQ enhancement baseline design, if the life is to be sustained in large arrays of modules.

In addition to these concerns over life and cost, our critical evaluation raised some other issues regarding Electrosource and their modules, as follows:

- The lead coating on the fiberglass is, like all lead-acid battery grids, susceptible to corrosion whenever the SOC is low. However, this may be particularly problematical in the Electrosource technology because of the thin layer of lead used and because of the method by which intercell connections are made.
- The intercell connections, i.e., the hydrophobically treated portion of the lead-coated fiberglass cloth, are themselves of concern.
- Horizon modules appear to offer no particular advantage with regard to partial depth of discharge cycling.

- Electrosource is a small company that has been in the “start-up” mode for a considerable period of time. The company does not presently appear to have strong financial backing. Markets they had hoped would develop have not materialized, and orders that they had in hand were canceled and have not, for the most part, been replaced.

The Electrosource technology thus shows a quite significant improvement in performance, but it appears that a battery system based on Horizon modules will be more expensive, compared to commercially available VRLA products.

Clearly, Horizon modules are not suited to the 8 hour “distributed generation” application discussed in Section 2, but our analyses indicated they should at least be considered for the other applications. Comparing the Electrosource module characteristics with the requirements and the baseline battery for restructured utility applications shown in Table 2-2 leads to the following conclusions:

- For transmission line stabilization: It appears that the cost will be almost double that of the baseline and that the life may be a little shorter, while the weight and volume appear comparable, with the baseline.

- For arc furnace ACE regulation: The weight and volume appear less than the baseline by about 35% and 25%, respectively. Given the shallow depth of discharge to which any lead-acid battery considered for this application will have to be designed, it appears that the cost of an Electrosource battery will be comparable with or perhaps somewhat more than the baseline.

- For PQ enhancement + peak shaving: The total weight will be less by perhaps as much as 35%, and the volume could be less by 25%, than the baseline. However, the module capacity is one-third that of the baseline, so more than three times as many modules are needed for the plant. The cost will be comparable, in our estimation, while the life will probably be lower than that of the baseline by a factor of almost two.

Although the Electrosource EV technology appears to offer some quite significant weight advantage, and a little smaller but still important advantage with regard to volume, the combination of expected capital cost and life are such that the technology will show little if any economic advantage over commercially available batteries. We believe that any economic benefit derived from the smaller weight and volume will be offset by either higher $/kWh cost or greater frequency of battery replacements. In response to a query, Electrosource did offer an informal expression of interest in working with EPRI on developing the technology for restructured utility applications. However, given all the factors cited above, only their HEV technology should be considered for a possible co-funded development effort at Electrosource. Reliable information on the Electrosource HEV battery will not be available for a about a year, so we recommend the technology be reviewed again at that time.

3.3 Optima Technology

3.3.1 Characteristics

The Optima Spiralcell™ was first developed at the Gates Rubber Company, but in 1992, the Optima group, the rights to the technology and the fixed assets associated with it were acquired by the Gylling Group of Scandinavia. Optima has been operated as a separate unit of Gylling since then.

The Optima battery, as it's name implies, is based on spirally-wound grids with recombinant, absorbent glass mat, VRLA technology. (5) High purity lead-tin alloys are used for the grids. Proprietary techniques have been developed to make connections from the spirally-wound plates and the terminals, and to effect intercell connections within a battery. Individual cells are packaged in cylindrical cavities in a battery box. The Optima approach leads to higher power capabilities for a given weight and volume than conventional flat-plate VRLAs. The first and still the primary Optima product is a Group 34 engine starting battery. However, Optima is also making and aggressively marketing a deep cycle battery and two types of marine battery. The deep cycle battery (called the Yellow Top™) has an expected cycle life of 220 to 350 cycles, and 2 to 3 years. It is intended for automotive use when there is a high drain, and for golf car and similar applications. The life of the deep cycle Optima battery is too short for us to consider it further for utility applications, so only the Optima starting battery will be assessed here.

Optima starting batteries were first made, beginning in 1994, in a leased facility, but in 1996-7, production was expanded in a new facility that can produce from 0.8 to 1 million starting and deep cycle batteries per year, depending on product mix. Sales increased from ~300,000 batteries in 1995 to nearly 440,000 in 1997.

In addition to the products on the market, Optima has provided some batteries for EVs, and is involved as a second tier sub-contractor to GM in the Partnership for Next Generation Vehicles work on electric hybrid vehicles. Several papers have been published on the HEV work, which provides some details of the performance that might be expected. The Optima HEV battery is based on the Yellow Top, but has a capacity of only 15 Ah. The peak power capability is 480 W/kg for 30 second discharges at 80% DOD. However, we understand the life expectancy of this battery to be of the same order as the Yellow Top, so it appears that without a great deal of further development, it will not be suitable for utility applications. For the present study therefore, only the Optima starting battery appears to be a suitable candidate for our assessment.

The Optima starting battery products are best exemplified by one of the company's major products, the "Red Top" 800 series. This is a BCI Group 34 battery, with a capability of 800 cold cranking amps (CCA) compared to 600 CCA for a standard starting battery, and 120 minutes of reserve capacity at 25 amps, i.e., 50 Ah at C/2. The power capability of the 17.2 kg battery is stated by Optima to be 10.2 kW, or ~570 W/kg, but a lower figure than this, perhaps 400 W/kg, can be all that could be relied on for discharges of more than a few seconds. This type of battery is not warranted for cycling, but is specified to be capable of ~ 50 deep cycles. In testing to the SAE standard for starting batteries, the Optima product was found to be capable of up to 12,000 starts, compared to only 4,000 starts for conventional starting batteries. However, the calendar life of Optima batteries is not expected to be significantly longer than other premium starting products on the market. Since it is a VRLA, the Optima starting battery does have a much lower rate of self-discharge than flooded products, so that the manufacturer claims that it's batteries can sit for up to 2 years without appreciable loss of performance. At retail, Optima starting batteries are priced at approximately 70% more than a premium flooded product, a reflection, we believe, of Optima's higher manufacturing and distribution costs rather than the perceived value of the product in the US marketplace.

3.2.2 Critical Evaluation/Assessment

The Optima module characteristics can be summarized, as follows:

- Nominal voltage: 12 volts
- Energy capacity at 2 hour rate: 0.67 kWh
- Module weight: 17.2 kg
- Module volume: 8.65 liters
- Power capability as starter battery, beginning of life: 6.2 kW
- Operating life: Up to 6 years (Prorated warranty period)
- Discounted retail price: $120 per battery
- Estimated OEM price, utility applications: $20 per peak kW

For the current assessment, given these projected characteristics, it appears that Optima batteries, as made at the moment, will be suitable only for the transmission line stabilization application. In this application, the Optima starting battery is the obvious choice for an outline design. It appears to have a higher power capability per unit of weight and volume, and one that will be delivered for a greater fraction of it's life, than the other lead-acid batteries, advanced or otherwise, considered in this assessment. It is estimated that the same number of Optima batteries as the baseline (57,600) would be needed for the 300 MW transmission line stabilization application. These would be arranged 960 in series and 60 in parallel, i.e., in the same way as the baseline. The weight and volume of the Optima batteries could be as much as 25% less than those of the batteries used in the baseline design. Moreover, we estimate that the cost of these batteries would be ~$20/kW versus $25/kW for the baseline. However, Optima personnel refer to the need for battery management in long strings of batteries, i.e., for the HEV. This will indubitably add to the costs for Optima batteries as compared to the baseline. The life of the Optima batteries is expected to be 6 years rather than 5 years for the baseline. The effect of this difference in life on life-cycle-cost can be expected to be quite small. In summary, the cost over life for Optima batteries should be approximately the same as for the baseline.

Our critical evaluation of Optima raised the following issues:

- The process for making Optima batteries is described by it's manufacturer as "… a highly unique, time consuming and technically complex operation, requiring stringent quality control at every stage." Moreover, in Optima's annual report for 1997 it was stated that "… starting and fine tuning the factory during 1995 and 1996 was much more difficult and costly than predicted" and "... batteries produced during that period have not always had the even, high quality that our customers have the right to expect." While the manufacturing difficulties will probably be overcome, in the end Optima batteries might have to be sold at an even greater premium than at present.

- The connections to the spirally wound plates and the intercell connections, could be problematical, because the long transverse plates require multiple contacts that have the potential for failure in the acid environment.

- The state of charge at which Optima modules would have to be held in anticipation of a transmission line event may not be conducive to long life.

- Optima is a relatively small battery manufacturer that is trying to break into a very competitive market. In addition, Optima made a small profit for the first time in 1997. The resources that Optima may be able to divert to products not in the main line of their commercialization endeavors will probably be small.

The Optima starting battery technology appears to offer some significant weight and volume advantages relative to the baseline design for transmission line stabilization, and the estimated capital cost over expected life is projected to be slightly better than the baseline. However, it does not appear to us that the advantages are sufficiently great to warrant any EPRI investment in a co-funded program on the Optima technology. We do recommend that EPRI monitors progress on Optima's work on batteries for HEVs, since if their life is improved over present expectations, these could become of interest for applications in restructured electric utilities.

3.4 Bolder Technology

3.4.1 Characteristics

Bolder is a publicly-held "development stage" company that was formed in 1991 by several engineers from Gates. Their absorbent glass mat VRLA technology involves the use of very thin, pure lead foils that, after coating with active material, are rolled on a mandrel to form a jelly-roll type cell. (6) These are called TMF™ cells by Bolder. The company is in the process of constructing and starting up a factory that should be capable of making 10,000 Sub-C cells per day by mid-1999. (Sub-C is a standard classification of rechargeable cells for portable electric tools.) Although the sub-C cell is very small, it being 9/5th the length of an equivalent type of nickel/cadmium cell, Bolder cells are extremely powerful. For example, it is said that a 1 pound set of six Bolder cells "…can repeatedly start a 3 liter truck engine normally started …" by a 40 pound conventional battery. In addition, some consideration has been given to using Bolder cells for HEVs, to the point where a Chrysler concept vehicle used a battery pack comprised of Bolder cells. As a result, despite the fact that Bolder cells are very small, they were included in the screening portion of the present study.

The TMF technology includes very large plate surface areas, and proprietary end connectors that provide a very low impedance connection between the plates and the terminals. The Bolder sub-C cell is rated at 2 volts and 1.2 Ah. Despite the low capacity, Bolder claims their cells can deliver pulse discharge currents of 1000 amps and they have been continuously discharged at 270 amps. Test data has been presented publicly that shows an 80A discharge for 25 seconds at an average voltage of ~1.8 V/cell, while the average voltage for a 270A discharge was 1.35 V. The cells can be recharged from low SOCs at 2.55 V/cell at up to 45A, but after 10 seconds, the current begins to fall and after 50 seconds it is only 50A. Data has also been presented that indicates that a life of 250 cycles to 100% DOD at 60A with recharges at 2.55V, are attainable in single cell testing, Testing of 12V packs at lower rates has approximately halved the cycle life relative to that for single cells. The selling price of Bolder cells has not yet been established. We estimate, from a rudimentary evaluation of the Bolder technology, that these cells will sell at an OEM price of $2-5/cell.

3.4.2 Critical Evaluation/Assessment

The Bolder technology is obviously only worthy of consideration for the very high power to energy applications discussed in Section 2, so that is all that will discussed here. Although the Bolder TMF technology exhibits exceptionally high power per unit weight and volume, the usable power from the cells will be significantly less than is indicated by the currents that can be drawn. This is because in order to keep power electronics costs in control, it will be necessary to limit the voltage swing between charge and discharge. Thus, Bolder cells would be discharged at no more than 100W each if they were to be used in utility scale equipment. As a result, it becomes clear that the even though the Bolder cells are very powerful for their size, it would take an exceptionally large number of cells to meet the requirements of the transmission line stabilization or arc furnace ACE regulation. Put more simply, Bolder cells cannot be considered utility-scale equipment. As a result, we recommend that no further consideration be given to the use of Bolder cells for restructured utility applications.

3.5 References

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4

BATTERIES WITH NICKEL OXIDE POSITIVES

4.1 Overview

There are a whole group of battery systems that are based on the use of nickel oxide for the positive electrode, a follows:

- Nickel/cadmium or NiCad
- Nickel/iron
- Nickel/hydrogen, NiH
- Nickel/Metal hydride, NiMH
- Nickel/zinc

These systems grew from the invention of the Edison cell, a rudimentary form of today's nickel/iron battery. The Edison cell became known for it's extreme ruggedness and long life in railroad signaling applications. This indicated to developers of ensuing battery systems that nickel oxide electrodes could be the basis of technologies that would have the long life that some customers demanded.

The characteristics of the nickel/iron and the nickel/zinc systems are such that it was deemed, during the planning stage of our study, that they would not be available in a form suitable for consideration for utility applications in the five-year time-frame of our assessment. The other three systems were included in the study, as discussed in the sub-sections below. First, however, we will describe some general characteristics of nickel oxide positives.

All the battery systems with nickel oxide positives utilize moderately concentrated potassium hydroxide as the electrolyte. The electrochemical reaction occurring at nickel oxide electrodes in discharge is as follows:

$$\mathrm{NiOOH} + \mathrm{H_2O} + e^- \rightarrow \mathrm{Ni(OH)_2} + \mathrm{OH^-}$$

The hydroxyl ions produced at the positives are consumed at the negatives, of course, to maintain electroneutrality. Since, in discharge, the hydroxyl ions produced at the positives are consumed at the negatives with the formation of water, the combination of the positive and the negative reactions leads to little net change in the concentration of potassium hydroxide electrolyte. The reverse of these processes occur in charge, of course.

Until *circa* 1990, nickel oxide positive electrodes in commercial products were made in two main forms:

- Pocket plate electrodes with metallic nickel grids, which exhibit relatively long lives, particularly in float applications, are used in some vented NiCad cells and are relatively less costly;

- Sintered plate electrodes, also with metallic nickel grids, which are of much higher performance and give rather long lives, but which require electrochemical impregnation and the use of significant amounts of expensive cobalt chemicals, so they are relatively more expensive. Sintered plate electrodes are said to be the only type that show the well-known memory effect of NiCads.

Starting about 1990, largely as a result of work on NiMH batteries, some new types of nickel oxide electrodes began to become available. These are discussed in relation to NiMH, below.

While the performance and life of all types of nickel oxide electrodes is exceptionally good, their cost is significantly greater than for the positive active materials for other batteries included in the assessment. Nickel has been selling for about $4/lb in recent years, and there appears to be no reason on the horizon why it should not in the long term continue to go up rather than come down. For a NiCad cell at 1.35V OCV, 3.5 lb./kWh of nickel is required for the electrochemical reaction, and a further approximately equal amount is required for unusable active material, grids, and so on. Thus, a NiCad battery manufacturer must expend about $28/kWh for nickel, as opposed to the lead-acid case where the raw lead cost, now for both electrodes rather than just one, is $15-20/kWh. For NiH and NiMH batteries, the situation is slightly worse because the cell voltage is lower, 1.25 versus 1.35. Counterbalancing this a little, of course, is the fact that the scrap value of batteries with nickel oxide positives is somewhat higher than those for other chemistries, but given the “cost of money” this is not enough to offset the high first cost.

Charge acceptance (the ability of battery cells to be efficiently recharged) is very good for all types of nickel oxide electrodes up to about 80% SOC. Above 80% SOC there is the potential for an increasing amount of oxygen evolution from nickel oxide electrodes, particularly at temperatures above 40 C. (In NiMH batteries, this potential for oxygen evolution manifests itself as a sharp decline in the coulombic efficiency, since any oxygen incipiently evolved immediately reacts with hydrogen migrating from the other electrodes to the nickel oxide electrodes.) For some NiCads, it has been observed that there is virtually no acceptance of charge above 80% SOC if the temperature is over ~40°C. This implies that batteries with nickel oxide positives will have to be thermally managed on the high side in order to maintain good charge acceptance. On the other hand, the low temperature performance of batteries with nickel oxide positives is much better than it is for lead acid batteries, which means than less care has to be taken with thermal management on the low side. Nickel oxide electrodes can be overcharged at low rates without degradation. Occasional overdischarge at low rates is also not detrimental.

In the following sub-sections, we will give our assessment of three batteries that utilize nickel oxide positives, nickel/cadmium, nickel/hydrogen, and nickel/metal hydride. The development programs that led to the advanced technologies we will assess were stimulated in part by the electric vehicle initiatives in the United States and in France. A primary incentive for some of the underlying research work was, however, the growth in the market for batteries for portable electrical and electronic equipment.

4.2 Nickel/Cadmium Batteries

4.2.1 Characteristics

The overall discharge reaction in a NiCad is as follows:

$$2NiOOH + Cd + 2H_2O \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

The cadmium electrode is extremely well-behaved electrochemically. It will accept charge up to 100% SOC, and in overcharge will smoothly evolve hydrogen without degrading the active material. The electrode reactions occur without any great voltaic losses at almost all SOCs. Like nickel oxide electrodes, cadmium electrodes are constructed in several ways, most often in the past in pocket plate form and, more recently, in plastic-bonded sheets. The pocket plate electrodes are less expensive and lower performing than the plastic-bonded variety.

NiCads can be made either as flooded-vented cells or in a starved electrolyte, recombinant form. In either case, NiCads can be overcharged at low rates without degradation, although overcharging the vented cells for long periods will mean that the cells will have to be watered. With good voltage control during float charging, the requirements for water additions to flooded cells can be held to very low levels. Good voltage control is in any case needed for long strings of NiCads since otherwise, thermal runaway can possibly occur. Both types can be occasionally overdischarged without damaging the cells.

Cadmium is a metal of low abundance in the Earth's crust, but despite this it is not a very expensive metal, varying between $2-4/kg. However, many of it's compounds are extremely toxic, and as a result, the cost of NiCads is greatly impacted by the cost to safely process cadmium compounds. The recycling of NiCads is not only desirable but in many places is mandated. The recycling processes are themselves fairly expensive because of cadmium's toxicity.

There are a large number of NiCad manufacturers around the world, but the Saft company, headquartered in France, together with it's US subsidiary Saft America Inc., has been the most active organization in developing and promoting NiCads for applications requiring larger capacity cells. Saft has sold a large number of NiCads for aircraft starting and for UPS use, the latter mainly in Europe for backup power at critical installations such as air traffic control facilities. Saft has been the only supplier of batteries to date for various French EV programs, in which NiCads were the preferred choice until a couple of years ago. Saft have also developed and constructed several special NiCads for HEVs, most particularly those for the New York Consortium hybrid electric bus. (1) As a result of this extensive experience, information obtained from Saft on their NiCad batteries was used exclusively in the present study.

