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# Utility Battery Storage Systems Program Report for FY95

Paul C. Butler

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# Utility Battery Storage Systems Program Report for FY95

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## Abstract

Sandia National Laboratories, New Mexico, conducts the Utility Battery Storage Systems Program, which is sponsored by the U.S. Department of Energy's Office of Utility Technologies. The goal of this program is to assist industry in developing cost-effective battery systems as a utility resource option by 2000. Sandia is responsible for the engineering analyses, contracted development, and testing of rechargeable batteries and systems for utility energy storage applications. This report details the technical achievements realized during fiscal year 1995.

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# Acronyms and Abbreviations

| | |
|---|---|
| AL | Albuquerque Operations Office |
| AML&P | Anchorage Municipal Light & Power |
| ANL | Argonne National Laboratories |
| ARPA | Advanced Research Projects Agency |
| B/C | benefit-to-cost |
| BES | battery energy storage |
| BEST | Battery Energy Storage Test (Facility) |
| BEWAG | Berlin Electric Utility |
| BMS | battery management system |
| C&D | C&D Charter Power Systems, Inc. |
| CE | coulombic efficiency |
| CEA | Chugach Electric Association |
| CI | constant current |
| c/S | central sulfur |
| CV | constant voltage |
| DA/DSM | Distribution Automation/Demand-Side Management |
| DG | diesel generator |
| DOD | depth of discharge |
| DOE | Department of Energy |
| DSM | demand-side management |
| EAC | environmentally assisted cracking |
| EE | energy efficiency |
| EMF | electromagnetic fields |
| EMI | electromagnetic interference |
| EOD | end of discharge |
| EPRI | Electric Power Research Institute |
| EV | electric vehicle |
| FMME | Facilities Management and Maintenance Expo |
| F/T | freeze/thaw |
| FY | fiscal year |
| GNB | GNB Industrial Battery Company |
| GTO | gate turn off |
| GVEA | Golden Valley Electric Association |
| IEEC | International Energy and Environmental Congress |
| IGBT | Integrated Gate Bipolar Transistor |
| ILZRO | International Lead Zinc Research Organization, Inc. |
| IPP | independent power producer |
| iR | internal resistance |

| | |
|---|---|
| IR | infrared |
| JCBGI | Johnson Controls Battery Group, Inc. |
| KCPL | Kansas City Power & Light Company |
| LFC | load frequency control |
| LPE | lithium polymer electrolyte |
| MGTF | Modular Generation Test Facility |
| NEDO | New Energy Development Organization |
| NEMA | National Electrical Manufacturers Association |
| NRECA | National Rural Electric Cooperative Association |
| OEM | Office of Energy Management (DOE) |
| OPALCO | Orcas Island Power and Light Company |
| ORNL | Oak Ridge National Laboratory |
| OUT | Office of Utility Technologies |
| PAM | positive active material |
| PC | personal computer |
| PCS | power conditioning system |
| PDI | Power Distribution, Inc. |
| PG&E | Pacific Gas & Electric |
| PLC | programmable logic controller |
| PREPA | Puerto Rico Electric Power Authority |
| PSE&G | Public Service Electric and Gas Co. |
| PSEL | Photovoltaic Systems Evaluation Laboratory |
| PV | photovoltaic |
| PVDF | polyvinylidene difluoride |
| RETSIE | Responsive Energy Technology Symposium of International Exchange |
| RFI | request for information |
| RFP | request for proposal |
| RFQ | request for quotation |
| SATS | static automatic transfer switch |
| SMES | superconductive magnetic energy storage |
| SMUD | Sacramento Municipal Utility District |
| SNL | Sandia National Laboratories |
| SOC | state of charge |
| SOW | statement of work |
| SPI | Silent Power, Incorporated |
| SPL | Silent Power, Ltd. |
| T&D | transmission and distribution |
| TCB | thermal compression bond |
| TES | thermal energy storage |
| TiN | titanium nitride |

| | |
|---|---|
| UBG | Utility Battery Group |
| UBS | Utility Battery Storage |
| UES | utility energy storage |
| UMR | University of Missouri – Rolla |
| vpc | volts per cell |
| VE | voltaic efficiency |
| VRLA | valve-regulated lead-acid |
| XPB | extended PB |
| ZBB | ZBB Technologies, Inc. |

# 1. Executive Summary

## Introduction

Because of the rapidly changing business environment for electricity supply in the United States, utilities and others will need to expand or modify their generation and transmission and distribution (T&D) resources in the future. Concerns about such matters as improved air quality and the potential health effects of electromagnetic fields (EMFs) may delay the modification of these energy resources. Therefore, utilities are currently examining alternatives to these upgrades in order to remain competitive in the marketplace.

One attractive alternative for utilities to consider is the use of BES. Batteries can be charged during off-peak periods and can provide the necessary energy to customers when it is needed. Batteries traditionally have been considered only as a load-leveling resource, but recently they have been investigated as a multipurpose UES option. Some of the potential benefits of BES are T&D deferral and improved power quality. Other potential benefits include increasing the reliability and dispatchability of renewable generation sources. A number of economic and environmental benefits for the utilities have been identified, but the acceptance of batteries as an energy storage option depends on the development of a low cost, reliable battery system.

The Utility Battery Storage Systems (UBS) Program is funded by the U.S. Department of Energy (DOE) Office of Energy Management (OEM), and is managed and conducted by Sandia National Laboratories (SNL). UBS Program staff are responsible for the engineering development of battery systems for use in utility energy storage (UES) and other stationary applications. Development is accomplished through cost-shared contracts with industrial partners. In addition to program management and technical direction of the contracts, SNL conducts analyses of the benefits of battery storage in utility systems and performs appropriate applied research activities. The performance and life of prototype batteries or components produced by development contractors are also characterized by SNL.

UBS is organized into five elements:

- Battery Systems Analysis
- Subsystems Engineering
  - Lead-Acid
    - Technology Development at GNB Industrial Battery (GNB)
    - Evaluation at SNL
    - Applied Research at SNL
  - Zinc/Bromine
    - Technology Development at Johnson Controls Battery Group, Inc. (JCBGI)/ ZBB Technologies, Inc. (ZBB)
    - Evaluation at SNL
  - Sodium/Sulfur
    - Technology Development at Silent Power, Inc. (SPI)
    - Evaluation at SNL
  - Electrical
- System Integration
  - PQ2000 AC Battery Development at Omnion Power Engineering Corp.
  - AC Battery Module Modification for the Hybrid Development Project at Omnion Power Engineering Corp.
- System Field Evaluation
  - Testing of PM250 AC Battery at Pacific Gas and Electric (PG&E)
  - Special Evaluation
- Industry Outreach

This report describes the progress made on each program element during FY95. One chapter is devoted to each element, except for Subsystems Engineering. Because most of the current UBS activity is performed within this element, progress is presented in several chapters by technology.

In the Battery Systems Analysis program element, UBS Program staff continue to study battery benefits and to quantify the value of these benefits to utilities. Thirteen key applications of battery storage for utility use have been identified. Some of these benefits have been tested and proven by battery systems in actual utility operation. In upcoming years, several other benefits will need to be verified in tests by utilities. System and feasibility studies will continue to be performed at specific utilities.

Work in the Subsystems Engineering element focuses on improving the subsystems that make up battery energy storage (BES) systems. The battery subsystem must have lower cost, higher performance, and better integration with other system components. Consequently, UBS Program staff are developing an improved battery technology, the maintenance-free valve-regulated lead-acid (VRLA) battery. When the existing cost-shared contract is completed, the technology will be ready for integration into utility systems. The use of improved near-term battery technologies, such as VRLA, offers the potential to increase the quantity and types of utility applications that can be served by battery storage compared to conventional lead-acid batteries. Under the UBS Program, the advanced battery technologies, zinc/bromine and sodium/sulfur, are also being progressed specifically for utility applications under cost-shared contracts. These advanced systems can favorably complement the near-term VRLA option in those applications where relatively high energy capacity is required (duration is ≥ 1 hr) and footprint/portability are important. Relevant applications include renewables, T&D facility deferral, and customer-side peak reduction.

Although a number of candidate advanced battery technologies are being developed with private and public funding, zinc/bromine and sodium/sulfur are felt to have the best chance of providing the desired benefits; these technologies are expected to be commercially available around the year 2000. These technologies have different sets of obstacles to overcome because they represent two radically different types of batteries. In this program, development is focusing solely on the needs for UES applications, which may be different from those for other applications, such as electric vehicles (EVs). While safety is the top priority for both EV and UES applications, the UES application requirements emphasize cost over weight- or volume-based performance specifications. During the course of this program, external development of emerging battery technologies (e.g., lithium polymer electrolyte (LPE), nickel/metal-hydride) will be closely monitored to determine whether a utility-specific activity is warranted.

For the electrical subsystem, UBS staff will develop standardized, modular power conditioning system (PCS) designs that will lead to lower manufacturing costs. The focus of this task is to improve the electrical subsystems, such as the power conversion system, the control systems, and the switch gear, by pursuing design standardization to lower manufacturing costs and by incorporating advances in power electronics to improve performance.

In the System Integration element, the program staff develop complete units that include energy storage devices, electrical power conditioning equipment, and other required ancillaries. A "modular" system design approach is being promoted in all UBS system engineering and system integration activities. This approach is viewed as the most effective way to reduce production costs as well as the one-of-a-kind engineering and design costs associated with most of the present systems.

In the System Field Evaluation element, field qualification of hardware that incorporates the prototype designs and associated manufacturing methods is completed. This activity represents the final step of this phase of engineering development. For the technology being developed under UBS, the qualification process involves the detailed characterization of performance, maintenance requirements, and reliability of integrated systems at relevant utility sites.

The UBS Program staff uses a variety of mechanisms to disseminate the latest battery information to utilities through its Industry Outreach program element. The program assists the Utility Battery Group (UBG) in its efforts to encourage utilities to examine the potential of battery systems. The UBG is a utility interest group composed of representatives from several utilities; manufacturers of batteries, converters, and systems; and consultants. The program also interacts with efforts by the Electric Power Research Institute (EPRI) to inform its utility members about battery systems, to develop battery storage evaluation software, and to quantify the benefits of battery storage. DOE and SNL regularly publish articles and attend engineering and utility meetings to inform the public about BES.

The highlights of the achievements for each of these projects for FY95 follow.

# Highlights

## Battery Systems Analysis

### Sacramento Municipal Utility District (SMUD) Feasibility Study

A feasibility study is being conducted with SMUD to determine the value of battery storage systems, especially in combination with renewable resources such as wind and photovoltaics (PV). The study showed that a battery system could capture some additional spinning-reserve and T&D benefits at a 500-kW PV site. The study also showed that the battery system can benefit both the wind and PV resource by only 20 to 60 discharges per year.

A draft of the final report has been submitted to SMUD for review and comment. The findings of this phase have been encouraging, and it is anticipated that SMUD will fund the follow-on phase II activity to refine the benefits estimate and develop a functional specification for the battery system.

### Chugach Electric Association (CEA) Feasibility Study

A major review was held in September 1995 of the CEA feasibility study for battery storage on the Alaska Railbelt utility network. The review was attended by over 23 personnel from CEA, the neighboring utilities of Golden Valley Electric Association (GVEA) (Fairbanks), Anchorage Municipal Light & Power (AML&P), and Fairbanks Municipal Utility, EPRI, and SNL.

The DYNASTORE generation cost model, developed by EPRI, is being used to quantify the battery system benefits, and the PSS/E model is being used to calculate the T&D benefits. Significant changes in system load have been identified and are being incorporated into the study.

GVEA included a 40-MW battery system in the planning and design of a new 138-kV transmission line linking Anchorage and Fairbanks. GVEA contracted with Power Engineers, Inc., to prepare the engineering design of the line and associated substations, including space for the battery system. A draft version of a functional specification that can eventually be used to purchase the battery system was released in July for comment. Comments have been received, and Power Engineers, Inc., is planning to release the modified specification in the near future as part of a Request for Proposal (RFP) package.

### Orcas Island Power and Light Company (OPALCO) Feasibility Study

OPALCO serves about 10,000 customers spread over 19 islands that are interconnected with submarine cables. This feasibility study, jointly funded by Oak Ridge National Laboratory (ORNL) and SNL, investigated the benefits of wind resource and BES for Orcas Island. This study identified three significant benefits:

- Deferral of the planned Lopez-Eastsound circuit upgrade to 69 kV;
- Energy displacement; and
- Monthly demand charge reduction.

The study concluded that a battery storage system located near the Eastsound substation could defer the planned circuit upgrade and capture significant benefits. The study identified two options for the battery system: (1) leasing the battery system for two years or (2) purchase of the battery system by OPALCO. The study estimated a benefit-to-cost (B/C) ratio of 3.68 for the lease option and 1.52 for the purchase option. The analysis showed that the purchase option captures greater benefits, because it is available for a longer period of time than the two-year operating period of the leased system. However, the purchased system has a lower B/C ratio because of the higher initial investment as compared to the initial capital investment required for leasing the battery system. This result confirms the intuitive assumption on the benefits of leasing, especially for smaller cooperatives and utilities, such as OPALCO, that may not want to assume the full responsibility of system ownership, or in the specific case where the nature of the application provides only a short window of opportunity in capturing high-value benefits.

A draft final report has been written and provided to OPALCO for comment before it is finalized and released.

### Market Feasibility Study

Recently, an Opportunities Analysis was performed to characterize the capabilities of and the opportunities for batteries to provide electric UES options. The study indicated that the total benefits that might result for U.S. utilities and for the nation from the implementation of BES systems on both sides of the utility meter could amount to $57 billion between 1995 and 2010. The opportunities uncovered in this analysis are more than an order of magnitude greater than the market as it exists today, thus raising the question as to whether there is indeed a significant realistic market for BES systems. The Opportunities Analysis was only an analysis of opportunities for BES applications, however; it was not a projection of any markets that might develop for BES. Further study is necessary to determine if there are potential markets that will cause BES businesses to make the investment necessary to develop viable products.

To that end, a Market Feasibility Study is being initiated through the UBS. SNL is considering all the options for conducting the study that will accommodate the interests of the stakeholders while preserving the objectives and desired outcome of the market feasibility study. In July, a request for information (RFI) was issued to solicit comments to the statement of work

(SOW) proposed for this effort. Comments received through this review process are being used to modify the SOW.

## Subsystems Engineering – VRLA

### Technology Development – GNB

All of the tasks in the multiyear VRLA battery development contract with GNB are completed. With the regard to the battery improvement effort, GNB is satisfied with the results of a final 500-hr test, under continuous overcharge conditions, of the basic design of the ABSOLYTE pressure relief vent; this test was performed after the assembly process was modified to raise the relief pressure. An umbrella-type pressure relief vent was also determined to be usable with certain specific battery designs. Cells constructed with different methods for accommodating positive plate growth remain on long-term test at 60°C. After 5 mo, there was no discernible difference among the samples and no behavior indicative of short circuits resulting from positive plate growth. Additional testing outside the scope of the contract may continue on these samples. Work on thermal management and charging was completed earlier in the contract with the development of a VRLA battery recharge profile that minimized temperature and pressure rise while providing an adequate recharge of a deeply discharged battery in less than 8 hr. A thermal model that can be used to predict the behavior of the ABSOLYTE VRLA battery was also developed. Several battery improvements to reduce the risk of ground faults were implemented. Two other developments to reduce ground faults, a nonconductive battery tray and a modified terminal-post seal design, have been shown to be feasible and will be implemented as customer demand increases, as experience with the design is accumulated, and as other tooling modifications need to be made. Evaluations of a leady oxide paste formulation for the positive electrode showed improved cycle-life capability with no detrimental effect on float life, so plans are in progress to use this material in certain deep-discharge cycling VRLA battery designs.

The battery advancement tasks in Phase 2 have also ended. While the basic performance characteristics of the MSB and LSB batteries have been demonstrated, manufacturing process and assembly difficulties were encountered during prototype sample builds of both designs. GNB is committed to the eventual introduction of these batteries as commercial products, but a systematic resolution of the manufacturing issues will extend the scope of this activity beyond the end of the current contract. Work on development of a copper negative grid was terminated earlier because of the unavailability of a suitable lead-coated copper wire. An evaluation of alternative positive-grid alloys has been completed, the conclusion of which is that the baseline MFX alloy is still the best option for use in batteries designed for utility applications. Tasks for testing of positive active material (PAM) additives and lower-cost separator materials have been discontinued because samples of interest could not be furnished by their manufacturers soon enough to evaluate before the end of the contract.

The development of BES system requirements and conceptual plant layouts under Task 2 was completed earlier in the contract, so there has been no further activity in that area. Task 3 has now also been finished. The costs for several recent BES system projects have been analyzed to determine the contribution of the battery for a typical system with a reasonable amount of energy storage capacity. Since the battery was found to constitute only 25-30% of the overall system cost, savings in the inverters and balance of the system have a larger potential to reduce overall costs. However, some cost reduction in the area is possible, and improvements to the ABSOLYTE II product that existed at the start of the contract were estimated to result in a reduction of the battery cost by 14% (in $/kWh) for the ABSOLYTE IIP. A comparison of the costs of the advanced battery designs using the ABSOLYTE II as a baseline was also made. Since these advanced batteries were optimized for high power uses, their advantages were more pronounced for short-duration, high-rate-discharge applications. In this type of use scenario, reductions in space, required footprint, and battery cost of up to 40-50% were projected for the advanced battery designs.

An approximately 250-kW/500-kWh VRLA battery is being furnished for a field test at the conclusion of the development program. GNB was selected to carry out this 4-yr test program on the basis of its proposal to use the battery as part of a system to provide power to critical loads at their Vernon, California, battery recycling center. The battery has been installed, and a final operational check of the system is nearing completion.

### Quantification of the Costs/Benefits of BES – University of Missouri - Rolla (UMR)

A revised final report covering the work done by UMR on their initial contract has been produced. Calculations of operating costs for an isolated utility were carried out with beta test versions of the DYNASTORE computer program. The effects on operating costs of incorporating a BES system for spinning reserve, load leveling, or frequency control were determined for a range of BES capacities from 40 MW to 500 MW.

Below 300 MW, operating cost savings are almost linear with battery system size. Inclusion of random forced outages of generating units in the simulations by a standard Monte Carlo method led to significantly larger cost savings for all three BES use scenarios. The results for the spinning-reserve and load-leveling applications were nearly identical because DYNASTORE counts excess battery capacity in the load-leveling mode as spinning reserve. Very little of the operating cost savings were due to load leveling in this case. The savings for the frequency control application were only about 20% of those for the spinning-reserve mode. Combining spinning reserve and load leveling gave the largest calculated savings found in this study.

SNL has placed a follow-on contract with UMR to use DYNASTORE to evaluate utility operating costs with and without BES for a grid-connected utility system. Data entry has been completed for this project, and the input has been checked for errors. Operating costs have been calculated for a base case without BES, and these were compared to actual utility operating costs as a final verification that the results were reasonable. The next task will be to calculate operating costs for various BES scenarios.

### Technology Evaluation – SNL

The ABSOLYTE II (original design) and ABSOLYTE IIP (intermediate design) deliverables sent to SNL from GNB were tested. Most testing on these two batteries in FY95 was performed to evaluate various GNB-recommended recharging regimes and to settle on a regime that is suitable for UES applications, and also to evaluate improvements incorporated into the intermediate design. Some frequency regulation and spinning-reserve tests were also performed on the ABSOLYTE IIP design towards the end of FY95.

### Applied Research – SNL

Processing engineers at SNL are depositing coatings by plasma spray onto various test samples to support research at GNB on ways to improve lead-acid battery performance. One of the two top-priority coating materials has been successfully deposited on substrates supplied by GNB and the specimens returned to them for evaluation. The results of microscopic examinations of these samples were quite favorable. Coverage seemed to be complete, and the coatings were tenacious. A source for feedstock powder of the second material has been identified, although it would be relatively expensive because of the precious-metal crucible liner material required for its preparation. For this reason, an alternative procedure of depositing the metal of interest, followed by conversion to the oxide in a subsequent heat treatment, has been suggested. Personnel from the SNL Thermal Spray Research Lab are in contact with GNB to discuss the best materials and approach to use in future work.

## Subsystems Engineering – Zinc/Bromine

### Technology Development – ZBB

Cycle-life testing continues on the 8-cell V-design battery stacks. The performance and cycle life of vibration-welded batteries have improved significantly since the beginning of the contract. Cycle life has increased from less than 260 cycles to greater than 1000 cycles. For example, Battery V1-79 completed 1036 cycles before the energy efficiency declined to 90% of the peak value of 76%. This battery remains on test and is presently achieving 64.5% energy efficiency after 1368 baseline cycles. Energy efficiency has also improved, from 73% to 78% in some cases.

Eight 60-cell battery stacks have demonstrated acceptable performance on baseline cycles and will be used for the 100-kWh deliverable battery system. All of the stacks achieved at least 75% energy efficiency on baseline cycling.

Polarization and internal resistance (iR) losses for several 8-cell, 1170-$cm^2$ battery stacks were compared. Generally, batteries built recently are much lower in resistance than earlier battery stacks. This decrease in resistance is attributed to the development of a low-resistance carbon plastic electrode material. Modifications incorporated into one battery (V1-80) have resulted in improved battery performance over the first 900 baseline cycles.

Several experimental battery separators have been found to have properties similar to or better than the standard zinc/bromine battery separator. One 8-cell battery stack was manufactured from each of two experimental separators and from the standard separator to examine the electrochemical performance. Reasonably good performance was achieved.

The weld integrity of a number of battery stacks was investigated by burst testing the battery stacks. During initial testing, the weld failed at about 17 psi for each of the two stacks tested. It was believed that this failure resulted from a slight taper in the end block. To eliminate the tapering problem, the end blocks were overwelded for the next set of tests. The overwelded stacks failed at about 20-22 psi along the side edge of the stack. Test results for end blocks with less taper (obtained from the manufacturer) were slightly better than the results obtained when the frame was overwelded to the end block.

Work continues on the fabrication of the 100-kWh battery system. The system has been connected to the PCS. Short cycles have been run on the system for calibration purposes and to test fault conditions. Efforts are being made to eliminate electrical noise in the system, which has caused periodic shutdowns and has delayed system testing.

### Technology Evaluation – SNL

ZBB delivered a 2-kWh, 8-cell battery to SNL for evaluation in August 1994. The testing goals for this battery were to determine cycle life under baseline, no-strip, and simulated utility profile conditions. Also of interest was how well the battery functioned under ZBB's microprocessor controller. This controller monitors battery stack voltages and currents, electrolyte levels, and the battery state of charge (SOC). It also regulates the circulation of complexed bromine through the stack during charge and discharge.

Test results indicated that, for the first four cycles, SNL was getting approximately 3% less coulombic and energy efficiency than ZBB, but these efficiencies were stable. Poor results were recorded for Cycle 5 because of a high-temperature alarm that caused the battery to sit on open circuit for approximately 1 hr. The efficiencies for Cycle 6 were at the levels of the first four cycles; however, software changes in the controller were needed to complete the cycle.

Cycles 7 to 14 showed a loss in coulombic and energy efficiency, and these efficiencies became unstable. During this time, controller problems were encountered. The programmable controller has a unique design and went through several design iterations after its fabrication; consequently, it is significantly different from the unit at SNL. Given the limited resources and funding, efforts to repair the battery control system at SNL were suspended in November 1994.

## Subsystems Engineering – Sodium/Sulfur

### Technology Development – SPI

SPI has been actively promoting the concept of distributed BES for utility and utility customer applications. A brochure depicting the integrated 300-kVA/300-kWh NaS-$P_{ac}$ BES system design was circulated to approximately 250 U.S. utilities to help them envision the benefits of electrical energy storage within their service territory. Utilities targeted initially were those paying relatively high costs of more than \$.08/kWh for electricity. These utilities are believed to be in the best position to take advantage of storage. A second mailing was directed to demand-side management (DSM) managers, who might best understand the value of storage in reducing the burden of peak load on their system. The responses have tended to emphasize applications that enhance power quality and extend outage protection, with some interest in coincident peak clipping. The smaller municipal and cooperative utilities have tended to look for tie-point applications, i.e., using storage at an appropriate tie-point to reduce a short coincident peak. Most utilities that have expressed an interest, however, are considering specific applications that benefit the customer side, eventually as a chargeable service option.

The detailed design and cost analysis of a NaS-$P_{ac}$ BES system rated at 300 kVA/300 kWh was completed. The system utilizes ten 40-kWh EV batteries from Silent Power, Limited (SPL), mounted five high in a structure behind the power converter envelope. The PCS is designed to deliver up to 500 kVA with four-quadrant operation. The entire system measures 7 ft (W) × 7-1/2 ft (H) × 8-1/2 ft (L) and weighs 8 tons. Based on battery production levels of 400-MWh per annum, the expected system price is \$189,000 or \$630/kW. The system takes advantage of a central processor to control the 10 batteries as well as the power converter. The front panel user interface is flexible and can be programmed for utility power dispatch or specific customer applications.

To serve as a prototype test unit, a smaller 30-kVA, 2-hr version of the NaS-$P_{ac}$ system design was completed. The design includes two series-connected prototype EV batteries integrated with a PCS rated at 50 kVA. A complete mock-up of the proposed design was assembled for the purpose of verifying design fit-up and to verify the proposed cooling scheme. The complete system, measuring 3 ft (W) × 3-1/2 ft (H) × 4-1/2 ft (L), is about the size of a 5-ton residential heat pump. In addition to serving as a test bed, the system may find application as a power source for commercial businesses requiring backup power. The price of this system in low volume is expected to be around \$30,000.

Significant progress relative to the development of a long-lived central sulfur (c/S) cell was made during the year. Reliability of the sodium seal was improved to the point where the cell design could be frozen, permitting cells to be built to characterize thermal cycling durability, safety, and production repeatability. During the course of this work, the options for sodium seal designs were narrowed to two candidates: a planar thermal compression bond (TCB) seal using 4032 aluminum alloy interlayer and a radial tapered TCB seal. The planar seal was desired from the standpoint of potentially low-cost manufacturability, but until the incorporation of the 4032 aluminum interlayer, it had poor thermal cycling (freeze/thaw, or F/T) durability. The tapered seal had been used successfully by SPL in their "Technology Demonstration" cell, but it had little potential for being a low-cost seal. During developmental F/T trials during this project, the planar seals actually proved to be incrementally more durable than the tapered seals. Unfortunately, more effort will be required to fully develop the TCB seal. Consequently, the viability of the c/S cell cannot be determined.

During initial thermal-cycle testing, none of the electrolytes fractured, a result that was highly encouraging because this was one of the primary concerns with a c/S cell configuration. Further, one cell of each seal type was subjected to F/T cycles while discharged to greater than 70% depth of discharge (DOD). The cell with the planar sodium seal was removed from test after sustaining 11 F/T cycles while fully charged and 10 F/T cycles while discharged. The cell with a tapered sodium seal sustained 10 F/T cycles while charged, and it failed (electrolyte fracture) on the ninth thaw while discharged.

Included in the final cell design were several modifications that have improved the safety performance of the cell during electrolyte failure. Ninety-nine cells were fabricated and placed on test. Safety testing of 20 cells was performed in two iterations. In earlier safety tests, three of five cells tested breached during the induced electrolyte failures. With improvements in the safety features of cells tested in the second iteration, the incidence of breaches was reduced to 1 in 15 cells. Further improvements in safety performance appear feasible.

Additional cells with titanium-nitride (TiN) coated current collectors were fabricated and tested. The results of these tests were somewhat better than those of earlier tests of cells with TiN-sputter-coated current collectors; however, TiN does not posses sufficient corrosion resistance to provide life equal to the traditional nichrome coatings.

As a part of the development of battery components, a new, more compact and efficient mode of cooling high-temperature batteries has been designed, assembled, and tested. At present, sodium/sulfur EV batteries are cooled by circulating oil through a plenum within the hot battery interior and rejecting this heat to ambient. The cooling scheme developed in this project for stationary applications transfers heat from the cell matrix to an isothermal surface maintained at constant temperature by a boiling fluid. A simple thermosyphon is utilized to circulate the fluid, thereby eliminating the need for a pump. The Fluorinert fluid, while relatively expensive, offers a safe (no fire- or flashpoint) and simple way of cooling the battery during sustained power operation.

During the year, the major contract deliverable, a 12-kWh battery, was tested at SNL. Testing was terminated after its capacity degraded to 75% of its initial rating (400 Ah). For the testing results, refer to the next section. Following the SNL testing, the battery was cooled and shipped back to SPI for posttest analysis. The battery was dismantled and examined. The overall visual appearance of the battery was quite good, with no evidence of cell breaching. Cell strings have been radiographed and the posttest analysis is continuing.

### Test and Evaluation – SNL

Testing of the 12-kWh, 400-Ah sodium/sulfur UES battery supplied by SPI was completed at SNL during this year. The commissioning of the battery and test system operational verification were performed during the first quarter of FY95. The capacity of the battery started declining in November 1994 and continued to degrade through February 1995. Data analysis indicated that a significant number of string failures may have occurred in Bank 1 or that an internal short had developed. The four banks of the battery were individually charged to balance the bank capacities. Nevertheless, the capacity of the battery continued to decline as testing continued. Testing was discontinued on February 20, 1995, with a calculated capacity of 296 Ah after 133 cycles. Two of the four test objectives were satisfied.

### Applied Research – SNL

SNL has had an ongoing effort to develop thermal fuses that would be suitable for use as a safety device in sodium/sulfur batteries. Test results on prototype cast metal fuses fabricated earlier in the year indicated that a slightly wider gap between the fuse leads would improve consistency of function when the samples were exposed to temperatures above the melting point of the metal alloy. A mold has now been fabricated that will allow fuses to be built with a larger range of gap widths. Alloys are now being formulated so that prototype fuses with various gaps can be cast with the new mold and then evaluated in a fusing test.

## System Integration

### Hybrid System Controller and PCS Development Project – Omnion

During the first quarter of FY95, fabrication and checkout of the Hybrid System Controller and PCS was completed at Omnion Power Systems. Early in the second quarter, a design modification was proposed to reduce the system input DC levels to less than 600 VDC to bring the system into compliance with the limitations imposed by the National Electrical Code. The modifications were completed in early February 1995 and did not affect the 31-kW rating of the system.

Witness testing of the operational hybrid PCS and power management system was conducted by Omnion engineers. All functions of the power management controller were successfully demonstrated. After the successful completion of the witness testing program, the Hybrid System Controller and PCS was delivered to the SNL Photovoltaic Systems Evaluation Laboratory (PSEL) in early April. At the PSEL, the Hybrid System Controller was interconnected with PSEL resources consisting of a 750-kWh battery, an 85-kW DG, and a 15-kW PV array. Shakedown testing was performed successfully. Following the shakedown tests, the Hybrid System was tested to verify seamless transfer among the various energy sources. In all cases, the Hybrid System successfully transferred between the sources with no disruption of power to the loads.

Following characterization testing at the PSEL, the Hybrid System was integrated with a fuzzy-logic controller to determine the performance of the system and controller in a simulated operational environment. This testing was completed in May 1995, and the system was placed into storage in June 1995. A complete report is being prepared by the PSEL test team and is expected in the first quarter of FY96.

### 250-kW Bridge Development Project – Omnion

A Preliminary Design Review for the 250-kW bridge was held at Omnion on September 23, 1994. At that meeting, a preliminary design specification was reviewed and full-scale development was initiated. Development of a single-phase bridge was completed, and testing began in January 1995. The testing goals were realized, and testing continued to yield information on the ultimate performance capabilities of the bridge.

At the end of the second quarter, full-power tests were being conducted to determine the thermal limits for the system. It was demonstrated during testing that all bridge components were capable of operating for at least 60 sec at full power.

During the third quarter, the complete 3-phase, 250-kW bridge and associated electronics were assembled and checked out. Thermal considerations indicated that the bridge could operate for longer periods, except for one component, the output filter chokes, which required minor modifications to extend their operating periods.

Full-power testing of the bridge and PCS was completed in mid-August 1995. All power components passed the 90-sec thermal bench test. Thus, the 250-kW bridge project was successfully completed during the fourth quarter of FY95.

### AC Battery Follow-On Tasks – Omnion

When the AC Battery Maintenance Contract with Omnion expired in early April, AC Battery assumed responsibility for coordinating PM250 retrofit activities that were in progress. While Delphi was evaluating a new battery, the AES 2010, for the retrofit, the modules and controllers were being tested in the Delphi container using Delco 2000 batteries.

Because of interference caused by the intense activity on the PQ2000 module development and battery selection, acceptance testing of the AES 2010 was delayed until late in the fourth quarter of FY95. Resumption of testing on the retrofitted PM250 at PG&E has been rescheduled for the third quarter of FY96.

### DOE Cooperative Agreement for PQ2000 Development – Omnion

Early in the first quarter of FY95, work began at Omnion on the Cooperative Agreement placed by DOE/Albuquerque Operations Office (AL) to support the design, fabrication, and testing of the first AC Battery PQ2000. The first meeting of the AC Battery PQ2000 Design Team was held in Milwaukee, Wisconsin, in January 1995. At this meeting, the preliminary design review was conducted and the initial schedule for developing the PQ2000 was presented.

The second meeting of the AC Battery PQ2000 Design Team was held in San Francisco in early April. At the meeting, Delphi Energy Systems reported that the Delco 1150 battery had been identified for potential use in the PQ2000 and was undergoing suitability testing. Delphi also reported that delivery of the eight PQ2000 modules with the full battery complement was on schedule. Power Distribution, Inc. (PDI) of Sandston, Virginia, was identified as the supplier of the static switch, a primary component of the PQ2000 system.

The final meeting of the AC Battery PQ2000 Design Team was held at Omnion in East Troy, Wisconsin, in early August. At the meeting, a decision was made to postpone the development of the DG startup control unit. Also, a request had been made to extend the run time from 10 sec to 20-30 sec. The team decided to stay with the original 10-sec specification.

The scheduled time for factory testing of the PQ2000 has slipped to late in the first quarter of FY96. As of the end of FY95, witness testing and customer acceptance testing was scheduled for December 28, 1995.

## System Field Evaluation

### Testing of the Hybrid System Controller and PCS – SNL

The Hybrid System Controller and PCS was delivered to the PSEL in early April 1995. After the Hybrid Controller was connected to existing PSEL resources, loads were provided and various reactive and resistive components were provided for power factor testing. After a successful shakedown test in which the Hybrid performed all functions called for in the SOW, the system was extensively tested for seamless power transfer under a variety of power factors and load magnitudes. Test results indicate that the system is able to make seamless transfers in all operational environments.

After completing the characterization tests, the Hybrid System Controller and PCS was connected to a fuzzy-logic controller to test the feasibility of using such a controller in an automated hybrid system. Initial results indicated that this type of controller has high potential in a hybrid environment. This testing was terminated in early June with plans to resume testing in FY96.

### Testing of AC Battery PM250 – PG&E

Throughout FY95, testing of the AC Battery PM250 at the PG&E Modular Generation Test Facility (MGTF) was on hold while the modules are being retrofitted with production (AES 2010) batteries at Delphi Energy Systems, Indianapolis, Indiana. Life-cycle testing of the PM250 prototype with the new AES 2010 batteries will resume during the third quarter of FY96, as soon as the PQ2000 vacates the test pad.

### Testing of AC Battery PQ2000

PG&E has developed a draft PQ2000 Field Test Plan. The draft was presented for review at the August 1995 PQ2000 Design Team meeting. The draft test plan was agreed to and the Design Team requested that PG&E and Omnion proceed with the development of a factory acceptance test plan, which should be ready by November 1995.

### Testing of Zinc/Bromine Factory-Integrated Battery System – PG&E

PG&E has been working with ZBB to develop safety plans and operating manuals for the system and to provide the documentation necessary for approval of on-site acceptance testing at PG&E. The necessary documentation has been completed, and approval was given to begin on-site acceptance testing.

## Industry Outreach

A major part of the FY95 Industry Outreach effort was taking the message of the benefits of BES to trade shows, conventions, and exhibitions. The targeted audience was utility executives, engineers, and the manufacturing sector. Five major electric utility and power-related events were attended during the year. These events were attended by more than 15,000 people interested in the electric power industry. UBS personnel chaired sessions, presented papers, and participated in the exhibits. Literature and brochures were handed out. The major theme presented at the exhibitions was that BES systems could save utilities and their customers money. These meetings emphasized not only reduced operating costs to the utilities but the much more important cost avoidance to manufacturing customers resulting from not having production interrupted. Power outages, voltage spikes and sags, and frequency irregularities trigger cascading detrimental and costly work stoppages. BES systems properly applied have the potential to reduce 95% of the power/voltage/frequency irregularities that cause production interruptions. Significantly reducing production interruptions can make the U.S. more competitive in world markets by reducing the cost of a major component of manufacturing. This message was delivered at the following events:

- Distribution Automation/Demand-Side Management (DA/DSM), San Jose, California, January 23-25/1995
- National Rural Electric Cooperative Association (NRECA), Orlando, Florida, February 25-28, 1995

- Globalcon/Responsive Energy Technology Symposium and International Exchange (RETSIE), San Francisco, California, April 18-20, 1995
- International Energy and Environmental Congress (IEEC), Richmond, Virginia, August 16-17, 1995
- PowerSystems World International, Long Beach, California, September 13-15, 1995

Other significant events associated with industry outreach were the Fifth International Conference on Batteries for UES and the Ninth Meeting of the UBG. These meetings were held concurrently in July 1995 in San Juan, Puerto Rico, and were hosted by the Puerto Rico Electric Power Authority (PREPA). San Juan was chosen for the conference site because PREPA had just inaugurated a 20-MW Battery Storage Plant for spinning reserve, frequency control, and voltage regulation. Whereas the economic and technical feasibility of BES systems has been shown in various parts of the world by demonstration plants later converted to commercial plants, the PREPA battery facility is the first plant to be developed as a commercially ready plant from its inception. After more than 1 yr of operation, the PREPA 20-MW BES system is a financial success for the utility. More important, however, power outages to the customers have been reduced significantly. This is a major boost to the manufacturing entities in Puerto Rico straining to compete in the world market. The Industry Outreach goal is to communicate successes such as the one in Puerto Rico so that the rest of America can achieve lower overall production costs and thereby stimulate employment.

# 2. Battery Systems Analysis

The purpose of the Battery Systems Analysis element is to identify high-value benefits of BES in a wide variety of utility applications. These activities will enable utilities to quantify the usefulness of battery storage and to make decisions regarding suitability to their applications. Widespread acceptance of this technology by the utility industry will eventually make it possible for utility planners to routinely include battery storage in their planning scenarios. Such acceptance is necessary for the eventual commercialization of this technology.

There are three subelements in the Battery Systems Analysis program element:

1. Applications Analysis/System Study
2. Feasibility Study
3. Opportunities Analysis

A "system study" is an initial screening study performed in cooperation with a host utility to identify and evaluate the potential benefits of BES to that utility. This screening-level study establishes a rough estimate of the battery's B/C ratio, using a limited examination of utility-specific operation and financial data as a basis. The exact size of the BES facility, its location in the utility network, and operational details of the BES system are not defined at this time.

The follow-on "feasibility study" goes beyond the initial system study and firmly establishes the quantitative value of BES to a higher level of confidence by examining detailed forecasts of utility operating costs and other operational parameters for the entire life of the BES project. A site-specific conceptual design of the BES system is included in the feasibility study to determine the cost of the battery system needed to generate these benefits.

A feasibility study is recommended if the results of the previous system study indicate a potential for a sufficiently high B/C ratio. There are no widely accepted norms for the B/C ratio that trigger a commitment to a feasibility study, but generally a ratio of 1.5 may be acceptable justification to proceed to the feasibility study phase. The results of the feasibility study lay the foundation for possible future BES projects and become an essential part of project planning.

The principal desired outcomes of the entire Battery Systems Analysis element are produced within the Opportunities Analysis subelement. As such, the results of the other two activities are directly used. First, the economic benefits at the national level are characterized; these must include the identification of market size, timing, and specific applications. System-level requirements for each application are defined, but working definitions of these requirements are needed to allow effective system design and engineering to proceed. The desired information includes system-level specifications related to power, energy, cost, and duty cycle along with any special needs such as power quality and/or general siting constraints (e.g., environmental, physical). Detailed design-specific information, such as the performance requirements for the various individual components of the system, their configuration, or their operating conditions, is not included. Finally, a study is performed to match battery technologies with specific applications.

## Tasks/Milestones

FY95 Milestones:

- Complete Opportunities Analysis (3/95) – completed; final report issued.
- Complete SMUD Feasibility Study, Phase I (7/95) – draft completed 4/95. Final release pending review by SMUD.
- Complete CEA Feasibility Study (9/95) – rescheduled to 3/96.

## Status

### SMUD Battery Storage Feasibility Study

A feasibility study is being conducted with SMUD to determine the value of battery storage systems, especially when used in combination with renewable resources such as wind and PV. The scope of the first phase of the two phase consisted of the following:

- Identifying two sites for potential installation of BES on the SMUD system, one site to support a PV application and the second for the 5-MW Solano wind project.
- Quantifying the B/C ratio for a battery system in each application with an emphasis on firming up estimates of the capacity of the variable output of the PV and wind systems.

Table 2-1 shows the variability in the output of the Solano wind farm for July-December 1994. Energy production is highest in the summer months and lowest in the winter months. The highest wind plant energy production correlates well with the summer SMUD peak load period. However, the hourly integrated output shows the variability of the wind generation and the opportunity of firming up the capacity with storage. Figure 2-1 presents a plot of the hourly integrated Solano wind plant output during July 1994. The plot shows the wind generation exceeding the 5-MW rating of the wind farm on several days during this period. It also shows the variability of the output, with the output spanning the entire range of the farm's 5-MW rating. Figure 2-2 shows a similar plot of the wind output, but for the 6 p.m. SMUD peak hour for the months of July and August 1994. The plot shows the absence of wind during the peak hour for some days and the variability of the available wind during other days during this period.

Similarly, the data from a 500-kW PV sites was analyzed. Currently, this site is assigned a 55% capacity factor with an effective rating of 275 kW. Adding a 225-kW, 2-hr battery system would allow the plant to effectively capture the full 500-kW nameplate rating of the PV system. The study showed that the battery system could capture some additional spinning reserve and T&D benefits at this site. The study also showed that the battery system can benefit both the wind and PV resource by only operating for 20 to 60 discharges per year.

The conclusions of the study were as follows:

- The results of this Phase 1 preliminary study indicate that battery storage can significantly enhance the economics and operational value of the Solano wind plant and the PV plant.
- The preliminary B/C calculations indicate that the break-even capital investment for battery storage installed to enhance the value of the 5-MW Solano wind plant ranges from about \$1520/kW to \$1300/kW. This applies to MW-scale battery storage plants up to 7.5 MW in capacity with 2 hr of storage located at the Solano wind plant site.
- The preliminary B/C calculations indicate that the break-even capital investment for battery storage installed to enhance the value of the 500-kW PV plant is about \$1300/kW. This applies to battery storage plants up to 225 kW with 2 hr of storage and located at the plant site.
- Approximately 20 to 60 battery charge/discharge cycles per year are required for both the Solano wind plant and PV plant applications. Thus, less expensive light-duty batteries will be adequate.

A draft of the final report has been submitted to SMUD for review and comment. The findings of this phase have been encouraging, and it is anticipated that SMUD will fund the follow-on Phase 2 activity to refine the benefits estimates and develop functional specifications for the battery systems.

**Table 2-1. Monthly Solano Wind Farm Capacity Factor**

| | |
|---|---|
| July 1994 | 69.5% |
| August 1994 | 46.3% |
| September 1994 | 38.9% |
| October 1994 | 21.0% |
| November 1994 | 12.4% |
| December 1994 | 3.8% |

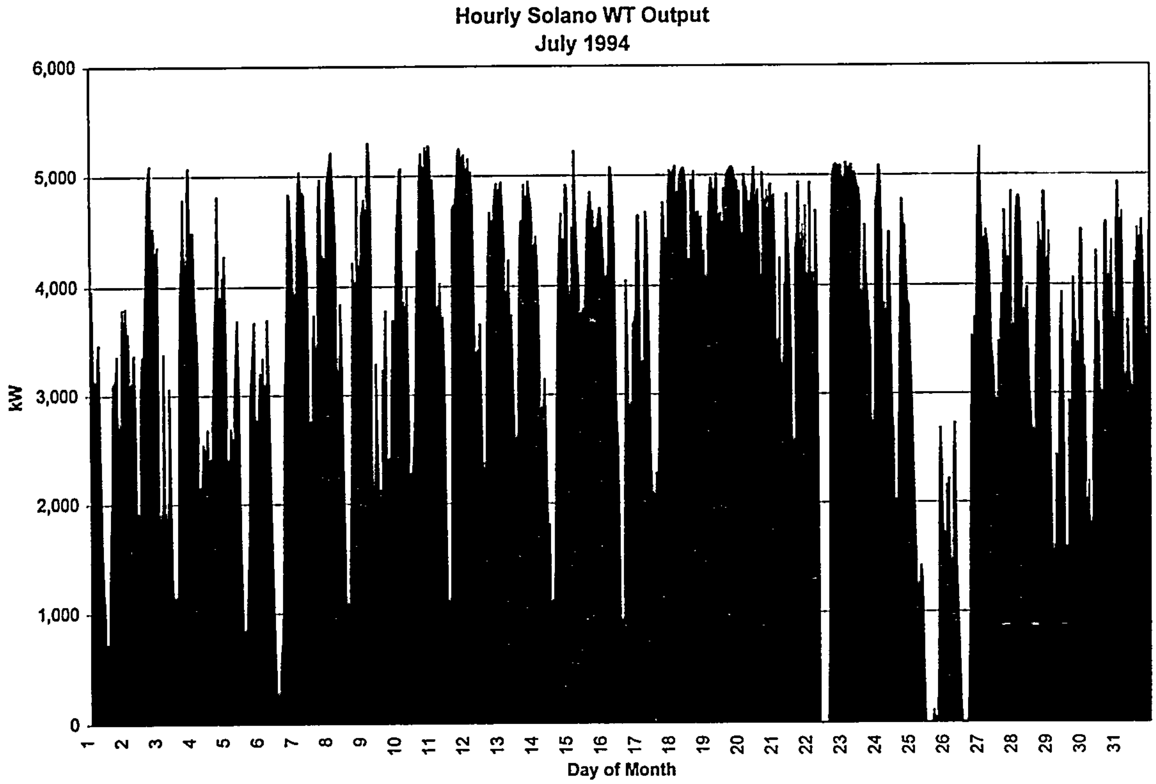



**Figure 2-1.** **Hourly Solano Wind Plant Output, July 1994.**

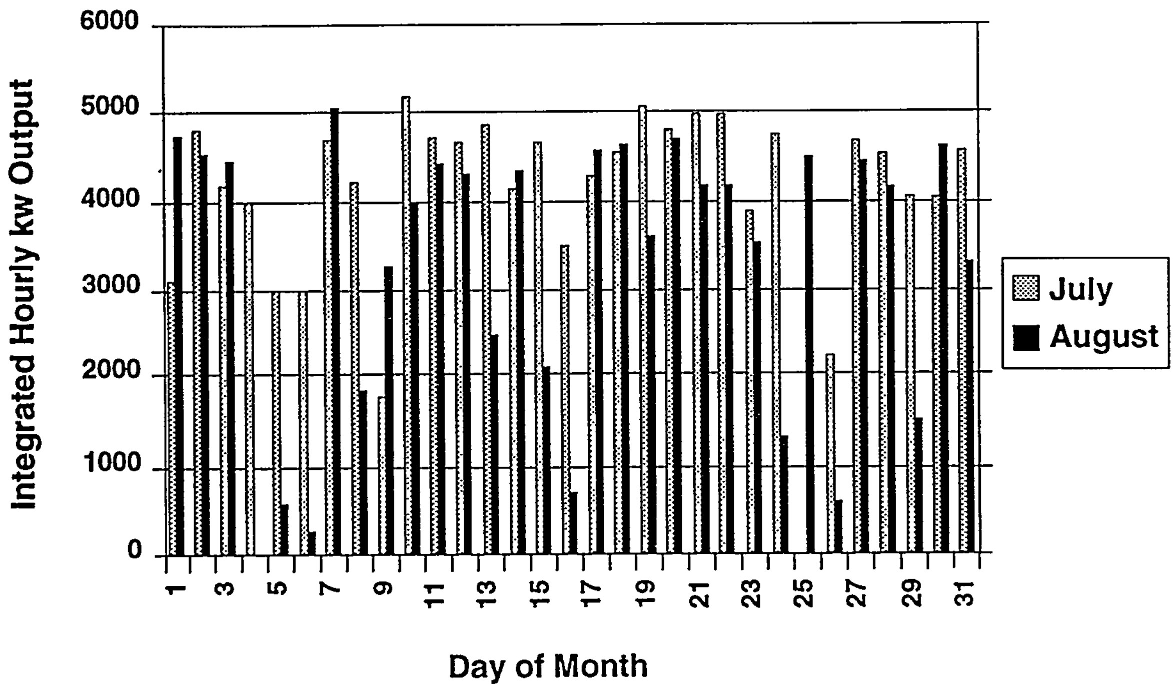



**Figure 2-2.** **Daily 6 p.m. Solano Wind Plant Output, July and August 1994.**

## CEA Feasibility Study

A major review was held in September 1995 of the CEA feasibility study for battery storage on the Alaska Railbelt utility network. The review was attended by over 23 personnel from CEA, the neighboring utilities of GVEA (Fairbanks), AML&P, and Fairbanks Municipal Utility, and EPRI and SNL.

A proposed 40-MW battery system for GVEA that will provide 20 min for spinning-reserve applications is being analyzed first. When that analysis is complete, a second battery will be evaluated for CEA of approximately the same power rating but with more storage capacity. This battery analysis is being coordinated with a Superconducting Magnetic Energy Storage (SMES) system being evaluated by EPRI and AML&P under an Advanced Research Projects Agency (ARPA) program.

Progress to date on the CEA battery study has involved the DYNASTORE generation cost model developed by EPRI, which is being used to quantify the battery system benefits. Also being used is an EPRI-developed battery model incorporated in Power Technologies, Inc.'s PSS/E model, which is being used to investigate the interaction of the battery with other system generators and the transmission system itself. Significant changes in system load, such as those resulting from the construction of a new gold mine in the GVEA area, have been identified and are being incorporated into the study.

Preliminary DYNASTORE results indicate very promising savings for generation applications for a battery system located on the GVEA system in Fairbanks. The study will conclude in the next few months and will culminate in a design specification for the viable battery systems defined during the analysis.

GVEA included a 40-MW battery system in the planning and design of a new, approximately 100-mile, 138-kV transmission line linking Fairbanks with a new clean-coal generation plant in Healy. The battery system would primarily provide spinning reserve to Fairbanks, eliminating the need for maintaining local generation in a hot standby mode. Its secondary function would be to provide transmission line stability. GVEA has contracted with Power Engineers, Inc., to prepare the engineering design of the transmission line and associated substations, including space for the battery system. Power Engineers' scope of work includes preparing a functional specification that can eventually be used to purchase the battery system. A draft version of the specification was released in July for comment by battery system suppliers and others. Comments on this document were received, and Power Engineers, Inc., is planning to release the modified specification in the near future as part of an RFP package.

## OPALCO Feasibility Study

A recent ORNL study showed that integrating solar and wind energy sources into the electric distribution system can provide significant, site-specific T&D and non-site-specific generation benefits. The results of this study suggested that in areas of high winds, MW-scale wind farms could capture such benefits and show significant economic value. One of the seven case studies included a preliminary B/C assessment of potential MW-scale renewable energy sources and BES applications in OPALCO's 25-kV distribution circuit. OPALCO serves the San Juan Islands in Puget Sound, north of Seattle, Washington.

OPALCO serves about 10,000 customers spread over 19 islands that are interconnected with submarine cables. Figure 2-3 shows the islands and substations in the OPALCO service area. The utility is winter peaking with a system load of approximately 48 MW in 1994. The customer base is predominantly residential, and the winter peak arises from the use of residential electric heating. The Eastsound substation (shown as substation 10 in Figure 2-3), which could be interconnected with either the wind farm or the battery system, is at the north end of Orcas Island. The peak load recorded at this substation during the most recent winter was approximately 6.5 MW. Figures 2-4 and 2-5 show, respectively, the peak day load shape and monthly peak loads for March 1994-February 1995 at this substation.

The feasibility study jointly funded by ORNL and SNL investigated the benefits of wind resource and BES for Orcas Island. This study identified three significant benefits, as follows:

- Deferral of the planned Lopez-Eastsound circuit upgrade to 69 kV;
- Energy displacement; and
- Monthly demand charge reduction.

The study concluded that a battery storage system located near the Eastsound substation could defer the planned circuit upgrade for two years and capture significant benefits. The study identified two options: OPALCO could either lease or purchase the battery system. The study estimated a B/C ratio of 3.68 for the lease option and a B/C ratio of 1.52 for the purchase option. The analysis showed that the purchase option captures greater benefits because the system would be available for a longer period than the 2 yr it would be

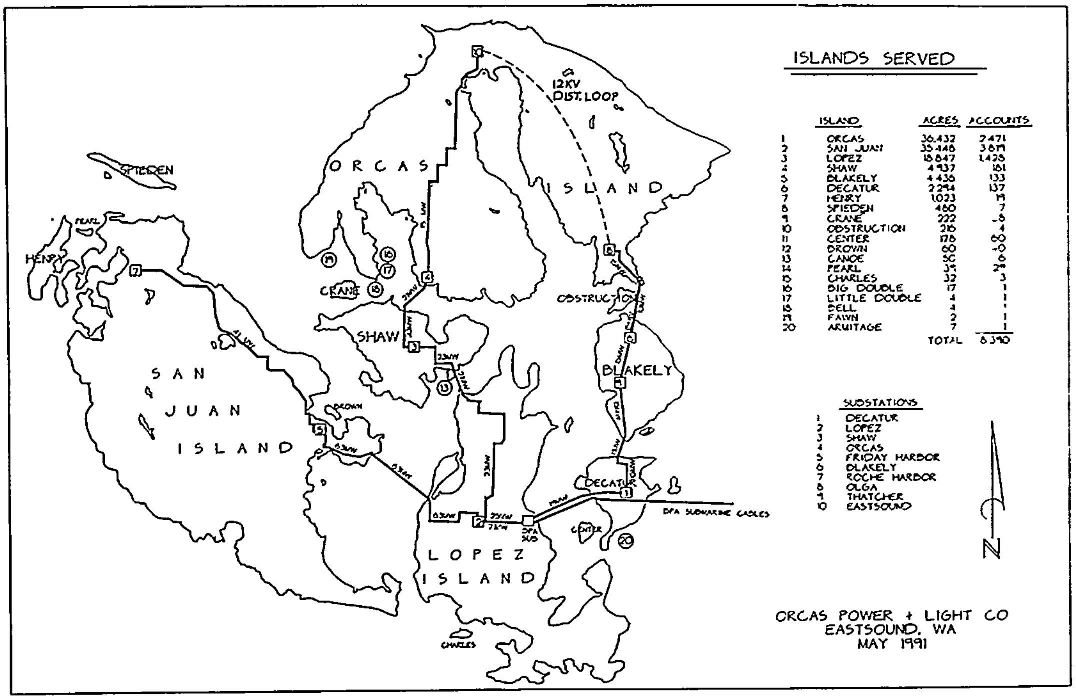



**Figure 2-3. Islands Served by OPALCO.**

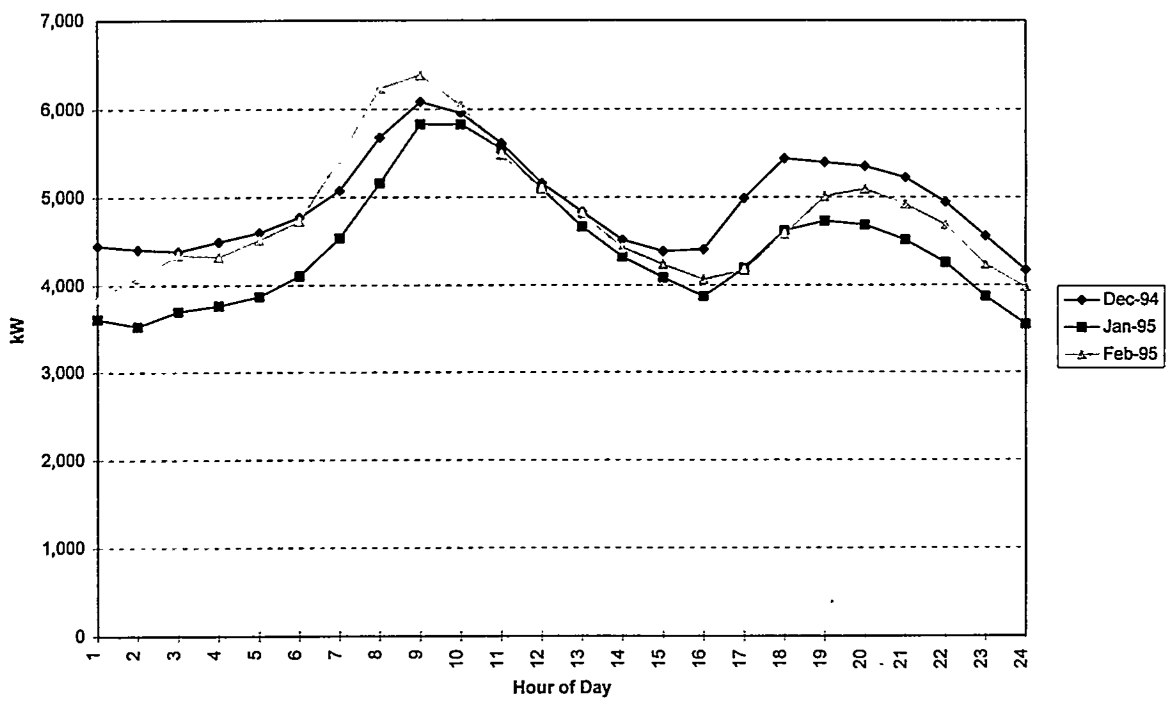



**Figure 2-4. Monthly Eastsound Substation Peak Day Load Shape: Winter 1994-1995.**

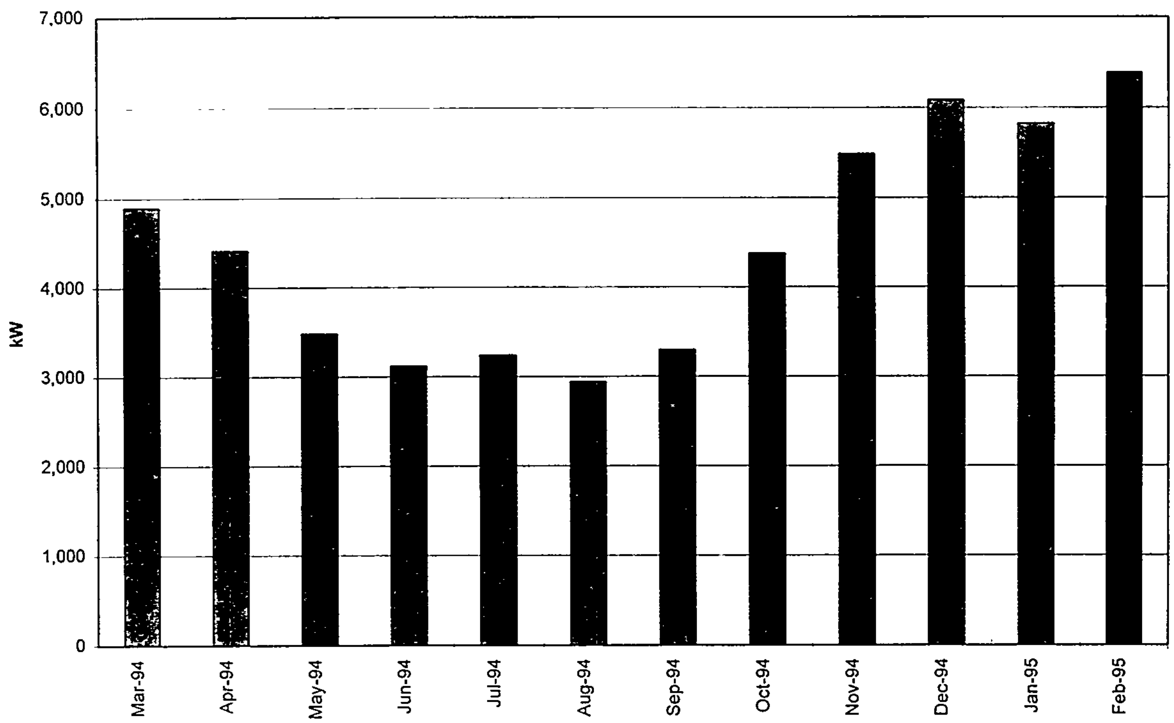



**Figure 2-5. Eastsound Substation Monthly Peak Loads: March 1994-February 1995.**

available were it leased. However, the purchased system has a lower B/C ratio because of the higher initial investment required as compared to that required for a lease. This result confirms the intuitive assumption on the benefits of leasing, especially for smaller cooperatives and utilities such as OPALCO that may not want to assume the full responsibility of system ownership and in the specific case where the nature of the application provides only a short window of opportunity for capturing high-value benefits.

A draft final report has been written and provided to OPALCO for comment before finalization and release.

## Market Feasibility Study

Development and demonstration of electric utility BES systems has been under way for more than two decades. However, significant markets for BES products have not materialized. In part this is because the sellers of BES systems have not perceived that the markets are of sufficient magnitude to make the investments required to develop BES products attractive to potential customers. In part it is also because potential BES customers have not recognized the value of BES systems or do not have sufficient confidence that their investment in BES systems, at current installed cost, will pay off. Indeed, in terms of actual and planned BES installations, the market situation today is little different from that in 1990, with a few BES projects actually under construction. On the other hand, the environment in which future BES systems will be sold has changed because utility deregulation has advanced significantly since 1990 and has become a major factor affecting the choices of utility industry decision makers.

Recently, an Opportunities Analysis was performed to characterize the capabilities of and the opportunities for batteries to provide electric UES options. The study indicated that the total benefits that might result for US utilities and for the nation from the implementation of BES systems on both sides of the utility meter could amount to $57 billion between 1995 and 2010. These benefits are maximized when BES systems are used at each site for 2 or more of the 13 feasible applications. For example, a BES installation might be used for both spinning reserve and frequency regulation in order to capture the maximum benefit at a specific site.

The opportunities estimated in this analysis are more than an order of magnitude greater than the market as it exists today, thus raising the question of whether there is indeed a significant market for BES systems.

The Opportunities Analysis cited above, however, was only an analysis of opportunities for BES applications. It was not a projection of markets that might develop for BES. Thus, further study is needed to determine if there are potential markets that will cause BES businesses to make the investment necessary to develop viable products.

To that end, a market feasibility study is being initiated through the UBS. The study will be conducted through a comprehensive survey of all battery system users, including IOUs, co-ops, independent power producers (IPPs), and large industrial customers, to identify potential markets in the 5-to-10-yr planning horizon. There is a well recognized need for such a survey, and a wide range of industry stakeholders have expressed a desire to participate in and support the market feasibility study. SNL is considering all the options for conducting the study that will accommodate the interests of the stakeholders while preserving the objectives and desired outcome of the study.

In July, an RFI was issued to a large group made up of consultants in the market study area, battery system vendors, and utilities with the purpose of soliciting comments to the SOW proposed for this effort. Comments received through this review process are being used to modify the SOW.

The International Lead Zinc Research Organization, Inc. (ILZRO) represents the research interests of the lead and zinc industries. The potential involvement and role of these interests in the Market Feasibility Study was discussed at a meeting held in September.

Most of ILZRO's members are in the primary metals industry, which is based in Europe and Japan. During this meeting, ILZRO's membership expressed an interest in pursuing an international market feasibility study that would complement the market feasibility study the UBS is performing in the U.S. It was felt that it would be mutually beneficial to pursue an expanded-scope project where the UBS conducts a market feasibility study in the U.S. and ILZRO conducts an international study. The results of the two studies would be combined and issued as a jointly sponsored publication.

ILZRO is also concerned about indications that the commercialization of BES technologies is not progressing as rapidly as its membership would like. Consequently, it has expressed an interest in participating more actively in the UBG with the hope that greater participation in this group will bring about faster commercialization. ILZRO is also interested in helping the UBS program overcome current barriers to commercialization and in helping to further the mutual interests of the Program and industry.

# 3. Subsystems Engineering – Valve-Regulated Lead-Acid

The VRLA battery subsystems engineering project has as its objective the development of advanced VRLA batteries. The goal is to have advanced VRLA designs that meet utility application requirements available for use in the mid to late 1990s. This would precede the commercial introduction of advanced battery systems, which is not expected before the year 2000. The central portion of this effort is a 4-yr, $2.83M cost-shared development contract with GNB. The objective of this development contract is to achieve performance improvements in VRLA batteries through better designs and processes so as to enhance their potential for widespread use in electric utility applications. A second objective is to quantify in conjunction with utility companies the benefits of these improvements in specific utility applications for which battery system requirements are defined. To ensure that appropriate issues were identified, two electric utilities participated in the project. SNL supported the GNB contract work by evaluating the performance of battery modules furnished at several stages during the contract and also by conducting material development and characterization studies on selected battery components.

The lead-acid battery has been in existence for over 100 yr and is used in a wide variety of energy and power storage applications, including vehicle engine starting, telecommunications standby power, forklift truck propulsion power, computer backup power systems, and naval submarine propulsion power. The widespread use of the lead-acid couple is the result of its good electrical performance capabilities under a wide range of operational scenarios, its ready availability, the relatively low cost of its materials and components, and its generally "user-friendly" characteristics. This is true from the time of its manufacture, through its operating lifetime, to the time of its disposal or reclamation for reuse in new lead-acid batteries. The lead-acid battery also has the potential to become a major element in the mix of technologies used by the electric utility industry for several energy and resource management functions within the utility network.

Technical issues that have been identified regarding the use of batteries in utility applications include uncertainty about lifetime, lack of understanding on how to apply battery systems, lack of operating experience, maintenance needs, system reliability issues, and desire to reduce initial investment. From previous utility BES demonstration projects, it was learned that battery maintenance could be a major issue in large-scale installations. The approach selected, therefore, was to focus future lead-acid developmental efforts in BES on VRLA batteries, which are designed to offer low-maintenance or maintenance-free characteristics.

Uncertainty about the lifetime of the VRLA battery is one primary concern of utilities. Unlike flooded lead-acid batteries, VRLA batteries designed for cycle service are only offered by a small number of battery manufacturers. Consequently, although real-time experience with VRLA batteries is increasing, the utility industry currently considers it insufficient to remove skepticism regarding VRLA cycle life. The experience gathered from earlier battery installations (e.g., Berlin Electric Company (BEWAG), Crescent Electric, and the Chino plants), has generated a positive reaction from the utility community. However, all of these projects used flooded-electrolyte lead-acid batteries, so there is a reluctance by utilities to immediately translate the results to VRLA systems. The data reported on VRLA battery tests carried out by Public Service Electric and Gas Co. (PSE&G) at the Battery Energy Storage Test (BEST) facility and by Argonne National Laboratories (ANL) have provided a good start. Data from the Utility Battery Storage Systems Program will help to further address the concerns of the utility industry. A final major market-related barrier to implementing large-scale BES systems is their perceived high initial cost. While improvements in battery performance and manufacturing processes should help to reduce costs, a better understanding of the benefits derived from using batteries could offset some of the concern regarding initial cost.

## Technology Development – GNB

### Tasks/Milestones

The GNB effort under this contract has involved three tasks. Task 1 is a two-phase activity performed by GNB that is intended to improve the performance and reduce the cost of VRLA batteries through changes in battery design, materials, and manufacturing processes. The objectives of Task 2 are to develop specifications and baseline conceptual battery system designs for two specific types of applications and to perform economic analyses of battery system costs for these same two cases. Task 2 has been led by UMR and has required extensive participation by two host utilities, PG&E and PREPA. Task 2 has been completed. Task 3, which is also being supported by UMR, seeks to quantify the costs/benefits of the improvements identified in Task 1 and to incorporate the improved VRLA battery system into the economic model developed during Task 2. Task 3 will draw on information from the host utilities and will require input on costs from GNB. This final task takes advantage of the DYNASTORE computer program for calculating the operating cost savings from incorporating different BES configurations on the host utility systems.