The characteristics of three separate NiCad battery options, which we thought before our analyses could conceivably be useful in one or other of the applications against which we are going to assess all advanced batteries, are shown in Table 4-1. All three cells described in Table 4-1 are prismatic and are designed to be operated in a vertical orientation. The values shown in the table for the two stationary cells were obtained from Saft on response to a request for information from them. The information on the HEV was extracted from a Saft publication. (1)

4.2.2 Assessment/Critical Evaluation

The cycle life and cost quoted by Saft for the recombinant, pocket plate cell is such that this does not appear to a good choice, in comparison with the baseline lead-acid batteries, for any of the applications discussed in Section 2. The cost per kWh of stationary-type flooded NiCad cells is clearly far too high to make them at all attractive for the distributed generation application, even with the long cycle life that is attainable. With regard to the other applications outlined in Section 2:

- PQ Enhancement + Peak Shaving: The flooded and vented stationary cell could perhaps form the basis of a design on a capital cost per year basis, i.e., $520/kWh and 20 years versus $200/kWh and 7 years cycles for the baseline, although the cost of money would somewhat counterbalance the longer life of the NiCads. However, the weight and volume of the NiCads would be significantly greater than that of

Table 4-1
Characteristics of Saft NiCad Batteries

	Stationary Sealed Cells	Stationary Vented Cells	Hybrid Electric Vehicle Cells
Technology	Recombinant with pressure relief valve, pocket plate electrodes.	Flooded and vented, sintered positive, plastic bonded negative	Flooded and vented, sintered positive, plastic bonded negative
Nominal cell voltage	1.35	1.35	1.35
Nominal disch. hours	5	5	1
Ah at nominal discharge rate	476	320	56
Average discharge volts at nominal rate	1.22	1.23	1.18
Average charge volts	1.45	1.5	1.7
Standby losses, %/day	0.25	0.6	~1
Cycles to failure (a)	900 at C/5 to 80% DOD	3500 at C/5 to 80% DOD	600k at 2C to 2% DOD (b)
Volume of cell, liter	19.0	11.4	Not specified
Weight of cell, kg	30.2	16.4	2.0
Useable energy, kWh	0.58	0.39	.066
Peak power at 0.8V at 50% DOD, kW	N/A	N/A	0.70
OEM price	\$460/kWh	\$520/kWh	\$1010/kWh, ~\$100/kW

(a) Notation such as C/5 indicates discharge at a current equivalent to discharge the Ah capacity of the cell in 5 hours. DOD is acronym for depth-of-discharge.

(b) Accelerated life tests were performed, at 40 C and with a higher duty cycle than required by the application

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VRLAs which were used for the baseline design. There would also be a far greater number of modules required, i.e., 25,000 versus 3,000. As a result of all these considerations, we do not believe that the NiCad used for our assessment is a good choice for this application.

- Arc Furnace ACE Regulation with Saft NiCad HEV cells: From the perspective of the life that has been demonstrated to date, the Saft NiCad HEV cell appears to be a good choice for this application, since the cycle life is projected, on the basis of accelerated testing, to be so high at shallow depths of discharge. On the basis of the cycle life and other information that has been presented, we estimate that at 20% DOD, the NiCad HEV cells would last for about 3.5 years, **if** the deeper cycles do not adversely impact the equivalent number of 100% DOD cycles, i.e., (600,000 2%DOD cycles) x (2%DOD) = (12,000 100%DOD cycles), that can be sustained. However, the capacity of this cell is so small that an enormous number of cells (380,000 versus 40,000 for the baseline design) would be required. The estimated cost of the NiCad HEV cells for this application is $25 million, versus $12 million for the baseline. The HEV cell is clearly not a good choice for this application.

- Arc Furnace ACE Regulation with Saft NiCad stationary vented cells: With these cells, a DOD of 10% would have to be used to attain a three year life for the cells (i.e., the same as the lead-acid baseline) if it is assumed that with shallow depths the equivalent of 5000 100% DOD cycles can be achieved. This assumed cycling capability represents some modest optimism given that 3,500 cycles at 80% DOD have been achieved to data. With a DOD of 10%, the estimated initial capital cost for the ~128,000 cells to provide the energy for ACE regulation is estimated to be ~ $26 million. While this is significantly more than the $12 million estimate for baseline, and the number of cells is greatly increased, the unknowns and uncertainties in the baseline, as compared to a stationary-vented NiCad, may make this worthy of further investigation. It is very roughly estimated that the weight and the volume of the cells, in this case, will be about half that of the baseline, making this another reason to further investigate the NiCad option.

- Transmission Line Stabilization: Given that this is more like a float application, and recognizing that NiCads can be allowed to stand at a partial SOC without degradation, this is an application for which stationary sealed (pocket plate) cells might be considered. Assuming these cells will last for 20 years in this type of occasional, very shallow discharge, and that they will deliver power for short (one-second) periods at the 2C rate, then from Table 4-1 the cost/life of these cells is projected to be ~$12/kW per year. Even with these optimistic assumptions, this is clearly not a good application to consider for NiCads.

In summary then, it appears that the stationary vented version of Saft NiCads, although projected to be more expensive and requiring a much greater number of cells than the lead-acid baseline, could have a higher probability of meeting the cycle life requirements for arc furnace ACE regulation. The ~128000 cells that we estimate would be required could be arranged in an array of, say, 8000 in series and 16 in parallel. The larger number of cells in series relative to the baseline design reflects the 0.8V/cell discharge voltage at which the power for ACE regulation is delivered by the battery.

Below is a list of the issues that we identified during our critical evaluation of NiCads for applications in restructured electric utilities. Of course, since NiCads are already sold in fairly large numbers, there are no “show stoppers” for this technology. There will be resource limitations with regard to cadmium, and to a lesser extent for nickel, if a large, world-wide, market for utility-scale batteries developed, but we think this is very unlikely given the high costs of NiCads. The issues for NiCads in the ACE regulation application are:

- There would have to be a very large number of cells in series in each string and this could lead to reliability problems that could require costly control circuits. With the high voltage strings, there is a some likelihood that ground faults will cause problems during start-up, and perhaps during operation but less so. Note that a greater number of NiCad cells are required in series for a given DC bus voltage, relative to lead-acid.
- The expected weight and volume of the cells implies that this is a system that could only be implemented at sites where significant land area is available, although early estimates indicate the land area requirement is less than that for the lead-acid baseline.
- There is some degree of uncertainty regarding the number of cycles that the NiCads will have to sustain to justify the investment in them, but we believe this is less than for lead-acid batteries.
- Thermal management will be needed on the high side to ensure the cells operate properly and have the expected life-time.
- Extra controls will be needed to ensure that all the cells are properly charged between ACE regulation discharges, that overcharge is properly limited so as to minimize water loss, and that there are no problems with thermal runaway in any of the cells.
- Occasional conditioning cycles may be needed to alleviate any problems resulting from the NiCad memory effect. (The instantaneous reserve cycles included in the application may be just what’s required for conditioning the cells.) While arranging for the conditioning cycles could be a problem, the fact there will be multiple strings in the battery plant should make it easier to ensure the necessary conditioning takes place at appropriate times.
- Auxiliary systems for cell watering and vent gas management will be required, with some additional costs.
- As in the baseline case, sectionalizing switches will be needed in each string to ensure the battery system can be assembled and maintained in a safe fashion.

As a non-technical comment, we would like to note that we think there will be, at best, a limited market for NiCads in utility energy storage. This is because of their high cost and the limited availability of materials.

The conclusion we reach from our analysis and critical evaluation of the Saft NiCad technology for restructured utility applications is, therefore, that this is a technology which, compared to the baseline design, appears to offer a higher probability that the cycle life we think is required by the economics will be met, albeit at a somewhat higher cost. As a result, and because Saft have indicated that they would be interested in doing so, we recommend that the possibility of a co-funded development project should be explored. We believe this project should initially be limited in scope to a more detailed examination of their technology for possible use in the arc furnace ACE regulation application.

4.3 Nickel/Hydrogen Batteries

4.3.1 Characteristics and Scoping Assessment

Nickel/hydrogen (NiH) batteries were invented in the late 1950s to provide a need in the nascent aerospace industry for moderate weight, very long-lived, reliable, robust, and abuse-tolerant batteries that would be cyclable without special conditioning cycles. The NiH battery is a hybrid of the sintered nickel oxide positives from NiCads and the hydrogen electrodes of alkaline fuel cells. Alkaline fuel cells were the power source of choice for aerospace missions in the late 50s and early 60s, and in fact have remained so. The hydrogen electrodes in fuel cells had already been proved to have a very long life by the time of the conception of the NiH battery. The overall discharge reaction in a NiH battery is as follows:

$$2NiOOH + H_2 + 2H_2O \rightarrow 2Ni(OH)_2$$

Note there is no change in the composition of the electrolyte in NiH batteries during cycling. However, during charge, hydrogen gas is generated, so, in the hermetically sealed cans in which the NiH cells are contained, the pressure rises. Maximum container pressures of the order of 750psig (~5000 kilopascals) are used to store the hydrogen gas for discharge in NiH batteries. The hydrogen pressure in the cell container at the end of discharge is approximately 100psig (~700kPa). The pressure is a direct measure of the state of charge of a NiH cell.

Both electrodes in NiH batteries are electrochemically very well-behaved. As presently built, NiH batteries will accept charge and can be discharged at relatively high rates. Like almost any other battery, they could be designed to discharge at very high rates at the expense of more weight, volume and cost per kWh of energy stored. NiH cells can be overcharged and overcharged almost indefinitely without damage, because there are side reactions that can take place to handle the anomalous conditions. In fact, the major side reaction that takes place, the reaction of hydrogen with the nickel oxide of the positive electrode, is one the major disadvantage of NiH batteries for terrestrial applications. This side reaction leads to a significant self discharge, as much as 15% of the capacity in the first 24 hours after charging, in NiH cells. However, it is an inherent feature of NiH cells that they can be cycled at partial states of charge indefinitely without degradation.

NiH batteries have been used to provide power during eclipses of solar powered communications satellites, and the like, for many years now. It has been shown that these batteries can be deeply cycled tens of thousands of times, and that they will perform without problems for ten and perhaps for as long as twenty years.

With this set of highly desirable characteristics, it is hardly surprising there have been several projects to try to make terrestrial versions of the technology. The greatest difficulty with this is that the cost of these aerospace quality batteries is said to be over $10,000/kWh, i.e., two orders of magnitude higher than desirable for utility applications. Some part of the high cost of NiH batteries is associated with the quality assurance and testing that must go into anything that is going to be spent into space. This can clearly be greatly reduced for terrestrial batteries, but care must be taken that it is not reduced to the point where the reliability of the product is compromised. A second factor causing high cost is associated with the design of NiH space batteries, which have individual cell containers, and a third factor is the amount of platinum that is used on the hydrogen electrodes. In projects conducted by Johnson Controls (a major battery manufacturer) and Eagle Picher (an aerospace supplier and at present the main manufacturer of NiH batteries in the US) in the 1980s, these cost issues were addressed. However, it was never possible to convince potential customers that the costs of NiH batteries, even with their very long life, would be affordable for terrestrial applications. In a more recent project, EECI (the contractor that performed the work reported on here) did a brief study for DOE to see if it might be possible to use specially designed, short discharge time, very long life, NiH batteries as the energy storage component of HEVs. (This is the type of battery that might be useful for the transmission line stabilization application, or possibly the arc furnace ACE regulation application, in restructured utilities.) Although this study showed that it was plausible that such a battery could be economically competitive, no developer was willing to take the risk of developing such a battery. A recent follow-up as part of the present work showed that no further work was planned on this NiH approach for HEV energy storage.

An additional issue with terrestrial NiH batteries is that they contain high pressure hydrogen. We think that this may be a considerable impediment to the commercialization of this technology for terrestrial applications.

Our assessment of the NiH technology is therefore, that in the form described above, this technology should not be given further consideration for restructured utility applications. Basically, after reviewing the available information we believe that a NiH battery with an energy to power ratio of one or more will never even approach the cost necessary for utility applications, and that it is very unlikely that a low cost, short discharge time battery will be developed in the time period of interest for the present study, if ever. However, there is a modified version of the NiH battery that could perhaps address the limitations of the aerospace technology, this being under development by Ergenics. The Ergenics technology will be assessed in the next sub-section.

4.3.2 Ergenics Technology, Characteristics and Assessment

The Ergenics version of the NiH battery, called by them the Nickel Hy-Stor™ battery, employs metal hydrides to store the hydrogen, instead of using pressurized gas. Ergenics is a privately-held company established in 1984 by acquiring from INCO (formerly the International Nickel Company) the research group working on, and the intellectual property related to, gas-metal interactions. The metals of interest to Ergenics are nickel alloys, since producing and selling nickel was and still is Inco's main business. One of the technologies that Ergenics acquired was the storage of hydrogen using the hydrides formed by nickel alloys. Ergenics later expanded this interest in hydrides to silver/hydrogen and more recently to NiH batteries.

The Ergenics technology is **<u>not</u>** a nickel/metal hydride battery (these are discussed in the next sub-section) but a nickel/hydrogen battery in which the hydrogen, stored as a metal hydride, is in a container separate from the electrochemical cells. (2) In fact, there is a reversible dryer for the hydrogen passing between the cells and the storage container with the metal hydride. The metal alloys used for the hydride storage are of the AB_5 type, where the "B" component is mostly nickel. The "A" component is a mixture of metals which Ergenics keeps proprietary. The AB_5 alloy contains about 1% hydrogen by weight at full charge. Ergenics prefers the AB_5 type alloys rather than the AB_2 type, because the latter are pyrophoric, although they do permit hydrogen storage up to 1.6% by weight. There is a 25% volume expansion of the alloy and heat is evolved as the hydride is formed, both of which factors must be handled in the design of the hydride container.

There is also a valve in the pipe between the cells and the storage container, which is only opened when the battery is charging and discharging. This keeps the self discharge loss to a minimum in Ergenics' cells. The use of the hydride rather than pressurized gas to store the hydrogen means that the pressure change during cycling is much lower than in NiH batteries, and the pressure at the top of charge is also lower. In fact, the temperature of the metal hydride is allowed to vary, in a controlled way, during charge and discharge, so there is only a relatively small variation of the pressure during most of a cycle. The pressure depends on the alloy and the operating temperature range chosen for the specific battery design, but is generally in the range of 0.5 to 3 absolute atmospheres.

Ergenics purchases sintered and impregnated nickel oxide positives, but make their own negatives. The negatives consist of a fibrous nickel substrate with nickel particles and platinum catalyst coated on it. The platinum loading is presently 1-2 mg/cm^2, although Ergenics would like to get this down to 0.1 mg/cm^2, as others, working on hydrogen electrodes for alkaline fuel cells, have been able to do. Ergenics have shown their cells perform in much the same way as those in NiH batteries, showing very long cycle and calendar life, and being cyclable from all states of charge and discharge without degradation in performance. For example, in testing of a 0.8Ah single cell, 50000 cycles to 5% depth were performed before about 20% degradation in performance was observed. The cells can also be overcharged and overdischarged without degradation, which means that many cells can be placed in series with a minimum of controls.

Ergenics have received funding from a variety of sources, and among the projects they presently have underway are included:

- A DARPA funded effort to develop, build and test a 20 kWh, 120 kW bipolar battery potentially for use in military HEVs. This battery was scheduled to be under test in the 2nd quarter of 1998.
- An effort funded by unspecified offshore industrial and utility partners to develop a 360Ah, 22-cell sub-module for utility battery energy storage. The sub-module is intended to be one of 12 in a 25kW, 4 hour module that the design shows will be 1140mm x 610mm x 845mm high. The sub-module was in development in early 1998. The cost for modules of this type, assuming production of 100, 1MWh units per year, has been estimated by Ergenics to be $550-600/kWh, including the power conversion equipment for a 4 hour discharge and subsequent charge, but excluding installation costs.
- An effort with an industrial partner to develop, build and test 80-115Wh/kg, spiral wound, cylindrical cells for electric bicycles. Many of these cells have been built and are under test at Ergenics. A high power version of this cell is under development for possible use in power tools.

Given this broad range of alternatives that Ergenics has under development, the company was asked the type of module they would suggest for use in the applications against which advanced batteries are being assessed in the present study. Table 4-2 shows the information received in response to this request. The nominal values in the table are based on a cell voltage of 1.25V. It is important to note with regard to this table that the information does not relate to hardware that has been built and tested, but the information comes from projections made by Ergenics based on the work they have underway with the sponsors listed above. The weights and volumes of these batteries remain to be determined after designs have been refined, but they are expected to be both smaller and lighter than lead-acid batteries of the same capacity, by a factor of very approximately 2.

With respect to the pseudo-bipolar cell-stack hardware that Ergenics has actually tested, the following information was received from the company. A 12-cell (15V), 2.8Ah bipolar stack is under test at Ergenics as part of DARPA project mentioned above. This stack has 129mm (4.9inch) circular electrodes, mounted in frames, and sealed in a stack using a bolted frame and O-ring approach. The cylindrical stack is approximately 8 inches long. The arrangement is termed pseudo-bipolar since the intercell electrical contacts are not continuous across the plates, but are made around the edges so that passages are formed to pass hydrogen gas to and from the electrodes and the hydride storage container. This stack has been shown to deliver 2.7Ah at the 4-hour rate, 2.3Ah at the ½ hour rate, and 2.2Ah (at an average of 12.5V) with a 16A discharge, i.e., the 5.7C rate. Pulsed current discharges at 8C (25A) can be sustained at over 12V for 90 seconds at 60% DOD.

No life estimates were given for these designs by Ergenics, but on the basis of other testing by this developer and by others on NiH cells, we think that the cycle life, possibly 10,000 deep cycles or more, could make these batteries attractive for the utility applications we are using to assess advanced technologies. However, it will probably be the calendar life that will be limiting, rather than the cycle life, for all the applications being considered in this study except for arc furnace ACE regulation. For the calendar life we think 10 years is probable and perhaps as long 20 years is possible. Where needed, we will use the intermediate value of 15 years for the life of Ergenics modules for our assessment.

Table 4-2
Projected Characteristics of Ergenics NiH with Hydride Storage Modules

	Monopolar	Pseudo-Bipolar
Nominal module voltage	50 V	150 V
Nominal cell capacity	360Ah, 0.45kWh	15Ah, 0.019kWh
Nominal discharge rate	C/3	C/1.5
Cell geometry	Prismatic	Circular pseudo-bipolar
Average charge voltage	1.48 V/cell	1.44 V/cell
Average discharge voltage	1.26 V/cell	1.20 V/cell
Number of cells in series in module	22	120
Number of modules in series in battery system	10	4
Number of modules in parallel in battery system	1	6 to 8
Self discharge	3% in first few hours then none if valve closed	3% in first few hours then none if valve closed
Round trip DC-DC efficiency during partial DOD cycling	85%	80+%
Module capacity	99kWh	2.25kWh
Battery system capacity	990kWh	13.5 to 18kWh (TBD later)

Note that no costs were submitted by Ergenics in relation to the hardware projections of Table 4-2. We will assume that the cost of the monopolar battery will be the same as the Ergenics cost estimate for a utility battery given above, i.e., $550-600/kWh or ~$40/kWh per year of life. We think the cost of the bipolar battery could be considerably higher than this, because it's higher power capability implies greater electrode area and therefore increased costs for the acquisition of parts. This implies a lower active material loading per plate, i.e., more electrode area, and therefore more cost/kWh. A very rough estimate of $1000/kWh, ~$70/kWh per year of life, will be used for the assessment of this technology. (We chose this estimated cost in part because of the value estimated by Saft for the high-power NiCad HEV battery discussed in the preceding sub-section.) We will assume the bipolar battery system of Table 4-2 can be discharged in pulses of a few seconds duration at the 8C rate and more-or-less continuously at the 5C rate, each at 1V/cell, as has been shown by

Ergenics for smaller stacks. Then, if the development of the 18kWh bipolar system is successful, it should be capable of ~115kW for short duration discharges and ~72kW for long duration discharges. These power capabilities equate to ~$160/kW (~$10/kW per year of life) for second long discharges and ~$250/kW (~$17/kW per year of life) for longer duration discharges.

A superficial comparison of the cost/life for the Ergenics technology with the values estimated for the baseline designs in Section 2, reveals that the only application for which the technology might be competitive is arc furnace ACE. Since in this application it is life and DOD that are the determining design factors, the monopolar design with lower $/kWh costs is our choice for an outline design. Assuming development of the monopolar module is successful, that lives of 10000 100% DOD cycles continue to be attained, and that the life of Ergenics cells is linearly dependent on DOD, then a DOD of 20% would lead to a life of 3 years (~50000 cycles at two per hour, 24 hours per day) in the arc furnace application. In fact, we think it may be possible that the life of Ergenics NiH cells will considerably exceed 3 years in this type of use. With 20% DOD, there still should be adequate energy available for instantaneous spinning reserve service, although not for as long a period as in the baseline case. According to the estimates given above, the cost for Ergenics monopolar battery modules for the arc furnace application with a 20% DOD would be ~$15 million, versus ~$24 million for the baseline battery.

It would take ~250 Ergenics monopolar modules (each 99kWh nominal, used to ~20kWh depth for ACE regulation, with 22 cells in series at a nominal 50V, see Table 4-2) for a battery system for the arc furnace ACE regulation application. The battery system arrangement proposed by Ergenics involves the use of 10 modules in series. It would require 20 such systems in series for the nominal DC bus voltage of 10000V or a total of 220 modules. Clearly, 220 is close enough to the 250 we estimate are needed to attain the minimum life required as to be within the margins with which the estimates can be made.

Our overall assessment and critical evaluation of the Ergenics technology is as follows:

- It appears that Ergenics monopolar modules, if successfully developed, could be a very attractive option for the arc furnace ACE regulation application, since the projected cost per year is about half that of the baseline lead-acid battery.

- The cycle life results obtained so far are very promising, but the very long cycle life capability of Ergenics cells must be verified in large cells before the promise of the technology can be confirmed.

- The requirements for control circuits to handle reliability problems in high-voltage battery strings should be far less onerous for the Ergenics battery than for most of the other batteries discussed in this report, because of the proven high reliability of

NiH cells and because of the bipolar stack arrangement. There should also be less problems with ground faults because the cells are hermetically sealed.

- It is too early to be able to accurately predict the weight and volume of Ergenics batteries, but for the arc furnace application these could be as much as ten times smaller and lighter than for the baseline lead-acid.
- Thermal management will probably be needed on the high side to ensure the cells operate properly.
- Nickel/hydrogen cells are particularly advantageous compared to other batteries with respect to overcharge, overdischarge, and partial DOD cycling. Unlike NiCads, no memory effect problems have been reported for NiH cells.
- There is a significant self discharge rate at full charge that is held to <3% per charge by the use of a valve between the cell stacks and the hydride storage. Use of such a valve will probably not be possible for the transmission line stabilization application, since discharge energy must be instantly available. However, the valve will not be needed for the arc furnace application since the battery will be continuously cycling.
- Ergenics batteries are fabricated in the discharged state and can be completely discharged, to zero volts, so there could be lower requirements for the sectionalizing switches that are otherwise needed for safe assembly and maintenance.
- The pressure of hydrogen in the storage portion of the battery, although much lower than in NiH cells, could still be problematical in large installations.
- The amount of platinum used in Ergenics cells is rather high, and must be reduced from both an availability and a cost perspective, if a market of any consequence is to develop for this technology.
- There is little likelihood that hardware, sized appropriately for utility applications, will be available for a sub-scale demonstration in five years. This is because the present hardware must be scaled-up, both in electrode area and in number of cells per stack, by too great an extent.
- Ergenics has indicated that, as a small, privately-held company, they do not have the resources to be able to co-fund development work for utility applications with EPRI.

It appears that the Ergenics technology could, with much more development, be an attractive candidate for the arc furnace ACE regulation application, but at a time that is beyond our 5-year window for detailed assessment. As a result of this conclusion and our evaluation above, we recommend that means to have a project at Ergenics funded solely by EPRI be explored. Since Ergenics already has projects funded by other organizations to develop larger, commercializeable batteries underway, any EPRI funding project could be relatively small and highly leveraged. A detailed, auditable cost and design analysis of an Ergenics battery for arc furnace ACE regulation would appear to us to be the most appropriate initial EPRI project.

4.4 Nickel/Metal Hydride Batteries

4.4.1 Description and Characteristics

Work on nickel/metal hydride (NiMH) batteries started in the mid-1980s when it became clear that there would be a rapidly growing market for improved batteries for portable electronics, particularly portable computers. The extremely long-life and high performance, relative to NiCads, of nickel/hydrogen batteries were already well known, and it was recognized that a superior means of hydrogen storage, at the electrode surfaces if possible, could lead to a superior battery. A variety of metal hydrides that would act as the negatives of cells with nickel oxide positives were quickly developed, and in a few years NiMH batteries for portable electrical and electronic equipment began to appear.

Around 1990, the California Air Resources Board began an initiative to try to make sure that electric automobiles would begin to become available in those parts of the state that most suffered from poor air quality. This, and similar initiatives in other states, led the US automakers to form the United States Advanced Battery Consortium (USABC) with the Department of Energy and EPRI. The initial goal of the USABC was to develop EV batteries that would help make the California initiative a reality. Later, with the formation of the Partnership for Next Generation Vehicles (PNGV) to develop technologies for advanced electric hybrid vehicles (HEVs), the USABC expanded it's goals to include batteries for HEVs. A good part of the development work on large NiMH batteries in the current decade, except for that going on in Japan, has been funded through various USABC projects, with a significant part of funding having been provided by the battery developers themselves. In the "Assessment" part of this NiMH battery sub-section, below, we will only address the characteristics of batteries developed under USABC and/or PNGV auspices, i.e., batteries developed by Saft (3) (see above under NiCad) and the Ovonic Battery Company. (4) Ovonic was formed as a subsidiary of Energy Conversion Devices, Inc. (ECD) to develop NiMH batteries based on the "disordered materials" originally invented by ECD's founder Stanford Ovshinsky. Other major battery manufacturers, such as Varta in Germany and Panasonic in Japan, have NiMH technologies that are similar in performance and life to those of Saft and Ovonic, so these will not be discussed further here.

Nickel/metal hydride batteries are electrochemically very similar to nickel/hydrogen batteries. However, the hydrogen generated during charge of a NiMH cell is absorbed by a metal alloy, forming a hydride, which is part of the negative electrode. As with other NiH batteries, the potassium hydroxide electrolyte is absorbed in an inert, porous separator material and is thus both immobilized and starved. The positive electrode is one of the forms of nickel oxide electrodes discussed in the Overview to this section. Each of the intending manufacturers of NiMH batteries have developed their own proprietary approaches for positive electrodes, but as far as we can tell, they all use some proportion of cobalt, with the high costs that is associated with the use of this metal, in their formulations. The negative electrode consists of metal alloy hydride compacted onto a conducting metallic (generally nickel) grid. Thus, the hydride-forming metal alloy is exposed to the electrolyte and to humid hydrogen gas. For this and other reasons, the life of NiMH batteries is a lot shorter than the nickel/hydrogen or Ergenics batteries discussed above, being generally of the order of 1000 cycles and 3 to 5 years. The discharge reaction in a NiMH cell are as follows:

$$NiOOH + MH + H_2O \rightarrow Ni(OH)_2 + M$$

- where M represents the hydride-forming metal alloy, and MH the hydride itself. There is some volume expansion of the alloy, perhaps as much as 25%, and heat is evolved, as the hydride is formed. The volume expansion and the heat evolution must be addressed in the design of NiMH cells, of course. The pressure rises during charging, as the hydrogen evolved is absorbed into the alloy as hydride, but as discussed in the preceding sub-section, the pressure rise is a small fraction of that in NiH batteries, generally being in the range of from atmospheric up to ~50 psig (350kPascals) at full charge. The pressure depends on the temperature so controls are necessary to make sure the pressure does not get too high. Large NiMH batteries are equipped with pressure relief valves set for 100 psig (700kPascals) or so.

A variety of alloys have been used, with most developers using the AB_5 type and Ovonic using the AB_2 type. (See discussion of Ergenics battery above for as summary of the metal hydrides.) The exact composition of the alloys used in specific batteries is kept proprietary by their developers. The AB_2 types contain very approximately 1% hydrogen by weight at full charge. It is thought that the “B” component of the alloys used by nearly all developers is mostly, but not exclusively, nickel. We think that the “A” component is generally mixture of metals, which can include lanthanides, i.e., rare earth metals, the lanthanides sometimes being the less expensive mixture of rare earth metals called Mischmetal; or titanium/zirconium-based alloys. AB_5 type alloys, with the same variety of metallic components as in the AB_2 types, which contain about 1.6% hydrogen by weight when fully hydrided, have higher chemical reactivity than the AB_2 types. This may account for the shorter life of Ovonic’s cells relative to other manufacturers. For either type of alloy, the cost of the metals, and of processing them to a form that is useful for NiMH batteries, is a concern to developers of the technology. In fact, the costs of the alloys for NiMH batteries is comparable on a weight basis with the costs for the cadmium chemicals that are used to manufacture NiCads. Since NiMH batteries have a higher specific energy, they are expected to be slightly lower in cost than NiCads.

Ovonic has been particularly active in the development of new hydride-forming alloys, (5) and the mark of their success in this area is that their NiMH EV batteries have a higher specific energy and energy density that other developers working in this field. In fact, as a result of their earlier research in this field, Ovonic licenses 16 manufacturers of NiMH batteries for use in portable electrical and electronic equipment. According to some recent patents, Ovonic claim to have invented hydride-forming alloys that have a higher weight fraction of hydrogen at full charge and that exhibit less volume expansion on hydride formation than other alloys. There are some Ovonic alloys that are said to be electrochemically active themselves, as opposed to having hydrogen gas as an intermediate in the hydride formation and decomposition, so that slightly higher OCVs (100mV or so) are observed for cells with hydrides of this type. These advanced Ovonic alloys have not yet been incorporated into the pre-production EV batteries that are being built, as far as can be determined.

Apart from the basic electrochemistry, there are other characteristics of NiMH batteries that are very similar to NiH. NiMH batteries can be overcharged and overdischarged without degrading the cells, thus making it far easier to string many cells in series than it is for many other battery technologies. There is also a marked drop in coulombic efficiency towards the top of charge, when the hydrogen pressure reaches it's highest levels. Then, an increasing fraction of the hydrogen migrates to the positive plates and reacts there with the nickel oxide in a self discharge reaction that is identical to the discharge reaction given above for NiH cells. Although the self discharge rate depends on the specifics of the cell design, it is of the order of 5% at a temperature of 25 C in the first day of stand following a full charge, and can be as high as 10%/day at 40 C.

Great advances have been made in NiMH batteries over the past decade, to the point where a number of auto manufacturers have announced their intention to use this type of battery in their EV offerings. Pilot manufacturing facilities have been established by Ovonic (through a joint venture with GM) and by Saft, among others. The specific characteristics of Saft's and Ovonic's NiMH batteries are discussed in the next sub-section of the report.

4.4.2 Assessment and Critical Evaluation of Saft and Ovonic Technologies

The characteristics of three different types on NiMH batteries are shown in Table 4-3. The characteristics for the Saft battery were sent to EECI in response to a query concerning the performance of their batteries, while the ones for the Ovonic batteries were extracted from several articles (4, 6) that this company has published. Note that both NiMH developers design batteries on the basis of a single cell approach (rather developing a multi-cell module with internal intercell connections), because this allows maximum flexibility in putting together a variety of module designs for various EVs. The EV cells are packaged in modules of 5 to 14 cells with interconnections between the cells being external to cells themselves. In EVs, single strings of cells, in general, make up the battery of 300V or thereabouts.

Table 4-3
Characteristics of Saft and Ovonic Nickel/Metal Hydride Batteries

	Saft EV Battery	Ovonic EV-90	Ovonic HEV
Nominal cell voltage	1.2	1.2	1.2
Nominal discharge hours (rate)	2	3	3
Ah at nominal rate	96	90	60
Average discharge voltage	1.23 V/cell at C/2	1.25 V/cell at C/3	0.88 for 10 s, 9C discharge pulses
Average charge volts	1.40 at C/3	1.4 at C/3	1.29 V/cell for 10 s, 9C charge pulses after 9C discharge pulses
Standby losses (a)	5% 1st day at 23°C 0.3%/day in 3 months	5% 1st day at 23°C 0.3%/day in 3 months	5-10% 1st day (b)
Cycles to failure, <80% of capacity	1200 at C/2 to 80% DOD	600 DST (c) cycles 800 cycles to 80% DOD	600 DST (c) cycles 800 cycles to 80% DOD
Calendar life	6 years (d)	5 years (d)	5 years (b, d)
Cell weight, volume	1.8 kg, 0.84 liter	1.6 kg, 0.68 liter	0.93 kg, 0.84 liter
Module energy density	140 Wh/l	165 Wh/l	170 Wh/l
Module specific energy	65 Wh/kg	70 Wh/kg	70 Wh/kg
Useable energy	0.118 kWh	0.113	.066
Peak power	0.25 kW for 30 sec. above 0.9V at 80% DOD	0.27 kW for 30 sec. above 0.8V at 80% DOD	0.59 kW for 10 sec. above 0.9V at 50% DOD

(a) Standby losses decrease exponentially with time from the end of charge, being rather high initially but falling to a relatively low level during the first few months after charging.

(b) Assumed to be approximately one-third worse than for EV cells, because of greater electrode area resulting from lower active material loading on plates. However, improved technology, giving better performance, was used in the prototype cells, so it will be assumed for our analysis that the HEV cells will cost 33% more, but last as long a time and for as many cycles as the EV cells.

(c) DST cycles are dynamic stress test (EV) cycles. In other testing, one-third more C/3 80% DOD cycles than DST cycles have been shown to be sustained before failure.

(d) Estimated from private communications with a variety of sources.

The characteristics for the EV cells listed in Table 4-3 refer to pilot production designs. Both Ovonic and Saft have been seeking improvements to their EV cells, and Ovonic in particular has reported some success in reducing the weight and volume in prototype EV cells. (6) Weight and volume reductions that translate to improvements in the energy density and weight by approximately 30% and 12%, respectively, have been reported. It is cells of the more advanced type than were used by Ovonic to build the pre-prototype HEV module the results of testing on which are shown in Table 4-3. The specific power capabilities of the HEV module are quite impressive, and this performance seems to have been achieved without sacrificing specific energy, because of the improvements in the technology that have been incorporated into these cells. Of course, it remains to be seen if these improvements can be smoothly incorporated into the GM Ovonic pilot production facility. Saft was informed of the uses to which it was intended the batteries on which we requested information from them might be put, but they have not made us aware of any information on an HEV version of their NiMH technology in a stage of development where it can be discussed in terms of restructured utility applications.

Neither Saft not Ovonic have recently made any announcements with regard to the absolute costs for their NiMH batteries. Information on the subject of costs of NiMH batteries is generally given in very broad terms. An analysis of some of the materials released when it was announced that GM Ovonic batteries would be made available as an option for GM's EV1 car, and other documents, indicates that the OEM price for the NiMH EV batteries will be about $450-500/kWh in early production and perhaps as low as $250-300/kWh in large scale production. These are prices that also seem to be consistent with the cost of NiCads, with which we believe the discussions in this section and above show NiMH batteries bear many similarities from a cost perspective, and which are already made in quite large numbers so that manufacturers have a good handle on costs.

The higher ends of the price ranges given above are associated with Saft's NiMH batteries, which use sintered nickel electrodes with electrochemical impregnation for the positives, and the lower end of the range with Ovonic batteries, which are lighter in weight than Saft batteries, and which are said to utilize lower cost techniques for manufacturing the positives. It is quite likely, in our opinion, and as discussed above for NiCads, that the cost of NiMH HEV batteries will be higher on a per kWh basis than for EV batteries.

In the absence of firmer numbers from developers, the following will be used for the OEM prices for the batteries characterized in Table 4-3, in production quantities of 10MWh/year or more:

- For the Saft EV battery: $300/kWh, which translates to $50/kWh per year of life or to $24 per peak kW per year.

- For the Ovonic EV battery: $250/kWh, which translates to $50/kWh per year of life and $21 per peak kW per year.
- For the Ovonic HEV battery: $330/kWh, which translates to $66/kWh per year of life and $7 per peak kW per year.

If these estimated OEM prices, together with the cycle lives given in Table 4-3, are compared to the costs and lives for the battery cells of the baseline designs given in Table 2-2, it becomes clear that NiMH batteries are unsuited for any of the applications being considered in this assessment. For the transmission line stabilization, the PQ enhancement plus peak shaving, and the distributed generation applications, the projected cost/life of NiMH cells is significantly greater than those for the baseline designs.

For the arc furnace application, the Ovonic HEV version of the NiMH technology **superficially** appears extremely attractive, while both the Saft and Ovonic EV technologies **superficially** appear close to competitive in OEM price to calendar life ratio. However, like the lead-acid baseline design, life will be limited by the cycling capability rather than by the number of years of service, so a DOD must be chosen such that the battery cells will last a reasonably long time, as now discussed.

For many battery chemistries, but not lead-acid, the total possible Ah throughput before failure according to a given criteria is, to a first approximation, independent of the DOD of the cycles. Thus, for Ovonic NiMH cells, it is expected that ~13,000 cycles to 5% DOD will be equivalent to the estimated cycle life of 800 cycles to 80% DOD. For Saft NiMH cells over 19,000 cycles to 5% DOD should be achievable. However, for the arc furnace ACE regulation application, there will be two 5MWh discharges per hour 24 hours per day, and an equivalent number of charges, of course, for a total of 17,520 "cycles" per year. Like the lead-acid case, therefore, the design for this application is driven not by the power requirement but by the capacity of battery required so that batteries do not have to be changed out too often. Even if a DOD of 5% is chosen for NiMH batteries, they would be expected to last approximately one year. With a DOD of 5%, the cost of a 5MWh battery would be $25 million for the Ovonic EV battery, $30 million for the Saft EV battery, and $33 million for the Ovonic HEV battery. The life of the Ovonic batteries is expected to be slightly less than one year, while that of the Saft batteries should be slightly over a year. This should be compared to an estimated life of 3 years and a total cost of $24 million for the lead-acid baseline.