The objective of the first phase of Task 1 is to improve current VRLA battery designs to match or exceed the performance of flooded batteries without sacrificing the inherent advantages of the VRLA technology. All of this must be accomplished at a cost equal to, or lower than, that of these competing designs. Technical efforts have focused on performance issues, such as vent valve reliability, thermal management, charging profiles, positive plate behavior, and ground fault prevention, that have been perceived by the utility industry as critical barriers to the widespread implementation of VRLA battery systems. An additional objective is to improve the consistency of cell performance through manufacturing process enhancements.

In Phase 2 of Task 1, GNB is completing the development of advanced VRLA battery designs optimized for high-power applications. The specific development efforts are investigating evolutionary and revolutionary changes in grid and active material makeup and electrolyte immobilization technique to improve the efficiency and life of the battery.

These various improvements in the VRLA technology were incorporated into products in stages and, in some cases, the intent of the incorporated changes was to produce designs that addressed the needs of specific utility applications. Figure 3-1 shows a flow chart of the product designations anticipated as a result of the development process. The ABSOLYTE II was an existing product marketed for telecommunications and other standby power applications when this work began. It has been replaced by the ABSOLYTE IIP intermediate product, which incorporates some of the improvements identified in Task 1, Phase 1. Commercial production of the ABSOLYTE IIP began during the first quarter of 1993.

The MSB product will contain many of the enhancements developed during Task 1, Phase 1, and is

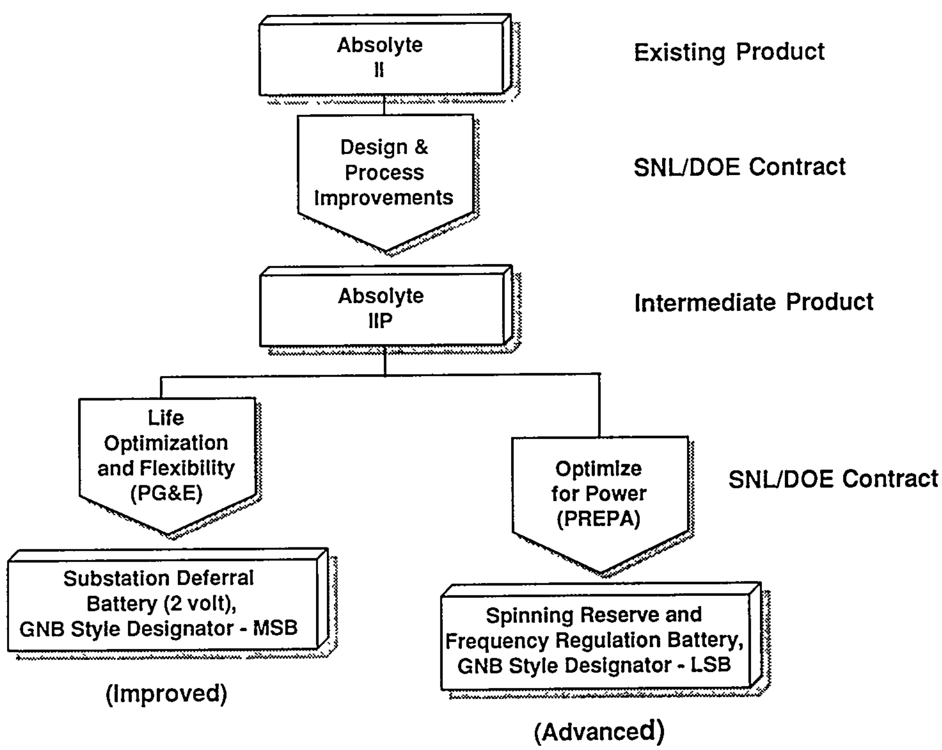



**Figure 3-1. Flowchart of Product Designations Anticipated during VRLA Battery Development Process.**

designated "improved." Introduction of the MSB product is scheduled for the first half of 1996. The LSB product will incorporate technology developed during Phase 2 of Task 1 and is therefore called "advanced." The LSB design is optimized for the power needed in spinning reserve and frequency regulation applications anticipated by PREPA. The advanced-design LSB VRLAs will not become available for site demonstrations until at least mid 1996.

FY95 Milestones:

- Finish DYNASTORE calculations on noninterconnected utility (12/94) – completed.
- Complete initial surface treatment trials on battery substrates at SNL (3/95) – completed.
- Deliver GNB battery for field test (8/95) – completed.
- Finish technology improvement and development tasks at GNB (9/95) – completed.

## Status

### Task 1/ Phase 1. VRLA Battery Improvements

*Vent Valve Reliability*

The pressure relief vent presently used in GNB's ABSOLYTE IIP VRLA battery is an assembly consisting of two plastic pieces and a rubber insert. The vent release pressure is a function of the dimensions of the plastic parts, the dimensions and durometer measurement of the rubber insert, and the dimensional tolerances achieved in the assembly of the part itself. The baseline operating characteristics and reliability of operation of this vent design were demonstrated during earlier studies under this contract.

Charging studies also completed earlier as part of this overall contract effort indicated that a slightly higher vent opening pressure would be desirable in order to reduce the battery recharge time to 8-10 hr or less following a relatively deep discharge. Utilities would prefer to recharge a BES system during off-peak hours when excess generating capacity is available; thus, an 8- to 10-hr recharge period was defined. The preferred vent operating pressure for this reduced-time recharge is 5-10 psig.

In this technical task, GNB evaluated various rubber compounds to increase the durometer measurement of the rubber insert, which has the effect of raising the relief pressure of the ABSOLYTE vent. A rigorous study of the assembly process also defined those parameters that had the most influence on the variability of the venting pressure of assembled units, and process aids and checks were implemented as a result. Other pressure relief vent designs were also tested. An umbrella-type pressure relief valve was identified as being usable in specific cell and battery designs where its smaller size is required. As a result of all of these tests, it was determined that the basic design of the ABSOLYTE vent produced the most reliable and best-controlled vent assembly.

The minor modifications in the assembly process required to raise the vent relief pressure into the 5-10 psig range have been implemented, and all ABSOLYTE IIP cells are now fitted with a vent produced in accordance with these new assembly parameters. The higher pressure relief vents have been installed on all new ABSOLYTE IIP cells produced during the last year with acceptable results. The final effort for this particular project task was to conduct an extended test of the higher-pressure ABSOLYTE IIP pressure relief vent to demonstrate its stability of operation. Sample cells were subjected to the same overcharge test that was used early in this contract to develop baseline performance capabilities for the original ABSOLYTE pressure relief vent.

Six ABSOLYTE 45A15 cells (rated at 315 Ah) were connected in series to form a 12-V battery. The cells were each fitted with the new pressure relief vents. In addition, a pressure transducer was installed on each cell to monitor the actual internal pressure of the cell. The string of six cells was then overcharged at a constant current of 10 A (approximately C/30) to force the cells to gas and build pressure, thereby causing the pressure relief vents to operate. The test was continued for 500 hr (approximately 3 weeks), during which time the vents operated repeatedly to release the excess gas pressure developed by the continuous constant-current overcharge. A typical 50-hr segment of the test (i.e., hours 250 through 300) is shown in Figure 3-2 and demonstrates the ability of the new, higher-pressure vents to consistently operate at about 5 to 7 psig. The sample operating steadily at 3-4 psi indicates a cell that has reached equilibrium recombination at this charge rate with no venting occurring.

*Positive Plate Growth*

The normal wearout mechanism anticipated in the VRLA battery is anodic corrosion of the positive grid structure. The product of this anodic corrosion reaction of the lead grid with sulfuric acid is lead dioxide. The density of lead dioxide is roughly 80% that of the lead metal from which the lead dioxide is formed during the corrosion process. As a result of this change in density,

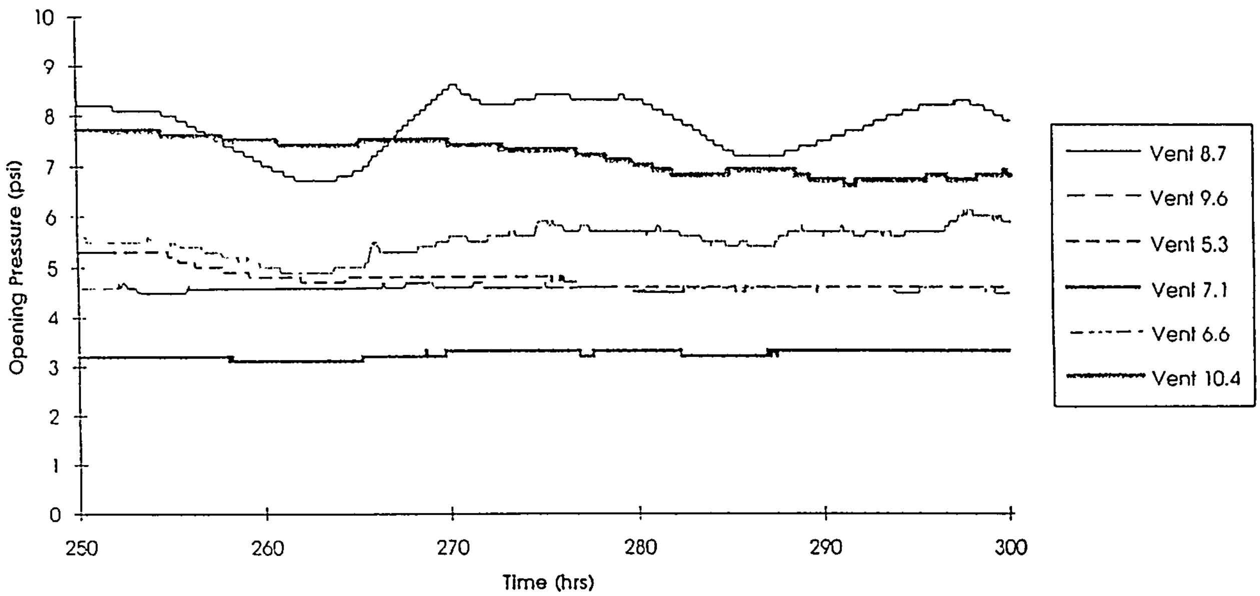



**Figure 3-2. Internal Battery Pressure during 50 hr of a 500-hr Continuous-Operation Test of Modified ABSOLYTE Pressure Relief Vents.**

the grid structure deforms and commonly undergoes what is referred to in the battery industry as "plate growth." The plate will tend to grow in the direction of least mechanical resistance; in the battery, this is typically along the grid frame opposite the side where the plate lug is connected to the terminal strap. The extent of growth is dependent on both the type of corrosion the grid experiences (i.e., surface erosion versus intergranular corrosion) and the actual length of the grid. A grid alloy that experiences intergranular corrosion will grow more than a grid corroding by a uniform surface erosion process. Additionally, as the battery size increases, both in terms of physical size and electrical capacity, plate growth can become a significant potential failure mode.

Grid growth can result in the loss of electrical contact between the PAM and the grid structure itself, and/or in the shorting of the positive plate to the underside of the negative plate strap. In addition to grid alloy composition and the physical shape of the grid, operating temperature and charging conditions can influence the rate at which the positive plate will grow.

GNB's ABSOLYTE cells use the patented MFX alloy in the positive grid. This alloy has excellent corrosion resistance characteristics, and the annual corrosion rate has been determined to be 1.8 mils/yr when maintained in overcharge at 25°C at a float voltage of 2.25 volts per cell (vpc). That is, under these charging conditions, the positive grid will corrode 0.0018 in. of its cross sectional radius each year. Further, the mechanism of corrosion for the MFX alloy is a surface erosion reaction that evenly corrodes the lead grid surface. This type of corrosion results in the least amount of grid growth.

Although the MFX alloy provides good resistance to plate growth, GNB has proposed incorporating other concepts into the cell design to provide additional protection against the deleterious effects of positive plate growth. These are (1) designing the positive grid so that dimensionally it is shorter than the negative plate, and (2) fitting the positive plate with an insulating boot that is designed to collapse as the positive grid grows and hence accommodate its growth.

The work that remained on this project task was the long-term life testing of batteries built with different variables to test alternative techniques for accommodating positive grid growth. The experimental variables in this test included the following:

1. Positive plates fitted with a collapsible boot; only the positive plates were wrapped with the separator material (Test Group CW).

2. Positive plates fitted with a collapsible boot; both the positive plates and the negative plates were wrapped with the separator material (Test Group C).

3. Positive plates fitted with the standard design boot; only the positive plates were wrapped with the separator material (Test Group S).

4. No boots fitted onto the plates; only the positive plates were wrapped with the separator material (Test Group N).

Cells from each of the test groups were started on an open-circuit-stand test and a float charge test at both room temperature and at temperature-accelerated (60°C) conditions. The float-charge samples were connected in series and were charged at a nominal 2.30 vpc. Test conditions are summarized in Table 3-1.

After completing 1 yr of testing, the room temperature samples were removed and that part of the test terminated. It was concluded that having avoided any early failures due to internal shorting, the room temperature samples would not provide any evidence for many years into the future, and therefore the testing efforts were redirected at the samples subjected to temperature-accelerated aging at 60°C. This increase in operating temperature has the effect of increasing the speed of the corrosion reactions occurring in the cell by a factor of approximately 11.3. Charging at 2.30 vpc instead of the recommended 2.25 vpc also accelerates the life-limiting reactions. GNB estimates that the temperature and voltage factors used to accelerate life in this test have the combined effect of making each month on test the equivalent of 1 yr of operation under the standard conditions (i.e., 2.25 vpc at 25°C).

All samples have completed 5 mo at 60°C, the equivalent of 5 yr operational lifetime in the field under "normal" conditions. When discharged following the 5-mo test period, samples on the float-charge test delivered on average approximately 100% of their rated capacity. There was no discernible difference in test performance among the samples built with different construction variables.

The samples that completed the five-month open-circuit-storage test at 60°C exhibited discharge capacities ranging from 75 to 90% of their rating. Although all of the samples in this test regime have exhibited a continual reduction in discharge capacity following each of the 1-mo open circuit storage periods, it does not appear that any of the cells has experienced the sudden or drastic loss of capacity that would be indicative of the development of a short circuit due to excessive plate growth. It is suspected that, at these elevated temperatures, the negative plates are experiencing a higher than normal self-discharge rate that resists reversal when the battery is given a boost charge at the end of each of the open-circuit test periods. Attempts are being made to restore these samples to their initial performance levels with additional boost charging. If this is successful in recovering capacity, these open-circuit-storage tests will be continued until the failure point is found. If capacity is not recovered, then the tests will be terminated at this point.

### *Thermal Management and Charging Analysis*

Elevated temperature has a deleterious effect on the life of any lead-acid battery. In flooded-electrolyte lead-acid batteries, types, the reduction in life is due to the acceleration of positive grid corrosion. In VRLA batter-

**Table 3-1. Summary of Test Conditions**

| Test Groups | Test Type | Temperature | Capacity Test Interval |
|---|---|---|---|
| CW, C, S, N | open-circuit stand | RT | 6 mo |
| CW, C, S, N | open-circuit stand | 60°C | 1 mo |
| CW, C, S, N | float charge | RT | 6 mo |
| CW, C, S, N | float charge | 60°C | 1 mo |

ies, in addition to the acceleration of the grid corrosion process, it is suspected that elevated temperatures may also induce failures caused by accelerated loss of water by gassing and diffusion through the container material and the pressure relief vent valve. As noted above, elevated temperature also accelerates the self-discharge of batteries that are in storage or on open circuit.

As part of this project task, GNB has developed a recharge profile for its ABSOLYTE VRLA batteries that provides adequate recharge of a deeply discharged battery in less than 8 hr, with a temperature rise of less than 10°C in the battery, and minimized gas evolution to allow for a maximum cycle lifetime. This recharge profile can be easily implemented into charger control logic, and consists of a three-step constant current (CI), constant voltage (CV), constant current (CI) regime.

Charge Profile Details

The initial inrush current is limited to 25 A/100 Ah of battery capacity, and the constant voltage portion is set at 2.32 vpc. The finish rate is set at 2 A/100 Ah of battery capacity. This recharge is terminated when the battery has been provided with an approximate 5% overcharge.

Thermal Model

In addition, GNB has developed a thermal model that can be used to predict the thermal behavior of the ABSOLYTE VRLA battery under discharge and recharge conditions. The model was verified by testing an ABSOLYTE battery pack under the discharge and recharge conditions that might be expected in a BES system over a one-week period. The results from the model and the actual temperature measurements made on the test battery were found to be in good agreement, as shown by the data presented in the report for the second quarter of FY94. Since the development of this model, GNB has used it several times to calculate the heat loads and ventilation requirements for BES systems that are being developed or proposed.

### *Ground Fault Elimination*

By their nature, utility-based BES systems will be large in capacity and will operate at relatively high DC voltages. As such, ground faults could pose serious safety risks to operators and utility personnel in addition to causing premature battery failure.

During this project, GNB proposed a technical approach to address this issue that identified five improvements in battery design and manufacturing to reduce the risk of ground faults resulting from electrolyte leakage in BES systems. Three of these improvements—a controlled electrolyte filling process, a redundant jar-to-cover seal process, and a sophisticated leak detection monitor—have been developed and integrated into the manufacturing process for the GNB ABSOLYTE IIP VRLA battery.

Also investigated as an improvement aimed at reducing ground faults was the use of nonconductive battery tray materials. Prototype samples of a nonmetal battery tray constructed of a high-strength plastic were fabricated and tested, with particular emphasis on thermal management. In the series of tests that GNB conducted on this battery tray, the temperature data monitored during overcharge provided evidence that, as was expected, the plastic tray was not as efficient as a steel tray at dissipating heat. Cells mounted in the plastic tray were susceptible to thermal runaway at lower overcharge voltages than cells mounted in the steel tray currently used in the ABSOLYTE IIP VRLA design. However, it should be pointed out that these overcharge voltages were still excessive compared to the recommended charging levels for this battery. The difference in heat retention between the two tray types could also be alleviated by the use of small cooling fans installed on the battery tray to aid in dissipating heat from the cells. The plastic tray design satisfactorily completed a seismic analysis using the load conditions defined for Uniform Building Code Zone 4 areas.

The cost of molds to fabricate these trays is significant however, and will, for the immediate future, limit the practicality of this approach. Standardization of battery sizing and greater customer demand for high-voltage battery systems would make these tray designs more viable in the future.

The final activity in this project task was to design a cell cover and develop a terminal welding process that would eliminate terminal-post seal leaks caused by excessive heat being transferred to the lead-to-plastic interface of the insert-molded terminal bushing. The present ABSOLYTE terminal post design is based on a copper-insert post that is welded to a lead bushing molded into the cell cover. Although this design approach provides a low-resistance intercell connection that is easy to install and assemble, the copper insert introduces manufacturing complications during welding that affect the integrity of the seal between the lead bushing and the plastic cover.

The approach GNB took to resolve these complications while retaining the advantages of a copper-insert terminal connection was to redesign the post assembly and cover to permit more lead to be cast around the inserted copper piece. This approach minimized the amount of heat required to make the weld to the lead bushing and thus avoided overheating the seal between the lead bushing and the plastic cell cover.

Samples of the bushing and the terminal post were fabricated and welding tests were completed to demonstrate the desired result of lower interface temperatures. GNB has incorporated this improved bushing/terminal post design into a new large-size, single-cell ABSOLYTE configuration for which new cover molds were already required. As experience with this design is accumulated, additional cell sizes will be considered for retrofit to this improved terminal post design as other modifications to the tooling need to be made.

### *Positive Active Material*

The positive electrode active material has a significant effect in determining the life of a lead-acid battery because it undergoes much greater crystal structure and morphological changes than the negative active material during the discharge and recharge operations. GNB evaluated a "leady" oxide material for use in the positive electrode to improve battery life under the severe discharge/recharge cycling conditions anticipated in utility BES applications. Cells using this leady oxide paste formulation were tested to evaluate their performance in operations requiring the battery to be deeply discharged and recharged.

During the test, the cells were discharged to 100% DOD at their C/5 discharge rate. Periodically, the cells were discharged at their C/8 rate to establish baseline capacity performance. The leady oxide samples were compared to cells fabricated using red lead oxide, which were used as experimental controls. The test was terminated after the samples had completed 600 cycles, with the leady oxide samples still providing more than 80% of their rated C/8 capacity and with the red lead oxide samples dropping to below 80% capacity.

In addition, 4-mo accelerated float-life testing at 80°C (the equivalent of 20 yr at 25°C) was completed on sample cells fabricated with both the leady and the red lead oxides. At the end of this test, the average retained discharge capacity for both the leady oxide samples and the red lead samples was 88% of the nominal rated capacity of the cell. These results indicated that, as anticipated, the starting oxide had no effect on the float-life performance of the cell.

Because of the improvements observed in the cycle-life testing, and because there were no negative effects on battery float life, plans are under way at GNB to convert certain of its VRLA battery designs, particularly those that are likely to be used in deep-discharge cyclic use, to the leady oxide positive paste formulation.

## Task 1/Phase 2. VRLA Battery Advancements

### *Cell Design*

This subtask consisted of two parts: an intermediate cell design that was evolutionary in nature and sought to increase the 8-hr capacity of the existing ABSOLYTE design, and an advanced concept that was revolutionary in nature and sought to maximize the short-duration power capability of VRLA cells in utility power regulation applications.

#### Intermediate Design (ABSOLYTE IIP)

The intermediate design product developed as part of this task effort has been introduced as a commercially available product.

#### 2-V Modular Battery (MSB)

Discussions with one of the host utilities for this project revealed the need for a modular battery suitable for "transportable" applications. Critical characteristics for this battery included minimum volume and weight and flexibility of installation. To obtain these features, reducing the operational lifetime to 5-10 yr was deemed necessary and acceptable.

Following the list of physical and performance characteristics considered necessary for this battery module, GNB developed a design based on a medium-sized modular battery package (approximately the size of a Group 27 automotive battery). The module is a 2-V unit that can be connected in various series/parallel configurations to achieve the desired voltage and capacity. This modular approach increases flexibility of installation and permits easy replacement of modules during the operational lifetime of the battery system. Furthermore, the battery was designed to be manufactured on GNB's automated production line for modular VRLA batteries of this size, which allows the battery to be readily produced in large numbers at reasonable cost. A BES system based on this design would allow a utility to minimize its initial investment while evaluating BES in their network. In addition, this approach could be used where temporary, seasonal, or other short-term conditions exist that could be resolved using BES.

Prototype samples were constructed and performance testing was completed to verify the projections made for the design. The prototype samples provided a 1-hr discharge at 340 A; at 700 A, the battery delivered 17 min of support time equivalent to 200 Ah. The prototype battery's performance versus discharge rate is provided in Figure 3-3. Cycle testing of a prototype battery was terminated after 77 cycles with the battery unable to

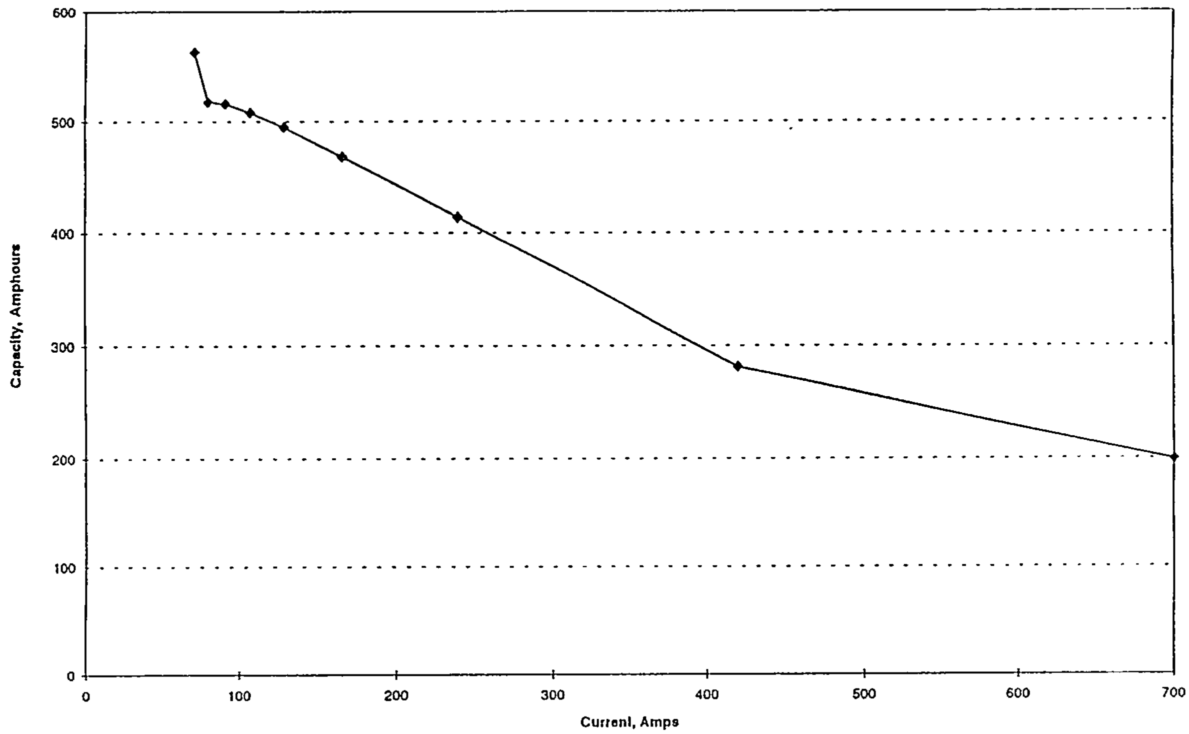



**Figure 3-3. Capacity as a Function of Discharge Rate for the 2-V Modular Battery (MSB).**

deliver at least 80% of its rated performance at a C/2 discharge rate. This premature loss of capacity during the cycle-life testing of the design was attributed to manufacturing difficulties encountered during the prototype sample build. In response to those difficulties, GNB has proposed modifications to the design of the module as well as to the production processes employed in its manufacture. These refinements remain to be tested and implemented. Since the 2-V MSB battery was designed for a specific application, and the market for that application has not developed as rapidly as expected, GNB has decided to pursue the completion of the manufacturing refinements as engineering time and experimental time on the battery's manufacturing line become available.

Advanced Design (LSB)

Present ABSOLYTE batteries are designed to provide the sustained operation typically required from energy storage systems. These batteries offer significant reductions in footprint, space, and weight when compared to conventional flooded-electrolyte batteries. However, a battery that has been optimized specifically for high-power applications such as voltage regulation can provide even greater savings in battery footprint, space, and weight. The advanced-design LSB battery has this as its objective.

GNB's original design concept for this battery was completed, and prototype cells were fabricated. During the assembly of these prototypes, several process and assembly issues arose that had to be resolved before the design could be considered reliable enough for utility applications. GNB has considered these issues and has looked at what equipment would be required to overcome the difficulties encountered during the prototype fabrication.

GNB has reached a decision to continue this project, albeit at a slower pace, so that each assembly and process issue can be resolved as it develops. This approach will extend this activity well beyond the scope of the present contract. Currently, a defined timetable for introducing the product is not available; however, it is GNB's intention to pursue this design and to introduce it after adequate reliability and performance testing have been accomplished.

### *Copper Negative Grid*

Historically, lead has been used as the material for the negative plate grid. The principal considerations in the selection of a lead alloy to be used in the negative plate grid are overpotential characteristics and strength; corrosion resistance is not a major consideration. Lead is a poor electrical conductor and other materials with higher conductivities, copper for example, could improve the high-rate discharge performance of the lead-acid battery. Although the copper substrate would have to be coated with lead to provide chemical corrosion resistance, the lead-coated copper grid would still significantly lower the cell's internal resistance, increase energy density, improve charge acceptance, achieve a more uniform current distribution over the length of the plate, reduce polarization, and improve active material utilization. GNB has proposed a grid design that uses lead-coated copper wires molded into a plastic frame as the current collector and electrode support for a high-power negative electrode.

Work has progressed slowly on this project task, primarily because of the unavailability of a suitable lead-coated copper wire. The fabricator that GNB identified as being capable of producing this material has made other commitments and plans that would preclude their manufacturing lead-coated copper wires. Lead-plated copper wire, which was being ordered to provide material to determine the relative performance improvement obtainable from this concept, has also proven to be unavailable. Because GNB did not know of another supplier capable of providing the lead-coated wire, and because the only known fabricator of this material was reluctant to produce materials for GNB, this task was terminated.

### *Positive Plate Design*

Three of the most basic factors that limit a VRLA cell's cycle lifetime are (1) positive grid corrosion, (2) damaging changes to the PAM structure, and (3) the formation of passivating films at the PAM-to-grid interface. This project task explored changes in the composition of the positive grid alloy to lower positive grid corrosion, and examined the potential benefits of additives to improve PAM stability and utilization.

#### Positive Grid Alloys

GNB uses patented MFX alloy in the positive grid of its ABSOLYTE batteries. This alloy corrodes by a uniform surface erosion process, which allows GNB to predict a 20-yr lifetime for the ABSOLYTE IIP battery at 25°C in a float application. The objective of this project task was to evaluate other lead-alloy compositions that corrode at slower rates than the MFX alloy to extend the lifetime of the battery in a utility application.

GNB evaluated several alloy compositions in comparison to the MFX alloy in a 12-V, Group 27 modular battery configuration. A total of seven experimental and two control lots were assembled and tested. Both accelerated float-life and accelerated cycle-life tests were completed. A detailed description of the charge regimes is provided in the report for the second quarter of FY95.

In the float-life test, the MFX alloy had the lowest and the "flattest" charge current curve, highlighting its stable operation under float-charge conditions (see Figure 3-4). The MFX alloy also exhibited the best cycle-life performance, completing 300 of the accelerated life-test cycles. The next best alloy delivered 250 accelerated discharge cycles, but exhibited tendencies for thermal runaway under float-charge conditions.

The results highlight the dilemma battery manufacturers face in designing and developing batteries: they are usually designed for either cyclic applications or for float applications. Battery alloys that are good for cyclic operation usually do not have good characteristics for float-charge applications, and vice versa. These tests also demonstrated the unique capabilities of the GNB MFX alloy under both cyclic and float charge applications. The results of these tests convinced GNB that the MFX alloy is still the best alloy to use in the positive grid of a VRLA cell for applications like those anticipated in utility use, where the battery will be subjected to both cyclic and float-charge operation.

#### Positive Plate Additives

The purpose of a plate additive is to help stabilize the PAM structure during cycling. A stabilized structure will create a framework that allows an increase in the active material porosity, thereby permitting an increase in the active material utilization and capacity without sacrificing cycle lifetime.

Little progress has been made on this project task since its inception because the materials identified in the literature are not readily available as commercial products. It appears that the investigators for the cited research not only examined the additives' effects in battery PAM, but also provided the tested additives after preparing or synthesizing the materials themselves. The few sources that GNB has been able to identify have been extremely reluctant to provide the appropriate materials for test, and GNB does not have the internal resources needed to prepare these additives. Although GNB did recently receive a small sample of chopped 25-mm-diameter titanium fiber for testing as an additive to the PAM, resources and time were no longer available under the scope of the contract to complete this experiment.

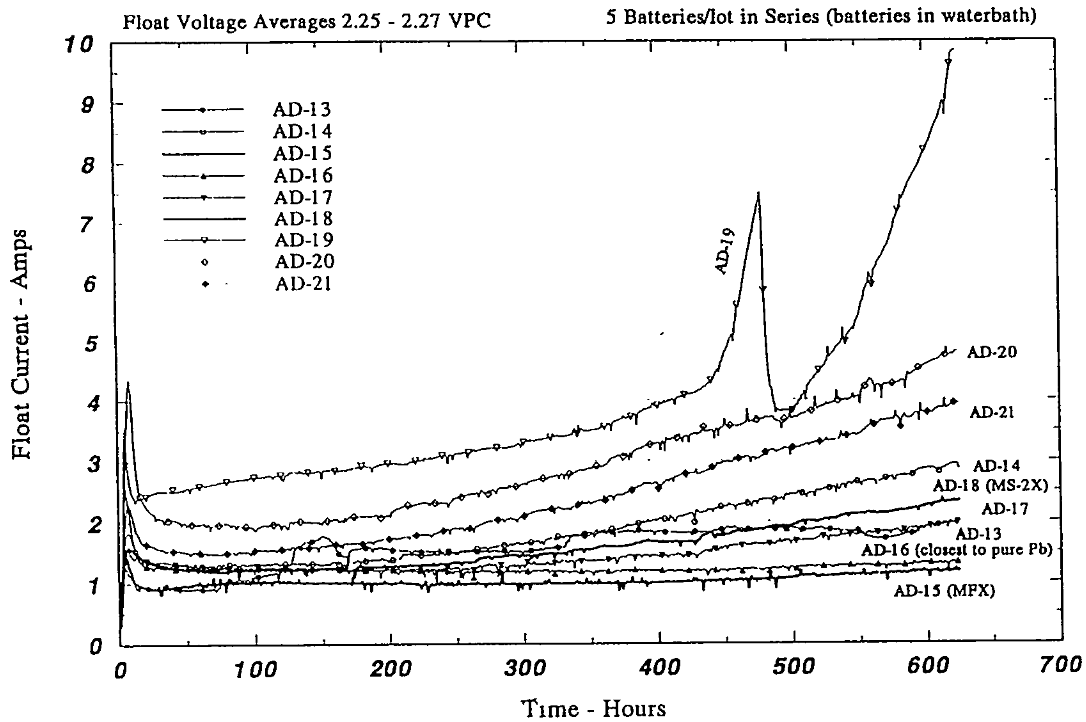



**Figure 3-4. Elevated-Temperature (60°C) Float-Charge Test Results on Experimental Positive Grid Alloys.**

*Electrolyte Immobilization*

The present ABSOLYTE VRLA battery design uses an absorbent microfiber glass mat that serves as the plate separator as well as the means of electrolyte immobilization. Overall, this glass mat has worked very well. Cost is the greatest disadvantage of using this material. Another less critical limitation is the wicking height of liquid in the glass mat, which limits overall cell height, as installed, to 24 in. or less. GNB overcomes this inherent limitation by constructing its battery systems so that the cells are mounted horizontally, thus making the effective height of the cell (relative to gravity) less than 7 in. This approach eliminates any stratification brought on by the wicking height limitations of the microfiber glass mat.

The objective of this project task has been to investigate lower-cost alternatives to the microfiber glass mat presently used in GNB's VRLA design. Specifically, the intent was to evaluate the addition of organic fibers to the material blend to reduce cost. Samples received earlier in this project proved to have reduced wettability and wicking. Furthermore, it was suspected that the organic fibers used in the material blends were being chemically oxidized by the sulfuric acid and lead dioxide indigenous to the lead-acid cell. This decomposition exhibited itself as generation of carbon monoxide and carbon dioxide gases.

This project was dependent on receiving samples from the various suppliers who provide separators for VRLA and flooded-electrolyte battery systems. No acceptable alternatives were found during this contract effort; therefore, GNB will continue to use the microfiber glass mat presently used in the ABSOLYTE VRLA design.

## Task 2. Baseline Design and Economics Study

In addition to the technical efforts to improve VRLA batteries for BES applications, GNB teamed with two host utilities, PREPA and PG&E, to develop system requirements and to conduct economic analyses relating to battery systems as part of their utility portfolio. UMR also assisted in defining the systems requirements for these installations and developed several conceptual plant layouts to meet these requirements using the various battery types being developed by GNB for BES installations. This work has been completed, and reports from UMR and the host utilities have been submitted to GNB.

## Task 3. Quantification of Costs/Benefits of Battery Improvements

The remaining task in this contract involved evaluating the cost impact of the battery improvements developed by GNB during Task 1. The intent was to use the system designs conceived and specified by UMR and the host utilities. For reasons beyond the scope of this contract, both host utilities, PG&E and PREPA, substantially completed their tasks and withdrew from this effort. UMR is now working under a separate contract with SNL.

As shown in Figure 3-1, this project effort began with an existing design, with plans to move forward to an "intermediate product" and eventually continue on to two specific, advanced designs that did not exist at the start of this effort. The intermediate design, GNB's ABSOLYTE IIP product, incorporates many of the improvements in manufacturing processes and enhancements developed during Task 1/Phase 1. It has been introduced as a commercially available product.

The two more advanced battery designs have been completed, prototypes have been constructed, and their performance capabilities demonstrated. Because these batteries were designed for specific applications, and because the applications have not developed as quickly as have the batteries, GNB has not released these designs for commercial production. Because accurate costs cannot be determined for a product not yet in production, estimates of costs based on similar materials and manufacturing operations must be used for these two battery designs.

In this task, GNB has compared the intermediate ABSOLYTE IIP design to the previous generation of the ABSOLYTE design (the ABSOLYTE II) to demonstrate the effect of improvements realized as the result of Task 1/Phase 1 of this contract. This analysis is valid because all of the BES installations presently being considered for near-term implementation are based on battery systems using the ABSOLYTE IIP cell design. In addition, projections of how the two new, specific BES systems compare to the ABSOLYTE II and IIP were made to demonstrate the advantages these designs provide in battery size and cost.

### *Battery Cost in BES Systems*

A good amount of attention has been focused on the cost of the battery in a BES system. An objective of this project was to improve VRLA battery performance while keeping the cost equal to, or lower than, that of competing designs. This was to be accomplished while maintaining the inherent advantages of the VRLA technology. Although the battery is a highly visible portion of a BES system, there are many other components that add to the overall cost.

As a result of GNB's participation in this project, GNB has reviewed the requirements for several projects where BES has been a prime candidate compared with other technologies. These projects specified total turnkey systems and integration of the BES system into the utility network already in place. GNB has been fortunate to have participated in the teams organized to conceptualize these projects and to provide estimates of total system cost.

The battery and the power conditioning equipment that converts the battery's DC power to AC power are the most visible components of a BES system. However, there are many other elements that must be considered in the design and installation that often amount to 50% or more of the cost of a BES system. These other elements include transformers, capacitor banks, switch gear, breakers, buildings, HVAC, site preparation, connection to the existing network, design engineering, installation/start up, training, local permitting, and transportation of components to the site.

A representative breakdown of the percentage of total system cost for a typical BES system with a reasonable amount of energy storage capacity (1.5-2 hr) is as follows:

| | |
|---|---|
| Battery | 25-30% |
| Inverters | 15-20% |
| Balance of Plant | 50-60% |

Obviously, there are many factors that influence the percentage of cost contributed by each of these principal elements of a BES system. Battery cost is a function of both discharge rate and the length of time that the battery is required to support the operation. Inverter cost is a function of the type of electronics used (Integrated Gate Bipolar Transistor (IGBT) or gate turn off (GTO)), power requirements, and black start capabilities, for example. Balance of system is highly dependent on the proposed site for the installation and how the BES system must integrate with existing electrical systems. Finally, engineering before, during, and after the installation of the BES system is a requirement to ensure proper equipment selection, installation, and operation.

### *Improvements Realized in the Intermediate Product Design*

Following are the quantified improvements achieved by the Intermediate Design ABSOLYTE IIP product compared to its predecessor ABSOLYTE II product:

- **Volumetric Space:** The volume of battery required per kilowatt-hour of energy stored was decreased by 15%.
- **Footprint:** The floor area of battery required per kilowatt-hour of energy stored was decreased by 15%.
- **Cost:** The price of the battery in dollars per kilowatt-hour was reduced by 14%, allowing for an annual inflation rate of 3%.

The comparisons listed were calculated using performance capabilities for the two battery designs at a 3-hr discharge rate. Both the ABSOLYTE II and ABSOLYTE IIP batteries are considered general purpose designs that have been adapted to energy storage applications.

### *Estimated Improvements for the Advanced Designs*

During the contract effort, GNB developed two additional designs using battery performance requirements provided by the two host utilities. The MSB design was the result of input from PG&E for a "transportable" battery system where battery size and cost were primary factors. The LSB battery was designed with input from PREPA to be a battery with high power capabilities for short-duration use in a frequency regulation application. Both of these applications require a higher-power/lower-energy storage capability than that existing with the ABSOLYTE II design.

Table 3-2 lists the improvements of the various designs developed under this contract relative to the baseline ABSOLYTE II design in terms of space and footprint required and estimated cost (dollars per kilowatt in this case). The comparisons are provided for discharge lengths of 15, 30, and 60 min. A comparison of the estimated battery lifetimes for the various designs is also provided. Except for battery lifetime, a value less than 1.00 demonstrates an improvement over the baseline ABSOLYTE II.

The following notations and observations are associated with the data in Table 3-2:

- All comparisons were made to the ABSOLYTE II product. Reductions in space and footprint requirements and in cost are improvements, and are represented in the table as a value less than 1.00.

**Table 3-2. Relative Improvements of VRLA Designs**

| | ABSOLYTE II | ABSOLYTE IIP | MSB Design | LSB Design |
|---|---|---|---|---|
| **Model No.** | **75A-17** | **90A-17** | **MSB-2V** | **LSB-1230** |
| Volume Required ($in^3$/kW) | | | | |
| 15-min rate | 1.00 | 0.84 | 0.19 | 0.58 |
| 30-min rate | 1.00 | 0.92 | 0.20 | 0.80 |
| 60-min rate | 1.00 | 0.99 | 0.29 | 0.89 |
| Area ($in^2$/kW) | | | | |
| 15-min rate | 1.00 | 0.84 | 0.96 | 0.51 |
| 30-min rate | 1.00 | 0.92 | 1.05 | 0.71 |
| 60-min rate | 1.00 | 0.99 | 1.36 | 0.78 |
| Cost ($/kW) | | | | |
| 15-min rate | 1.00 | 0.85 | 0.54 | 0.61 |
| 30-min rate | 1.00 | 0.93 | 0.59 | 0.85 |
| 60-min rate | 1.00 | 1.00 | 0.77 | 0.94 |
| Life | 1.00 | 1.00 | 0.50 | 1.20 |

- Both the MSB-2V and the LSB-1230 battery designs were specifically optimized for short-duration high-rate discharge applications. Their advantages are therefore more pronounced at these higher discharge rates. For example, space reduction at the 15-min rate shows the greatest improvement.
- As the discharge time is extended, the battery becomes more an energy storage system than a power storage system; hence, the degree of improvement becomes smaller with the advanced designs. This is a direct result of the fact that both of the advanced designs were optimized for high-rate, short-duration applications.
- To achieve the significant improvements in space requirements and cost demonstrated by the MSB battery design, a reduction in lifetime was accepted. The comparison data show that for the same level of power for 15 min, the MSB requires only about 20% of the volume required for the equivalent ABSOLYTE II design, and has about one-half the cost of the ABSOLYTE II product. However, the trade-off for these space and cost advantages is a reduction in life.
- The LSB was designed to provide reductions in space and cost while demonstrating an improvement in lifetime for high discharge rate, short duration applications. This is clearly highlighted in Table 3-2.

### Final Battery Deliverable for Field Test

As part of this contract, a moderate-sized battery was to be furnished by GNB for a field test at the conclusion of the development program. The approximate size of this battery is 250 kW/500 kWh. Because of uncertainty about the availability of batteries using the 2-V MSB and the LSB designs, an ABSOLYTE IIP battery was selected as the field test deliverable.

SNL issued an request for quotation (RFQ) early in the third quarter of FY95 for a contract to conduct testing using the deliverable as part of a BES demonstration. GNB was selected to perform this 4-yr effort and a contract was signed early in October 1995. GNB will use the recently installed BES system at the GNB Vernon, California battery recycling center for these tests.

## Quantification of Utility Cost Savings from Using Batteries – UMR

This task was activated during FY94 by placing an SNL contract with UMR to use the DYNASTORE computer program to perform calculations of utility operating costs with and without BES on the system. UMR completed work on the contract early in FY95 and submitted a final report during the second quarter. This report was subsequently revised and an updated copy was completed in the fourth quarter. In this initial study, UMR calculated generating costs for a medium-sized utility system that was not interconnected with other utilities. Operating costs are just one part of the cost/benefit picture and must be combined with battery developer cost estimates and utility benefit projections to reach an overall conclusion regarding the cost-effectiveness of batteries in a particular situation.

DYNASTORE is a computer program designed and developed by EPRI to help determine the cost savings of energy storage. This production costing program uses chronological data as opposed to the more conventional load duration curves so that start-up costs and minimum up and down time constraints can be included in the unit commitment process and subsequent cost calculations. DYNASTORE dynamically models the unit commitment and economic dispatch processes over a selected time period and dispatches energy storage devices in the same manner as it does generating units. The effects of scheduled maintenance and forced outages can also be studied with the program. Use of DYNASTORE requires extensive knowledge of the program and its input and output routines. A workshop given by EPRI and the developer was attended in order to gain familiarity with the program. Beta test version 4.0 of DYNASTORE was initially used to calculate the production costs reported for this project. The work was completed with version 4.1.

Several methods of production cost simulation are provided for in DYNASTORE. Those methods are deterministic, standard Monte Carlo, and antithetic Monte Carlo. The differences between each of these methods deal with the issue of generating unit availability. The deterministic method assumes that there are no forced outages. In this method, all generating units are considered to be available at all times, except for any units that may be on a maintenance outage. The standard Monte Carlo method uses a pseudorandom number generator to simulate random forced outages based on the generating unit reliability data specified as part of the program input. Antithetic Monte Carlo sampling methods improve the convergence of the standard Monte Carlo method. The antithetic Monte Carlo algorithm alternates standard and antithetic Monte Carlo iterations. If the random number for the standard Monte Carlo sample is $r_i$, then the antithetic of that number, $a_i = 1 - r_i$, is used for the antithetic sample.

The utility studied in this project is isolated from interconnection with other utilities. Data were obtained on typical load profiles for several weeks in different seasons, and peak loads of 2750 and 2850 MW were estimated for the years 1996 and 1997, respectively, using their projected annual load-growth rate. Information was also obtained on existing and planned generation units. For 1996 and 1997, the maximum generation capacity of the 58 units will be 5135 MW. The effect on operating costs of BES systems used for spinning reserve, load leveling, and frequency control were considered. A range of BES capacity from 40 MW to 500 MW was analyzed in order to determine the optimum size.

Figure 3-5 shows the results of the annual operating cost calculations for 1996 and 1997 when the BES system is used for spinning reserve only. The curve labeled D was calculated by the deterministic method, those labeled M were obtained with the standard Monte Carlo approach, and those labeled A were calculated using antithetic Monte Carlo sampling. Both 12 and 24 Monte Carlo iterations were used in these calculations, and the results were identical. Therefore, only 12 iterations were used for the rest of the BES use scenarios. Since the spinning reserve requirement for this system (15% of peak load) is slightly more than 400 MW for both the 1996 and 1997 simulation years, savings from using batteries began to level off above 300 MW. Below 300 MW, the operating cost savings were almost linear with battery system size. Including random forced outages by using Monte Carlo simulations resulted in significantly greater operating cost savings for all BES system sizes.

The calculated results for load leveling were nearly identical to those for the spinning reserve scenario. This is related to the fact that DYNASTORE, when operated in load-leveling mode, credits any BES system capacity not needed at a specific instant of time toward the spinning reserve requirement. Therefore, the closeness of the production cost savings for the load leveling and spinning reserve applications indicates that most of the savings are due to spinning reserve, with very little due to load-leveling. The calculated savings from using batteries for load frequency control (LFC) were much lower than for spinning reserve, as shown in Figure 3-6. Inclusion of random forced outages also results in less of an increase in operating cost savings for the LFC use scenario than it did for spinning reserve. A comparison of the standard Monte Carlo results for all three use scenarios is shown in Figure 3-7 for the 1996 simulation year.

A final evaluation of operating costs that was made involved combining the previously studied use scenarios in pairs. No significant enhancement in cost savings was discovered in any of these cases. In most situations, the savings were close to the average of the values obtained when all of the BES capacity was used in each of the two individual applications.

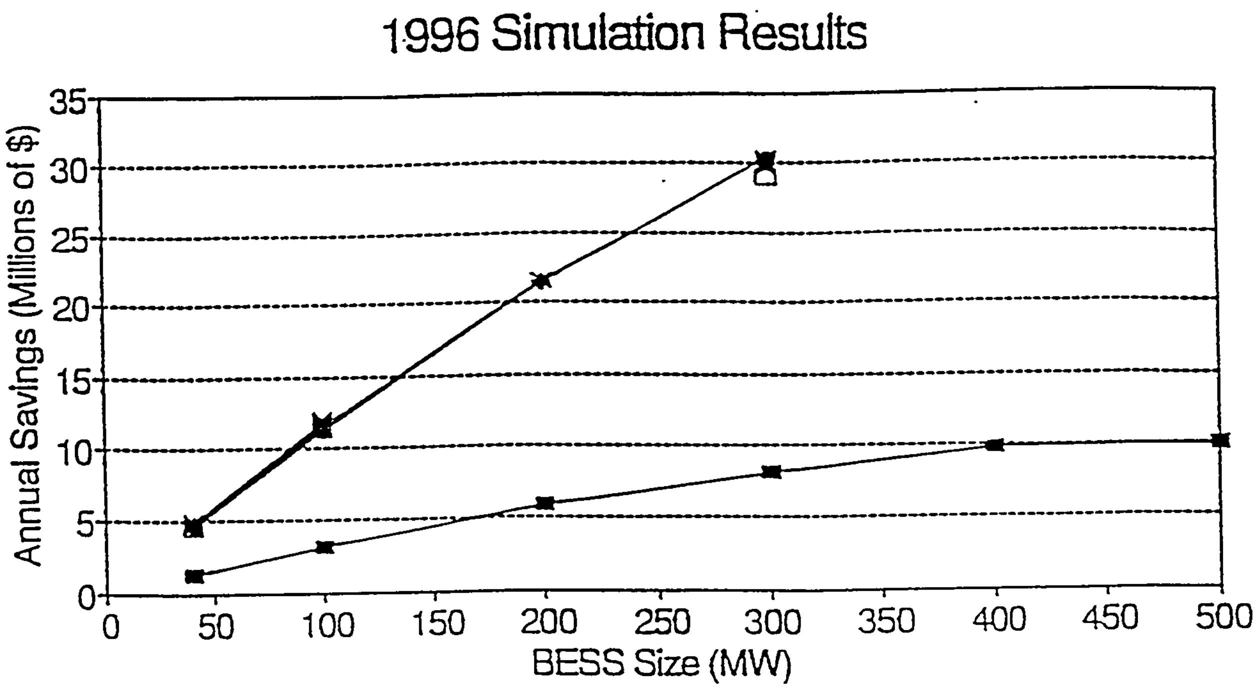
Earlier in the year, a contract was placed with UMR for a follow-on study where DYNASTORE would be used to perform an operating cost study of a grid-connected utility system. The results of this new study would provide a useful contrast to the analysis of an isolated utility system that was carried out under the initial contract with SNL. Student personnel have been assigned to this project and trained in the use of DYNASTORE. Input data required by the program were received from the utility, Kansas City Power and Light Co. (KCPL), an EPRI member whose system was the subject of this analysis. The utility has been very cooperative in supplying the large quantity of detailed data required for accurate modeling of their system using DYNASTORE. Entry of the KCPL data into DYNASTORE has now been completed and reviewed with them.

A spreadsheet was programmed to add fixed costs to the fuel and other variable costs calculated by DYNASTORE. This was done to allow the utility to check the calculated costs against their actual operating costs for a base case without storage. After several rounds of checking the data with KCPL, the calculated costs are now very close to the actual costs. The utility has agreed that these costs are close enough to consider the cost model to be "acceptable/valid." Work is proceeding to determine operating cost savings afforded by BES systems for the following applications: load leveling that includes spinning reserve, spinning reserve only, load leveling only, and LFC.

## Technology Evaluation – SNL

In the last quarter of FY94, a test plan was written to evaluate the performance of three series-connected, Type 100 A-25 modules that were sent by GNB to SNL in December 1993 as intermediate design deliverables. This plan included the following testing objectives for the ABSOLYTE IIP battery, which were pursued further in FY95:

1. Confirm the electrical performance ratings under various constant-current loads.



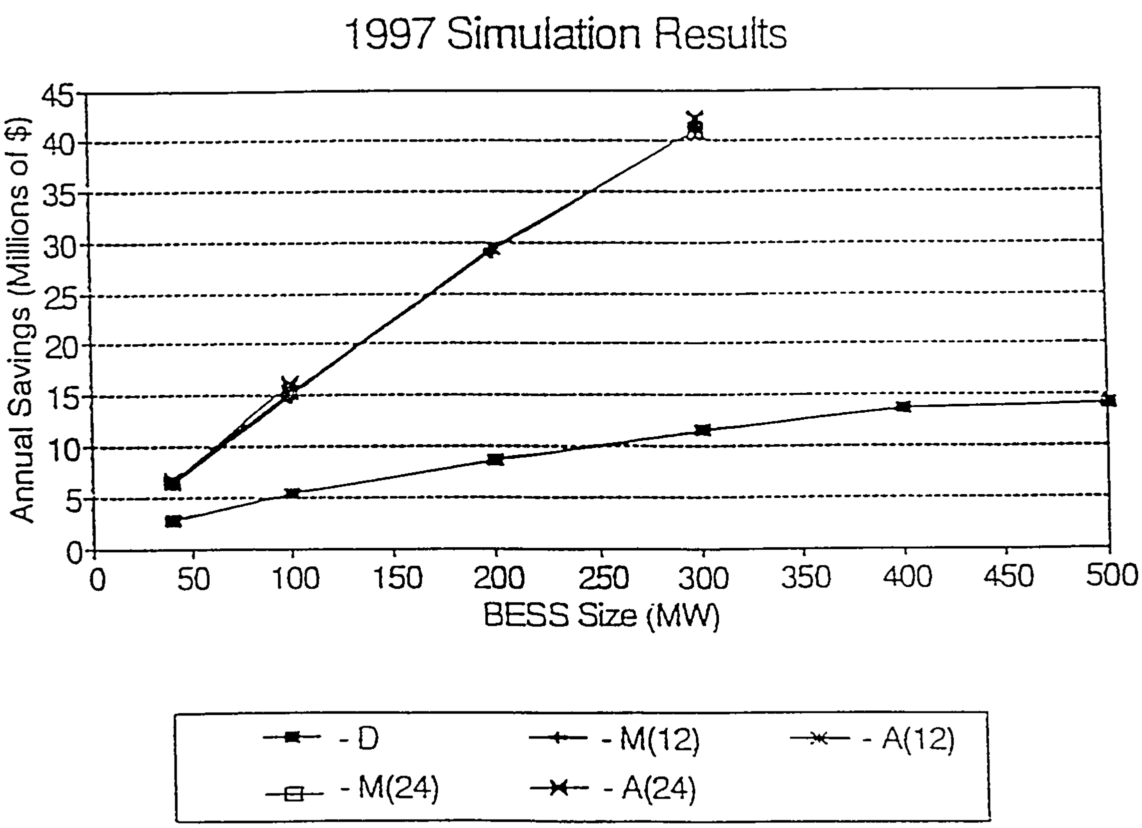




**Figure 3-5.** **Calculated Annual Operating Cost Savings when the BES System is Used for Spinning Reserve.**

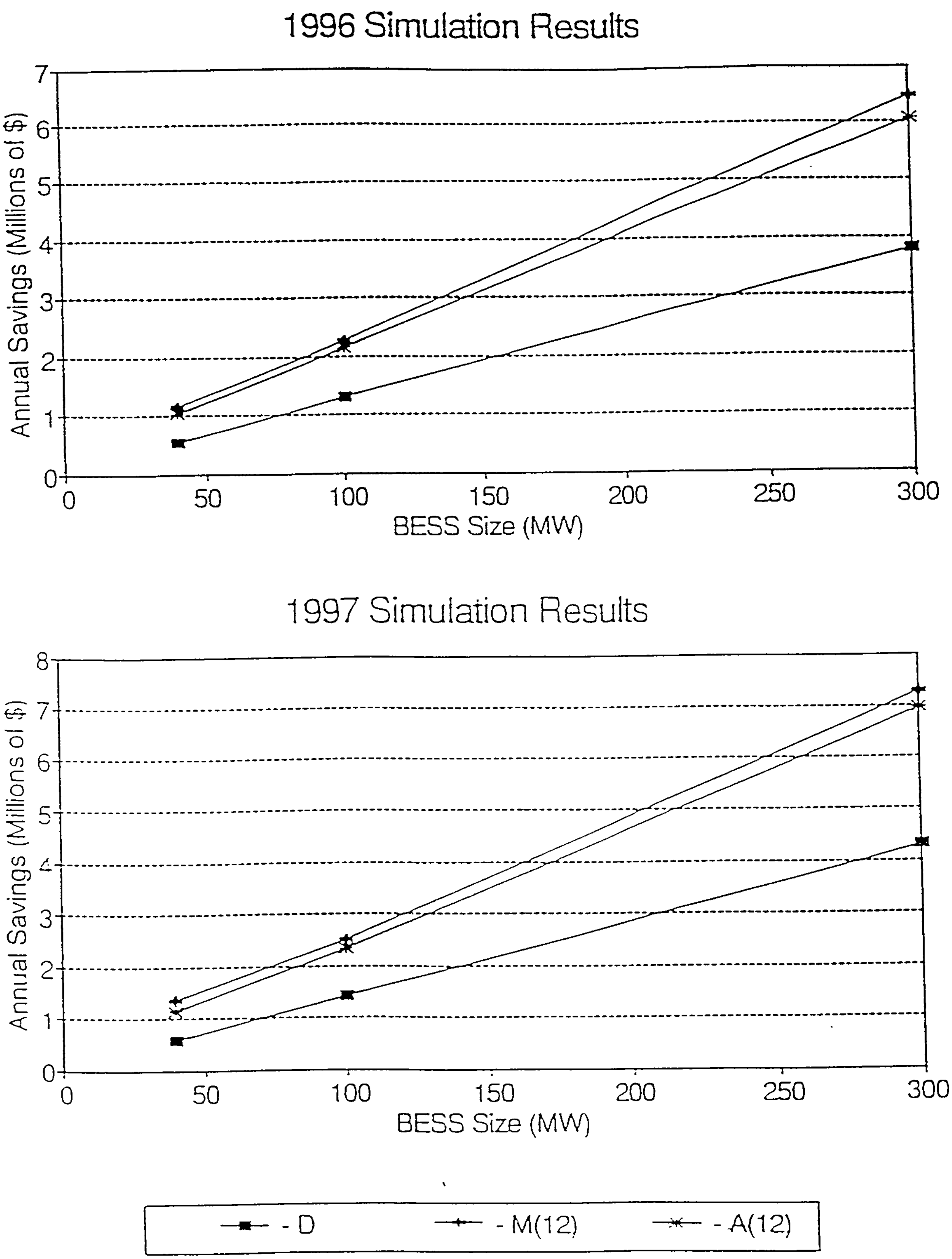



**Figure 3-6.** **Calculated Annual Operating Cost Savings when the BES System is Used for LFC Only.**

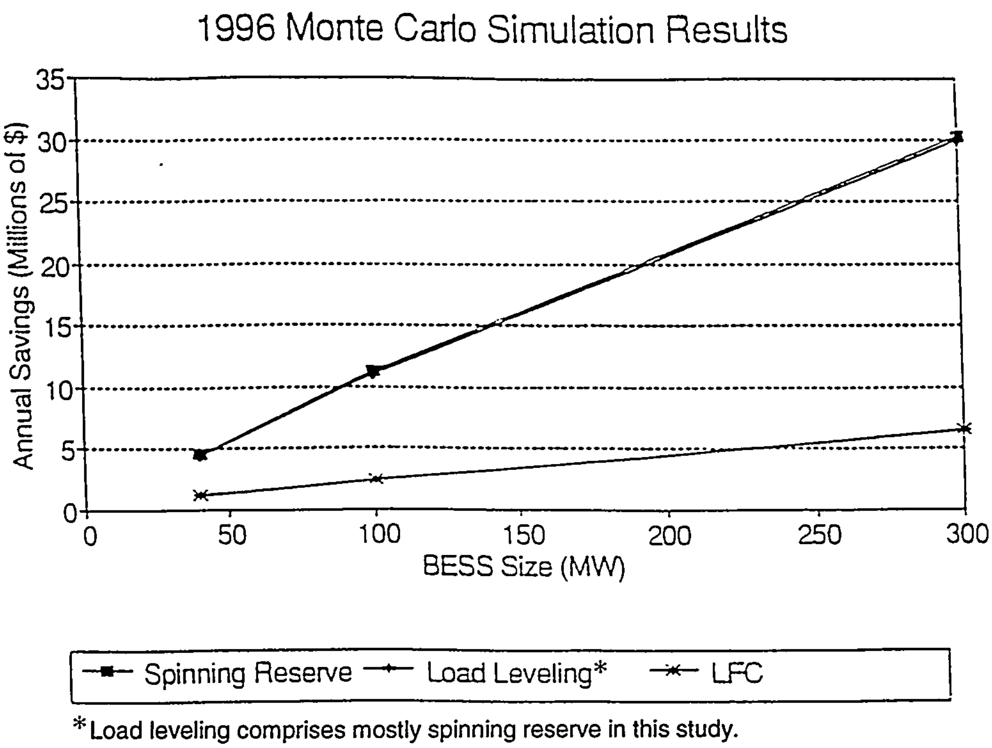



**Figure 3-7. Comparison of Annual Operating Cost Savings for Three Different BES System Use Scenarios.**

2. Evaluate the capability to meet area/frequency regulation and spinning reserve requirements for UES applications.

3. Possibly, determine the service life of the battery while using area/frequency regulation and spinning reserve cycles. (This objective was to be considered after completion of the second objective.)

Details of tests performed in the first three quarters of FY95 are not covered in this particular report, but can be found in their respective quarterly reports. This report provides only an overview of the activities for those quarters. However, fourth quarter activities are covered in detail at the end of this section, since they have not been reported yet.

While pursuing the first objective listed above, which involved performing constant-current discharge tests at the C/8 (150 A), C/2 (428 A), and C/18 (74 A) rates, a few observations that were made led to the performance of more constant-current testing for much of the rest of FY95.

Although these tests initially confirmed that the ABSOLYTE IIP performed about as rated, which is 1200 Ah at the 8 hr rate to an end-of-discharge (EOD) voltage of 1.75 vpc, a trend of declining capacity with successive cycling was noted. This raised concerns regarding the recharge regime that was prescribed by GNB at that time, which is defined in Table 3-3 as Normal Overcharge A. Further, as indicated in Table 3-3, this recharge regime required 23 hr to complete (excluding the 2-hr rest period at the end of the recharge), which is unsuitable for UES applications. Instead, the battery should be capable of being fully recharged from 100% DOD within an 8-hr period. The Normal Overcharge B regime of Table 3-3 was then prescribed by GNB in order to reduce the actual completion time. However, it was found that use of this regime resulted in an even higher rate of capacity degradation as a function of successive cycling.

This led to several studies aimed at determining a recharge regime that would be suitable for UES applications in terms of both completion time and discharge capacity stability. The various regimes that GNB recommended to SNL in pursuit of this regime are all listed in Table 3-3.

## Table 3-3. Various Regimes Used for Recharging the ABSOLYTE II and IIP

| Recharge Regime Name | Recharge Regime Specifics | Required Time to Complete Regime | |
|---|---|---|---|
| | | ABSOLYTE II | ABSOLYTE IIP |
| Normal Overcharge (A) | CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 7% overcharge, OC for 2 hr | -- | 25 hr |
| Normal Overcharge (B) | CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 24 A, CI (24 A) for 2 hr, OC for 2 hr | -- | 11.5 hr |
| Normal Overcharge (C) | CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 7% overcharge, OC for 8 hr | -- | 31 hr |
| Normal Overcharge (D) | CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 24 A, CI (24 A) until 7% overcharge, OC for 8 hr | 16.5 hr | 17.5 hr |
| Normal Overcharge (E) | CI (300 A) until 2.40 vpc, CV (2.40 vpc) until 24 A, CI (24 A) until 7% overcharge, OC for 8 hr | -- | 16 hr |
| Boost Charge | CI (300 A) until 2.35 vpc, CV (2.35 vpc) until 24 A, CI (24 A) for 8 hr, CV (2.35 vpc) for 48 hr | -- | 64 hr |
| Intermediate Charge | CI (120 A) until 2.35 vpc, CV (2.35 vpc) until 90% SOC, OC for 5 min | -- | 3 hr |
| Refreshing Charge | CI (300 A) until 2.40 vpc, CV (2.40 vpc) until 24 A, CI (24 A) for 2 hr, OC for 8 hr | -- | 16.5 hr |

*CI = constant current CV = constant voltage OC = open circuit vpc = volts per cell SOC = state-of-charge*

Figure 3-8 illustrates discharge capacity degradation rates when Normal Overcharge C and D regimes were used for recharging. Note that Normal Overcharge C and D regimes were the same as the A and B regimes, respectively, except that the open-circuit time period at the end of each was 8 hr instead of 2 hr. The extra time at the end of regimes C and D did not seem to have an effect on the degradation rate, but was added to minimize temperature effects on battery life. Also, note that regimes A and C are distinctly different from B and D in that they utilize a long taper-charge finish. In comparison, regimes B and D use a short, higher-level constant-current finish.

As shown in Figure 3-8, the resulting capacity degradation rate was quite different for capacity measurements that followed taper-charge finishes (Normal Overcharge C curve) as compared to those that followed constant-current finishes (Normal Overcharge D curve). In fact, there is a trade-off between the two. As noted in Table 3-3, the time required to complete the taper-current regime is nearly twice that required for the constant-current regime; however, use of the constant-current regime causes the rate of capacity degradation to nearly double.

GNB recommended giving the ABSOLYTE IIP a boost charge (also defined in Table 3-3) whenever the measured discharge capacity drops to or below 960 Ah, which is 80% of the nominal 1200-Ah rating. Assuming that the rate of capacity loss is linear from 1200 Ah to 960 Ah when using each of the Normal Overcharge C and D regimes, and assuming that the starting level of measured capacity is 1200 Ah, the ABSOLYTE IIP would require a boost charge approximately once every 50 cycles when using the taper-current finish regime (C) or once every 25 cycles when using the constant-current finish regime (D). Since this is such an aggressive recharge regime, amounting to the equivalent of approximately a 120 to 125 percent overcharge, GNB recom-

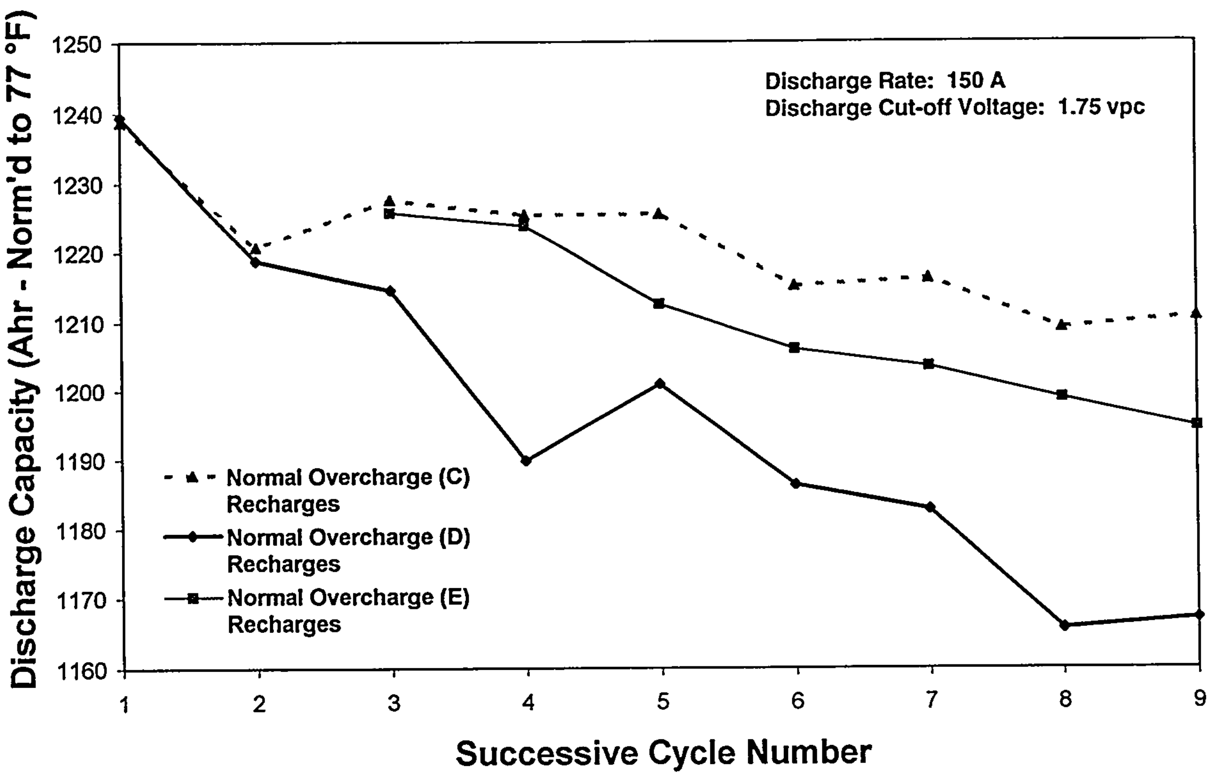



**Figure 3-8. ABSOLYTE IIP Discharge Capacity Loss Rate for Various GNB-Recommended Recharge Regimes**

mended using it sparingly, especially since, during the 8-hr, 24-A constant-current step, the battery voltage is allowed to increase to up to 2.65 vpc. Although this limit was never reached for any boost charges that were performed on the SNL test unit, a voltage of 2.60 vpc was reached, and this is well above the voltage at which gassing of this battery occurs. With the battery voltage held at this level for extended periods of time, significant amounts of water could be lost, which would reduce battery life due to dry-out.