Apart from their costs, NiMH batteries appear quite attractive for utility energy storage, as can be seen from the following issues raised in our critical evaluation of the technology:

- High-voltage battery strings should be easier to handle with NiH cells because the cells are sealed except for the pressure relief valve. However, it must be noted that a greater number of cells are required in series for a given DC bus voltage, because of the lower cell voltage of NiMH relative to lead-acid.

- The weight and volume of NiMH batteries should be less than half that for the baseline, a very significant benefit.
- Potentially expensive high-side temperature control will be necessary to avoid difficulties with charging the nickel oxide positives and to keep self discharge losses to an acceptable level.
- The self discharge rate at full charge for NiH cells is of the order of 5% the 1st day, so coulombic losses with continuous cycling could be significant. On the other hand, the voltage efficiency of NiMH cells is as good or better than lead-acid cells. On the other hand, there is a greater difference between the top-of-charge OCV and that at bottom of discharge for NiMH that there is for lead-acid, which could have an impact on the cost of power electronics.
- Overcharge, overdischarge, and partial DOD cycling are all possible without degradation for NiMH cells, and there is no memory effect as far as has been reported.
- NiMH batteries can be completely discharged to zero volts without damage, so fewer sectionalizing switches should be needed for safe assembly and maintenance, with a small but significant cost benefit.
- The pressure of hydrogen in NiMH cells could be raised as a safety issue for large batteries, although we think it is more a “competitive” issue than anything.
- There is a relatively high degree of uncertainty with regard to the cost and life of NiMH batteries, as they might be applied in utility situations.

Despite these advantages, we recommend that EPRI only maintain a watching brief on NiMH batteries, and do not pursue any co-funded development projects for utility applications on this technology.

4.5 References

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(5) "Enhanced charge retention electrochemical hydrogen storage alloys and an enhanced charge retention electrochemical cell", S. Ventakatesan, et al, US Patent 4728586, 1988

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5

FLOW BATTERIES

5.1 Overview

Work on flow batteries, in which some or all of the reactants and products of the electrochemical reactions are pumped to and from external storage tanks to the electrodes in the cells of the battery, has been underway more or less intensively since their invention by the author of this report in 1968. (1) The original work on flow batteries involved zinc/chlorine electrochemistry, and within the next 20 years investigations began into the use of zinc/bromine, iron/chromium redox, zinc/ferri-ferrocyanide semi-redox, iron/iron semi-redox, and vanadium/vanadium redox chemistries. In the work on most of these flow battery chemistries, multi-kWh, multi-cell batteries have been built and tested. In some cases, batteries of hundreds of kWh of capacity have been developed. As far as has been announced, it is only programs on zinc/bromine (ZnBr) batteries and vanadium redox batteries (VRBs) that are continuing at present, and it is technologies based on these two systems that are assessed in this section of the report.

All of the flow batteries that have been built utilized bipolar or pseudo-bipolar cell stacks for the multi-kWh batteries, since the characteristics of flow batteries are particularly amenable to use of this geometry. In addition, carbon in one form or another is favored as an electrode material in flow batteries because the electrochemical reactions take place on carbonaceous materials with low polarization; because it is corrosion resistant; and because carbon is a low cost material. Bipolar electrode arrangements are favored with carbon-based electrodes because the electronic conductivity of carbon is very much lower than that of metals, and are much favored by electrochemical technologists because they allow for very straightforward connections between cells in series. Bipolar cell-stacks also ensure a high uniformity of current density in individual cells, thus maximizing performance and life of the cell stack. However, bipolar cell stacks are usually quite difficult and expensive to manufacture, and it has proved difficult to make them so there aren't leaks of electrolyte between the cells and to the outside.

Use of a flowing electrolyte, or flowing electrolyte<u>s</u> since both ZnBr batteries and VRBs have separate flow streams in the positive and negative compartments of each cell, confers several advantages on a battery.

1. The same electrolytes are used in all the cells of the battery so all cells are always at the same state of charge. Moreover, measurement of the state of charge of the electrolyte is tantamount to measuring the state of charge of the entire battery. Since the electrolytes contain at least one of the reactants or products, state of charge of flow batteries can be gauged by a concentration measurement.

2. The flowing electrolyte provides a degree of uniformity between cells that is not otherwise possible. This means that a poorly-performing cell cannot adversely impact the performance of the entire battery, as is often the case with strings of, for example, lead-acid cells.

3. The flowing electrolyte provides a convenient means to thermally manage flow batteries, something that has proven quite difficult for conventional battery systems.

4. The flowing electrolyte provides a means to chemically manage the electrolyte(s) for the entire battery, so that, for example, individual cell watering, as is required for flooded lead acid or nickel cadmium cells, is not required.

There are, however, some disadvantages to flow batteries, the most critical of which are as follows:

1. The pumps and plumbing add cost and complexity to the battery. This is important because batteries are already one of the higher-cost options that customers can use to solve their energy and power supply problems, and energy storage is itself seen as adding complexity to an energy supply system.

2. The plumbing carrying the flowing electrolyte provides a parallel shunt current path between the cells that are in electrical series. This not only reduces the efficiency of the battery but can, unless properly handled, also become a hazard because it can lead to hydrogen and oxygen evolution in the cells close to the ends of the cell stacks.

3. The power for the pumps represents a parasitic load on the battery, which again reduces efficiency. This disadvantage is related to the second one, above, because the more the plumbing is reduced to lower the pumping power losses, the higher the shunt current losses become, and vice versa.

4. The last major disadvantage of a flow battery, and the one that has proven the most difficult to deal with practically, is that flow batteries have a tendency to leak unless designed and built extremely carefully. Leaks have been quite problematical for all flow battery development programs in the past, more from a philosophical than an actual point of view, but problematical nonetheless.

Since it was perceived by corporate managers and institutional funding agencies that the above advantages far outweighed the disadvantages, significant funds have been expended on flow batteries over the past thirty years, with much of the effort having been directed towards utility applications. Although work has been abandoned on all but two of the flow batteries, much of the experience gained on the others has proved useful to those on which work continues. In the following sub-sections, we give our assessment and a critical evaluation of the ZnBr and the VRB systems.

5.2 Zinc/Bromine Batteries

5.2.1 Characteristics

There have been a number of efforts to develop zinc/bromine batteries in the last twenty five years. The ZnBr battery technology to be discussed in this sub-section stems from work on this system that started at Exxon in the early 1970s. Exxon continued with this work, first with corporate funding and later with co-funding from DOE, until the mid-1980s. At this time Exxon management decided to license the technology that had been developed, and license agreements were negotiated with Johnson Controls, Inc., a major US lead-acid battery manufacturer; with Meidensha of Japan, a small lead-acid battery producer; and with SEA of Austria, at that time a unit of the largest Austrian steel company. In the mid-1990s, Johnson Controls sold off the technology they had in turn developed to ZBB Technologies, a subsidiary of ZBB Pty., an Australian company that had been independently developing their version of the technology. ZBB Technologies declined to participate in the current assessment. Meidensha had the mission from NEDO to develop ZnBr batteries for electric utility load leveling as part of the Japanese Moonlight Project. Their work culminated in 1991 with the demonstration, with only partial success, of a 1MW/4MWh battery. Although work has continued in Japan, it is at a much lower level than previously, and no details are available on the progress that has been made. The SEA work was focused on developing better components, particularly cell stacks, for ZnBr batteries, utilizing the basic technology developed by Exxon. SEA have been very successful at developing a leak-free and durable cell stack and system, that has been used in a number of EVs in Austria and Germany. In the mid-1990s, having become an independent company, SEA sold the ZnBr technology to Powercell, a new US company formed specifically to attempt to commercialize the Exxon/SEA ZnBr technology. SEA continues to be involved in development and pilot line manufacturing of ZnBr batteries, but now as a unit of Powercell, called Powercell GmbH. It is the Powercell ZnBr technology that has been assessed in the current study.

The basic features of the Exxon version of the ZnBr technology, which have been retained in the Powercell ZnBr batteries that are being made in small numbers today, (2) are as follows:

- Circulating electrolytes, with two separated flows into each cell and flow **past** the zinc and bromine electrodes. Microporous polyolefin sheets used to separate the zinc and bromine electrode compartments.

- Conductive carbon/plastic composite bipolar electrodes made by a proprietary extrusion process for low cost. High surface area carbon "attached" to the bromine faces of the sheets to facilitate electrochemical reaction.

- Mixtures of organic amines dissolved in the electrolyte that act as bromine complexing agents, which after bromination become a separate phase (a bromine oil) that is stored in a tank outside of the cell stack. The bromine oil is fed back into the electrolyte, with a separate pump, for discharge. A valve separates the bromine storage tank from the electrolyte stream flowing through the positive compartments.

- Another tank is used to store electrolyte for the negative zinc electrodes, although the electrolytes get mixed through the microporous separators in the cells. The electrolyte includes conductivity enhancing additives such as potassium chloride, but is slightly acidic.

The discharge electrochemical reaction in ZnBr battery cells is as follows:

$$Zn + Br_2 \rightarrow ZnBr_2$$

The OCV of a ZnBr cell is 1.87V at the top of charge. During charge, metallic zinc is deposited as a smooth film onto one face of the carbon-plastic composite by electrolysis of the zinc bromide which is the major component of the aqueous electrolyte. On the other face of the composite, bromine is evolved, as dilute solution in the electrolyte, and reacts chemically in the solution with the dissolved complexing agent to form the bromine oil that separates in the storage tank. During discharge, the reverse of these processes occur. The electrochemical reactions occur with only small polarization in both charge and discharge, so voltaic efficiencies of 90% or so are observed for ZnBr cell stacks. The main side reaction is the self discharge reaction of dissolved bromine diffusing through the microporous separators, to the zinc electrodes. Coulombic efficiencies in the range of 90-95% are generally obtained. During stand, only the bromine remaining in the cell stack, <5% of the total, is available for self discharge. A second side reaction that occurs is hydrogen evolution, but this is to a barely detectable extent so it does not cause problems with ZnBr battery design or operation. In fact, Powercell ZnBr batteries are sealed with a relief valve set to a high enough pressure that it will open only in the case of an extreme emergency.

ZnBr cells can be overdischarged to a limited extent without damage, and need to be completely discharged occasionally to return the bipolar electrodes to a clean state. The complete discharges do not damage the cells in any way, but rather should be considered conditioning cycles. The required frequency of the conditioning cycles depends primarily on the depth of discharge of the intervening discharge/charge cycles, being about 30 cycles at 80% DOD, and a higher, not yet definitively determined, number of cycles at shallower DODs. Since the same electrolytes flow in all the cells of the stack, ZnBr batteries cannot be easily overcharged unless the charger controls fail. Even in the case of failure of the charge control, ZnBr cells can sustain a significant level of overcharge without any long-term damage, because there is an excess of zinc bromide in the electrolytes flowing in the cells.

The vapor pressure of bromine over the bromine oil, and therefore over the electrolyte, is rather low, so despite the fact that bromine is extremely toxic, studies have shown that even in the event of a major spill of the liquids in ZnBr batteries, there will be little danger to bystanders unless the accident occurs in a confined space. In the worst accident that did occur with a ZnBr battery, no permanent injuries were reported for anyone involved.

The main contribution of SEA (see above) to ZnBr batteries has been the development of a reliable cell stack. SEA took the original flow frame approach licensed to them by Exxon and greatly modified this with more-simple frames and external piping to the cells. This approach means that a better balance between shunt current and pumping power losses can be designed into the cell-stacks. SEA also did the manufacturing engineering that allows cell stacks of their design to be built reproducibly and leak-free. SEA makes all the cell-stacks for Powercell batteries in a pilot manufacturing plant in Austria.

Over the years, hundreds of multi-kWh ZnBr batteries have been built and tested. The specific energy of the more recent of these batteries has been in the 60-80Wh/kg range, while their volumetric energy density has been in the range of 60-80Wh/liter. The latest battery to have been put under test that is relevant to the current assessment is a 100kWh system with an integrated power conversion unit (PCU). The PCU has a peak discharge power capability of 50kW that is matched to the power capability of the battery. (3) This system is designed to be stacked up to four high, so as to minimize the floor area requirements, this being possible with ZnBr batteries because their overall density is about half that of lead-acid or nickel-based batteries. The system is designed to be a "full-time" UPS and a peak shaving system, with the separate interfaces to the electricity supply and to the load being both 3-phase, 480VAC. Testing is underway at two sites with 50kW/100kWh batteries. However, Powercell now believes that a 100kW/100kWh unit would be a more economic choice for utility energy storage applications, and this is the module size they are now in the process of developing.

The design of the cell-stacks has been frozen for the moment, and it is the developer's intent, for applications which require larger capacity batteries and higher AC voltage interfaces, that a number of modules, complete with power conversion units, will be paralleled on the AC side. For up to 1MWh systems, 100kWh/100kW peak power modules will be used. For larger systems, Powercell are in the process of designing a 1MWh module with a peak power capability (PCU short term power rating) of about 1MW, and hope to build and begin test such a module during 1999. As currently thought, the same cell stacks will be used in all these modules.

The active materials of ZnBr batteries (zinc bromide and bromine complexing agent) and the other components of the electrolyte are relatively inexpensive when purchased in the quantities needed for a few MWh of battery production per year, in the range of \$10-20/kWh. Other materials of construction, with exception of the microporous separators, being basically carbon and plastics, are also inexpensive. There are other items which are more expensive, such as pumps, pump motors, electronic controls, and other battery auxiliaries. However, few of these auxiliaries are required in each battery, so the fractional part they will contribute to the total cost will be relatively small in large ZnBr batteries when production rates get higher than at present. At the moment, these auxiliaries are quite expensive, however. The same is true for the power conversion units that Powercell is planning to include in all the battery systems for stationary applications that they sell. In addition, the cost to manufacture reliable ZnBr battery cell-stacks, and to then assemble these into a complete battery system, is at the moment quite high.

As a result of all these factors, and because Powercell is a small, privately-held company that must be able to make a good return even on early sales, the costs for Powercell ZnBr battery modules is going to be quite high, approximately \$850/kWh for a 100kWh system including the 100 peak-kW integrated PCU, for the first few MWh of sales. If sales expand then we think it may be possible that some considerable reduction in this cost, perhaps by as much as 25%, can be anticipated. The unit costs of the 1MWh battery + 1MW PCU module on the drawing boards, should also be less than that of the 100/kW100kWh unit, by an amount that, in the absence of any costs from Powercell, Symons/EECI estimates will be equivalent to approximately one-third of the \$/kWh cost of the smaller module for the first-of-a-kind unit, or \$600/kWh.

5.2.2 Evaluation and Assessment of Powercell Zinc Flow Battery

In response to a query concerning the batteries Powercell would propose might be used for the applications against which we are assessing all batteries, we received the response summarized in Table 5-1. This table indicates that the same cell design and similar cell-stack designs are used for each of the three batteries concerning which Powercell responded. Efficiency information was sent for only one of the batteries, the EV battery, but the voltage time data that Powercell also sent indicates that the modules for utility energy storage will have similar efficiencies. What is perhaps most important to note, however, is that the basic building block of Powercell batteries, the cell-stack, is of significant capacity (~20kWh) and voltage (~200V), so that fewer of these have to be put in series and parallel to make a utility-sized battery than for most of the other batteries considered in this assessment.

Table 5-1
Design and Performance of Powercell ZnBr Batteries

	20kW/20kWh EV batteries currently in pilot production	**100kW/100kWh Next stage system design, includes PCU**	**1MW/1MWh Proposed module for large-scale storage**
Cell-stack capacity	105Ah	105Ah	105Ah
Cells in series per stack	128	108	108
Stacks in parallel/module	1	6	30
Stacks in series/module	1	1	2
Average discharge voltage/module	197V	166V	332V
Nominal discharge current	26A	150A	750A
Round trip efficiency to 100% DOD, and for cycling to end of useful discharge (a) (b)	69%, 74%		
Estimated cycle and calendar life (c) (d)	1000 cycles to 100% DOD 5 years		
Number of pumps	1	6	30
Estimated price		$85k including PCU	$600k including PCU (d)
Footprint, modules only		22 kWh/m^2 One cell-stack high	115 kWh/m^2 6 cell-stacks high

(a) Shunt current losses appear as part of these DC to DC efficiencies. Tare losses (mostly for pumps) amount to 4% round trip.

(b) ZnBr cells must be totally discharged very 20 to 50 cycles for maximum performance. The efficiency for a 100% DOD discharge is less than one to the end of the useful discharge because the negative electrodes are incompletely covered with zinc.

(c) The inexpensive carbon/plastic electrodes are the component which limits cycle and calendar life. The lives of the more-expensive electrolyte and other components is expected to be significantly longer than shown.

(d) Symons/EECI estimates based on previous analyses of developer data and information.

If the proven and expected characteristics of ZnBr batteries described in this and the preceding sub-sections are compared with the requirements and baseline designs for the four applications against which we are assessing advanced batteries, then:

- For the transmission line stabilization application, we note the Powercell stacks are not capable of delivering high power, so this does not appear to be an application worth considering for ZnBr.

- For the arc furnace ACE regulation application, the expected cycle life at small DODs, as projected linearly (as appears appropriate for ZnBr) from the observed values at 100% DOD, is not nearly high enough to warrant further consideration of this application.

- For the PQ enhancement + peak shaving application, Powercell batteries superficially appear to offer some promise, so this is discussed in detail below.

- For the distributed generation application there is a requirement for rather long storage times that could only be met with Powercell ZnBr batteries by decreasing the operating current density by a factor of two. This would adversely impact the $/kWh costs and the efficiency, which are in any case expected to be rather high and relatively low, respectively, for some time to come, in such a way as to make this application uneconomic for ZnBr batteries.

In the PQ enhancement + peak shaving case, it is necessary to make the comparison differently from the assessments of other advanced batteries, because Powercell intends to market their ZnBr batteries as complete systems, including UPS-like power conversion equipment sized for their customer's requirements. Therefore, we will compare the expected capabilities of Powercell 100kW/100kWh modules (see Table 5-1) with the GNB Vernon battery energy storage plant, which has a very similar function to that intended for the Powercell modules.