In order to minimize the need to perform a boost charge, GNB then recommended the Normal Overcharge E regime, which is similar to the Normal Overcharge B and D regimes except that the charge voltage is set at 2.40 vpc instead of 2.35 vpc. More specifically, this regime was recommended as a possible method of reducing the rate of capacity loss that resulted with use of the B and D regimes without increasing the completion time. As shown in Figure 3-8, this regime accomplished exactly that, and it even required 1.5 hr less to complete than the B and D regimes (again excluding the rest period at the end of the recharge). Consequently, Normal Overcharge E was determined to be the most suitable recharge regime for the UES applications. However, the effect on cycle life of increasing the charge voltage is unknown at this point.

One interesting observation that was made when using the boost charge on the ABSOLYTE IIP is that its complete effect was not apparent until at least two consecutive discharges following the boost charge (with normal overcharging in between). In other words, the measured discharge capacity values continued to increase for the second, the third, and sometimes the fourth discharge following the boost charge. In one instance, the measured values continuously increased 58 Ah from the first discharge to the fourth discharge following the boost charge.

In the third quarter, more 100% DOD (1.75-vpc) constant-current discharge testing was performed, but at C/2 (433-A) and C/20 (68-A) rates. This series of discharges also utilized the Normal Overcharge E regime for recharging. Results, which were reported in the third quarterly report for this fiscal year, indicated that the Normal Overcharge E regime produced relatively stable capacity measurements for these discharges as well. Figure 3-9 shows a Peukert plot for these measurements, as well as those for the C/8 discharge tests. Note that all measured discharge capacity values are overlapped to

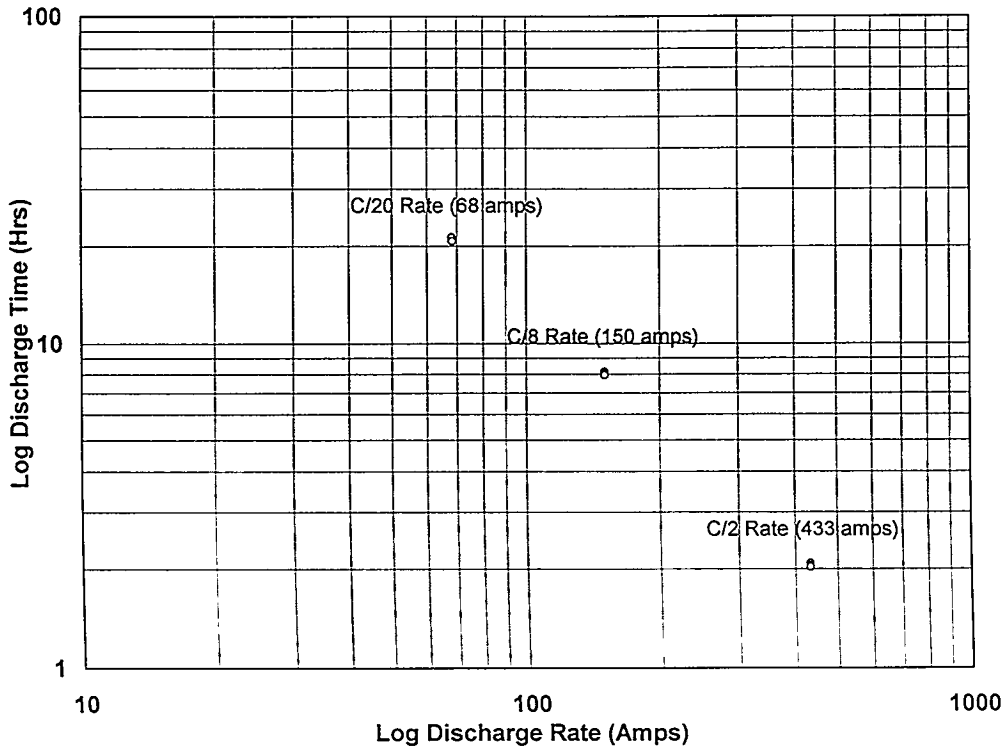



**Figure 3-9. Peukert Plot of ABSOLYTE IIP Discharges.**

demonstrate the stability of the capacity for each series of discharges.

Also in the third quarter of FY95, the ABSOLYTE II battery (original design), which was sent to SNL earlier in the GNB contract, was placed back on test in preparation for characterization testing similar to that performed on the ABSOLYTE IIP battery. More specifically, the objective was to evaluate improvements from the ABSOLYTE II design to the ABSOLYTE IIP design. Like the ABSOLYTE IIP battery, the ABSOLYTE II battery is made up of three modules (Type 85A-25), each consisting of three 2-V cells, which are all connected in a series arrangement. Each module of the ABSOLYTE II design has a rated nominal capacity of 1040 Ah at the C/8 rate (130 A) to an EOD voltage of 5.25 V (1.75 vpc).

Initial C/8 constant-current tests to a 1.75 vpc cutoff (100% DOD) showed that the ABSOLYTE II delivered approximately 1250 Ah of capacity, which was not only substantially higher than its rating of 1040 Ah but was also even a little higher than that delivered by the ABSOLYTE IIP. This was somewhat misleading, however, as the discharge currents were set at slightly different levels. Although both series of discharge tests were intended to be done at a GNB-specified C/8 rate, the ABSOLYTE II actually lasted approximately 10 hr to the EOD voltage of 1.75 vpc under a constant 130-A load, instead of the expected 8 hr.

This prompted further constant-current discharge testing of the ABSOLYTE II in the fourth quarter of FY95, but under a constant 150-A (instead of 130-A) load in order to make a direct comparison of discharge capacity measurements for the two battery designs. Table 3-4 shows the results of these tests for the ABSOLYTE II design, as well as those at the same discharge rate for the ABSOLYTE IIP. It should be noted that the Normal Overcharge D regime of Table 3-3 was used to recharge each battery prior to each discharge cycle. Each measured capacity shown has been normalized to a start-of-discharge temperature of 77°F using a compensation factor of 3 Ah/°F.

The results shown in Table 3-4 indicate that available capacity of the ABSOLYTE II design is very comparable to that of the ABSOLYTE IIP design. In fact, as illustrated in Figure 3-10, these data suggest that the original design of the ABSOLYTE II actually provides

## Table 3-4. ABSOLYTE II and IIP 150-A Discharge Capacities when Using Normal Overcharge D Recharge Regime

| ABSOLYTE II | | ABSOLYTE IIP | |
|---|---|---|---|
| Cycle # | Measured Capacity (Ah) Normalized to 77°F | Cycle # | Measured Capacity (Ah) Normalized to 77°F |
| 38 | 1214 | 57 | 1219 |
| 39 | 1216 | 58 | 1215 |
| 40 | 1200 | 59 | 1190 |
| 41 | 1200 | 60 | 1201 |
| 42 | 1208 | 61 | 1186 |
| 43 | 1208 | 62 | 1183 |
| 44 | 1204 | 63 | 1166 |
| 45 | 1210 | 64 | 1167 |

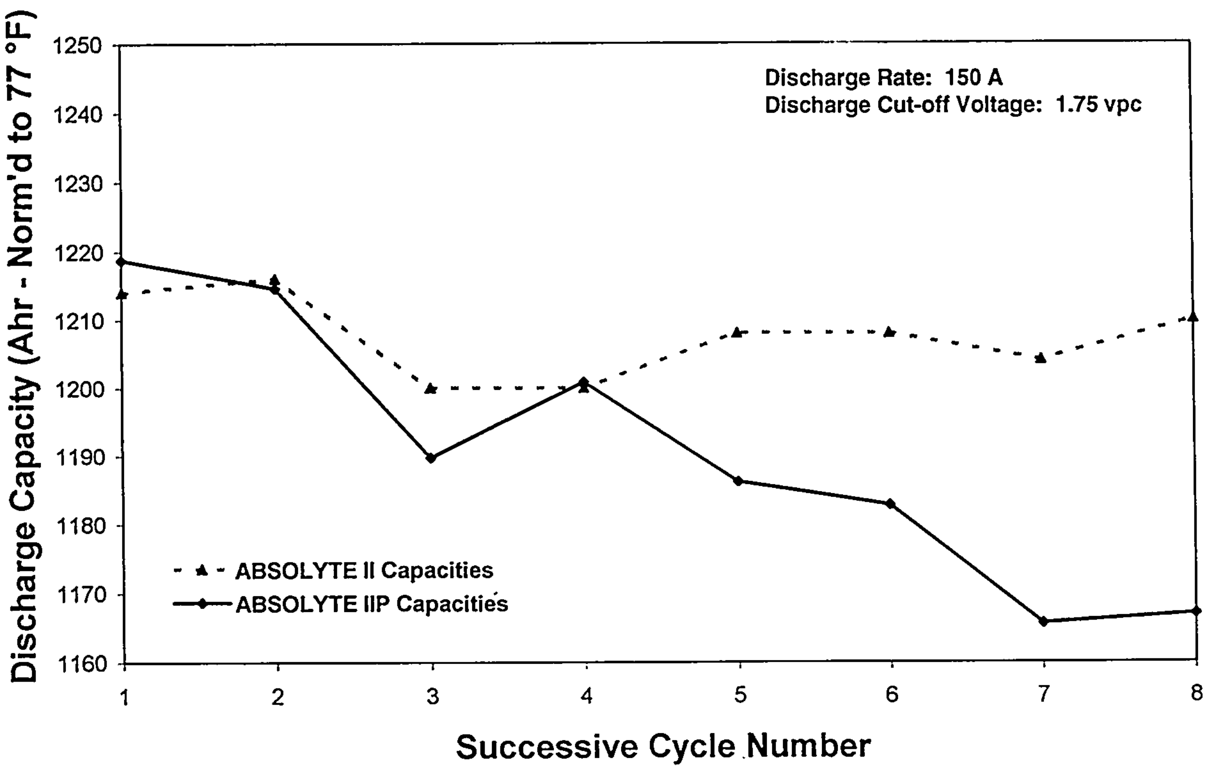



**Figure 3-10.** ABSOLYTE II and IIP Discharge Capacity Loss Rates when Using Normal Overcharge D Recharge Regime.

for a more stable capacity output. These data further suggest that the ABSOLYTE II design accepted a charge more readily than the ABSOLYTE IIP design. Furthermore, it was observed that when using the Normal Overcharge D regime to recharge each battery, the ABSOLYTE II design reached the 107% cutoff criterion 1 hr sooner than did the ABSOLYTE IIP design. It was also observed that, even though the average temperature at the start of recharge for the ABSOLYTE II tests was approximately 2°C lower than that for tests of the ABSOLYTE IIP, the average peak temperature during recharging of the ABSOLYTE II was approximately 2°C higher than that for the ABSOLYTE IIP. The average start-of-charge temperature for the ABSOLYTE II recharges was approximately 27°C, while the average start-of-charge temperature for the ABSOLYTE IIP recharges was approximately 29°C. The average peak temperature for the ABSOLYTE II recharges was approximately 45°C, while the average peak temperature for the ABSOLYTE IIP recharges was 43°C.

Preparations for frequency regulation and spinning-reserve testing of the ABSOLYTE IIP were also made in the fourth quarter of FY95. Each of the two tests has been defined similarly to a test performed in the SNL evaluation of the C&D Charter Power Systems, Inc. (C&D) flooded lead-acid battery (12 cells) in FY93-FY94 for PREPA. These tests were reported on in the "Utility Battery Storage Systems Program Reports for FY93 and FY94." Just as for the C&D Battery evaluation, frequency regulation and spinning reserve tests of the ABSOLYTE IIP will be combined, as shown in Figure 3-11. The UES cycle shown in Figure 3-11 was designed to take approximately one week to complete. As indicated by the diagram, the first part of the UES cycle for testing the ABSOLYTE IIP will comprise several sessions of frequency regulation separated by intermediate charges, which are defined in Table 3-3. The frequency regulation sessions will be followed by a spinning-reserve discharge, and then a final refreshing charge (also defined in Table 3-3), to bring the battery back to 100% SOC. For the C&D Battery tests, frequency regulation sessions were performed between 92% and 72% SOC. For the ABSOLYTE IIP tests, however, the SOC range will be shifted down slightly, to between 90% to 70% SOC, to ensure proper charge acceptance on intermediate recharges. SOC for these tests will be based on a rated capacity of 1200 Ah and an assumed coulombic efficiency (CE) of 100%. The spinning reserve profile for the C&D Battery consisted of constant power for the first half followed by a linear ramp to zero for the second half. The same profile will also be used for the ABSOLYTE IIP.

Power levels for the various portions of the UES cycle will be scaled to ratings of the ABSOLYTE IIP

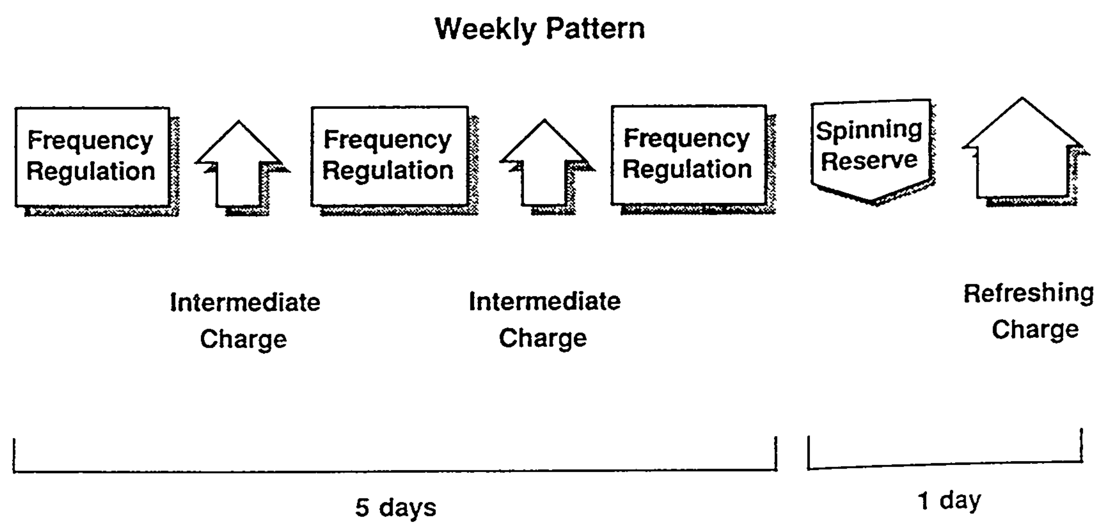



**Figure 3-11. Diagram of the UES Cycle That Was Used for PREPA/C&D Battery Testing.**

battery from estimates of the PREPA BES system operating parameters, which were calculated by United Engineers and Constructors (now Raytheon Engineers and Constructors). The PREPA BES system is a 20-MW/14.1-MWh facility that consists of 6000 2-V/2000-Ah cells configured in six parallel strings. It was installed primarily to provide frequency regulation and spinning reserve on the island of Puerto Rico. United Engineers and Constructors found that frequency regulation at this site could be represented by three power levels with operating times in the ratio of 1:2:13. These were used by SNL to set up a basic 160-min building block, or what is called a "subcycle," that is composed of 32 asymmetrically arranged 5-min segments as shown in Figure 3-12.

Table 3-5 lists the power levels estimated for the PREPA BES system and the corresponding scaled values that will be used for the ABSOLYTE IIP battery. Due to tester limitations, however, the scaled constant power level of the spinning reserve part of the UES cycle is not actually achievable for the ABSOLYTE IIP (nine series-connected, 2-V/1200-Ah cells). Therefore, the actual power level that will be used for spinning reserve will be 90% of the scaled value. In order to partly compensate for the reduced power, the length of time of each half of the spinning reserve profile will be extended from 15 min to 16.7 min.

A few frequency regulation sessions were completed on the ABSOLYTE IIP beginning in the last month of FY95. Additionally, one spinning reserve test was also completed. However, the two tests were not yet combined into one cycle as discussed above and as shown in the UES cycle of Figure 3-11. Instead, in order to first ensure proper operation of each test, they were performed separately. All of the other details discussed above for each of these tests, however, were applied.

To begin with, seven frequency regulation sessions were performed consecutively, each one followed by an intermediate recharge. The first frequency regulation session of the ABSOLYTE IIP began with the battery at 100% SOC and ended when the battery reached 70% SOC. At that time, the battery was given an intermediate charge to bring it back up to 90% SOC. Following the first frequency regulation session and intermediate charge, the same was repeated six more times, but with the battery operating between 90% and 70% SOC. As shown in Table 3-6, 27 160-min subcycles were accomplished in a 72-hr period for the first session, and 17 to 18 subcycles in approximately 45 to 48 hr for those following. Figure 3-13 shows plots of actual voltage, current, and power responses of the ABSOLYTE IIP during the ninth subcycle of the first 90-to-70% SOC frequency regulation session (the second session of the overall

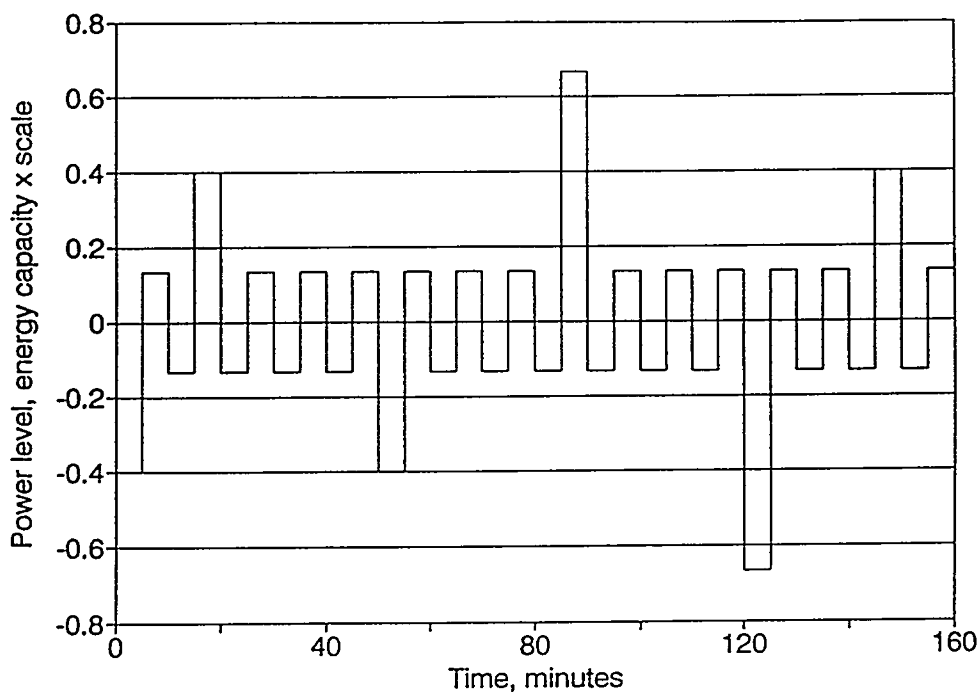



**Figure 3-12. Basic 160-min Subcycle That Serves as a Building Block for Frequency Regulation Testing.**

**Table 3-5. ABSOLYTE IIP Power Levels Scaled from the PREPA BES System**

| Application | PREPA BES System Power Levels (MW) | ABSOLYTE IIP Scaled Power Levels (kW) | ABSOLYTE IIP Actual Power Levels (kW) |
|---|---|---|---|
| Frequency Regulation | 2.0 | 1.12 | 1.12 |
| Frequency Regulation | 6.0 | 3.37 | 3.37 |
| Frequency Regulation | 10.0 | 5.62 | 5.62 |
| Spinning Reserve, constant | 21, 15 min | 12.64, 15 min | 11.38, 16.7 min |
| Spinning Reserve, ramp | 21 - 0, 15 min | 12.64 - 0, 15 min | 11.38 - 0, 16.7 min |

**Table 3-6. Length and Number of Subcycles for ABSOLYTE IIP Frequency Regulation Sessions**

| Session # | Length of Session (hr) | Number of Subcycles Completed per Session |
|---|---|---|
| 1 | 71.8 | 27 |
| 2 | 47.5 | 18 |
| 3 | 47.5 | 18 |
| 4 | 46.4 | 17.5 |
| 5 | 44.9 | 17 |
| 6 | 44.9 | 17 |
| 7 | 44.9 | 17 |

test). Note that the largest power charge peak could not be maintained at a constant level for the 5-min segment duration. This was caused by the high SOC of the battery and its reaching the voltage limit of 21.15 V (2.35 vpc), which was set to protect the battery from excessive gassing during frequency regulation operation. By the last subcycle in this session, this voltage clipping effect diminished, since the battery SOC had decreased by then.

Figure 3-14 shows a temperature profile for one of the frequency regulation sessions (the third session) and the following intermediate recharge, which is representative of the other sessions and recharges as well.

Following the last intermediate charge, a spinning-reserve test was then performed as specified in Table 3-5. During this test, the battery SOC dropped from 90% to 66%, a difference of 24%. A subsequent refreshing charge was then applied to the battery to bring it back to 100% SOC.

By the end of FY95, approximately 130 deep-discharge cycles, approximately 10 frequency regulation sessions, and one spinning-reserve discharge had been applied to the ABSOLYTE IIP since SNL received it from GNB. Approximately 50 deep-discharge cycles had been applied to the ABSOLYTE II as of the end of FY95.

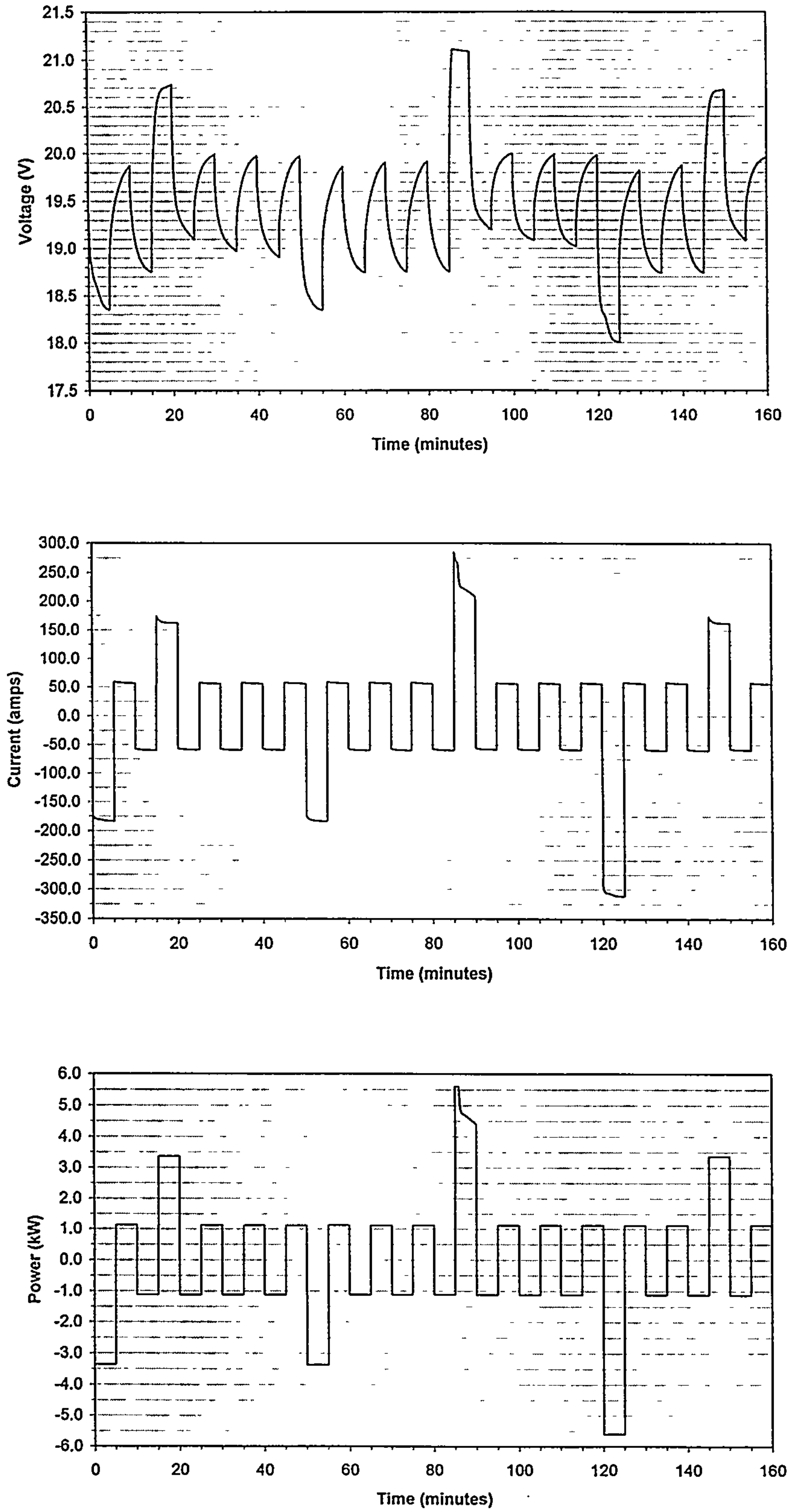



**Figure 3-13. Voltage, Current, and Power Responses of the ABSOLYTE IIP during a Middle Subcycle of a Frequency Regulation Session.**

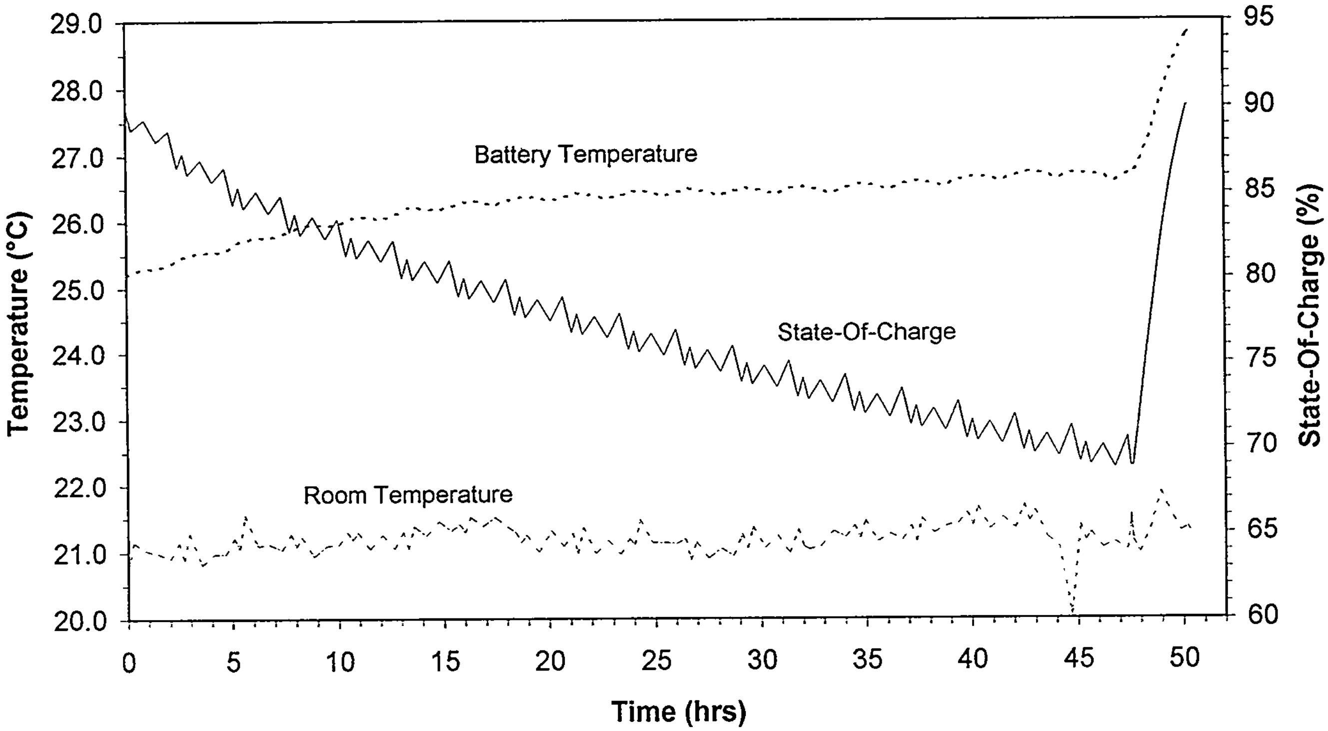



**Figure 3-14. Typical Battery Temperature Profile during a Frequency Regulation Session on the ABSOLYTE IIP.**

The next scheduled tests for the ABSOLYTE IIP in the upcoming quarter are more frequency regulation and spinning-reserve tests, but with the two combined as shown in the UES cycle of Figure 3-11. Plans for the ABSOLYTE II in the upcoming quarter include C/2 and C/20 constant-current discharge testing for comparison to results for the ABSOLYTE IIP design, and also more C/8 constant-current discharge testing, but using the Normal Overcharge E regime for recharging, since it has been determined to be the most suitable recharging regime for utility applications.

## Applied Research – SNL

SNL is thermally spray-depositing metal and metal-oxide coatings onto cell components in support of advanced lead-acid battery research at GNB. Earlier in the year, coatings of one of their two top-priority materials were successfully deposited and 12 coated samples were sent to GNB for testing and evaluation. Initial evaluations of these samples using visual observation, reflected light microscopy, and scanning electron microscopy at GNB were very encouraging. Coverage of the substrate surfaces was complete, although not uniform, and integrity of the substrate was maintained during the coating process. The coating was tenacious and had a rough surface texture. Porosity of the coated layer was somewhat lower than desired, but could be improved by adjustment of the spray parameters. Generally speaking, GNB showed interest in discussing tests with other substrates and alternative coating materials.

The second coating material has been more challenging, because there is no known commercial source that can provide a feedstock powder with the proper characteristics for plasma spray deposition. Ames Laboratory, a DOE lab in Ames, Iowa, has a special high-pressure gas atomization facility that may be able to produce the necessary feedstock material. SNL has been working with Ames to identify a crucible liner material that will not react with the molten metal oxide of interest. A series of experiments with several candidate liner materials indicated that a rhenium coating applied to the crucible should prevent undesirable reactions during the gas atomization process. Unfortunately, rhenium is a costly precious metal, and making plasma spray powder with a rhenium-coated crucible would be relatively expensive (SNL estimates about $15-20K would be required to prepare the crucible and make the necessary powder for this project). For this reason, a more cost-effective alternative is currently being explored with GNB. That possibility is to spray-deposit the metal of interest and then convert it to a metal oxide with a postdeposition heat treatment. GNB has expressed considerable interest in this approach, although a final decision on how to proceed has not yet been made. Personnel from the SNL Thermal Spray Research Lab will be visiting GNB soon to discuss other coatings that could be investigated and methods for applying them.

# 4. Subsystems Engineering – Zinc/Bromine

The UBS Program is currently supporting projects to develop advanced battery systems, such as the zinc/bromine battery, for utility applications. The potential advantages of the zinc/bromine technology include high specific energy (70-80 Wh/kg), rapid recharge (2-4 hr), deep discharge capability (100%), a finite self discharge, and a built-in thermal management system. Mass production manufacturing techniques and inexpensive raw materials will result in a potentially low-cost battery system ($150/kWh) with a stack replacement cost of $50/kWh. Previous efforts in the zinc/bromine program emphasized component development and improved manufacturing techniques, but recently the focus has shifted to battery system integration and field evaluations.

The zinc/bromine battery differs from conventional lead/acid batteries in that the electrolyte is circulated and stored externally to the battery stack. The battery consists of battery stacks, electrolyte storage reservoirs, and an electrolyte circulation system. Flowing electrolyte is necessary to ensure uniform zinc plating on the anode, to separate the reactive bromine from the electroplated zinc in the battery stack, and to improve the thermal management of the system.

A bipolar electrode design is used in the battery. During charge, zinc is electroplated on the anode, and bromine is evolved at the cathode. A complexing agent in the electrolyte is used to lower the reactivity and vapor pressure of the elemental bromine, which reduces self-discharge and significantly improves battery safety. The complexed bromine is removed with the flowing electrolyte and is stored in a reservoir external to the stack. On discharge, the complexed bromine is returned to the battery stacks, where zinc is oxidized to zinc ions and bromine is reduced to bromide ions. The electrochemical reactions during charge are given as follows:

| | |
|---|---|
| Overall: | $ZnBr_2 \rightarrow Zn + Br_2$ |
| Anode: | $Zn^{2+} + 2e^- \rightarrow Zn$ |
| Cathode: | $2Br^- \rightarrow Br_2 + 2e-$ |
| Bromine Complex: | $QBr^- + nBr_2 \rightarrow Q(Br_2)_nBr^-$<br>$QBr^-$ = Complexing Agent |

$QBr^-$ = Complexing Agent

The zinc/bromine battery stack contains nearly 100% plastic materials, except for a thin metal screen on the back side of the terminal electrodes, which is necessary to direct the electrical current in the x-y direction of the battery stack. The plastic electrodes contain carbon for electrical conductivity and glass fibers to improve dimensional stability. The separators are composed of microporous silica-filled polyethylene and allow ions to transfer from one side of the cell to the other. Each electrode and separator are welded into an injection-molded, glass-filled polyethylene frame that contains channels and diverters to distribute the flowing electrolyte uniformly across the face of the electrodes.