The Vernon battery system provides 5MW of power for a short period and 3MW for 1.5 hour (4.5 MWh) for standby power and peak shaving at a lead-acid battery recycling plant. As discussed in Section 2, the Vernon energy storage system comprises VRLA cells with an integrated PCU and control system. The cost for the Vernon system, which was sold in 1995 as a turn-key package up to the 4160V, 3-phase AC supply bus, was $4.2 million on a "first-one-of-a-kind" basis. This included some engineering costs, as well as all the system components in the turn-key package, including the switchgear needed for the system to operate as a standby power supply. GNB/GE have said that the batteries and battery accessories represented 32%, the PCU 19%, and that balance of plant, including installation, electrical work, engineering, etc., ~50%, respectively, of the total cost. Of this, **we** think that approximately half of BOP costs are electrical costs or are engineering costs that are already included in design of the Powercell modules, since the latter are "packaged" and set-up in an on-line UPS mode. Thus, the portion of the Vernon that is comparable with the estimated selling price of the Powercell modules, i.e., the VRLA battery cells and accessories, the PCU, and the electrical components to provide backup power capability, is ~$3 million. The cost for Vernon cells, accessories, PCU and non-site-specific engineering, etc., is therefore estimated to have been ~$600/peak kW, and ~$670/kWh. These are the values that may be compared with those estimated for the 1MW/1MWh Powercell module, i.e., ~$600/kW and ~$600/kWh. Thus, we project that the first one-of-a-kind 5MW peak, 5MWh energy storage plant for PQ enhancement + peak shaving using Powercell modules will cost slightly less than the GNB Vernon battery system.

As far as our critical evaluation of the Powercell ZnBr technology is concerned, the following issues appear important:

- ZnBr batteries have all the advantages and disadvantages of flow batteries listed above.
- ZnBr batteries have been subjected to relatively intensive development for EV, solar and utility applications over a 25 year period. Despite this and the fact that the Powercell technology is inherently low-cost, cost estimates from the developer are rather high. Recent design and cost studies are not publicly available, so it is not possible to assess the accuracy of the developer's estimates.
- Since a bipolar cell-stack arrangement is used, with up to 128 cells in a single stack, far fewer modules will be required in series for a utility battery that for most of the other systems assessed. There should therefore be fewer reliability problems from this perspective than for other batteries. The smaller number of modules and the double case arrangement used for Powercell ZnBr batteries should make ground faults less problematical than for other batteries.
- The combination of high specific power and low density means that ZnBr batteries can be stacked, so that their footprint is expected to be more than three times better than for lead-acid after aisles and other space allowances have been taken into account. Stacking will complicate maintenance and repair of the modules, however.
- The projected cycle life of ZnBr batteries has already been demonstrated to be at least as good as the lead-acid baseline. The cell-stack and pump costs, the only parts that it is expected will have to be replaced in a twenty-year period, represent a small part of the total costs, so repair and replacement costs should be significantly less than for the baseline.
- Counterbalancing the low maintenance and repair costs are charging costs for ZnBr batteries, since the efficiency of this system is lower than any other considered in this assessment. The low efficiency results from a higher internal resistance than many other technologies, and from coulombic, shunt current, and tare (pumping power) losses. Thermal management will be needed to ensure the cells operate with reasonable efficiency.
- Controls are needed for ZnBr batteries to ensure proper operation. The reliability of the controls and of the pumps have to be reckoned with in the design and add

capital and maintenance costs. (The capital costs have already been included in the battery module costs above.)

- There should be less of a requirement for sectionalizing switches with Powercell modules because ZnBr batteries can be completely discharged, to zero volts, without damage.
- ZnBr batteries can be overcharged (although the controls normally prevent this), fully discharged, reverse charged for short periods, and left in a discharged state for long periods of time. While they can be charged and discharged from any state-of-charge, without damage or shortening of the cycle life, occasional complete discharge conditioning cycles will be needed every 20-50 partial DOD cycles.
- Although studies indicate that Powercell technology will be safe, and a double case arrangement is used to further enhance safety, there is a possibility that ZnBr batteries will not be acceptable to utilities because they contain bromine. This is presently not regarded as a show stopper, however.

There is some uncertainty concerning the cost of Powercell batteries, but despite this it appears from the above assessment and evaluation that ZnBr batteries could be less costly on a life-cycle-cost basis than baseline lead-acid battery for PQ enhancement + peak shaving. In addition Powercell ZnBr batteries should have a significantly smaller space requirement than lead-acid batteries. As a result of these and the critical evaluation above, we recommend that EPRI attempt to arrange a co-funded project with Powercell. Powercell have already indicated that, under the right conditions, they could be interested in such a co-funded project. We suggest that the focus of such a project should be an auditable cost and design analysis of their system for the PQ enhancement + peak shaving application, and that this should be backed up if possible with some long-term testing of one of their 100kW/100kWh modules.

5.3 Vanadium Redox Battery

5.3.1 Characteristics

Work on redox batteries, in which both reactants and products of the charge and discharge reactions are dissolved ionic species, started at NASA in the early 1970s. The NASA work, and later work at the Electro-Technical Laboratory (ETL) in Japan, involved iron and chromium chloride electrolytes. In the 1980s, the Australian University of New South Wales (UNSW) and ETL separately started development of vanadium redox batteries (VRBs). VRBs are favored because their average OCV (1.4V) is much higher than the average OCV of iron-chromium redox batteries (1.1V). Later, UNSW licensed the technology they developed (and continue to develop) to a private electric power producer in Japan called Kashima-Kita, a subsidiary of Mitsubishi. ETL transferred their technology to Sumitomo, but also collaborated with Kashima-Kita. Kashima-Kita's interest in the technology stems from the fact that the company has developed a process for extracting, transporting and burning oil tars (Orimulsion) which have a relatively high vanadium content. This, together with Kashima-Kita's flue gas particulate trapping process gives the company an inexpensive vanadium resource. In the last year, USNW has sold their rights in VRBs to Pinnacle LLC, an Australian company. Since information on UNSW/Kashima-Kita VRBs was made available to us by Pinnacle, we used this technology in our evaluation. In any case, the Sumitomo technology was not sufficiently different from that of UNSW to warrant a separate assessment.

VRBs are based on redox reactions at both the positive and negative electrodes of the cells of these flow batteries, and both the reactants and products remain dissolved in the electrolytes in the positive and negative compartments of each cell, throughout the charge and discharge processes. (4) Both electrolytes consist of vanadium sulfate (dissolved in sulfuric acid and water) in different oxidation states, as shown in the discharge reaction for electrolyte in positive electrode compartment, or what we call the "posilyte", that follows:

$$V(V) + e \rightarrow V(IV)$$

- and that for electrolyte in negative electrode compartment (negalyte):

$$V(II) \rightarrow V(III) + e$$

The cell reaction is completed, and electroneutrality maintained, by passage of a hydrogen ion (H^+) through the ion exchange membranes that separate the positive and negative electrode compartments of all the cells of a VRB. The ion exchange membranes also prevent mixing of the posilyte and negalyte. Although they both contain "vanadium" sulfate, the composition of the two electrolytes are quite different by virtue of the different oxidation states of the vanadium ions they contain, so mixing them would result in a loss of ampere-hour efficiency of the VRB cells.

At the top-of-charge the posilyte is 95% V(V)/5% V(IV) sulfate, and the negalyte is 95% V(II)/5% V(III) sulfate. At bottom of discharge, the posilyte is 5% V(V)/95% V(IV) sulfate and the negalyte is 5% V(II)/95% V(III) sulfate. The OCV of the cells of a VRB changes quite significantly during discharge, from 1.55 V at top-of-charge to 1.25 V at bottom-of-discharge with 2 molar electrolytes. This variation in OCV with SOC is more than for many battery systems, and carries with it some potential cost penalties in power conversion units. On the other hand, the variation of OCV with SOC provides an accurate way to gauge the absolute state of charge of the cells, and provides easily-measurable signals to stop charge or discharge. Moreover, VRB cells can be overcharged and overdischarged, within the limits of the capacity of the electrolytes, and can be cycled from any state of charge or discharge (i.e., subjected to partial DOD cycling) without permanent damage to the electrodes or electrolytes. It is thermodynamically possible for hydrogen to be evolved from the negatives of VRBs, but it is said that with the types of electrode materials used, hydrogen evolution is found not to be problematical.

Vanadium is a somewhat more costly material than the lead used in lead-acid batteries. Approximately 4kg/kWh of vanadium, as sulfate, is required at 90% utilization and assuming an average discharge voltage of 1.25 V/cell, so at $6-7/kg (current price for vanadium chemicals according to UNSW) the cost for acquisition of the active materials for a VRB would amount to ~$25/kWh. This can be compared with ~$20/kWh for the lead for a lead-acid battery. By the time the purchased vanadium chemicals have been processed for use in a VRB, UNSW estimates costs for the two vanadium sulfate electrolytes of $30-50/kWh, depending on the number of batteries built each year.

There are other components beyond electrolytes in a VRB, of course. The electrodes at which the redox reactions occur consist of graphite felt. This felt provides a large surface area for the reactions and helps maintain a uniform flow through electrode compartments, thus helping ensure high voltaic efficiencies. The felt in the positive and the negative electrode compartments of the bipolar cell stacks is compressed between the membrane and the positive and negative current collectors, respectively, so there is good electrical contact between each piece of felt and its corresponding current collector. Thus, the cell components - a current collector, a piece of felt, a membrane, a piece of felt, then another current collector- are stacked up so as to form a collection of cells in electrical series. The whole cell stack is terminated at each end with thicker current collector plates to allow take-off of the current to the user's load. The thicker end plates also provide a means to ensure that the stack of cells is compressed uniformly.

With regard to the cost of VRB cell-stacks, very little quantitative information is available, but several qualitative observations can be made. First, we should note that the cost for power and the cost for energy are essentially unrelated for VRBs, as noted above. Second, the cost discussions in Japanese publications do not appear to us to provide a reliable means to assess possible price ranges in the US. Third, UNSW, the only organization from which VRB cost projections are available in any detail, being a university, is probably not a very reliable source of cost information, and Pinnacle has not yet been involved to a great enough extent to have developed business-oriented cost projections. Fourth, and most important, the cost of VRB (and other redox battery) cell stacks is critically dependent on the acquisition of ion exchange membranes and carbon felt materials, both of which are presently high but both of which are expected to drop dramatically in cost as production volume increases in response to increased use for VRBs and for other non-battery applications.

On the basis of proprietary studies performed for other clients on a variety of electrochemical systems, Symons/EECI projects that the OEM selling price of VRB cell stacks, without any electrolyte, will be ~$450/kW in quantities of 1MW per year, and ~$300/kW in quantities of 20MW per year.

Since the reactants at and the products of the electrode reactions are all dissolved in one or other of the two electrolytes, there is a significantly larger volume of electrolyte required for VRBs than is necessary for other batteries. This volume of electrolyte is too large to be contained in the spaces between the electrodes. The electrodes must in any case be kept as close together as possible in order to minimize the internal resistance of the cells. As a result, much of the posilyte and negalyte for the reactions at the electrodes is contained in tanks which are external to the cells, particularly for batteries for which the ratio of energy capacity to power capability is relatively high. A tank (or set of tanks for a very large battery) is required for the posilyte and a separate tank (or set of tanks) for the negalyte. Pumps and inter-connective plumbing are also required to carry the posilyte and the negalyte to the cells from the storage tanks, and to return the two spent electrolytes from the cells to their respective tanks. The use of the external storage tanks can be advantageous, however, since the energy storage component (the tanks) and the power producing component (the cells) can be sized quite separately.

The cycle life of VRB cells is expected to be relatively long. According to VRB cycle data obtained from UNSW, cycle lives of 1000 or so to 100% DOD of rated capacity, in the shorter term, and perhaps up to 2000 in the longer term, seem to be a reasonable expectation. The calendar life of VRB cell-stacks is projected to be from 5 to 8 years due to degradation of the membranes.

UNSW have recently built several multi-kWh batteries with 2M electrolytes and 1500 cm^2 electrodes as technology demonstrations, the largest being a 16-cell, 4kWh/1kW system and 36-cell, 12 kWh/4 kW system. Kashima-Kita currently have a 200kW/4 hour VRB operating with 1.8M electrolytes, and as of March 1998 have successfully cycled the battery more than 150 times to 100% of it's rated capacity. (5) Sumitomo have built a 400kW/2 hour system using 1M electrolytes, and by August 1997 had cycled their VRB for 240 cycles without problems. (6)

5.3.2 Evaluation and Assessment of Pinnacle VRB Technology

The VRB technology was added to the assessment, at the request of EPRI, late in the study. Pinnacle, which by this time had purchased all the USNW rights in the VRB technology, was then sent a query about what designs they would propose for the applications they thought would be appropriate among those that at that time we were going to assess all advanced batteries. The distributed generation application, for which Pinnacle and others had advised their technologies might be most appropriate, was not at that time one of those we planned to use. Pinnacle therefore responded to our query with some detailed information on the batteries they have under test, as opposed to giving specific design information. As may be clear from Section 5.3.1, VRBs, as presently designed, are not well suited to any applications involving less than a few hours of storage time, because the internal resistance of the cells is relatively high. In fact, in one Sumitomo publication, (6) it was stated that pumped hydro, which generally has rather long storage times, was the technology against which VRBs should be compared.

Since the VRB technology is so different from all the others in the study, and because we have only a small amount of information available on VRBs compared to most of the other batteries we have assessed, it is necessary to use a quite different approach for evaluating VRBs than the others, as described in the following. On the basis of estimates cited in the *Characteristics* sub-section, we project that the cost of VRBs, including installation up to the DC busbar of the PCU, will be very approximately $50/kWh in quantities of a few 10s of MWh per year **plus** $400/kW in quantities of ~5MW per year. Such a system might be expected to last for seven years and/or 2000 deep cycles by the time it is ready for a full-scale demonstration, but may only be capable of 5 years and/or 1000 cycles at the sub-scale demonstration level. The cost of the first 5MW/40MWh battery for distributed generation will therefore cost, very approximately, $4 million up to the DC bus of the PCU. This might be compared to a cost of $4.8 million only for the cells of the lead-acid battery of the baseline design. According to this analysis, VRBs might be an attractive choice for the distributed generation application if 8 hours of storage are required, and if the VRB can indeed last 2000 cycles and 8 years.

Our critical evaluation of VRBs is as follows:

- VRBs have all the advantages and disadvantages of flow batteries listed above.

- VRBs are at a much earlier stage of development than many of the other advanced systems assessed in the current study. The batteries that are under test in Japan are, compared to the ZnBr batteries of the last sub-section, quite crude in their design. Detailed design and cost studies have not been performed and do not include explicit allowances for pumps, pump-motor drive electronics, tanks, plumbing, battery system controls, and packaging materials, so the VRB costs cited above should be regarded only as "rule-of-thumb" estimates.

- The use of fully soluble redox couples and inert electrodes means that there are no electro-recrystallization electrode processes, so there is an expectation of a long cycle life. However, cycle life testing is as yet at a relatively early stage, and the cycle life testing is being performed with materials that are not yet finalized.

- Relatively large amounts of vanadium chemicals are required. They weigh a lot and the concentrations of vanadium chemicals that can be used are such that the electrolytes with the active materials are rather large in volume. Use of higher concentrations carries with it as yet unknown problems.

- VRBs can be fully discharged (but not reverse charged), left in a discharged state for long periods of time, and can be charged and discharged from any state-of-charge, without damage or shortening of the cycle life. Reversal or overcharging of one cell in a series string are not possible since all the cells are filled from the same electrolyte tanks, and the cells are therefore always at the same state of charge.

- The variation of OCV with SOC provides a means to measure the state of charge of the cells. The wide variation of OCV with SOC could mean that the PCU for a VRB will be higher than that for a lead-acid battery.

- The storage capacity is determined by the volume and the concentration(s) of the electrolytes, while the battery stack, which determined power capability, can be sized independent of the storage capacity.

- Graphite felts and exchange membranes of indeterminate cost in high volume must be used in the electrode compartments of each cell so that high charge discharge efficiencies can be attained. Moreover, the membranes appear to be the life limiting component of the cells.

- Vanadium chemicals in solution are less harmful to people and the environment than the active materials in other advanced batteries, e.g., lithium, bromine.

Pinnacle VRB have expressed a cautious expression of interest in working with EPRI to further the development of their system for utility applications. In the light of our critical evaluation and the assessment, albeit limited, given above, we recommend that EPRI explore the possibility of co-funding a cost and design study for the distributed generation application, with experimental work to back up the cost and design analysis performed by UNSW.

5.4 References

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6

HIGH TEMPERATURE BATTERIES

6.1 Overview

At higher temperatures, i.e., above 250°C, non-aqueous, molten salt electrolytes have low resistivity, and electrochemical reactions proceed with low polarization. As a result, for more than four decades, various research and development groups have been trying to develop high temperature batteries. The absence of water in a highly-conducting electrolyte is advantageous because the side reactions leading to potentially explosive hydrogen and oxygen cannot occur. This makes it possible to use high-voltage, low equivalent weight alkali metals, i.e., lithium and sodium, in a battery. In fact, most of the high temperature batteries that have been investigated use either lithium or sodium as the negative active material. These metals are not particularly corrosive in the absence of water, but the positive active materials with which the alkali metals have been coupled, e.g., sulfur, are quite corrosive at higher temperatures. The major difficulty with developing high temperature batteries is the corrosion that inevitably occurs in them.

From the early 1970s until the mid-1980s, two high temperature battery chemistries, lithium/iron sulfide and sodium/sulfur (Na/S) received the most attention. Work on lithium/iron sulfide systems was slowly abandoned for commercial applications in the mid to late 1980s, so this chemistry will not be addressed further here. At about the same time, however, intensive development work was initiated on the sodium/metal chloride systems, particularly sodium/nickel chloride (Zebra) batteries, which are structurally quite similar to the Na/S system. In this section of the report, we will address the Na/S and the Zebra battery systems.

Both the Na/S and Zebra batteries use a solid electrolyte known as beta-alumina (beta), which conducts only sodium ions, to separate the sodium, a liquid above 98^0C, from the positive active material. At 300^0C, beta''-alumina, the form used in Na/S and Zebra batteries, has a conductivity that is about the same as sulfuric acid at room temperature. Much of the effort on Na/S cells has been expended in developing better beta-alumina electrolytes and in developing manufacturing pilot plants to produce the material at high quality.

Beta-alumina is of course a ceramic, and it must be sealed to a "header" of non-conducting alpha-alumina in order to make a satisfactory cell. As a result, the only geometry that has been at all successful for this electrolyte is a closed-end cylindrical tube, like a large test-tube. Another, larger, closed-end cylindrical tube, made of coated steel or aluminum, contains the beta tube. The whole cell is hermetically sealed. Collections of individual cells are electrical connected in series and parallel arrays to form batteries. A significant fraction of the development effort for Na/S has gone into the development of highly-performing, long-lived cells.

6.2 Sodium/Sulfur Battery

Na/S batteries are based on the following reaction:

$$2\text{Na} + 3\text{S} \rightarrow \text{Na}_2\text{S}_3$$

With more sodium, it is theoretically possible to discharge Na/S cells to sodium sulfide (Na_2S), but in order to allow operation at ~300^0C with liquids in both the positive and negative compartments, the amount of sodium in Na/S cells is limited to that corresponding to Na_2S_3. There are two regions in discharge, the 2-phase region from 0% DOD to 60% DOD when liquid sulfur and liquid sodium pentasulfide are present in the positive compartment and the OCV is invariant at 2.08V, and the single phase region when sodium pentasulfide and sodium trisulfide form a homogenous phase and the OCV varies from 2.08V at 60% DOD to 1.78V at 100% DOD.

Na/S cells have been made with sodium in the center of the beta tubes and on the outside, there having been proponents with supporting arguments for and against both arrangements. These arguments are not particularly important from an assessment perspective, the important issues being how much the cells cost and how long will they last. What does need to be accounted for in all cells, however, is the following:

- Maintaining good electronic contact between the negative current collector, the metallic sodium negative active material, and the beta, given the large change in volume of the sodium, which passes from the negative to the positive during discharge.

- Arranging for electronic and electrolytic contact between the positive current collector and the beta, especially at the top of charge when non-conducting pure sulfur fills the positive compartment. In almost all practical cells that have been built, this is handled by inserting carbon felt or mat into the positive compartment of each cell.

- The choice of cost-effective materials for the positive current collector and for containment of positive active materials in central-sodium cells, given the highly corrosive nature of the sodium polysulfides.

Na/S cells always operate at 100% coulombic efficiency until they fail. Upon failure, generally as a result of fracture of the beta tube, Na/S cells exhibit a relatively high electrical resistance. Na/S cells cannot be overcharged, since the voltage rises rapidly and ultimately the beta fractures. Overdischarge of Na/S cells, to anything more than $Na_2S_{3,}$ to any great extent causes irreversible damage to the positive electrode leading to capacity loss, but sodium must be available for such an overdischarge to occur. However, there are clear voltage signals for both overcharge and overdischarge, so this can generally be avoided, and the fact that the coulombic efficiency is 100% helps ease control of charge and discharge. All the factors outlined in this paragraph must be taken into account in the design of large arrays of Na/S cells in series and parallel, i.e., multi-kWh batteries, this having been the subject of much of development effort in Na/S battery programs.

Work on Na/S batteries started in 1963 with the discovery, by Kummer and Weber at the Ford Motor Company, of the ionically-conducting properties of beta-alumina. The material was almost immediately incorporated into working cells. Beginning around 1970, there was a proliferation of efforts worldwide on the development of Na/S batteries. By the mid-1980s, two US, several Japanese, and two European companies had aggressive efforts to develop the technology. Many of the projects in the 1970s and 1980s were directed to EV applications, although there were some significant programs to develop the technology for electric utility load leveling. By the mid 1990s, however, almost all of these efforts had been more-or-less abandoned, except for a New Energy Development Organization (NEDO) project in Japan to build and test a Na/S battery for load-leveling. Symons/EECI estimates that close to $1 billion was spent, worldwide, trying to develop the Na/S technology. Much of the effort on Na/S battery technology is more or less directly applicable to Zebra batteries, however.

The NEDO project in Japan has been underway for some time, it being originally part of the Moonlight program of the 1980s. NGK Insulators and Tokyo Electric Power Company (TEPCO), in a recent paper, (1, 2) gave an update on their progress in the project, for which they have been in the process of building and testing a 6MW/48MWh Na/S battery. The battery design called for using 240 modules each with a 25kW capability, of which 200 have been installed so far. The 25kW modules comprise 480 cells with a capacity of 248Ah (8-hour rate) which is equivalent to ~500Wh. The cells are arranged 6 in series, 10 in parallel, and then 16 in series, presumably so that cell failures can be managed without overly compromising the reliability of the module. The discharge rating of the module is 283A at an average of 93V. The 200 modules in the plant, which is installed at TEPCO's Tsunashima sub-station, are arranged in three units, with slightly different electrical arrangements, but with all units having a DC bus voltage (average discharge) of ~930V. The first and second units have been in operation since early 1997, while the third unit was brought on-line in January 1998. No details of physical size of the plant are available, but a photograph given in the paper shows compact, weatherproof units. Very little information on the operation of the plant so far have been divulged, except that the DC-DC round trip efficiency is said to be 91.5%, and if the power for keeping the modules hot is included, then the efficiency drops to 89%.

Sodium/sulfur batteries will not be assessed as part of the current study because the Japanese developers proved unwilling to share information on their work or to consider discussing the possibility of jointly-funding a program with EPRI. However, EPRI should consider approaching the Central Research Institute for the Electric Power Industry (CRIEPI) to try to get more details on the work that has been going on. Since Na/S systems cannot be assessed at this time, of the high temperature batteries only the Zebra system will be assessed and critically evaluated in the current study, as now discussed.

6.3 Sodium/Nickel Chloride (Zebra) Battery

6.3.1 Characteristics

Sodium/nickel chloride (Zebra) batteries have been under relatively intensive development since the mid-1980s at Beta R&D Ltd. in the UK, although some research had been conducted on the system since the late 1970s, first in South Africa at the Anglo-American Company and then in England at the Harwell Atomic Energy Establishment. Since the early 1990s, the work has been funded by, and further development has been conducted by, AEG of Germany. Zebra batteries have been tested extensively in quite a large number of EVs, and pilot manufacturing facilities have been established to build small lots of 20+kWh batteries. (3) Zebra batteries are still quite strongly favored for EVs in Germany, although they do not seem to be the subject of much attention in the US. Information and data for the current assessment and critical evaluation were obtained from the open literature and in documentation submitted to us by AEG Zebra Battery Marketing GmbH, through the auspices of Beta R&D Ltd.

Although structurally similar to Na/S batteries, and sharing the same advantages and problems with the sodium electrode as the other beta battery, the positive electrodes of Zebra batteries are quite different. Zebra cells are always made with the sodium on the outside of the beta “test tube”, so the cell case, made of mild steel, acts as the negative terminal of the cell. The positive electrode active material is nickel chloride, which is a solid at the desired operating temperature of 275-350^{0}C. The discharge reaction in Zebra cells is:

$$\mathrm{Na} + \tfrac{1}{2}\,\mathrm{NiCl_2} \rightarrow \mathrm{NaCl} + \tfrac{1}{2}\,\mathrm{Ni}$$

The OCV of a Zebra cell is 2.58V. As in Na/S cells, sodium ions pass through the beta electrolyte from the negative to the positive during discharge. Unlike Na/S cells, however, the products of the discharge reaction in the positive compartment, metallic nickel and common salt, are solid at the cell operating temperature. In addition to the nickel current collectors, therefore, a porous nickel matrix is included in the positive electrode compartment to provide electronic conductivity to and from the active materials. A second electrolyte, sodium chlor-aluminate, $NaAlCl_4$, which melts at 185^0C, provides ionic conductivity between the positive active materials and the beta''-alumina primary electrolyte. The sodium chlor-aluminate also dissolves the sodium chloride generated during discharge. Zebra cells are constructed in the fully discharged state, i.e., with no metallic sodium, in order to try to minimize manufacturing costs.

Unlike Na/S cells, there are mechanisms (reactions) in Zebra cells that allow moderate amounts of overcharge and of overdischarge without damage. There are also clear voltage signals in Zebra cells to indicate the end of normal charge and normal discharge. When Zebra cells fail prematurely, by fracture or cracking of the beta tube, they do so in a closed circuit condition, due to the formation of metallic aluminum in the cracks of fractured beta. As a result of these factors, and because Zebra cells operate at 100% coulombic efficiency, it is relatively easy to assemble reliable Zebra batteries from groups of cells in series and parallel. Up to 5% of the cells can fail in a Zebra battery before replacements must be made to return the battery to an acceptable performance level.

Individual champion Zebra cells have been cycled up to 3500 times without failure, but Zebra batteries are expected to have a life of 1000+ cycles before all the cells will have to be replaced because their performance has dropped below acceptable levels. The calendar life of Zebra batteries has been demonstrated to be 5 years, but the developers believe that 10 years may be possible. In addition, Zebra cells can be cycled at partial states of charge indefinitely without damage or any shortening of their lives. Unlike Na/S cells, Zebra cells can be thermally cycled many times without permanent damage, and to prove this, an entire Zebra battery was thermally cycled more than 40 times. The immunity to damage by thermal cycling apparently results from the fact that the sodium chlor-aluminate electrolyte contracts on freezing and freezes in a form that is relatively soft, so that neither the beta tube or the alpha header are damaged.

Most of the development work on the Zebra system has been done with the EV application as the goal. (4) AEG Zebra have developed some novel approaches in order to improve the power capabilities of Zebra cells, including using beta tubes with a cruciform or clover leaf cross-section (their so-called monolith design) and using an additive (iron chloride) in the positive mix to help give high "pulse" power. The energy density has been improved by using outer cell cases with a square rather than a circular cross section. The presently favored cell capacity (32Ah, corresponding to 75Wh) and peak power/delivered energy specifications reflect what AEG Zebra think the requirements are for small cars. On the other hand, the specific energy (87Wh/kg) and energy density (139Wh/l) that have been proven for Zebra EV batteries are higher than any of the other batteries considered in this assessment, with the possible exception of the lithium systems discussed in the next section. Much work has been done to demonstrate that Zebra batteries will be safe even under severe crash conditions.

6.3.2 Evaluation and Assessment of AEG Zebra Technology

In response to a query that included a brief description of the applications against which advanced batteries were to be assessed, AEG Zebra sent the information shown in Table 6-1 for systems that have already been built and tested.

Table 6-1
Characteristics of Modules Proposed by AEG Zebra for Restructured Utility Applications

	EV Module, Type 1	Test Module, Type 2
Cell capacity	32 Ah	32 Ah
Average discharge voltage	2.37 V/cell	2.37 V/cell
Nominal cell capacity	75 Wh	75 Wh
Arrangement of cells in module (a)	87 in series x 4 in parallel	220 in series x 6 in parallel
Number of cells in module	384 cells	1320 cells
Nominal voltage of module	218 V	550 V
Nominal capacity of module	27 kWh	100 kWh
Round trip DC-DC energy efficiency, full charge/discharge	85 %	
Round trip DC-DC energy efficiency, partial DOD cycling	88 %	
Module weight (b)	335 kg	
Module dimensions, l x w x h (b)	903 mm x 676 mm x 315 mm	
Module footprint, before stacking, with no allowance for service aisles, etc.	42 kWh/m^2	
Module cost at 10MWh/year production rate		$300/kWh AEG Zebra projects $150/kWh at higher production rates (4)

(a) The electrical arrangement of the cells in the module was not specified by AEG Zebra, but it is assumed that this arrangement has been made in such a way as to maximize reliability given the failure characteristics of the cells.

(b) AEG Zebra modules include a vacuum insulated, double-walled box and air or oil cooling for thermal management and safety.

The table shows that, even though the cells used for the outline design are low in capacity (~75Wh), and that there are consequently a large number of cells in each module, the test module that AEG Zebra apparently suggests for utility applications is moderately large in capacity (100kWh) and has a high voltage (550V).

If the calendar life of the modules is assumed to be 7.5 years, i.e., intermediate between 5 years that has been demonstrated for modules and 10 years that AEG Zebra believes is their potential, then the first cost over life for these modules is projected to be

$40/kWh per year. The peak power capability of the modules AEG Zebra proposes for utility applications is expected, numerically, to be ~1.5 times their energy capacity, so that a 100kWh module will have a peak power capability of 150kW. These projections translate to $200/peak kW or $27/peak kW per year. As with other advanced batteries, however, it must be recognized that both the costs and the life are projections that must be subjected to validation later. The projections made herein are somewhat optimistic, in our estimation.

Concerning the projections for AEG Zebra battery modules, the requirements for restructured utility applications and the baseline lead-acid battery designs discussed in Section 2, our assessment is as follows:

- Transmission line stabilization: AEG Zebra cells and modules do not currently exhibit a high specific power capability, and it appears unlikely to us that they can be designed to do so at acceptable cost. The current projections for annual cost for peak power from AEG Zebra modules, $25/kW per year, is 5 times greater than the baseline. Therefore, despite the fact that Zebra modules have a relatively high nominal voltage, and are projected to last 1.5 times as long as the lead-acid baseline batteries, we do not think this is a suitable application for the technology.

- Arc furnace ACE regulation/instantaneous reserve: The life expected of AEG Zebra cells with frequent, shallow DOD cycling is something of an unknown, since no testing has been done in this mode, as far as we are currently aware. There is some evidence to suggest that the life of beta batteries is as much calendar time dependent as it is ampere-hour throughput dependent, as opposed to the situation with most batteries. If this proves to be the case, then it is possible that a Zebra battery cycled from 90% to 80% DOD and back might have a life as long as three years, i.e., the same as estimated for the baseline battery cycled to 3% DOD. With this 3 year life with 90-80% DOD cycling as an assumption, it would mean that 500 Type 2 (100kWh nominal, see Table 6-1) Zebra modules would be required for the arc furnace application. These could be arranged 20 in series, 25 in parallel in order to meet the DC busbar requirements. There would be adequate capacity in these modules for an occasional instantaneous reserve discharge, and these should not impact life to any great extent. The estimated cost for these modules would be $15 million, as compared to $24 million for the baseline battery cells. Zebra batteries appear therefore to be a potentially attractive option for the arc furnace application, but the underlying life assumption behind this conclusion must be clearly recognized.

- PQ enhancement + peak shaving: The optimistically projected cost over life for AEG Zebra modules is one-third higher than the baseline, so we do not think this is a suitable application, particularly given the assumptions underlying the projections for the Zebra technology.

- Distributed generation: The $/kWh cost for AEG Zebra batteries is twice, and the projected cycle life is half that for the baseline, so the technology will be uneconomic for this application.

The AEG Zebra technology has a number of advantages and disadvantages as compared to other advanced batteries, as shown in the following critical evaluation:

- Zebra batteries operate at 275-350^{0}C so they must be enclosed in a double-skinned, vacuum-insulated box, but thermal management is relatively easy. On the other hand, heat losses represent a parasitic load, albeit small, and there is a negative reaction, psychologically, from potential customers. There is similar psychological negativity with regard to the safety of the Zebra system, but like concerns over the operating temperature, we believe this is not based on facts.
- The measured efficiency of Zebra batteries, even including heat losses, is rather high as compared to other batteries, since the coulombic efficiency of good cells is always 100%, while failed cells are essentially out of the circuit.
- The power capabilities of Zebra batteries are not as high as might be expected given the operating temperature, and are not adequate for some utility applications.
- Although they have a high specific energy, Zebra batteries do not have a particularly high energy density, so they will have to be stacked several modules high in order to save floor space as compared to the lead-acid baseline.
- Despite the fact that Zebra batteries have been under intensive development for almost 15 years, there are no cost and design studies available for utility applications. Thus, it is difficult to fully assess the technology.
- The projected life of Zebra batteries in the arc furnace application, the only one of those we used in our assessment for which the technology appears suitable, is quite uncertain.
- Sectionalizing switches will be needed with AEG Zebra modules in the same way as they are for the lead-acid baseline.
- Zebra batteries can be overcharged and overdischarged for short periods (although the controls normally prevent this) without long term damage to the cells. Zebra cells can be charged and discharged from any state-of-charge, without damage or shortening of the cycle life. Zebra batteries can be thermally cycled to ambient temperature tens of times without loss of performance or life.
- The capacity of the individual cells of Zebra batteries is currently rather small so a very large number of cells will be needed for a utility scale energy storage plant. Counterbalancing this somewhat is the fact that the characteristics of Zebra cells are

such that they can be packaged into modules of rather large capacity and high voltage. This means that fewer Zebra modules are required in series for a utility battery than for most of the other systems assessed, so that relatively few electrical connections have to be made on site. (Electrical connections made in a factory on a production line can be expected to be more reliable than those made on site.) Additionally, ground faults should be less problematical for Zebra batteries than for other batteries. Despite all these factors, however, we think the small cell capacity is, overall, a negative characteristic of current Zebra cells.

As indicated in Section 6.1, all of the Zebra battery development efforts have been focused on EVs. No work has been done so far on utility energy storage applications. Since AEG Zebra perceives that the interest in EVs in California seems to be waning, they are now turning their attention to other possible customers for their technology, such as electric utilities. One tangible indication of this is their expressed interest in finding a way of working with EPRI to develop their system for utility energy storage. Since our assessment and evaluation indicates that Zebra batteries might be an attractive option for the arc furnace ACE regulation application, we recommend that further contact with AEG Zebra be made with the intent of exploring a co-funded development effort. An adapted design, with projected costs, of the Zebra battery for the arc furnace application, together with some shallow DOD cycling tests to confirm our expectations of Zebra cell life, would seem to us to be the most appropriate starting point for a co-funded effort with AEG.

6.4 References

(1) “Development of Compact Sodium Sulfur Battery”, E. Kodama, at al, Proceedings of EESAT ’98 (1998 Conference on Electric Energy Storage Applications and Technologies), Page 77, 1998

(2) “Development of Compact Sodium Sulfur Battery and Present Situation of Application in Japan”, by Y. Kurshima, Proceedings of the Fall Meeting of the Energy Storage Association, 1998

(3) “Zebra Z11 in BMW Test Carriers”, H. H. Kranz, et al, CD ROM of Proceedings of EV14, 1997

(4) “Third Generation of ZEBRA Batteries in Research”, C-H. Dustmann, CD ROM of Proceedings of EV14, 1997

7

AMBIENT TEMPERATURE LITHIUM BATTERIES

7.1 Overview

Battery chemistries with lithium as the negative electrode have always been attractive to electrochemists, because of all the metals, lithium has the lowest equivalent weight and theoretically gives cells with the largest voltage. These two factors mean that among all the metals that could be battery negatives, lithium provides the possibility of the greatest number of watt-hours per unit of weight. Converting this possibility into a practical, commercial, rechargeable battery has been a very long process, however, in part because lithium is so active that it is difficult to find solvents that can be used for the electrolytes of lithium batteries. Of course, molten salts in high temperature batteries are suitable electrolytes, but many experts feel that ambient temperature lithium batteries are more practical.

In this section, we will evaluate, and assess if appropriate, two ambient temperature lithium (ATL) battery types, lithium-ion and lithium-polymer batteries. The electrolytes used in these two types of ATL batteries are very different, an organic solvent with dissolved lithium salts for the former, and a ionically-conducting polymeric film in the other. In each case, of course, the lithium must be coupled with an appropriate positive electrode active material, many types of which have been investigated over the past thirty years, but of which only a few will work satisfactorily and can be cycled for a long time with the electrolytes that are compatible with lithium. In fact, none of the solvents used in ATL batteries are truly stable. They rather rely on the formation of a stable passivation layer on the lithium, which prevents further reaction between the lithium and the solvent but allows passage of lithium ions so that the charge and discharge reactions can proceed reasonably unimpeded. The formation of the passivation layer leads to some unrecoverable losses in capacity in the first cycle of most ATL batteries, but otherwise seems to work quite satisfactorily.