Alternating electrode and separator flow frames are then welded together between glass-filled polyethylene end blocks to form a sealed battery stack. A patented end block design was developed to maintain dimensional stability of the battery stack under pressure. The electrolyte normally flows through the battery stack under a pressure of 6-8 psi, but tests have demonstrated that the burst strength of the stack is about three times the operating pressure.

## Technology Development – ZBB

The objective of the zinc/bromine technology development project is to develop and evaluate low-cost, long-life prototype modules that demonstrate the performance required for utility applications. This project is being conducted primarily through a cost-sharing contract with an industrial partner. At the end of FY94, JCBGI sold the zinc bromine technology to ZBB. A new contract was placed to continue the work because ZBB hired the key JCBGI employees working on the project.

The objectives of the Zinc/Bromine Battery Development Project are to design, fabricate, and evaluate a zinc/bromine battery system suitable for electric utilities. During Phase 1 of the contract, the soundness of the battery technology was demonstrated by satisfying a number of predefined criteria including the following:

1. Demonstrating leak-free battery stacks.

2. Demonstrating steady long-term operation by achieving over 100 cycles with less than a 10% drop in energy efficiency.

3. Achieving energy efficiencies of approximately 75%.

4. Demonstrating six consecutive, no-strip cycles.

5. Verifying battery cost of $150/kWh or less.

6. Addressing safety issues associated with the battery.

In Phase 2, new larger cell stacks, designed for an electric utility battery, were developed while core technology research continued. The end product of Phase 2 of the zinc/bromine development contract is the demonstration of a 100-kWh system at the PG&E MGTF in San Ramon, California. If this demonstration turns out favorably, and if utility interest is great enough, larger systems may be tested in the future.

Major progress during the course of the contract included minimizing leaks and improving battery performance by refining battery components and manufacturing techniques.

## Tasks/Milestones

The major goals of the ZBB contract are as follows:

1. Deliver a factory-accepted module to PG&E for test.

2. Complete a mutually agreed upon test plan at PG&E.

Milestones:

- Deliver 100-kWh system to PG&E (7/95) – rescheduled to 12/95.
- Complete testing of 100-kWh system at PG&E (11/95) – rescheduled to 4/96.
- Complete contract development report (12/95) – rescheduled to 5/96.

## Status

### Battery Testing

#### *Eight-Cell V-Design Battery Stacks*

The V-design battery stacks (1170 cm$^2$) were originally developed to demonstrate the feasibility of the vibration welding process for sealing battery stacks. These stacks are presently being used for cycle-life testing.

The standard cycle used for gathering baseline data consists of a 4.5-hr charge at 20 mA/cm$^2$ followed by a discharge at the same current to a cutoff voltage of 1.0 vpc. The battery is then fully stripped to zero charge. The amp-hour information collected during the strip can be used to differentiate between transport losses (bromine diffusion through the separator and shunt currents) and residual losses (nonuniform zinc plating and poor electrolyte flow distribution).

The performance and cycle life of 1170-cm$^2$, vibration-welded batteries have improved significantly since the beginning of the contract, as seen in Table 4-1. The end of life is considered to be a decline of 10% from the peak energy efficiency for the battery stack.

Batteries V1-53 through V1-57 were manufactured early in Phase 1 of the contract and averaged 71.8% EE over an average of 290 baseline cycles.

A lower-resistance carbon plastic electrode material was developed and tested in batteries V1-72 through V1-77. Battery V1-76 achieved slightly higher energy efficiency than the others as a result of the use of low-resistance terminal electrodes. This series of batteries achieved an average cycle life of 447 cycles and an average energy efficiency of 74.6%.

Battery V1-79 was manufactured using optimized cathode-layer pressing processes. This battery completed 1036 baseline cycles before the energy efficiency declined by 10% from the peak value of 76.0%. Testing of this battery stack will continue until the performance declines by 20% from the peak to provide an understanding of how system degradation proceeds.

Battery V1-80 was manufactured using low-resistance terminal electrodes and a cathode activation layer with a very high surface area. The terminal electrodes were about 50% lower in resistance than previously prepared electrodes, and the cathode layer had about 3 times the surface area of the electrodes used in Battery V1-79. The improvements incorporated into battery V1-80 have demonstrated higher energy efficiencies and should extend the life expectancy of the battery.

Batteries V1-84 through V1-86 were manufactured using experimental battery separators that demonstrated about 25% lower resistance and 30% lower bromine transport than the standard zinc/bromine battery separator in beaker-scale tests.

Test results for individual 1170-cm$^2$, V-design battery stacks tested during the last year are given in the following sections.

## Table 4-1. V-Design Battery Stack Performance

| Battery Number | Manufacture Date | Cycle Life | Average Energy Efficiency (%) | Peak Energy Efficiency (%) |
|---|---|---|---|---|
| V1-53 | 3/91 | 325 | 72.6 | 74.6 |
| V1-54 | 4/91 | 218 | 71.0 | 74.4 |
| V1-55 | 4/91 | 366 | 71.7 | 74.2 |
| V1-57 | 4/91 | 250 | 71.4 | 75.9 |
| Avg. | | 290 | 71.8 | |
| V1-72 | 10/92 | 504 | 73.3 | 75.3 |
| V1-76 | 1/93 | 325 | 76.4 | 77.9 |
| V1-77 | 3/93 | 513 | 74.7 | 76.7 |
| Avg. | | 447 | 74.6 | |
| V1-79* | 6/93 | 1368 (1036) | 71.7 (73.5) | 76.0 |
| V1-80* | 2/94 | 938 | 76.8 | 79.0 |
| V1-84 | 5/95 | 25 | 71.9** 74.4*** | 77.7 |
| V1-85 | 5/95 | 20 | 46.4** 72.5*** | 75.1 |
| V1-86* | 6/95 | 34 | 78.3 | 80.2 |

* Denotes Test in Progress
** Includes all cycles.
*** Does not include cycles with insufficient second phase.

<u>V1-79 (1-kWh)</u>

Battery V1-79 was the first V-design battery stack to complete 1000 baseline cycles with no leaks and less than 10% degradation in performance. The battery completed 1036 cycles before the energy efficiency declined to 90% of the peak value of 76.0%. Baseline cycling will continue on this battery stack until the performance declines by 20% from the peak. Figure 4-1 shows that the battery stack is presently achieving 64.5% energy efficiency after 1368 baseline cycles.

<u>V1-80 (1-kWh)</u>

Battery V1-80 has completed 938 baseline cycles, with the most recent cycle providing 87.0% coulombic efficiency (CE), 82.1% voltaic efficiency (VE), and 71.4% energy efficiency (EE) (see Figure 4-2). The battery stack was prepared using improved manufacturing techniques to obtain low-resistance terminal electrodes and a cathode activation layer with a high electrochemical surface area. The performance of this stack over the first 80 cycles was inconsistent because of an insufficient amount of bromine in the electrolyte. Because of the large surface area of the cathode layer, additional bromine had to be supplied to keep the concentration in the electrolyte sufficient to maintain consistent cycling operation. The performance of this stack has declined by 9% from the peak energy efficiency of 79.0%.

<u>V1-83 (1-kWh)</u>

Battery V1-83 was manufactured to evaluate an experimental battery separator material. The separator material used in this battery stack was higher in resis-

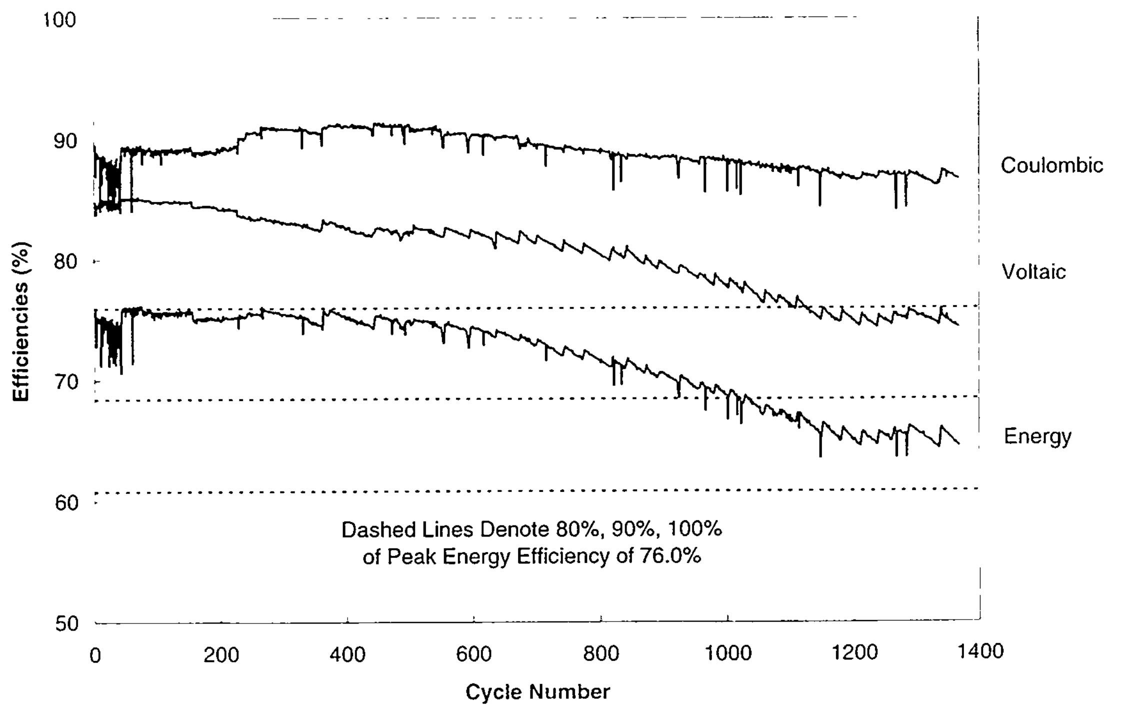



**Figure 4-1.** **V1-79 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack).**

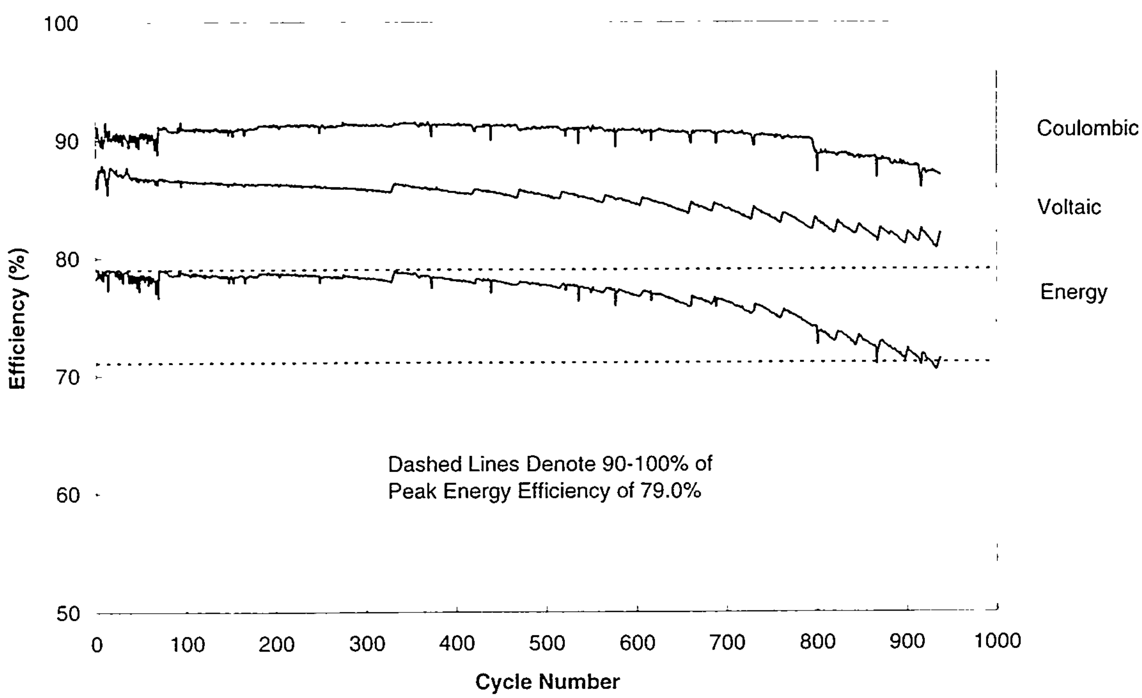



**Figure 4-2.** **V1-80 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack).**

tance and bromine transport than the standard material. The energy efficiency was about 5% lower than for battery V1-80, which corresponds closely to predictions made using a computer simulation that was based on the properties of the separator. The battery completed 77 baseline cycles, with the most recent cycle giving 84.7% coulombic efficiency, 83.0% voltaic efficiency, and 70.3% energy efficiency. Figure 4-3 shows the baseline cycle performance for battery V1-83. This battery was taken off test to make room for other batteries to be tested.

V1-84 (1-kWh, Experimental Separator)

Battery V1-84 was manufactured with an experimental separator that had previously demonstrated good properties in beaker-scale separator testing. The battery completed 25 cycles with somewhat inconsistent results, as seen in Figure 4-4. The battery did achieve 77.7% energy efficiency, but the bromine transport appears to be very sensitive to the rate of complexed phase circulated during discharge. Efficiencies varied from 77.7% to 71.6% depending on the amount of complexed phase circulated. Previous batteries manufactured with the standard separator were not as sensitive to this flow rate. It is probable that the variations are caused by a higher than normal rate of crossflow from one side of the cell to the other. The separators used in this stack were warped and difficult to weld into the flow frames because they were hand- rather than machine-made.

The battery demonstrated very low coulombic efficiency on Cycle 17, but this was caused by an insufficient amount of complexed phase being circulated during discharge. The valve was set at the same position as during the previous seven cycles, but the complexed phase cut off during Cycle 17. The most recent cycle achieved 82.3% coulombic efficiency, 86.6% voltaic efficiency, and 71.3% energy efficiency. The voltaic efficiency for this battery stack is very good, but the coulombic efficiency has been inconsistent. This battery stack was taken off test to make room for more recent battery builds.

V1-85 (1-kWh, Experimental Separator)

Battery V1-85 was manufactured with another experimental separator that also demonstrated good properties in beaker-scale separator testing. This separator material had a different internal structure than the material used in Battery V1-84, and the oil extraction process step was performed using production-scale equipment. This produced samples that were flat and easy to weld into frames.

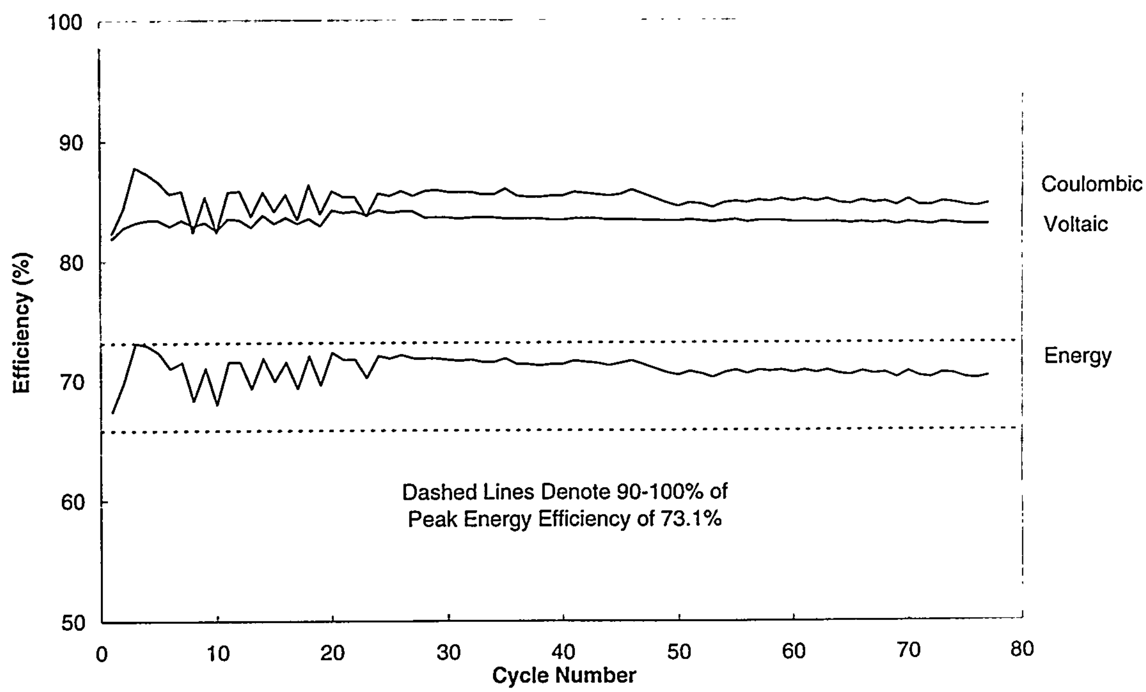



**Figure 4-3.** **V1-83 Baseline Cycle Efficiencies (1-kWh, 8-cell with experimental separator).**

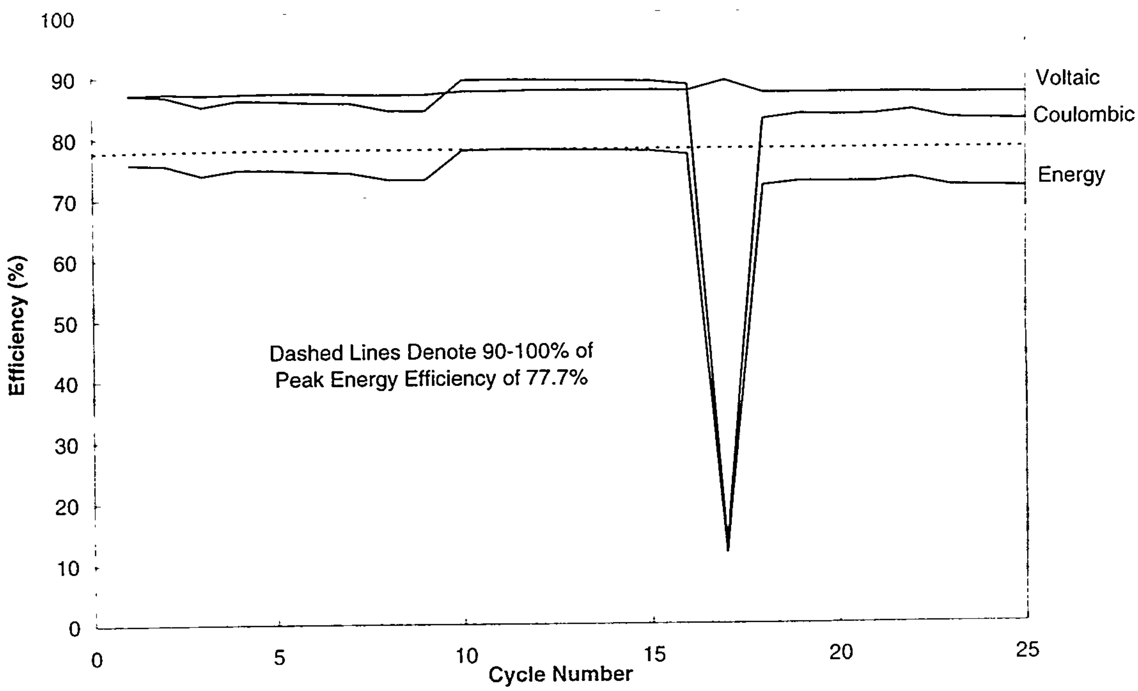



**Figure 4-4. V1-84 Baseline Cycle Efficiencies (1-kWh, 8-cell with experimental separator).**

This battery has completed 20 cycles with inconsistent results, as seen in Figure 4-5. The most recent cycle gave 86.0% CE, 86.3% VE, and 74.2% EE. The inconsistent performance for this stack is caused by the lack of flow of complexed phase during discharge. The complexed-phase valve has become plugged on a number of cycles, causing incomplete discharge of the battery. It is probable that the solenoid valve, which was used for testing other battery stacks, is corroded and not capable of opening all the way.

V1-86 (1-kWh, Experimental Separator)

Battery V1-86 was manufactured using an experimental battery separator. This was the same separator as that used in battery V1-85, but a posttreatment was used on the separator following the manufacturing process. The battery has completed 34 cycles, with the most recent cycle achieving 89.5% coulombic efficiency, 87.5% voltaic efficiency, and 78.3% energy efficiency, with 6.3% transport and 4.2% residual inefficiencies, as seen in Figure 4-6. This battery achieved a peak energy efficiency of 80.2% on baseline cycling and an energy efficiency of 81.2% on cycles without stripping. This is the highest efficiency obtained for a battery stack with this design.

### *8-Cell, 2500-cm$^2$ Battery Stacks*

The active area of the battery stack was increased from 1170 cm$^2$ to 2500 cm$^2$ to reduce the part count and to lower the cost of a utility battery system. The channels and diverters of the 2500-cm$^2$ flow frame were designed to minimize shunt currents and to improve the flow of electrolyte across the face of the electrodes. The new design uses a glass-filled plastic end block to maintain dimensional stability, which eliminates the need for metal inserts and improves the recyclability of the battery stack.

Several problems were discovered after the postmortem analysis of the first 2500-cm$^2$ battery stacks. Complexed-phase bromine was not being evenly distributed over the face of the electrodes. The complexed phase had a tendency to transfer into the anolyte side of the cell, and some external leakage was observed. Part of the problem was that some of the diverters and flow channels were not forming a complete weld with the adjacent frame. Additional seals were added to the diverters and vanes and the heights of existing seals were increased to improve the distribution of second phase. The leakage problem has been minimized by reducing sink marks during the injection molding pro-

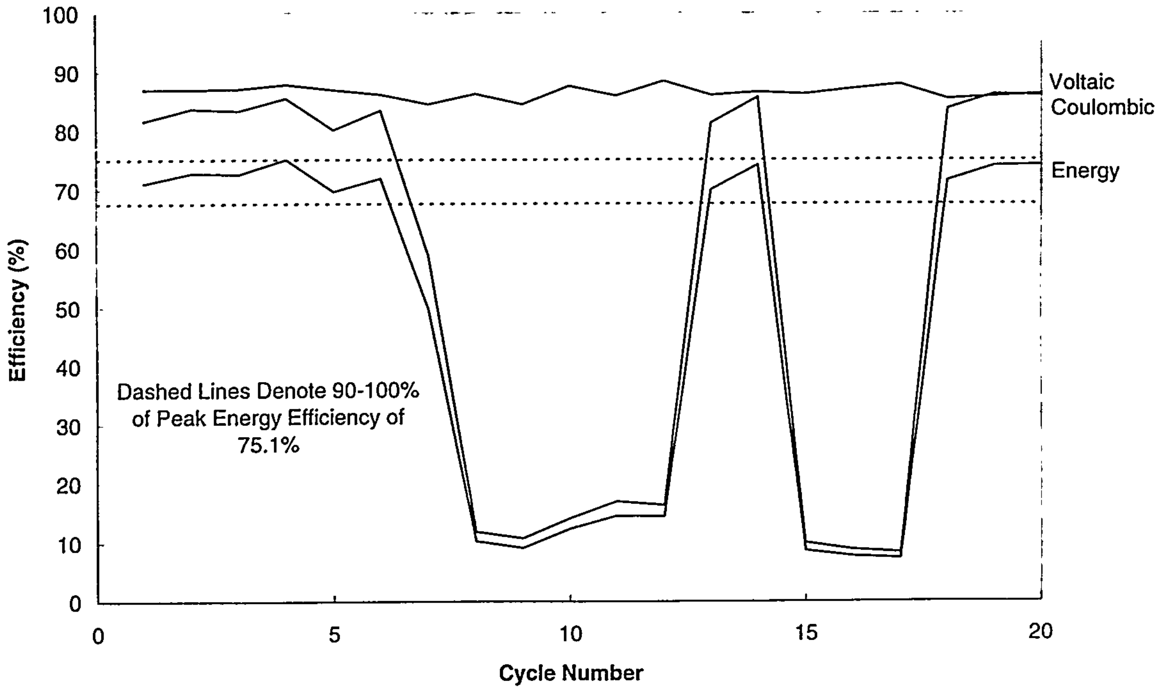



**Figure 4-5.** **V1-85 Baseline Cycle Efficiencies (1-kWh, 8-cell with experimental separator).**

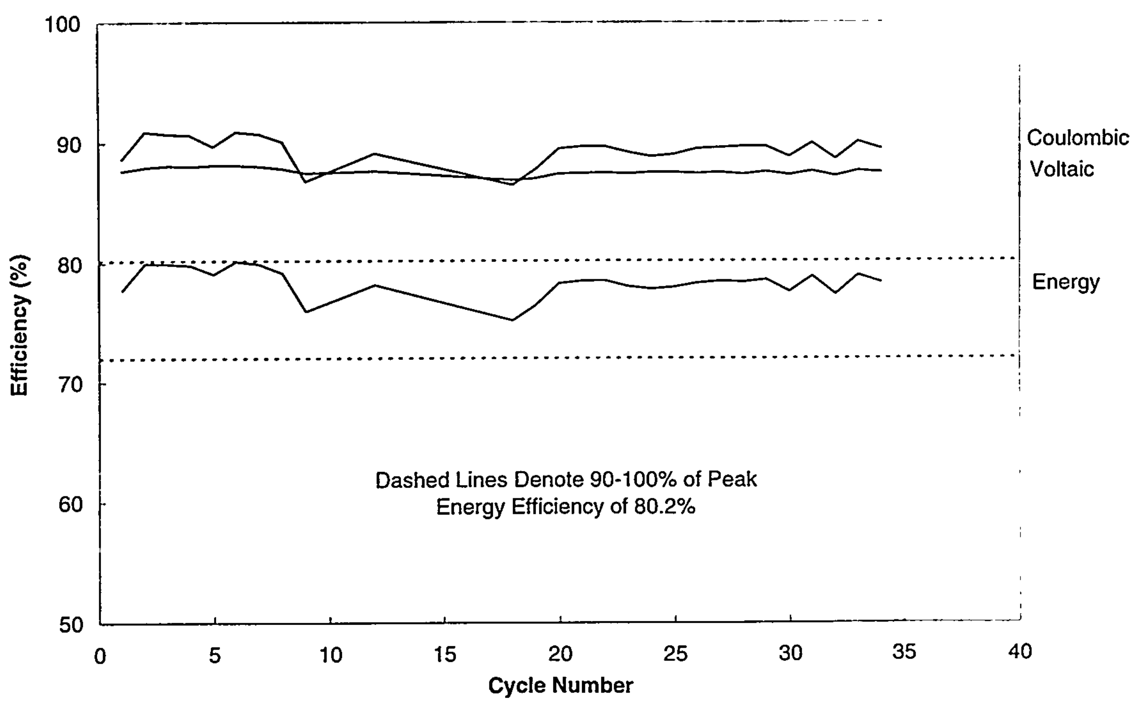



**Figure 4-6.** **V1-86 Baseline Cycle Efficiencies (1-kWh, 8-cell with experimental separator).**

cess. The quality of the welds in areas where weld beads cross a flow channel on the adjacent frame was improved by adding additional weld beads in this area.

Scaling up from 8-cell stacks to 60-cell stacks uncovered a problem with slippage of the end block in the vibration welding machine. The end-block tooling for the welder was modified to minimize the slippage. Also, minor problems with the vibration welder surfaced during development, but modifications have been made to eliminate the errors and to improve the consistency of the process.

The 2500-$cm^2$ battery stacks are being developed as the building block for large utility battery systems. Battery stacks with eight cells are manufactured to demonstrate the performance and weld integrity of the larger flow-frame design. Test results for these battery stacks are given in the following sections and summarized in Tables 4-2 and 4-3.

*V25-27-08 (2-kWh)*

Battery V25-27-08 was cycled 10 times before a small leak was observed on the top of the stack. The stack was performing consistently at about 76.6% energy efficiency. The battery was found to have an incomplete weld that was probably due to the taper of the end blocks or the welding parameters. Following this battery build, more uniform end blocks were obtained and burst tests were performed to examine welding parameters.

V25-30-08 (2-kWh)

Battery V25-30-08 was manufactured using a new vibration welding technique. The battery performed consistently for 12 cycles before the second-phase valve remained closed during a set of four consecutive baseline cycles. The performance declined dramatically because only the aqueous portion of the catholyte was circulated during discharge. The second-phase valve was opened and the battery was completely stripped before resuming baseline cycling. The performance on Cycle 16 then returned to the original efficiencies (see Figure 4-7), indicating that the battery was not permanently damaged by cycling with the second-phase valve closed. This battery was taken off test and burst tested to inspect the integrity of the vibration welds. Burst tests were performed on both V25-30-08 and V25-32-08

**Table 4-2. 2500-Series Battery Performance (8-Cell Stacks)**

| Battery Number | Number of Cycles | Peak Energy Efficiency (%) | Avery Energy Efficiency (%) |
|---|---|---|---|
| V25-01 | 10 | 64.9 | 40.8 |
| V25-02 | 9 | 76.1 | 71.2 |
| V25-04 | 20 | 74.8 | 74.1 |
| V25-05 | 12 | 75.8 | 70.7 |
| V25-06 | 30 | 77.1 | 73.9 |
| V25-07 | 14 | 77.4 | 74.7 |
| V25-10 | 24 | 77.3 | 76.2 |
| V25-12 | 7 | 70.7 | 57.3 |
| V25-13 | 23 | 78.3 | 76.6 |
| V25-27 | 10 | 76.7 | 75.6 |
| V25-30 | 17 | 76.8 | 75.5 |
| V25-32 | 28 | 70.0 | 67.9 |
| V25-33 | 127 | 71.1 | 70.2 |

## Table 4-3. 2500-Series Battery Performance (60-Cell Stacks)

| Battery Number | Number of Cycles | Peak Energy Efficiency (%) | Avery Energy Efficiency (%) |
|---|---|---|---|
| V25-09 | 4 | 73.0 | 70.0 |
| V25-11 | 10 | 77.0 | 76.2 |
| V25-14 | 7 | 72.0 | 71.3 |
| V25-15 | 12 | 78.1 | 73.8 |
| V25-16 | 5 | 76.8 | 75.7 |
| V25-19 | 6 | 75.2 | 73.0 |
| V25-20 | 4 | 76.4 | 75.3 |
| V25-21 | 7 | 74.1 | 73.2 |
| V25-22 | 6 | 75.4 | 75.0 |
| V25-23 | 11 | 75.4 | 73.1 |
| V25-24 | 9 | 73.0 | 71.6 |
| V25-25 | 5 | 75.5 | 74.0 |

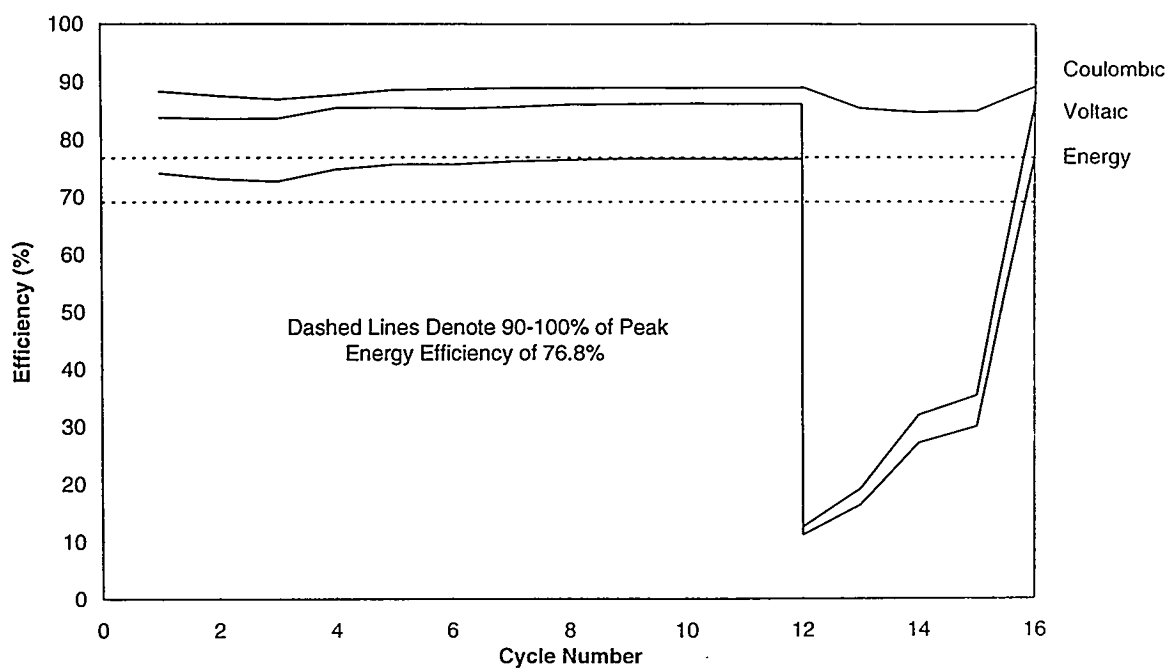



Figure 4-7. V25-30 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack).

to compare the strength of the welds. The results of these tests are given in a later section.

V25-32-08 (2-kWh)

Battery V25-32-08 was manufactured to examine different vibration welding parameters than those used for battery V25-30-08. It completed 20 baseline cycles, with the most recent baseline cycle achieving 79.7% coulombic efficiency, 87.9% voltaic efficiency, and 70.0% energy efficiency, as seen in Figure 4-8. This battery was manufactured with the same separator material used in Battery V1-83 (a separator material that gives lower efficiencies than the standard material). The primary objective of this testing was to examine the integrity of the vibration welds using the new manufacturing technique.