As a battery negative, lithium has high performance potential but it does not work very well electrochemically. There is a tendency for the formation of dendrites during lithium electrodeposition while charging. Dendrites can (and did in some earlier ATL cells) cause shorts which in turn ignited fires involving the flammable solvents used inside the cells. The passive films on the lithium inhibit discharge. Moreover, the conductivity of the electrolytes that are stable in lithium cells and the polarization characteristic of the positives that are used are such that much lower current densities must be used than in aqueous or high temperature batteries. This translates to a requirement for very large electrode surface areas in ATL batteries, which increases manufacturing costs. In any case, lithium, lithium chemicals, some of the positive active materials, the electrolyte components, and the electrode substrates are all quite expensive compared to the corresponding materials in lead-acid batteries. This makes it difficult to keep the selling price of ATL batteries to an acceptable level for applications that require a lot of energy storage or many kW of power. In addition, the electrochemistry of ATL cells is not well behaved compared to aqueous systems, This also will be addressed briefly in sub-sections related to specific technologies, below.

Like NiMH batteries, work on ATL batteries intensified in the 1980s as developers and manufacturers realized the potential markets for batteries for portable electronic equipment. (The development of lithium-polymer batteries proceeded along a different route since, as it will be seen below, this is a technology that is mostly suited to large-capacity batteries.) The first market entries involved the use of metallic lithium, but these were withdrawn from the market when the safety problems with these began to materialize. A number of organizations then began work on lithium-ion (Li-Ion) batteries, in which the negative is lithium intercalated into a carbonaceous material such as hard coke or graphite. The first Li-Ion product, from Sony, appeared in 1990, and the market for these batteries has exploded since then. Many of the Li-Ion developers have positive electrode materials that are working quite well, and other, more desirable (less costly, lower equivalent weight, higher voltage) positive active materials with which they are experimenting but cannot as yet make highly performing, long life cells.

With the formation of the USABC in 1991, and corresponding efforts in Japan and Europe, the value of using the Li-Ion technology for EVs began to be evaluated. Within a few years, there were a number of projects, funded by the USABC and others, to develop Li-Ion batteries for EVs. One of the most prominent of these has been underway at Sony, where 100Ah lithium-ion cells with lithiated cobalt oxide as positives have been assembled into modules and tested. The amount of information available on the Sony work is very limited, and in any case, cobalt is not regarded as a material that, in the long run, could be used to produce cost-competitive Li-Ion batteries with the capacities needed for EVs or for utility applications.

The lithium-ion and lithium-polymer batteries to be evaluated in this section of the report are the specific technologies of particular developers, Saft for lithium-ion and 3M/Quebec Hydro for lithium polymer. In each of these cases, the choice of positive active material has been frozen, at least for now. This work will be summarized for each type in the corresponding sub-sections below.

7.2 Saft Lithium-Ion Batteries

7.2.1 Characteristics

The Saft lithium-ion (Li-Ion) battery is based on the use of two intercalation compounds of lithium, a carbon-based material for the negative and a nickel-oxide based material for the positive. (1) The chemistry exhibits the highest OCV, 3 to 4 volts, of all the batteries assessed in our study. There are no large phase transformations at either electrode during cycling so, in the absence of other reactions, the system should be able to sustain long cycle life.

As the basis for the positive electrode, Saft has chosen to use lithiated nickel oxide (Li_xNiO_2 where $x <= 1$) because of it's electrochemical performance and cost. With the nickel oxide as a starting point, new materials of the type $Li_xNi(1-y)M_yO_2$, where M is one or more other metallic elements, have been evaluated for improved specific capacity, cyclability and stability. The proprietary materials finally selected by Saft still have nickel as the major component, and their crystalline structure is essentially the same as lithiated nickel oxide. The negative electrode material is essentially composed of graphite, which is the cheapest carbon type usable for this application that still potentially gives a large specific capacity (350 Ah/kg) at a low voltage (< 0.5V) relative to metallic lithium. The maximum capacity that can be attained with carbonaceous materials corresponds to C_6Li, or approximately 10 parts by weight carbon to 1 part by weight Li, but in practice not all the lithium can be removed from the carbon or graphite in discharge, so somewhat more graphite than 10 times the weight of lithium is needed. The double intercalation Li-Ion cell is sometimes a called a rocking chair cell.

The non aqueous electrolyte is a solution of lithium hexafluorophosphate ($LiPF_6$) in a mixture of organic carbonates, such as propylene carbonate. The mixture of solvents used was found by Saft to give a stable passivation layer on the lithiated carbon surface, which is needed to insure the long term cyclability. Choosing an appropriate ratio of the components in the electrolyte is important for good low temperature behavior of Li-Ion cells.

The OCV of Li-Ion cells depends on the SOC, being about 4 volts at 100% SOC and about 3.2V at 100% DOD. This OCV variation provides a means to easily determine the SOC of Li-Ion cells, and means that cells can be connected in parallel without significant capacity variations developing. The high cell working voltage (averaging ~3.5V) means that fewer cells are required in series for a given DC bus voltage than are needed for other battery systems.

There are no reactions that can occur on overcharge or overdischarge (i.e., no internal electrochemical "shuttle" mechanisms like water oxidation-reduction in aqueous systems) so careful monitoring and control of the end of charge and end of discharge voltages is required. Overcharging Li-Ion cells can cause safety problems since metallic lithium can be formed. Overdischarge cause irreversible damage to Li-Ion cells. On the other hand, the coulombic efficiency is high (>99%), and the heat evolution that is an issue for lead-acid batteries at the end of charge is not a problem for Li-Ion batteries. There is an explained capacity loss of 5-10% per month on stand for most Li-Ion cells, presumably including the Saft cells discussed in more detail below.

The first generation of cells built by Saft were prismatic 100 Ah cells. These did not perform as well as had been hoped, and had a charge capacity that was probably too large for some of the electric cars for which Saft was aiming to market this system in Europe. Therefore, for the second generation, Saft has designed, built and tested spiral-wound cylindrical cells with a rating of 44 Ah at C/5 rate. These cells have a specific energy of 143Wh/kg, an energy density of 322Wh/l, and a specific power (at 80% DOD, to 2.5V minimum, with cells at 20°C) of 345W/kg. The temperature range of operation of these cells is -10 to 50°C.

Discharged to 3V, the new cylindrical cells give 95% of their rated capacity of the C/2 rate and ~80% at the C rate, after a five hour constant current then constant voltage charge to 4V. A pulsed peak specific power ~800W/kg at 0% DOD, and of ~200W/kg at 100% DOD have been measured with the cells at 20^0C. At low temperatures, the power capability is reduced, mainly because of the properties of the organic electrolyte, so that at -10°C, ~200W/kg at 50% DOD can be attained.

Cycle life testing has been performed on the 44 Ah spiral-wound cylindrical cells under various discharge conditions, including both continuous discharges at different rates and EV-type discharge. About 0.05% capacity loss/cycle from 0 to 250 cycles has been observed so far. Saft indicates that this confirms previous tests performed on a 4.5 Ah size cell over more than 600 cycles. This rate of capacity loss corresponds to a 20% loss in 400 cycles, which is quite a lot short of Saft's goal of 1000 cycles with less than 20% loss of capacity.

Six of the cylindrical cells are assembled into a 1kWh module which Saft claims to have a specific energy of 128Wh/kg, an energy density of 202Wh/l, and a specific power (at 80% DOD, to 2.5V/cell minimum, with module at 20°C) of 300W/kg. The voltage of the module can be varied from 8V to 24V top-of-charge OCV, depending on customer needs. The plastic structure of the module includes a cooling system, based on "liquid refrigerating fluid" according to Saft. A control system monitors individual cell voltages and limits charge and discharge so that the module will be safe and so it is not abused.

Modules connected in series will make up an EV battery assembly, but none of these have been built by Saft as yet. Batteries of Li-Ion cells will be thermally managed using a liquid cooling/heating network through the modules. Electrical management will be achieved by means of a two level hierarchical control system. A centralized sub-system will monitor all the module control sub-systems, see above, and will communicate with the end use equipment. Using modules of the type described above, Saft expects their first generation complete battery system, that is being built in 1998, will have the following characteristics:

- Specific energy: 100Wh/kg
- Energy density: 150Wh/l
- Specific power: 190W/kg
- Cycle life to 100% DOD while maintaining > 80% initial capacity: 300

Saft was hoping to construct a pilot plant for the manufacture of a hundred 40kWh batteries per year by the end of 1998, but we understand this may have been delayed because of the scaling back of the California EV Initiative. Saft has not released any costs, as far as we have been able to tell, but a variety of other experts, including other battery developers, seem to think that the OEM price of 40kWh Li-Ion batteries will be in the $300/kWh range for a few MWh per year of production. (3) Given the costs of materials in them and the other components such as the controllers that are needed, we think it is very unlikely that the cost of Li-Ion batteries will be below $200/kWh at any level of production.

In addition to the main part development program that relates to EV batteries, Saft (like some other advanced battery developers with contracts with the USABC) have been performing research on batteries for HEVs. (2) In the only set of tests on which results have been reported, an AA Li-Ion cell with a capacity of ~3Wh (~1Ah) according to our calculations, was cycled 120,000 times to 3% DOD with 10 second, 9A discharges and charges completed in a 60 second cycle period. The cycle life of this very high rate, and therefore quite costly, cell has not been reported, but it would appear that Li-Ion cells can sustain more ampere-hours of throughput at shallow DODs than at high DODs, or that Li-Ion cells designed for very high rates have a longer cycle life than cells designed for high energy capacity. No results on versions of this technology scaled up from 1Ah to a capacity more appropriate for utility energy storage applications (or even for EV-sized cells) are as yet available.

7.2.2 Assessment and Critical Evaluation

In response to a query regarding the Li-Ion batteries they would like considered for the applications we are using to assess batteries in the current study, Saft provided the information shown in Table 7-1. The Li-Ion batteries of Table 7-1 are said by Saft to be operable in temperatures from -10^{0}C to 50^{0}C, albeit with reduced performance at low temperatures. It should be noted that Saft did not offer a high rate cell of the type being developed by them for HEVs as one of the design options in response to our request, probably because this technology is still at an early stage of development.

Table 7-1
Characteristics Projected by Saft for their Li-Ion Battery Modules for Restructured Utility Energy Storage Applications

	Module Type 1	Module Type 2
Ampere-hour capacity of cell	44 Ah	44 Ah
Average discharge voltage	3.6 V/cell	3.6 V/cell
Nominal cell capacity	160 Wh	160 Wh
Arrangement of cells in module (a)	6 in parallel	2 in series x 3 in parallel
Number of cells in module	6 cells	6 cells
Nominal voltage of module	21.6 V	7.2 V
Nominal capacity of module	1 kWh	1 kWh
Round trip DC-DC energy efficiency	Not specified	Not specified
Module weight (b)	7.7 kg	7.7 kg
Module dimensions, l x w x h (b)	116 mm x 175 mm x 232 mm	Same
Module footprint, before stacking, with no allowance for service aisles, etc. (b)	49 kWh/m^2	Same

(a) Overcharge and overdischarge controls at cell level to protect module and surroundings.

(b) Li-Ion cells are orientation insensitive so could be stacked so as to minimize floor area requirements, within floor loading limits, of course.

Saft did not make any projections with regard to cost in response to our request for information on their system, but as outlined above, experts seem to think Li-Ion modules produced at a few MWh/year will cost OEMs ~$300/kWh, including all necessary electronic controls, cooling system and packaging. As discussed above also, it is expected that after packaging into batteries, the Li-Ion technology with 44Ah cells will show a specific energy of >100Wh/kg, and energy density of >150Wh/l, and a specific power of 190W/kg. In their response to our query, Saft indicated that a life of 1000 cycles to 100% DOD would be attainable in the future, although it should be noted that to date only 300 cycles were achieved before the capacity fell to < 80% of the initial capacity. No indications of calendar life have been given except that Saft expects to meet the USABC calendar life goals of 5 years in the short term and 10 years in the long term. For our study, we will assume a moderately optimistic calendar life of 7.5 years with 150 cycles per year corresponding to a life of ~1000 deep cycles.

Our assessment of Saft's Li-Ion battery technology as compared to the requirements for restructured utility applications discussed in Section 2 is as follows:

- Transmission line stabilization: Using the values estimated above, the cost over life of a Saft Li-Ion battery module is projected to be $21/(peak kW) per year if a few MWh of Li-Ion batteries are produced. This is more than 4 times higher than that for the lead-acid baseline, so it appears that even with high volume production, the Li-Ion technology will not be economically competitive with lead-acid.

- Arc furnace ACE regulation: The expected cycle life at small DODs, as projected linearly from the optimistic projections for 100% DOD, does not appear to us to be high enough to warrant further consideration of this application in the five-year timeframe of our assessment. However, the promising data obtained for small, high-power cells by Saft is an indication that in the longer term, this may be an application in which Li-Ion batteries may be competitive with the baseline. There is inadequate data at present to be more definitive than this.

- PQ enhancement + peak shaving: From the projections listed above, we can calculate that the amortized first cost of Li-Ion modules will be ~$40/kWh per year for a few MWh per year of production, and perhaps a little less than $30/kWh if large-capacity Li-Ion batteries are produced in very large numbers for other applications. In comparison with the baseline lead-acid at $29/kWh per year, this appears to be a possible application for Li-Ion batteries. However, it must be understood that there is a high degree of uncertainty with regard to both the costs and the life of Li-Ion batteries, so this application can be regarded as a possibility only.

- Distributed generation: The cost over life for Li-Ion battery modules, even optimistically projected, is more than twice than for lead-acid, so this does not appear to be a good prospect for Li-Ion batteries.

We would like to make the following points with regard to our critical evaluation of the Saft Li-Ion battery:

- The performances that Saft has been able to achieve are extremely impressive for a Li-Ion battery with nickel oxide positives, or for any other battery for that matter. If these could be translated into a battery for the PQ enhancement + peak shave application, for example, Saft Li-Ion batteries would be one-quarter the weight and occupy one-half the volume of lead-acid batteries providing the same service, so would not have the same site-restrictions as the baseline battery for this application.

- The materials used to construct Li-Ion cells are quite expensive and there is a need for careful processing with large areas of electrode materials per unit of product. Small Li-Ion batteries for portable computers and the like are presently sold for more than $1000/kWh and although this price is expected to drop some in the future, we think that the commercialization of large Li-Ion batteries at $300/kWh will be very difficult.

- The cycle life that has been achieved to date is not adequate for EVs, and falls far short of what would be required for electric utility applications, particularly given the high costs that are projected for batteries with this chemistry. Even with the fully-developed cycle life (1000 deep cycles) and very high volume production costs ($200/kWh) that are optimistically projected, the cost over life costs for Li-Ion batteries would not be cost-effective for most utility applications.

- Li-Ion batteries require control of overcharge, for safety, and overdischarge, for long life, at every cell of each module. Besides being expensive and possibly not adequately accounted for in the cost estimates, this type of approach to attaining acceptable safety and long life may not be acceptable for the very large batteries required for utility applications.

- The efficiency of Li-Ion batteries should be higher than most of the other batteries evaluated in continuous partial DOD cycling. However, there is a troubling loss of capacity on long term stand (Saft estimates this at 0.5% per day) some part of which appears to be unrecoverable, so Li-Ion may not be useful in any application that does not involve cycling regularly and frequently.

- Approximately half as many Li-Ion cells as in the case of lead-acid, and only one-third as many as in the NiCad or NiMH cases, would be required to be connected in series to reach the desired DC bus voltage. In addition, many of the intercell connections would be made in the module manufacturing plant rather than in the field.

- Counterbalancing the high cell voltage, however, is the fact that it appears to have been difficult to build Li-Ion cells of more than a few 10s of ampere-hours of capacity. We believe it will take significantly more funds to develop cells and modules of a capacity appropriate for utility-scale batteries, and developers may perceive there may not be markets to support such development efforts.

Given our assessment of the Saft Li-Ion battery, and all the other factors discussed in this sub-section, we think the technology warrants further evaluation. We therefore recommend that EPRI initiate discussions with Saft to discuss the possibility of a co-funded effort to do some testing and to perform some analyses to evaluate Li-Ion batteries for restructured utility applications.

7.3 3M/Hydro-Quebec Lithium-Polymer Batteries

7.3.1 Characteristics

The Lithium Polymer Battery (LiPB) technology has been under development for more than twenty years at Hydro-Quebec (H-Q) for electric vehicle and stand-by power applications requiring significant amounts of energy storage. LiPBs were added to the roster of those being funded by the USABC in 1993-4, and the 3M Company was selected, with H-Q as a sub-contractor, to develop this system for possible use by US automakers in their EV offerings around 2003. The 3M/H-Q alliance attempts to combine H-Q's extensive experience in LiPBs with 3M's expertise in thin film coating processes and manufacturing know-how. The 3M/H-Q team have had three co-funded projects with the USABC, the first in 1993 to demonstrate the LiPB concept at the cell level, the second in 1996 to perform engineering hardware design and prototyping of battery modules, and then follow-on funding in late 1997 to transform the prototypes into real battery modules, and for cost reduction and performance improvement activities. By 2000, the USABC projects at 3M/H-Q are supposed to culminate in full-sized development LiPB packs. It should be noted that in this regard, the LiPB technology does not fall within the five-year time-frame for hardware for a utility demonstration so we are unable to assess this in the same way as other advanced batteries. Despite this, we will provide an evaluation of the 3M/H-Q technology in this report for future reference.

The 3M/H-Q cell chemistry involves what they describe as "an all-solid-state electrochemical cell" consisting of metallic lithium as the negative and a metal oxide positive, that acts as sink for lithium ions. (4) The two electrodes are separated by a thin ionically-conductive polymer membrane acting both as an electrolyte and as a separator between the electrodes. The negative is made of an ultra-thin lithium foil acting both as the lithium active material and a current collector. The positive electrode comprises a reversible intercalation compound of vanadium oxides (VO_x) blended with polymer electrolyte and carbon to form a plastic composite. Vanadium oxide is relatively inexpensive compared to the positive active materials in other ATL batteries. The positive is backed with a "low cost" metal foil current collector. The polymer electrolyte, which is the Li-ion conductor, consists of a solvating aprotic polymer, e.g., polyethylene oxide (PEO), with a dissolved lithium salt, $Li(CFSO_2)_2$. In order to obtain an acceptably low internal impedance, the temperature of LiPBs are maintained in the range of 60^0C to 80^0C. The discharge reaction in LiPBs is, therefore:

$$Li + VO_x \rightarrow Li_yVO_x$$

- where the values of x and y have not been disclosed by 3M/H-Q, as far as we are aware.

Using machinery being developed for the purpose, a LiPB cell is made by laminating five thin layers together:

1. An insulator
2. A lithium foil negative
3. Solid polymer electrolyte (SPE)
4. A metal oxide positive
5. A metallic positive current collector.

The total thickness of the cell laminate is less than 100 microns. A finished EV battery will contain "miles" of the laminate, according to 3M/H-Q publications, because the current densities that can be supported by the electrodes are very small. The laminate can be either spirally-wound in a jelly-roll configuration for cylindrical cells, or can be flat-rolled into a rectanguloid or stacked flat to give prismatic cells. Flat roll prismatic cells have been selected for EV applications because 3M/H-Q say they provide the highest energy density, better cycle life performance and improved design flexibility. During lamination, the lithium foil and the positive current collector are offset so contact can be made along the full length of their lateral edges. 3M/H-Q have developed innovative approaches, including metal spraying, for the inner cell connectors that are said to allow efficient current collection and good current distribution. The cells are individually sealed in a can, with a rupture disk to avoid explosions in case the LiPB is exposed to a fire, and are then connected in series and parallel arrays to form batteries with external connectors.

A discharge voltage range between top of charge and bottom of discharge of 3.2 to 2.0 volts is defined by 3M/H-Q as the reversible capacity range required to achieve long cycle life and to enhance safety. The cell voltage is used to gauge the SOC of LiPB cells. LiPB cells cannot be overcharged and will be damaged by overdischarge, although 3M/H-Q have built buffers into both charge and discharge so LiPBs are not as sensitive in this regard as Li-Ion cells. However, electronic overcharge protection is still required, and has been developed by 3M/H-Q and included in all their batteries, to regulate the maximum voltage **of each cell** during charging. As an additional performance and safety feature, each battery module is equipped with a fast-acting by-pass (shunting) device. The electronic controls also manage heating and cooling of LiPB cells to keep them in the range of 60-80^{0}C needed for good performance and life. Counterbalancing these negative features of the LiPB technology is the fact that the coulombic efficiency of LiPB cells is close to 100%.

Prismatic lithium polymer cells in the range of 10 to 100 Ah capacities and series-connected modules of 15 to 20 volts have been built and tested. The discharge curves of an 11 Ah lithium polymer cell show a 1.2C rate discharge capacity of 67% of the rated capacity. Under the USABC contract, the first LiPB modules at the 1.8 kWh level, with 87Ah cells, have been produced and tested. This module showed a peak power capability of 4.8kW at 0% DOD and 3.6kW at 80% DOD. More than 200 EV-type cycles to 80 % DOD had already been achieved on this type of module with cycling continuing, at the time of publication of a paper on this system.

Cycle life testing on the first generation of 6.7 Ah capacity prismatic cells with an EV discharge profile to 80% DOD and an 8-hour rate charge showed that after 585 cycles, the coulombic efficiency was at 96% and the capacity approximately 60% of rating. The next iteration of cell design is expected to show some significant improvement over this, and ultimately, the developers expect full EV batteries to show a life of 1000 deep cycles.

7.3.2 Critical Evaluation

On the basis of the results summarized above and cell laminate design improvements they have in hand, 3M/H-Q have targeted the following performances for a battery module with 119Ah prismatic cells intended for use in a full size EV battery:

- Energy capacity of 2.4 kWh at 20.4V average discharge
- Specific Energy of 155 Wh/kg and an energy density of 220 Wh/l
- Specific power of 315 W/kg

This is a module which 3M/H-Q plans to have developed and for which they plan to be ready to begin doing the manufacturing engineering for a pilot production line during 1998. There are no 3M/H-Q estimates of the possible selling price for LiPBs, but on the basis of the costs for other systems and the materials, components, and manufacturing that will have to go into batteries of this type, we think it is very unlikely that OEM prices for LiPBs in quantities of a few MWh per year will be less than $300/kWh. Even with very high production levels, we think that prices in the range of $250/kWh are the best that can be expected.

Many EV modules of the type outlined above would be required for a multi-MW utility energy storage plant, so given the present state of the technology, we think it may be up to a year or so before 3M/H-Q will be ready to prepare a first cut at a cost and design analysis for a utility application. As a result, an assessment of the LiPB technology for restructured electric utilities is clearly not appropriate at this time. Our critical evaluation of the 3M/H-Q LiPB technology is as follows:

- If successfully developed, the 3M/H-Q technology would be the highest performing of all those considered in our study. A 2.4kWh LiPB module would be 25% of the weight and half the volume of the same capacity VRLA cell.

- The average discharge cell voltage is 25% more than lead-acid, but there is an almost 40% change in the discharge voltage from 0% DOD to 100% DOD, so there will be added costs for the PCU for LiPB-based battery energy storage plants.

- There appears to be a higher degree of design flexibility inherent in the LiPB technology than in many other systems. However, this comes at the expenses of "miles" of laminate in an EV-sized battery.

- LiPBs appear much safer than developers at first thought they might be. Crush tests do not result in a safety hazard since the lithium metal foil is encapsulated by the solid polymer electrolyte. Water immersion tests on complete 100 Wh cells and crushed cells show very limited and very slow reaction with lithium. LiPBs endure external temperatures up to 180°C without venting through the rupture disk. The SPE, being a solid, cannot leak out if the cell packaging fails, nor will it vent hot solvent or gases if the cell unduly heats. This precludes damage to adjacent equipment and avoids hazards to end users.

- The battery monitoring and control system, which utilizes a two level hierarchical control architecture that interfaces with the OEM's system controller, appears quite complex and is likely to be costly. The wiring to bypass cells will also add cost to LiPBs.

- LiPBs will have to operate at temperatures of 60- 80^0C to obtain the desired energy and power levels, so heating and a thermal management system is needed. With an outside ambient of 0^0C, 200W of heating will be needed for a 40kWh EV battery with conventional insulation. This represents a self discharge loss of 12% per day, although it would probably be a lot less for a utility-sized battery and would of course be less for most of the year in the US. On the other hand, the high operating temperature simplifies heat rejection substantially, and means that installations in hot climates do not have to be actively cooled.

- The optimistic estimates of cost and life for LiPBs that can be made at present are such that significant improvements will have to be made before this a technology that could be considered for utility applications, unless there are particularly severe space or operating temperature constraints that can justify a high-priced solution to an electricity supply problem.

- Since the manufacture of Li-Polymer batteries involves high-speed coating of plastic material in a dry room/clean room environment, large production volumes are needed to bring the costs down to a level where the technology could be acceptable for utility applications. In other words, a large up-front investment is required by the manufacturer in order to get into the market.

Since developments continue to be made at a rapid pace, our recommendation for the LiPB technology is that EPRI continue to maintain a watching brief on it for utility energy storage applications, but not take any action with respect to this technology beyond this at this time.

7.4 References

(1) “Progress in Li Ion Battery system for Electric Vehicle”, M. Broussely, et al, CD ROM for EVS 14, 1997

(2) “High Power Lithium-Ion for Hybrid Electric Vehicles”, M. Saft, et al, CD ROM for EVS 14, 1997

(3) “Panel discussion - Lithium-Ion Batteries:, J. Hardin, Chair, 12th Annual Battery Conference, Long Beach, 1997

(4) “Lithium Polymer Pack Design”, C. L’Etourneau, et al, CD ROM for EVS 14, 1997

8

SUMMARY AND CONCLUSIONS

8.1 Summary and Discussion of Assessment

In the preceding Sections of the assessment, we have critically evaluated fourteen advanced battery technologies. Of these, ten were found sufficiently promising to warrant a more detailed assessment. The more detailed assessment was performed in relation to four model energy storage applications for restructured electric utilities, and by making detailed comparisons with the outline designs for lead-acid batteries that might be usable in those four applications. The results of the assessments are summarized in Table 8-1.

An examination of this table shows that there were three battery technologies that were found to be much superior, four technologies were found superior, and four more technologies might be potential candidates in the future, for one of the applications used for the assessment. We define much superior as meaning that, on the basis of the available information, it looked as if the technology would be significantly more economically attractive on a cost over life basis, and would have better characteristics, such as lighter weight or better cyclability, than the lead-acid baseline. We define superior candidates as those for which there was evidence to support a finding that they would either be more economically attractive, or economically equivalent and better performing than the lead-acid baseline. We define possibly better candidates as those for which there is evidence of economic attractiveness and technical superiority, but for which inadequate information could be obtained or which are unlikely to be developed to a point where a sub-scale demonstration of a utility application would be possible within the five year time-frame we established for our study.

It should be noted that we did not attempt, in this study, to quantify economic attractiveness of batteries in an absolute sense for the four model applications, nor yet did we try to quantify the potential markets for batteries in these applications. Analyses such as these would have been far beyond the scope of the study. We **did** obtain or make estimates of the OEM prices for cells or modules of all those advanced batteries we assessed. We also semi-quantitatively evaluated the impact of the battery technology on the costs of the balance-of-battery-plant and on the costs of the power conversion unit for those batteries for which this appeared important. The cost for the AC-side electrical work was assumed to be the same for all the batteries assessed, at least within the limits with which we were able to perform the study.

Table 8-1
Comparison of Advanced Battery Technologies to Baseline Lead Acid Batteries for Energy Storage Applications in Restructured Electric Utilities

	Transmission Line Stabilization	Arc Furnace ACE Regul'n	PQ Enhancement + Peak Shaving	Distributed Generation
Brief Description	300MW cyclic 1/month when transmission close to limits	80MW 5MWh/10 min. 2/hour round the clock	PQ 10MW, 10 sec. round the clock Peak Shave 5MW, 10MWh, 150/yr	5MW, 40 MWh 100/year When favorable economics
Advanced Batteries				
Much superior		Ergenics NiH (1)	Powercell ZnBr	Vanadium redox
Superior (2)		Delphi VRLA (3) Saft NiCad	Zebra (Na/NiCl$_2$) Lithium ion	
Possibly better (4)	Electrosource VRLA Optima spiral-wound		Lithium polymer	Sodium/sulfur (5)
Baseline				
Lead-acid type	Maintenance free truck SLI	Flooded enhanced-life UPS	Deep cycle VRLA	Flooded lift truck
Cost/Life	\$5/kW per year	\$8 million per year	\$29/kWh per year	\$15/kWh per year

(1) Developer resource limited; unable to co-fund development for utility applications

(2) Recommend holding discussions with developer about possible co-funded project

(3) Delphi has sold technology to East Penn, discussions should be deferred.

(3) Recommend reviewing again in a year or so.

(5) TEPCO and NGK Insulators have 6MW/40MWh battery operating. Unable to assess adequately. EPRI might try to follow up with CRIEPI to get more information

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We also made or obtained estimates for the life that could be expected for each of the advanced batteries assessed, and identified characteristics that could lead to higher operating costs. These are all factors that were taken in account in determining whether an advanced battery technology was superior to the baseline battery or not.

At the beginning of the study, we decided that, in order to keep the evaluations and assessments to a manageable level, it would be necessary to limit:

- The number of battery chemistries to be evaluated;
- The number of battery technologies to be assessed;
- The number of potential applications in restructured electric utilities against which we would assess advanced batteries.

We do not believe that these limits in any way compromise the study. First, all those battery chemistries for which there have been announcements concerning development projects that could conceivably be appropriate for utility applications were included in the study. Second, battery technologies were assessed that appeared to be applicable within restructured electric utilities and that are thought representative of all those being developed. Thirdly, the applications against which advanced batteries were assessed encompass a wide range of power and energy capabilities, and a variety of duty cycles, so these are also believed to be representative.

The greatest limitation of the study is not one of the limits that we found necessary to place on it, but the availability of reliable information on the advanced batteries that we assessed. The most important issue for acceptance of batteries by electric utilities is their life-cycle-cost in relation to the value they provide. Issues of secondary importance are the physical space the battery might occupy and any special conditions that might have to be met, e.g., conditioning cycles or public relations relating to safety or environmental impact. As far as life-cycle-cost for the battery portion of an energy storage plant is concerned, the largest component of this is the amortization cost for the battery, i.e., cost over life. However, estimates of first cost for future production are notoriously difficult to obtain, as much for advanced batteries as for anything that is not yet in production. Moreover, for a high degree of confidence, life tests should be performed according to the duty for which the battery is to be used. This has not been done for any of the applications used here to assess batteries, and very little life testing has been done with any duty cycles relating to utility use. As a result, the error bands for the cost over life estimates in this report are probably rather high. On the other hand, those battery technologies that were determined to be economically attractive in the study were better than the lead-acid baseline by a considerable amount, and when a technology was unattractive, it was projected to be more expensive than the lead-acid baseline by a factor of two or more.

8.2 General Discussion and Conclusions

It can be seen from Table 8-1 that in the main part of the report a recommendation was made that EPRI consider holding discussions with seven advanced battery developers to investigate the possibility of a joint development project on utility applications. It has already been determined in each of these cases that the developer in question is willing to consider some sort of joint project. However, it is NOT recommended that

EPRI fund all such projects to which consideration is given, even if there were funds available to do so, which we know there are not. A commercialized product results not just because the technology on which it is based meets customer's needs, but also because the developer has the corporate resources to make it happen, with **corporate will** to make the development successful being just as important a resource as financial backing. Only technological merits have been evaluated in the current study. The reason we think that it could be important for discussions to be held between EPRI and developers' personnel is so that the level of the corporate will to be successful in the utility market can be determined. Thus, the suggestion being made in this report is that only one or two projects for which there is the greatest corporate commitment be funded, assuming of course that funds are available to do so.

In several of our discussions with advanced battery developers, another issue was raised which needs to be addressed. This is the "chicken-and-egg" problem related to early markets. The difficulty is that utility markets will only develop if battery costs can be offset by the value derived from the use of the battery. However, for the first few sales, batteries will have high costs because the volume of production is so low. When the current study was initiated, it appeared that there might be a small but significant EV market that could help defray the costs of the first entries into the utility market. It is now becoming apparent that battery developers may be looking to niche utility markets to help defray cost of entry into what now appears might be a much smaller EV market. We think it is very unlikely that utility markets will support others because the niche, high value energy storage applications do not have a much higher value than those in a fully-developed market. This is because these niche applications can be served by a number of technologies, sometimes including storage and sometimes not, against which advanced batteries will have to compete. In addition, there are no longer the institutional funds to buy-down (subsidize) the early market costs that there used to be. Before developers will buy-down these early market costs, they will have to become convinced that the markets are worth such an investment. EPRI clearly has a role to play in this process, although that role is unlikely to be buying-down the high first market costs.

For three of the four applications used to assess advanced batteries in the current study, we were able to identify advanced battery technologies presently under development that it appeared would be much superior to the lead-acid baseline. For the transmission line stabilization application, however, the only advanced batteries that looked conceivably competitive are very similar to the baseline. This application, with one cycle per month, a very short discharge time, a need for both discharge and charge during the infrequent duty cycles, and a high DC busbar voltage, requires an energy storage device that is quite different from a conventional energy storage battery. It is therefore suggested that EPRI consider initiating work to conceptualize and evaluate unconventional electrochemical approaches for solving the transmission line stabilization problem.

Electric utilities already use a lot of batteries, not for energy storage in the conventional sense but to provide standby power to T&D sub-stations and to generating stations. In the restructured environment we think there is going to be even greater attention to the costs of equipment such as to provide standby power than there was in the past. As we have performed the current study, we have uncovered a few instances where advanced battery developers are considering provision of standby power to electric utilities as a possible market opportunity. The requirements for electric utility standby batteries have not been very well established, however, so it is difficult to generalize using the findings of the current study. This is an area that we think requires a separate study, and that any such study should involve users of electric utility standby batteries. Pending such a separate study, we think that it is possible to say that a battery chemistry with high specific energy, very low inherent costs, low stand losses, very long calendar life, and one that can be built in relatively high voltage modules, would be most attractive for this application.

Great advances have been made in advanced batteries over the last decade or so because of market forces resulting from the growth of portable electronics and because of the potential electric vehicle and hybrid electric vehicle markets. We anticipate that there will continue to be these advances, particularly in relation to HEVs, so a continuing assessment of advanced battery technologies for restructured utility applications appears appropriate.

As far as the applications and technologies that have been addressed in the current study are concerned, however, it is clear there are a number of advanced battery technologies that are being commercialized or approaching commercialization for other applications that appear to be economically superior to the lead-acid baselines. There are other advanced battery technologies that are further away from commercialization, and for which there is less information available, which we think could be economically competitive for utility applications in the longer term. Moreover, most of these advanced battery technologies would require a lot less space than the baseline designs of lead-acid batteries for these utility applications. These advanced battery technologies are sufficiently attractive, we think, that they warrant direct discussions between EPRI and developer personnel with a goal of establishing co-funded development projects to expedite the availability of these lower cost energy storage options for restructured electric utilities.

A

BATTERY ASSESSMENT FORM

The form shown on the next page was used to solicit information from the developers of many of the advanced batteries assessed in the study described in this report.

Name and telephone number of person responding				
Company developing or manufacturing battery system				
Battery data/information for which chemistry: Positive? Negative? Electrolyte? Separator?				
Can cells be overcharged and/or over-discharged without damage or dangerous outcomes? Are any special charging approaches needed?				
CHARACTERISTIC	**RESULTS for largest CELL built and tested**	**RESULTS for largest MODULE built and tested**	**RESULTS for largest SYSTEM built and tested**	**PROJECTIONS for largest SYSTEM designed**
Nominal cell voltage				
Cell OCV at top of charge				
Cell OCV at bottom of discharge				
Cells hermetically sealed or sealed with pressure relief (or the like) or vented?				
Is each module or is the system sealed or not? How?				
How are toxic materials in battery managed? What precautions to prevent human exposure?				
Cells prismatic or cylindrical?				
Best to orient cells vertically or horizontally or not important?				
Monopolar or bipolar or pseudo-bipolar arrangement of cells within module?				
Nominal A-hr capacity/cell				
Nominal discharge rate, C/hours				
Useable Ah-hr capacity per cell at nominal rate of discharge				
Average charge voltage				
Top of charge voltage				
Average discharge voltage				
Bottom of discharge voltage				
Provide charge & discharge voltage versus time curves? Y/N?				
Number of cells in parallel/module				
Number of cell in series/module				
Number of modules in parallel/system				
Number of modules in series/system				
Active standby losses, % of kWh capacity per day				
Round trip DC-to-DC energy efficiency, full charge-discharge cycling, %				
Round trip DC-to-DC energy efficiency, partial DOD charge-discharge cycling, %				
Depth of discharge for cycle tests, %				
Number of cycles to failure				
Measure by which failure counted				
Failure mode? Cause of failure?				
Height of unit, mm				
Length, prismatic unit, or diameter, cylindrical unit, mm				
Width of unit, mm				
Weight of unit, kg				
Estimated OEM price in quantities of 10 MWh/year, $/cell or $/module or $/system				
Would your company, under appropriate conditions, be interested in funding a joint development effort, with EPRI, on this battery system for utility app's?				