V25-33-08 (2-kWh)

Battery V25-33-08 was manufactured to investigate an alternative adhesive for the cathode activation layer. The battery stack contained the same experimental battery separator used in battery V25-32-08. This battery has performed very consistently over the first 127 baseline cycles, as seen in Figure 4-9, with the last cycle giving 81.8% coulombic efficiency, 86.0% voltaic efficiency, and 70.3% energy efficiency. The performance did decline slightly at Cycle 17 because of a faulty solenoid valve that caused the heat exchanger to remain on during the entire cycle. This valve was fixed, and cycling of the battery was resumed. This battery is being used for no-strip cycling and to examine the cycle life of the alternative adhesive.

### *60-Cell, 2500-cm$^2$ Battery Stacks*

Eight 60-cell battery stacks have demonstrated acceptable performance on baseline cycles and will be used for the 100-kWh deliverable battery system. Six stacks are needed for the battery system, and two additional stacks will be used as spares. All of the stacks achieved at least 75% energy efficiency on baseline cycling.

## Other Battery Testing Results

### *Battery Polarization and iR Losses*

Polarization and iR losses for several 8-cell, 1170-cm$^2$ battery stacks are compared in Figures 4-10 and 4-11, respectively. Figure 4-10 shows that the polarization for early batteries (V1-54 and V1-76) began to increase rapidly at about 250 cycles, but did not increase as rapidly for the most recent battery builds. Battery V1-80 gave the lowest polarization over the first

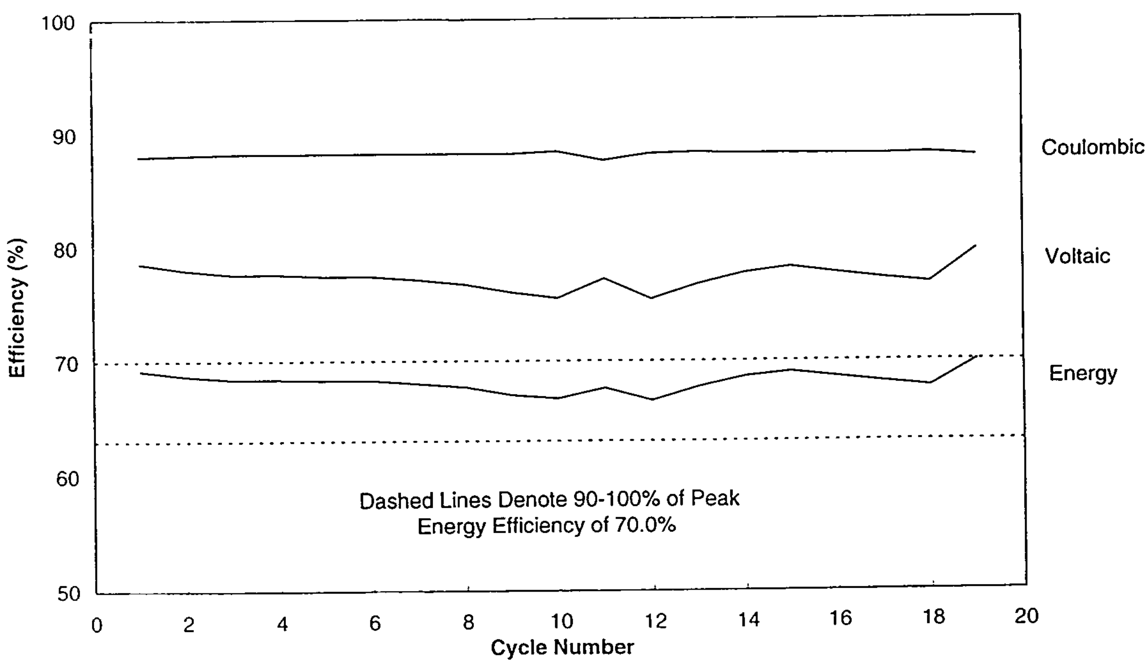



**Figure 4-8. V25-32 Baseline Cycle Efficiencies (2-kWh, 8-cell with experimental separator).**

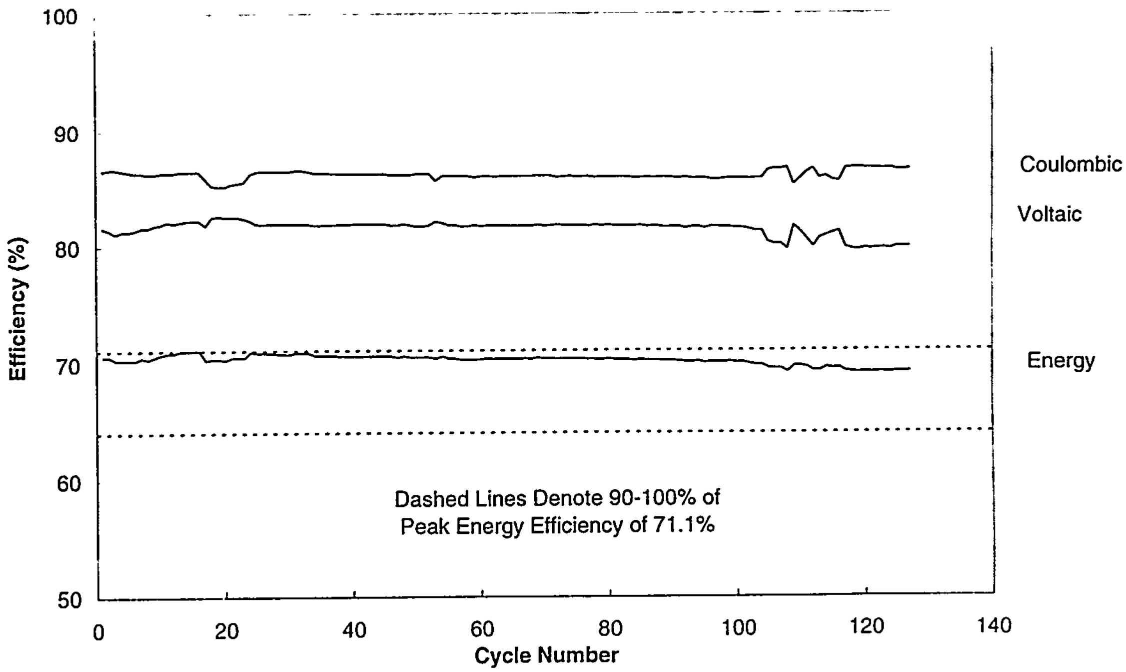



**Figure 4-9.** **V25-33 Baseline Cycle Efficiencies (2-kWh, 8-cell with experimental separator).**

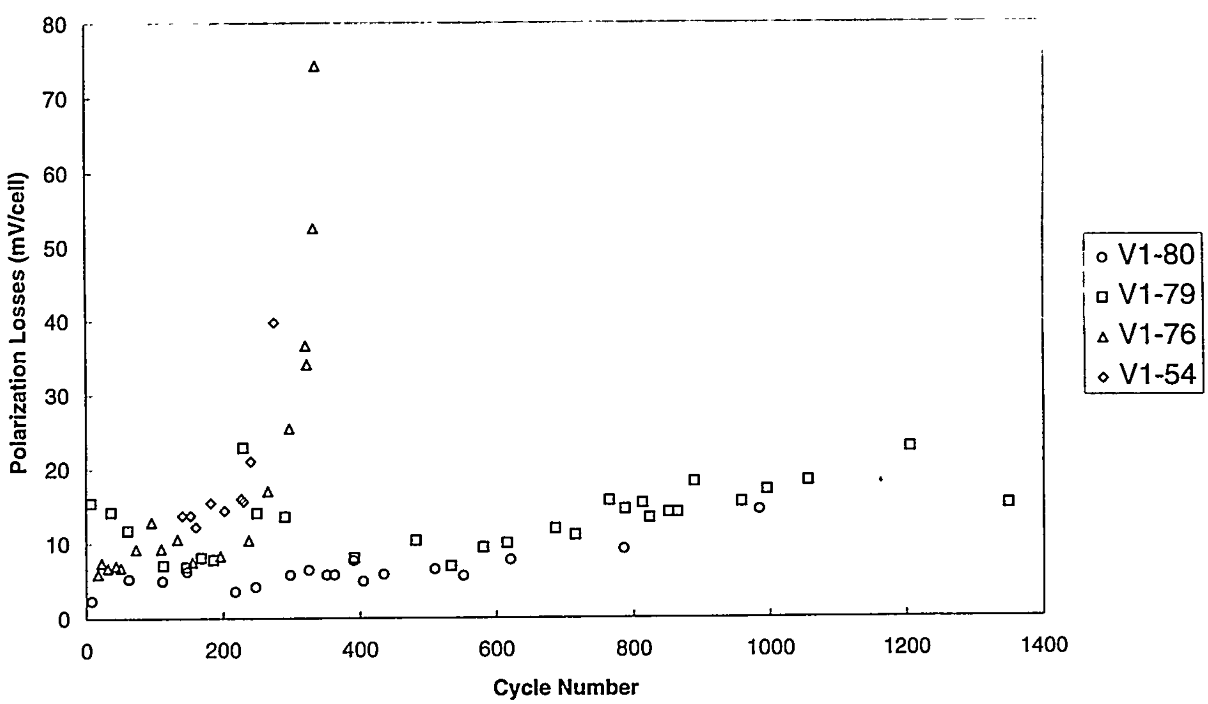



**Figure 4-10.** **Battery Polarization Losses vs. Cycle Life.**

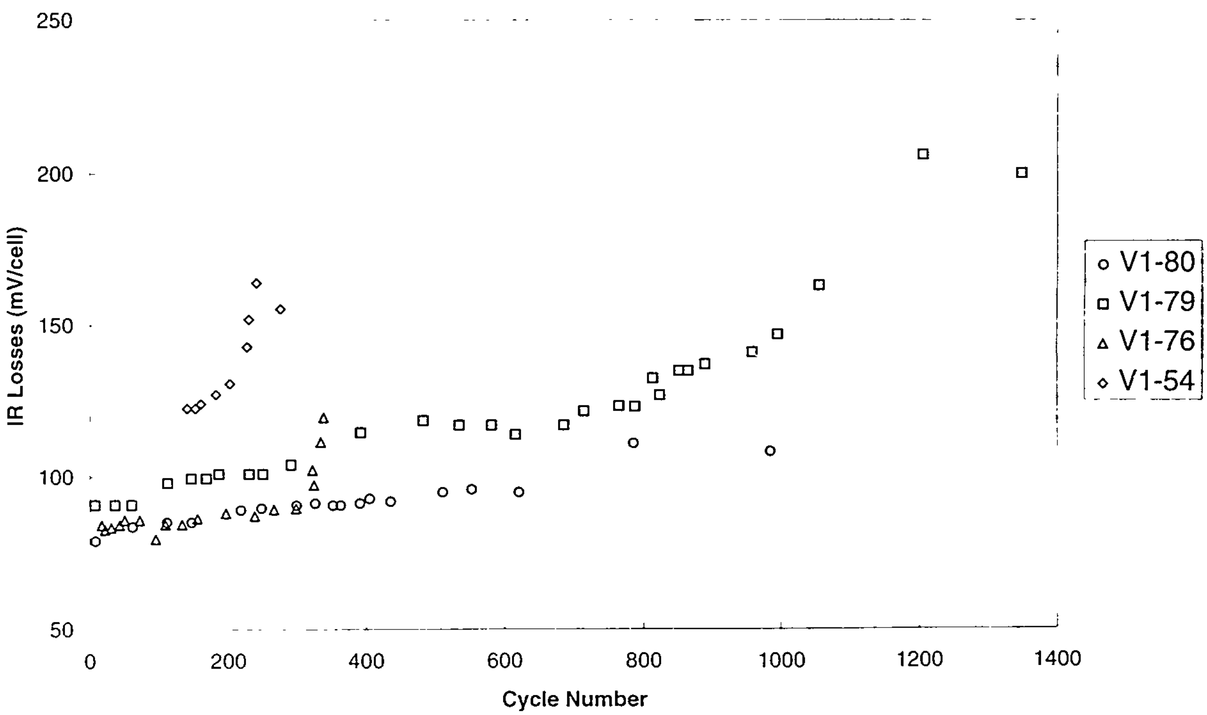



**Figure 4-11. Battery iR Losses vs. Cycle Life.**

900 cycles because it was built with a newly developed large-surface-area cathode activation layer.

Figure 4-11 shows that batteries built recently are much lower in resistance than earlier battery stacks (e.g., V1-54). The decrease in resistance results from using a newly developed low-resistance carbon plastic electrode material. Batteries V1-76 and V1-80 gave very low iR losses because they were built using recently developed low-resistance terminal electrodes. The modifications incorporated into battery V1-80, including low-resistance carbon plastic, a cathode activation layer with a high surface area, and improved terminal-electrode manufacturing techniques, have resulted in improved battery performance over the first 900 baseline cycles.

### *No-Strip Cycling*

After the zinc/bromine battery is discharged to 1.0 vpc, it is usually completely stripped of any residual zinc by connecting the battery across a resistor. This stripping ensures that there is a smooth electrode surface for the deposition of zinc at the beginning of each cycle. It also simplifies data collection for the battery by allowing differentiation between transport and residual inefficiencies.

Although it is recommended, the battery does not need to be stripped after every cycle. The time needed to completely strip the battery may not be available in all cases, and the capacity remaining in the battery before stripping can be used during the following cycle.

Results of no-strip cycling performed on three 2500-cm$^2$ battery stacks are given in Table 4-4. The second cycle of the no-strip set showed an increase in coulombic efficiency for each battery stack, but the efficiencies dropped off rapidly on each successive cycle. The coulombic efficiency for the first cycle without strip is initially higher because a portion of the zinc normally lost to stripping is retained in the battery.

The efficiencies for a good-performing battery stack should level off following the second cycle of a no-strip sequence. The progressive decrease in efficiency results from an accumulation of zinc on the anodes, most likely in zones of lower activity. From observations made in earlier teardowns, these zones are located in the corners, away from the flow entry points, and along the center rib. Warps in the electrode material can also create low-activity zones where the electrolyte gap is very thin.

The coulombic efficiency for battery V25-30-08 declined much more rapidly than that for the other two

## Table 4-4. Performance of Battery V25-07-08 during Consecutive Cycles without Stripping

| Battery Number | Cycle Number | Coulombic Efficiency (%) | Voltaic Efficiency (%) | Energy Efficiency (%) |
|---|---|---|---|---|
| V25-07-08 | 6 | 85.4 | 84.5 | 72.1 |
| | 7 | 88.0 | 84.3 | 74.2 |
| | 8 | 83.2 | 84.8 | 70.6 |
| | 9 | 81.6 | 85.3 | 69.6 |
| V25-32-08 | 21 | 75.5 | 88.3 | 66.7 |
| | 22 | 83.2 | 88.3 | 73.5 |
| | 23 | 82.1 | 88.1 | 72.4 |
| | 24 | 82.4 | 87.6 | 72.1 |
| V25-33-08 | 34 | 81.8 | 86.4 | 70.7 |
| | 35 | 83.7 | 86.8 | 72.6 |
| | 36 | 83.2 | 86.9 | 72.3 |
| | 37 | 82.7 | 87.0 | 71.9 |
| | 38 | 82.3 | 87.0 | 71.6 |
| | 39 | 82.1 | 87.0 | 71.4 |

battery stacks. Similar results were observed for early V-design, 1170-$cm^2$ battery stacks, apparently as a result of poor electrolyte flow distribution. This battery stack did have a center-weld failure in one of the cells that could have caused nonuniform flow of electrolyte over the face of the electrode.

### Materials Development

#### *Cathode Activation Layer*

The cathode activation layer is a carbon coating that is applied to the bromine side of the carbon plastic electrode and is then hot pressed into the plastic. This high-surface-area coating is necessary to compensate for the relatively low exchange current density for the bromine/bromide reaction on carbon. The life-limiting mechanism for earlier battery stacks was associated with the deterioration of the cathode activation layer, causing a rapid increase in polarization near the end of battery life. Cathode layers with a higher surface area have demonstrated low electrode polarization and increased life expectancy. A great deal of work has been done in the past to increase the electrochemical surface area of the bromine electrode.

#### *Electromechanical Surface Area of Cathode Layer*

The electroactive surface areas of bromine test electrodes are measured using a cyclic voltammetric method. The technique measures double-layer capacitance, which is directly proportional to the electroactive surface area of the electrodes. Using this technique, a cathode layer with a high surface area has been developed and is presently being tested in battery V1-80. These bromine electrodes had surface areas of 10,000 to 15,000 $cm^2/cm^2$, compared to 2000 to 3500 $cm^2/cm^2$ for previous battery builds. These new cathode layers have shown low polarization of 30 to 40 mV at 250-$mA/cm^2$ discharge rates and are expected to improve the life expectancy of the battery. The high-surface-area cathode layer has demonstrated very good performance over the first 900 cycles for battery V1-80.

#### *Cathode Layer Adhesive*

A conductive adhesive is used to bond the cathode activation layer to the carbon plastic electrode substrate in the zinc/bromine battery. Polarization and surface area results for several adhesives are compared to the standard product in Table 4-5. The results indicate that each of the alternative materials could be a potential replacement for the standard adhesive. Each of these materials was also found to have good resistance to bromine.

## Table 4-5. Cathode Layer Properties for Various Types of Adhesives

| Adhesive Type | Polarization at 250 mA/cm$^2$ (mV) | Electrochemical Surface Area (cm$^2$/cm$^2$) |
|---|---|---|
| Standard | 35 | 12,453 |
| Sample A | 42 | 12,876 |
| Sample B | 44 | 14,375 |

Sample A is a commercial adhesive and was used to fabricate the electrodes used in Battery V25-33-08. The battery has performed consistently over the first 127 baseline cycles with a very low overvoltage of 0.5 mVpc at a discharge rate of 14 mA/cm$^2$. Sample B was not used in a battery since it was not a commercial product.

### *Separator Development*

The separator in the zinc/bromine battery provides a barrier between the two sides of the electrochemical cell. It needs to allow the exchange of ions from one side of the cell to the other with minimal transport of bromine. The important parameters for the separator are the resistivity and the rate of bromine diffusion. In the past, a trade-off between the two properties was observed, but a large amount of effort has been made to minimize both of the separator characteristics.

The resistivity is measured in standard electrolyte using a cell with known electrode dimensions. It is determined by the difference between measurements with and without the separator in place. The bromine diffusion is a measure of the amount of bromine to transport from one side of a diffusion cell to the other over time. One side of the cell contains a 100% SOC catholyte; the other side contains a 100% SOC anolyte that is completely free of bromine.

A large number of separator materials were manufactured and tested for resistivity and bromine transport. In Table 4-6, the properties of the two most promising experimental battery separators are compared to those of the standard zinc/bromine battery separator. Each of these samples was manufactured using production-scale equipment. It can be seen that both the resistivity and bromine diffusion of the experimental samples are better than those of the standard separator material. An 8-cell battery stack was manufactured from each production material to examine the electrochemical performance. Battery V1-84 was manufactured with separator 9502-10TA and batteries V1-85 and V1-86 were made with separator 95064-TA. Reasonably good performance was achieved for each of these battery stacks. Battery V1-86 achieved the highest efficiencies of any battery to date.

The transport of bromine through the separator in a zinc/bromine battery can be attributed to two possible mechanisms. The separator may be wetted by the bromine complex to allow elemental bromine to transfer from one side of the separator to the other. A second possibility is that the bromine in equilibrium with the aqueous phase diffuses through the separator. To estimate the contributions from the two forms of transport, two different diffusion tests were run. The first experiment was run with a combination of complexed bromine and aqueous-phase catholyte. The second used only aqueous-phase catholyte with no complexed bromine. In this second experiment, the aqueous-phase catholyte had previously been in equilibrium with the complexed bromine, after which they were allowed to separate. The results of these diffusion tests are given in Table 4-7.

It can be seen that both mechanisms contribute significantly to the bromine diffusion. The contribution from the aqueous phase is 45-70% of the total amount of bromine that diffuses through the separator. Also, the samples that gave the lowest bromine transport in the presence of complexed phase (9502-10TA and ISFS-TA) had a higher percentage of bromine transported from the aqueous phase.

## Battery Design and Manufacturing

### *Battery Stack Manufacturing*

The weld integrity of a number of battery stacks was investigated by subjecting the battery to internal air

## Table 4-6. Experimental Separator Results

| Separator Type | Thickness (mils) | Resistivity (Ω-cm) | Bromine Diffusion (mole-cm/sec/cm²) |
|---|---|---|---|
| Standard | 23.5 | 23-25 | $1.97 \times 10^{-10}$ |
| 9502-10TA | 27.0 | 17.6 | $1.30 \times 10^{-10}$ |
| 95064-TA | 23.0 | 17.5 | $1.39 \times 10^{-10}$ |

## Table 4-7. Bromine Diffusion for Experimental Separators Contribution from Complex and Aqueous Phases

| Separator Sample | Bromine Diffusion (Aqueous and Complex) (mole-cm/sec/cm²) | Bromine Diffusion (Aqueous Only) (mole-cm/sec/cm²) | Ratio Aqueous/Complex |
|---|---|---|---|
| Standard | $2.13 \times 10^{-10}$ | $1.13 \times 10^{-10}$ | 0.53 |
| 9502-102T | $4.96 \times 10^{-10}$ | $2.63 \times 10^{-10}$ | 0.56 |
| 9502-10TA | $1.40 \times 10^{-10}$ | $9.86 \times 10^{-11}$ | 0.70 |
| ISFS-T | $4.85 \times 10^{-10}$ | $2.20 \times 10^{-10}$ | 0.45 |
| ISFS-TA | $1.41 \times 10^{-10}$ | $8.56 \times 10^{-11}$ | 0.61 |

pressure increasing at 1-psi increments every minute until the stack burst. Initial testing was done on two 8-cell, 2500-cm$^2$ battery stacks. One stack was prepared with the standard flow frames, while the other stack was manufactured using flow frames that were highly packed during the injection molding process. Each of the stacks burst at about 17 psi, and in each case the failure was between the first flow frame and the end block. It was believed that this failure resulted from a slight taper in the end block.

Another set of burst tests was performed on stacks in which the frames adjacent to the end blocks were overwelded. Overwelding was done in an attempt to eliminate the problem caused by the tapering of the end block. These stacks failed at about 20-22 psi, and the failure was along the side edge of the stack as opposed to the top. This is the burst pressure that should be achieved if end block parts without any taper can be produced.

Following this set of tests, end blocks with much less taper were obtained from the vendor. Two 8-cell, 2500-cm$^2$ battery stacks (V25-30-08 and V25-32-08) were manufactured using different vibration welding techniques to compare the integrity of the welds. The stacks were cycled about 20 times and then rinsed. Battery V25-30-08 failed at 18 psi, while V25-32-08 failed at 23 psi. Both stacks failed at the weld between an end block and the adjoining flow frame. An additional stack, manufactured using the same method as V25-32-08, also failed at a pressure of about 24 psi. These results were slightly better than the results obtained when the frame was overwelded to the end block. Under normal operating conditions, the battery stack is subjected to a pressure of 7-8 psi, so a safety factor of 3 times the operating pressure is built into the battery stacks.

### *100-kWh Deliverable Battery Design*

The original 100-kWh deliverable battery proposal called for six battery stacks, two electrolyte reservoirs, and a support structure. The SOW for the contract was changed to require delivery of a self-contained, stand-alone peak-shaving system to be connected to the utility grid at PG&E. A three-module configuration was selected so that the battery modules could be electrically connected both in series and in parallel. Details of the 100-kWh battery design and progress in the manufacture of the system will be discussed in the following sections.

The demonstration unit consists of a 100-kWh stand-alone system housed in a portable chemical storage vault. It contains three battery modules, each rated at 33 kWh for a 2-hr discharge. Each module consists of two 60-cell, 2500-$cm^2$ battery stacks connected in parallel, a pair of reservoirs, and an electrolyte circulation system. Each module is capable of sustaining a 200-A discharge at an average 91 V for 2 hr.

The battery system is designed to comply with Zone 4 earthquake requirements. This is accomplished by using an epoxy-coated steel frame to support the module, with the reservoirs inserted into the structure of the frame and the two battery stacks located between the reservoirs. The stacks are attached to the frame by plastic-coated steel cords to restrain the stacks in the x, y, and z directions in the case of an earthquake (See Figure 4-12).

Each reservoir accommodates a recessed sump area in the cover where the pumps are located. The anolyte reservoir uses one pump, while two pumps are used to circulate both the catholyte-aqueous and complexed-bromine phases. Brushless DC motors run centrifugal pumps that are mounted vertically inside the recessed area of the reservoir covers. The inlets to the pumps are located below the liquid level in the reservoirs, which eliminates the need to prime the pumps. The majority of the plumbing is composed of fused polyvinylidene fluoride (PVDF) and is located inside the reservoir to minimize leakage from the system. Minor leaks from this plumbing would be contained inside the reservoirs.

The plumbing from the reservoirs to the stacks is made of reinforced viton, which was chosen because of its flexibility. The entire module is located inside of a larger spill tray that can contain any minor leaks from the system.

Liquid-level sensors are located at the top of each reservoir. The analog sensors are accurate to 0.25 in. and supply data to the battery controller. The data is used to maintain constant electrolyte levels in each reservoir by adjusting pump speeds. Leak-sensing wires

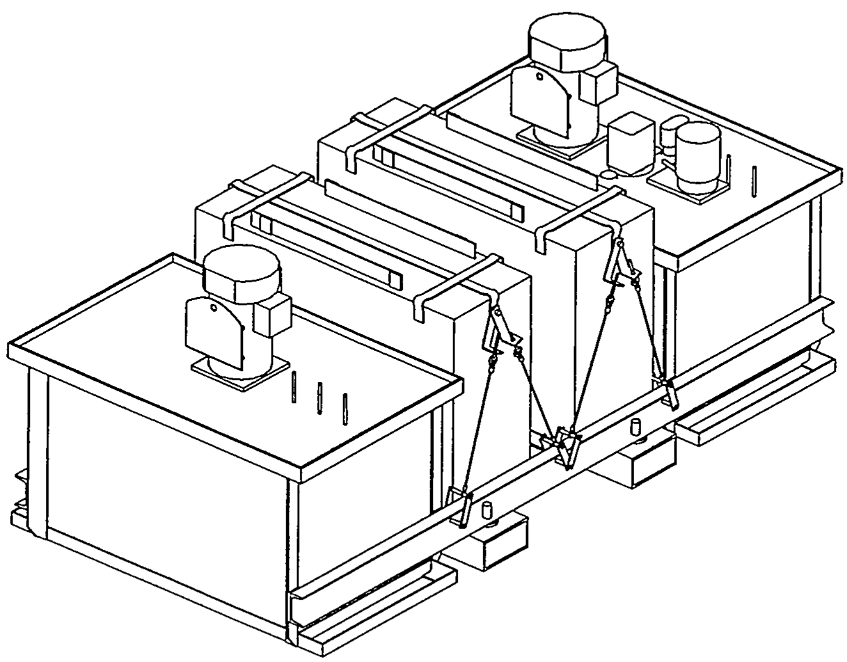


**Figure 4-12. Depiction of an 11-kWh Battery Module.**

are located in the module spill tray and in each reservoir sump area. They will indicate minor leaks of electrolyte into either location.

A module weighs more than 700 lb when dry, and over 1800 lb when filled with electrolyte. The modules have been designed to be movable using a forklift. A finite element analysis was run on the structure to ensure adequate strength, and the final design was reviewed by an outside consultant for verification.

The three modules will be housed in a 9'1" × 8'6" × 8'3" Haz-mat building. The building is divided into four quadrants; three quadrants contain battery modules and the remaining isolated quadrant houses the heat exchangers, a bromine scrubber, and electrical panels. The building contains a spill containment sump in addition to those for the individual modules. Additional safety devices include bromine and hydrogen sensors and an accelerometer for earthquake detection. Seismic Zone 4 requirements apply to the station as well as to the Haz-mat building.

The 100-kWh system is designed so that batteries can be electrically connected either in parallel or in series. The system is designed to sustain a 200-A discharge at an average 273 V for 2 hr. Each module has an open-circuit voltage of 109 V. The battery system operating characteristics are given in Table 4-8.

An extensive data collection system has been developed to verify the need for battery subsystems. Parasitic losses from the pumps, heat exchanger, and control systems can be quantified; and a paging system, which will be automatically activated in the case of a potentially hazardous condition, has been installed. An internal load-management system has been integrated into the system by running all of the auxiliary equipment, such as the heater, scrubber, etc. off of a single 30-A circuit. Therefore, if the scrubber needs to be activated, the heater will automatically be disconnected from the circuit to avoid exceeding the 30-A rating.

### *Battery Controller and Software*

Each battery module is monitored and operated by a programmable logic controller (PLC). Each PLC has 2K bytes of user memory and is capable of data acquisition through a full-duplex, RS232C serial port. They monitor module voltage, stack current, motor currents, and electrolyte levels in the reservoirs.

A microprocessor controller coordinates the overall operation and safety of the system. The controller monitors system voltage and currents, electrolyte temperatures, bromine and hydrogen concentrations inside the building, building temperature, ambient temperature, and peripheral current.

The battery controller also monitors for a number of conditions potentially hazardous to the system and its surroundings. When one of these conditions arises, the controller will completely shut down the system. Some of these conditions include an electrolyte or coolant leak, an earthquake, high levels of bromine or hydrogen, high indoor temperature, and manual emergency stops.

The software to run the 100-kWh battery system contains a disk that can be installed on any personal computer (PC). It makes use of Windows applications. The software gives the user the ability to monitor battery voltage, current, and SOC.

## Table 4-8. 100-kWh Battery Operating Characteristics

| | Typical | Maximum |
|---|---|---|
| Charge Voltage | 360 V | 378 V |
| Charge Current | 100 A | 150 A |
| Open Circuit Voltage | 328 V | |
| Discharge Current | 100 A | 200 A |
| Low Voltage Cutoff | 180 V | |
| Strip Current Cutoff | 0.5 A | |

### 100-kWh Battery Status

Four 33-kWh battery modules, each consisting of two battery stacks, two reservoirs, and a circulation system, have been manufactured. Three of the modules will be used for the 100-kWh battery deliverable. The additional module will be used as a spare.

An Ansul-supplied and -certified fire suppressant system has been installed in the 100-kWh building. The system consists of a dry chemical and a propellant that distributes the chemical to each of the four quadrants in the building. The system will be activated automatically by excessive heat in any of the quadrants, or it can be activated manually from outside the building. Also, a heater and heat exchanger have been installed so that the system can be operated in cold or hot weather.

The wiring for the 100-kWh deliverable battery system has been completed. Three 33-kWh battery modules have been installed in the 100-kWh building. Communication between the PC and all four PLCs using the battery software has been accomplished, and the electrical boards are completed. Calibration of the voltage and current for the modules and the final logic and data acquisition software have been completed. The major components of the system have been installed and are in the process of being tested. Software has been used to control the batteries from the PC. The control screens are completed and the pumps, scrubber, and heat exchanger can be controlled from the PC.

Short cycling of these modules through a cycling unit and through the PCS has been initiated for calibration purposes and to test fault conditions such as overcharge, overvoltage, and bromine detection. Electrical noise in the system caused periodic shutdowns and has resulted in delays in qualifying the battery system. Efforts are being made to eliminate this problem.

# Technology Evaluation – SNL

## Evaluation of 8-Cell Stack

One of the last deliverables from the utility battery contract with ZBB was a 2-kWh, 8-cell battery (V25-37-8) with a commercially available PLC adapted to control the 2-kWh stack. This battery was delivered to SNL in August 1994. A major change from previous batteries tested at SNL was the increased flow-frame size (1200 $cm^2$ to 2500 $cm^2$). The testing goals for this battery were to determine cycle life under baseline, no-strip, and simulated utility profile conditions. Also of interest was how well the battery functioned under the microprocessor controller. This controller monitors battery stack voltages and currents, electrolyte levels, and the battery SOC. It also regulates the circulation of complexed bromine through the stack during charge and discharge, and shuts the system down if the battery is overcharged, or if the current or voltage exceeds the safe operating limit.

A total of 14 charge/discharge cycles, at a zinc loading of 90 $mAh/cm^2$, were run. Below is the cycling regime used by ZBB and SNL.

- Charge at 50.5 A for 4.5 hr with an upper voltage limit of 16 V (2.0 vpc).
- Place the battery in open circuit for 1 to 5 min to collect open-circuit voltage data.
- Discharge at 52.5 A for 4 hr with a voltage cutoff of 8 V (1.0 vpc).
- The battery was stripped of zinc at regular intervals. This is done after the battery is discharged to 1.0 vpc and is accomplished by shorting the battery through an appropriately-sized resistor. For this 2-kWh-sized battery, a 1-ohm, 600-watt resistor was used.

A plot of efficiency vs. cycle number for these 14 charge/discharge cycles is shown in Figure 4-13. The results indicated that for the first four cycles, SNL was getting approximately 3% less coulombic and energy efficiency than ZBB, but these efficiencies were stable. During the discharge portion of Cycle 5, a high-temperature alarm of 40°C was reached. The battery sat on open circuit for approximately 1 hr before the temperature limit was changed and the discharge restarted. Because of this, poor results were recorded for Cycle 5, and this cycle is not displayed in the plot. The efficiencies for Cycle 6 were at the levels of the first four cycles; however, software changes in the ZBB controller were needed to complete the cycle. SNL continued to have problems with the software and, on October 24, 1994, a ZBB representative visited SNL to work on these problems. From cycles 7 to 14, a loss in coulombic and energy efficiency was seen, and these efficiencies became unstable. During this time, additional controller problems were encountered. The programmable controller has a unique design and went through several iterations after its fabrication. Hardware and software issues were recognized early in its testing at SNL, resulting in significant design changes on the 100-kWh control system. Because the 100-kWh control system is significantly different from the unit at SNL, and because resources and funding are limited, efforts to repair this unique battery control system were suspended.

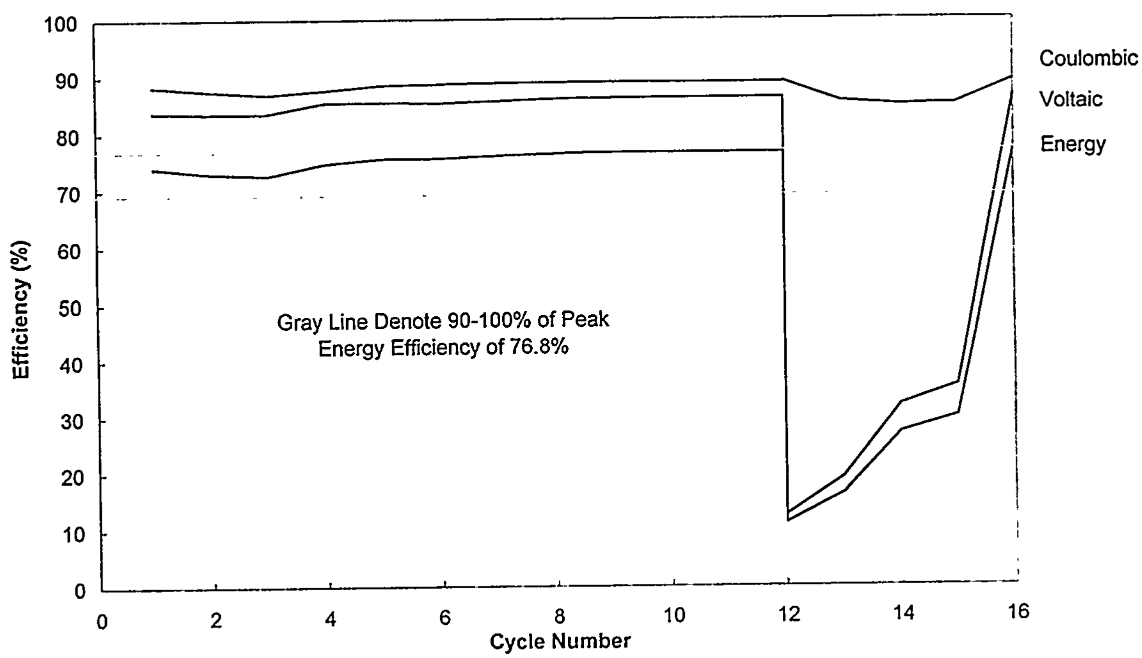



**Figure 4-13. Efficiency Data for ZBB Zinc/Bromine 8-Cell Stack at SNL.**

# 5. Subsystems Engineering – Sodium/Sulfur

The sodium/sulfur technology is being developed for UES applications primarily because it can satisfy the footprint and portability requirements of certain UBS applications better than conventional battery options. This advantage is enhanced if an energy/power ratio greater than one is required. Other benefits of this technology include the capability to accommodate multiple applications with a single battery and insensitivity to changes in ambient conditions. System analyses performed to date indicate that the sodium/sulfur technology can be used in many UBS applications. Customer and transit system peak reduction, renewables, and distribution facility deferral have been determined to be among the best applications for this technology.

The long-term goal of this UBS Program subelement is to ensure that a viable sodium/sulfur technology will be available for utility applications to enhance markets that will be or are being served by conventional battery technologies. FY95 marks the final full year of hardware design development being performed under a contract with SPI. Additionally, SNL directly supports the SPI efforts by evaluating the performance of selected deliverables and by developing a thermal fuse to improve battery safety characteristics.

## Technology Development – SPI

The development of a UES sodium/sulfur technology is following a structured and phased strategy. Successful completion of this long-term effort will yield a system suitable for commercial marketing. The phases on which progress was made during the past year include (1) conceptual battery engineering to provide the basis for entering into relatively expensive battery-system-level engineering development, and (2) initiation of prototype battery engineering to qualify the production processes and final product configuration. This work is being performed under a 5-yr, $3.1M cost-shared contract that was placed in mid-1991 with SPI.

Under this contract, relevant utility applications are being identified, specific cell and battery hardware is being developed, preliminary engineering of utility battery modules is being completed, and, finally, a full-scale battery plant is being designed. An integral part of this work is the formulation of a solid definition of battery requirements, an activity that, with increased involvement of the utility industry, can finally move forward. The continued need to reduce capital (first) cost and improve service life at the battery level is the focus of the development activity, because these two areas remain the key issues impeding commercialization. In addition, attention is being focused on battery configuration and maintenance strategies, effective thermal management systems, battery safety during both intended and accident situations, and ultimately on reclamation.

Of relevance, development of the sodium/sulfur technology for mobile applications at SPI's sister organization, SPL, is proceeding along a similar, but accelerated, path. Those improvements that are applicable to both types of end uses (e.g., manufacturing technology, some materials and components, safety features) are incorporated into this UES effort. Work under this project focuses solely on the specific needs for UES applications. As discussed below, SPI plans, for cost and availability reasons, to fabricate the initial UES systems by directly incorporating EV batteries.

## Tasks

The tasks being performed under the SPI contract include the following:

1. Assessment of UES applications
   1.1 – Utility-application identification
   1.2 – Utility-application evaluation and selection
   1.3 – Detailed battery specification preparation
2. UES Cell and Battery Component Development
   2.1 – Preliminary UES battery design
   2.2 – Cell component development
   2.3 – Cell development and qualification
   2.4 – Battery component development
3. Preliminary Engineering Development of UES Modules
   3.1 – Module design
   3.2 – Module fabrication
   3.3 – Module evaluation
   3.4 – Commissioning support
4. Full-Scale Battery Plant Design
   4.1 – Utility-battery design
   4.2 – Performance and cost analysis

FY95 Milestones:

- Finalize the long-life utility cell design (3/95) – completed 3/95.
- Determine the viability of the long-life utility cell design (9/95) – completed 9/95.

## Status

### UES Application Assessment

A significant part of this project is devoted to characterizing utility applications and their requirements relative to advanced sodium/sulfur BES. Despite the advantages of smaller size and weight, the question remains whether these features are important to a user, i.e., a utility or a utility customer. The basis for the proposed NaS-$P_{ac}$ system design was a "turn-key" electrical energy storage system that offered a convenient size from the standpoint of transportation and that would be unobtrusive in a small industrial or commercial outdoor setting. At 300 kVA (500 kVA peak)/300 kWh, the system offers sufficient energy storage to be dedicated to an industrial user, an industrial process line, or a commercial center. Larger loads of 1-2 MW could be served by paralleling units. An additional 1 hr of energy storage could be offered, if required, by adding a battery block extension to the basic unit.

In addition to size and weight advantages, the cost of sodium/sulfur batteries is expected to be fully competitive with that of commercially available batteries when manufactured in high volumes. Such volumes may require a combined EV and stationary utility BES market, at least initially. The need for active thermal management adds a cost burden that all battery systems will have to include when located outdoors. In the case of sodium/sulfur, thermal management has always been included as part of the price.

The final difference in BES system design philosophy involves system maintenance. Many systems require periodic maintenance; battery packs are scheduled for replacement, as necessary. For example, flooded lead-acid batteries must be watered periodically. A sodium/sulfur battery, on the other hand, is a sealed package, typically 300 VDC and 30-40 kWh. The only maintenance that can be performed is replacement. The battery is designed to operate at rated capacity with some failed cells. A unique feature resulting from the way cells are interconnected is that the battery voltage remains essentially constant in spite of any cell failures. This constant-voltage feature is a benefit to PCS operation.

Sodium/sulfur batteries will have a minimum prorated, five-year warranted life. Thus, no maintenance will be required for 5 yr. Interestingly, the PCS will likely need capacitor change-out at about that same time. A 5-yr service interval, then, is a reasonable span taking into account the wear-out mechanisms of the PCS and the battery. Other battery systems, however, may require periodic and scheduled maintenance, implying the need for on-site personnel to monitor and service the equipment.

Small footprint, portability, and low life-cycle costs are the advantages of the NaS-$P_{ac}$ system that need to be emphasized when considering this system's potential role in a utility market. To facilitate an understanding of these advantages, SPI produced a brochure for utility personnel and their customers describing the benefits that this system can offer in particular applications. To determine whether the stated benefits are important to potential users, brochures were mailed to approximately 250 utilities. The list of utilities was developed initially from a database prioritized by the high cost of energy purchases (>$.08/kWh). SPI is indebted to Brendan Kirby at ORNL for providing this list. One difficulty that was encountered was in directing the brochure to the right department within the utility, since the brochure was relevant to several different departments (engineering, corporate planning, customer accounts) within each utility that might or might not have been in communication with one another. This remains a problem. A second mailing was compiled from the top 100 utilities with significant commitments to DSM programs. In this case, the brochure was simply directed to the DSM program manager. Each mailing included the post card questionnaire shown in Figure 5-1.

The utility responses came from diverse locations around the country, including Maine and Massachusetts on the east coast; California in the west; and Nebraska, Wisconsin, and Michigan in the central part of the country. Of the 15 to 20 follow-up inquiries, 65% thought the projected price of BES was acceptable. Fifty percent of the respondents thought that their utility would be interested in ownership; 33% saw the customer-side benefit, and the balance believed that both utility-side and customer-side applications existed in their service territory. The largest category of application was utility power quality, followed by customer-side, peak clipping, and DSM applications. There was overwhelming support for the NaS-$P_{ac}$ features and a mixed reaction on participation in a demonstration project.

The brochure appeared to interest certain utilities facing specific problems and, perhaps, those facing local competition as a result of deregulation. Except for the DSM mailings, it was difficult to judge whether the

(1) At a price of $0.50/watt for a "turn-key" system, do you see battery energy storage (BES) as having a benefit within your utility or in customer side applications?

☐ Yes ☐ No

(2) What is your primary interest (use/perceived benefit) in BES?

| | | | |
|---|---|---|---|
| ☐ | Dispatchable Clean Distributed Generation | ☐ | Spinning Reserve |
| ☐ | Seamless DSM Program | ☐ | T&D Deferrals |
| ☐ | Utility Power Quality | ☐ | Peak Demand Reduction |
| ☐ | Customer Side Power Quality/Reliability | | |

(3) Do you see advantages to any of the features associated with the NaS-$P_{AC}$ system design?

| | | |
|---|---|---|
| Compact/Portable System Design | ☐ Yes | ☐ No |
| 5 Year No-Maintenance Batteries | ☐ Yes | ☐ No |
| Outdoor Siting (Insensitivity to Ambient) | ☐ Yes | ☐ No |

(4) Would your utility be interested in participating in a NaS-$P_{AC}$ demonstration program?

☐ Yes ☐ No

**Figure 5-1. Questionnaire Distributed to Managers of Utility Demand Side Management.**

information was circulated to the right parties within the utilities. What seems most important is that the mailing occurred during a time of major upheaval in the utility industry, when the merger outbreak was just starting and employee downsizing was imminent. These events likely affected the number of responses.

It was noteworthy that of those who thought the cost of BES was excessive, most felt that it had to stand on its own merits in a single application and that efforts to assign credits back down the line, perhaps all the way to generation, were not realistic. For example, if BES were applied at a distribution station to defer a transformer upgrade to handle the summer AC load (T&D benefit), the cost of BES must be weighed against the cost of on-site generation, like portable diesel generators (DGs) at $277-$350/kW. No other credits, such as air quality, extended service outage protection or, perhaps, unit commitment (generation credit), should be considered.

Regarding customer-side outage protection, it was noted in conversations that there probably exists a handful of customers in every utility service territory that need some sort of protection. The fundamental question is, "What are they willing to pay for this protection?" The answer will likely vary according to their perceived production losses. An example of a good customer-side application is a plastic extrusion forming operation that occasionally experiences a service outage. The outage causes dimensional problems in the product and results in rejection of the lot. With losses of $30,000 per incident possible, it only takes one occurrence a year (typically 1-2 incidents actually occur each year) for the next five years to repay the expense of a BES system. Typically, 1/2 hr to 1 hr of energy storage would be required to provide sufficient ride-through time to shut down the line for an extended outage period.

In the new utility atmosphere, which appears to be aimed at improving the utility-customer relationship, it may prove that BES systems can serve vital functions in the future. Peak shaving is one such function. For example, with current utility demand charges ranging from $10-20/kW across the nation, the investment for a BES system costing $500/kW for an hour of storage can, in principle, be paid back in 25-50 mo. However, it may be difficult to find applications that have sufficiently distinct peaks to make the investment worthwhile; missing one peak per month substantially reduces the return on investment.

For both the customer and the utility to obtain benefits, the utility must assume some of the risk. With innovative electricity options and real-time energy pricing, the means for measuring cost-effectiveness will differ significantly from current methods. Additionally, wide acceptance of BES will not occur until a number of successful, cost-effective demonstrations are in operation, sufficient to capture the attention of utility CEOs, CFOs, and unregulated electric service investors.

## UES Cell & Battery Development

The majority of the hardware development activities in this contract are performed within this task. The primary products are a UES sodium/sulfur cell and selected battery hardware applicable to the specific and selected UES applications. During FY95, work focused on completing and qualifying the hardware developed during previous years.

### *UES Battery Design Study*

This activity is complete and resulted in the original modular NaS-$P_{ac}$ system design. The design was based on the use of 75-kWh sodium/sulfur replaceable battery packs with a 480-VAC, 3-phase, 300-kW line or self-commutated power converter, in which the maximum battery voltage was limited to 540 VDC. The battery was designed to fit behind the 7.5-ft height and 7-ft width dimensions of an available PCS. The overall package, with 1- or 2-hr energy options, was designed to be easily transportable by truck and could be contained in a standard seabox. The evolution of this early design occurred in Task 4.

#### Cell Component Development

SPI's sister organization, SPL in Runcorn, England, has been focusing on the development of a cell for EV applications for over 20 yr. This subtask involves the development of a cell strictly for UES applications. A c/S cell configuration was chosen as ideal and was sized to directly use SPL's extended PB (XPB) electrolyte. The c/S configuration was chosen over a typical central-sodium design because of its potential for longer service life. This improvement was clearly demonstrated with a similar cell, designated TD, designed and tested at SPL. Having the sulfur electrode contained within the ceramic electrolyte eliminates the need for expensive and often ineffective coated, corrosion-resistant containers. Though the TD cell exhibited long life during testing, it was not a practical cell in terms of cost effectiveness or energy density.

The objective of this task is to develop a c/S cell that will overcome the limitations of the TD cell and preserve the long life. The major changes relative to the TD design were the use of planar TCB metal-to-ceramic seals rather than tapered, radial TCB seals and the placement of the sodium reservoir around the electrolyte rather than at the base of the cell. In addition, before c/S cells can be seriously considered for UES applications, two fundamental questions have to be answered: (1) Will the beta"-alumina electrolytes in c/S cells survive F/T cycling? and (2) Will c/S cells have adequate safety characteristics? In general, the effects of the developments described in this subsection are discussed in the "Cell Design Verification" section of this chapter.

#### Sodium Seal Development

In response to the determination last year that environmentally assisted cracking (EAC) at the aluminum/alpha-alumina interface was the probable cause for sodium-seal failure during F/T cycles, a number of possible solutions were identified to reduce or eliminate one of the three conditions necessary for EAC to occur: (1) sodium contact with the bonding alloy, (2) stress on the bond, and (3) use of a nonsusceptible bonding alloy.

Of the of alternatives evaluated, only two proved to be successful enough to merit serious consideration in the final cell design. These were the planar seal, which had been under development throughout the program, in which a 4032 aluminum alloy interlayer was used (shown in Figure 5-2) and the tapered, radial seal that had been successfully used by SPL in their TD cell (shown in Figure 5-3).

Five cells of each configuration were fabricated and tested to determine their F/T durability. Initially the cells were heated to operating temperature and cycled electrically several times to confirm operability. Then the cells were fully charged, cooled to room temperature, reheated to operating temperature, and electrically cycled at least twice. This regime of a single thermal cycle coupled with several electrical cycles was then repeated. The results of this testing are shown in Table 5-1. Both groups of cells performed reasonably well; however, one cell with a tapered seal failed during its second heat-up. One cell of each type also failed from electrolyte fracture when a computer program error caused the test system to attempt discharge of the cells while they were frozen. None of the other cells on test were affected by the accident.

One cell of each type was also subjected to F/T cycling in the discharged state after having already sustained 10 or 11 F/T cycles while fully charged. The electrolyte in Cell 124 (tapered seal) failed during its nineteenth freeze. Cell 123 (planar seal) was removed from test for a posttest examination after sustaining a total of 21 F/T cycles, with 10 occurring while the cell

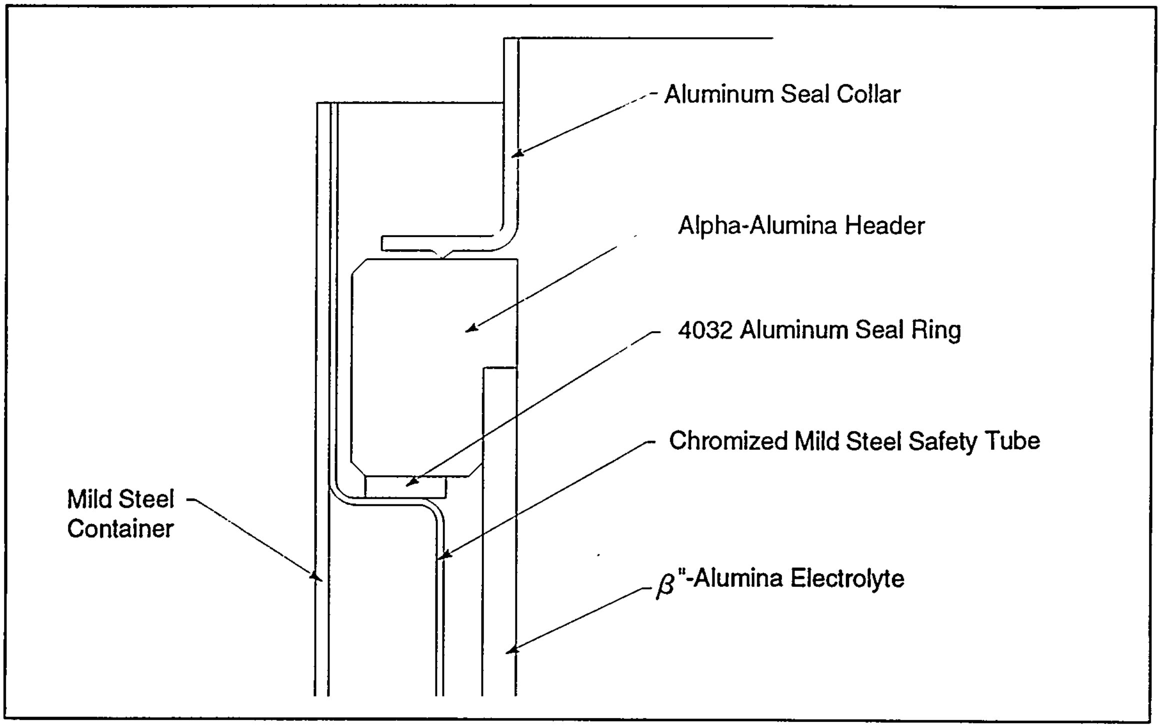



**Figure 5-2. Schematic Diagram of Planar Seal Configuration.**

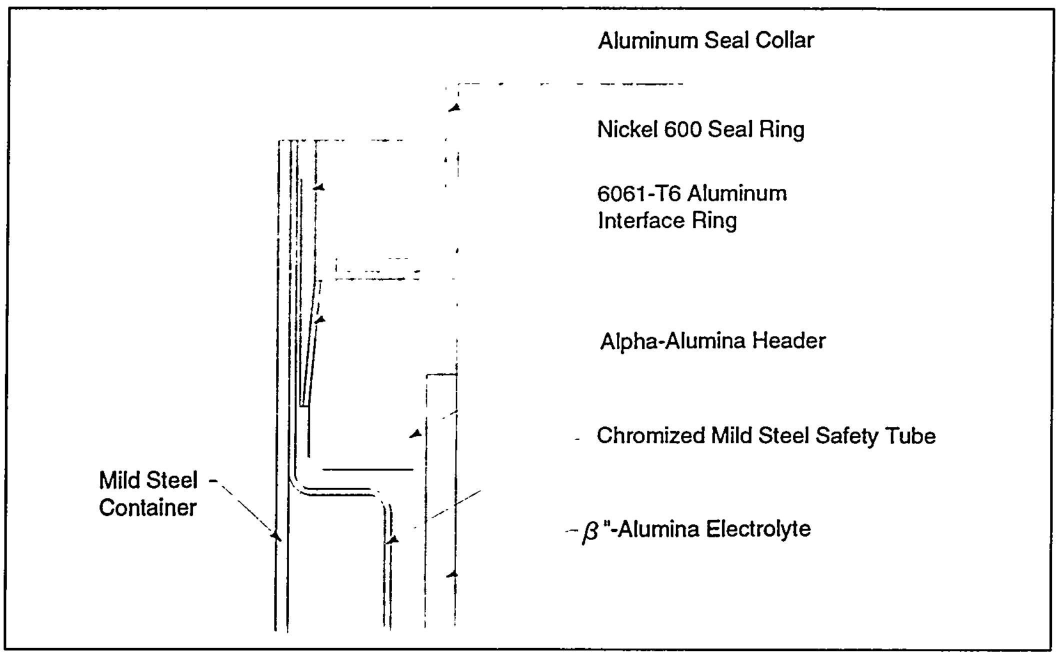



**Figure 5-3. Schematic Diagram of Tapered Seal Configuration.**

## Table 5-1. Preproduction Seal F/T Durability

| Cell Number | Electrical Cycles | F/T Cycles | Status |
|---|---|---|---|
| 105 Planar | 310 | 13 | Off test. Al weld leakage. |
| 115 Planar | 460+ | 12 | On test. |
| 116 Planar | 48 | 9 | Off test. Discharged while frozen. |
| 121 Planar | 267 | 10 | Off test. |
| 123 Planar | 410 | 21<br>10 while discharged | Off test. Removed for seal evaluation. |
| 124 Tapered | 165 | 18<br>8 while discharged | Off test. Electrolyte failed on 19th thaw. |
| 125 Tapered | 154 | 10 | Off test. Failed during charge. |
| 126 Tapered | 25 | 8 | Off test. Discharged while frozen. |
| 127 Tapered | 9 | 1 | Off test. Failed during second thaw. |
| 128 Tapered | 148 | 10 | Off test. Degraded performance during cycling. |

was discharged below 70% DOD. Cell 115, with a planar seal, remains on test, undergoing an F/T cycle every 100 electrical cycles.

Based on the results of the F/T testing of the two seal types and the overall objective of the cell development effort (to move in the direction of a more cost-effective and manufacturable cell), the planar sodium seal was chosen for the final design.

### Sulfur Seal Development

Until the time of the cell design freeze (see "Cell Design Verification" below), type 6061 aluminum alloy had been used for the sulfur seal rings. The final closure of the cell is made by welding the cap/current collector assembly, also made from 6061 aluminum, to the sulfur seal ring. During this welding operation, hot cracking of the weld sometimes occurred. If cracking was observed during inspecting of the welds, reworking them by hand was often effective in repairing the defective welds. Sometimes, however, the flaws in the weld were so small that they were not noticed during inspection. These resulted in minor leakage of sulfur or sodium polysulfides during cell testing.

To eliminate hot cracking of the sulfur-side aluminum weld, the type 6061 aluminum sulfur seal ring was replaced with a type 5086 seal ring. Welding of 6061 to 5086 is much less likely to result in hot cracking. Type 5086 aluminum had been tried as an interlayer in earlier sodium seals and was known to be bondable to alumina. However, the F/T durability of such bonds on the sulfur side was unknown.

Two cells were placed on test to asses the durability of the bond. One of the sulfur seals failed after four F/T cycles, and the second failed after seven; these results are unacceptable. Hence, type 6061 aluminum was selected for the remainder of the production cell builds.

### Current Collector Development

Titanium nitride (TiN) is a promising coating for preventing corrosion and passivation of aluminum current collectors. The first group of cells fabricated with sputtered TiN coatings on the aluminum alloy current collectors exhibited poor electrical performance and limited service life. A posttest analysis (PTA) of the current collectors showed that most of the sputtered TiN coating had corroded away, allowing the aluminum substrate to passivate.

A second group of three cells was assembled and placed on test during the first quarter of 1995 in which the aluminum current collectors were coated with TiN applied by ion plating. This coating, by virtue of being more uniform and less porous, was expected to perform somewhat better than the previous coatings, according to the developer of the process, Advanced Modular Power Systems.

All three cells performed very well electrically relative to both of the earlier TiN cells and the standard cells with Nichrome-coated current collectors. Cells 138 and 140 showed initial resistance values of around 15 mΩ, values that decreased as cycling continued. While Cells 137 and 140 have completed more than 325 electrical cycles and remain on test, they are beginning to show an increase in resistance. The resistance of Cell 138 showed an increase in resistance around Cycle 90. General performance of this cell degraded during further cycling, and the cell was removed from test after completing 180 electrical cycles when its resistance became too high to allow continued cycling by the test system. A PTA performed on this cell again showed that loss of the TiN coating was the source of the rising resistance.

### Safety Feature Development

To assess the effectiveness of the safety features of the initial c/S cell design, five cells were intentionally failed by overcharging. The results are summarized in Table 5-2. The criteria for the safety tests are no temperature excursions above 500°C and no breached cells. Because the actual outcome did not meet these criteria, several changes were made to the cell design for incorporation into the final cell builds. These included a reduction of the safety tube diameter by 0.5 mm to reduce the amount of sodium available to react in the event of an electrolyte failure, and the use of a finer sand in the electrolyte/safety tube annulus to reduce the rate at which sodium can flow from the reservoir to an electrolyte fracture. Though a further reduction in the safety tube diameter would be desirable, the variations in the outside diameter of the electrolyte allowed by the current specifications precluded it, as all of the electrolytes for the remainder of the current program had been manufactured by that time. The use of the Grafoil® insulators at the top of the sulfur electrode may not have been fully effective because they were hand cut and did not fit tightly around their perimeters, thus allowing bypass of hot sodium polysulfides. To obtain a tighter, more uniform fit, a die was fabricated for cutting the graphite washers.

### Battery Component Development

To sustain a discharge over a 2-hr duration, it is necessary to cool the battery to limit temperature rise. While oil cooling is used for the EV batteries in the current NaS-$P_{ac}$ design (see the "Full-Scale Battery Plant Design" section), it seems advisable to consider a simpler approach for UES applications, one requiring less maintenance and fewer parts. A cooling system was designed centered around a reflux boiler that uses gravity to provide the head required to drive circulation, thus eliminating the need for a pump. The cooling system utilizes Fluorinert® as the working fluid. This fluid is a chemically inert, fluorinated hydrocarbon having no fire or flashpoint. Control is established using a simple, electrically operated control valve located below the res-

**Table 5-2. Safety Test Summary**

| Cell 609SES100- | 111 | 112 | 129 | 131 | 133 |
|---|---|---|---|---|---|
| Voltage @ Failure | 50 | 55 | 15 | 25 | 25 |
| Max Temperature °C | 525 | 400 | 630 | 507 | 456 |
| Breach/Location | Bottom | No | Top | No | Top |
| Na Seal Type | BN Coated | BN Coated | Planar | Planar | Tapered |
| Safety Features | Floating Safety Tube | Floating Safety Tube | 15 mil Grafoil in safety tube/electrolyte annulus; Grafoil insulators at top of sulfur electrodes | | |

ervoir/condenser. During operation, the fluid begins to boil as it enters the plenum located in the middle plane of the hot battery. The vapor is collected and returned outside the battery to the condenser space above and adjoining the reservoir. An aluminum fin is attached to the condenser/reservoir volume to dissipate the heat into an air column. From there, the heat is rejected through a vent atop the NaS-$P_{ac}$ system envelope. The midplane of the battery is essentially an isothermal surface held at the boiling point of the fluid. Heat is extracted from the cell matrix above and below the plane, limited by thermal conduction of intermediate layers. In this way, each cell experiences the same axial-thermal gradient over the entire battery planform area.

For most UES applications, a heat removal rate of up to 1500 W from each 40-kWh battery is required. Rather than initiating cooling after the battery has reached some elevated set-point temperature, cooling will begin at the inception of discharge and continue throughout discharge. This approach lowers the cooling rate requirement by a factor of nearly three.

SPI has completed an experiment that simulates a single plenum of the flow path as described above. A drawing of the apparatus is provided in Figure 5-4. A 1-ft pressure head was chosen initially to represent the height of a reservoir attached to the top of an EV battery. To simulate the battery heat transfer environment, an evaporator tube length was chosen consistent with the actual path within the battery, and rod heaters mounted in aluminum blocks were employed around the evaporator tube. A number of thermocouples were mounted along the length of the evaporator to measure temperature uniformity. A water-cooled calorimeter was fabricated around the condenser/reservoir volume. All components of the system were well instrumented and insulated to minimize extraneous heat losses.

Testing was performed over a range of heater input power levels. Heat removed at the calorimeter was measured in each case. Two Fluorinert® fluids were tested, FC-70 and FC-5312, with boiling points of 250°C and 215°C, respectively. As demonstrated in Figure 5-5, with 161 W of heater input, the cooling system was able to reduce the temperature in the evaporator from battery operating temperature (300°C) to the boiling point of the fluid within six minutes. Results of the heat-transfer testing are summarized in Figure 5-6. The difference between the heater input and the heat rejected at the calorimeter was verified as being caused by heat losses through the heater leads and the insulation. The tests demonstrate the simplicity and high efficiency of the approach. Specifically, the system can transport up to 165 W over a single 7-mm-diameter branch run until limited by returning vapor back-pressure. In practice, a

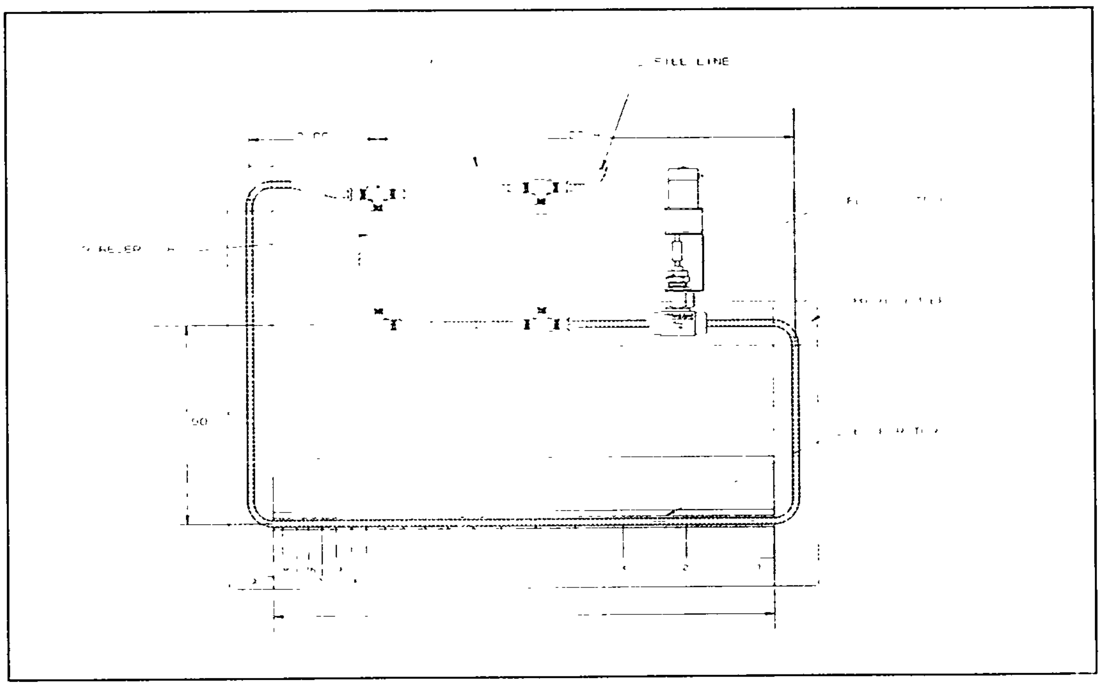



**Figure 5-4. Schematic Diagram of Thermosyphon Experimental Apparatus (dimensions are in inches).**

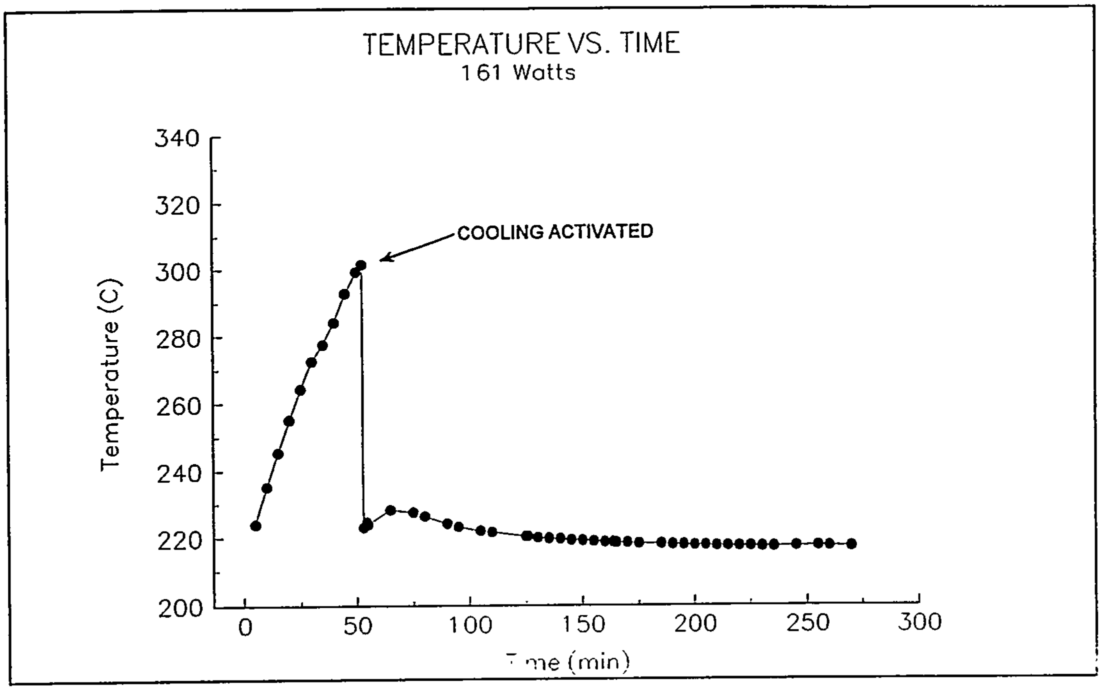



**Figure 5-5.** **Evaporator Temperature as a Function of Time.**

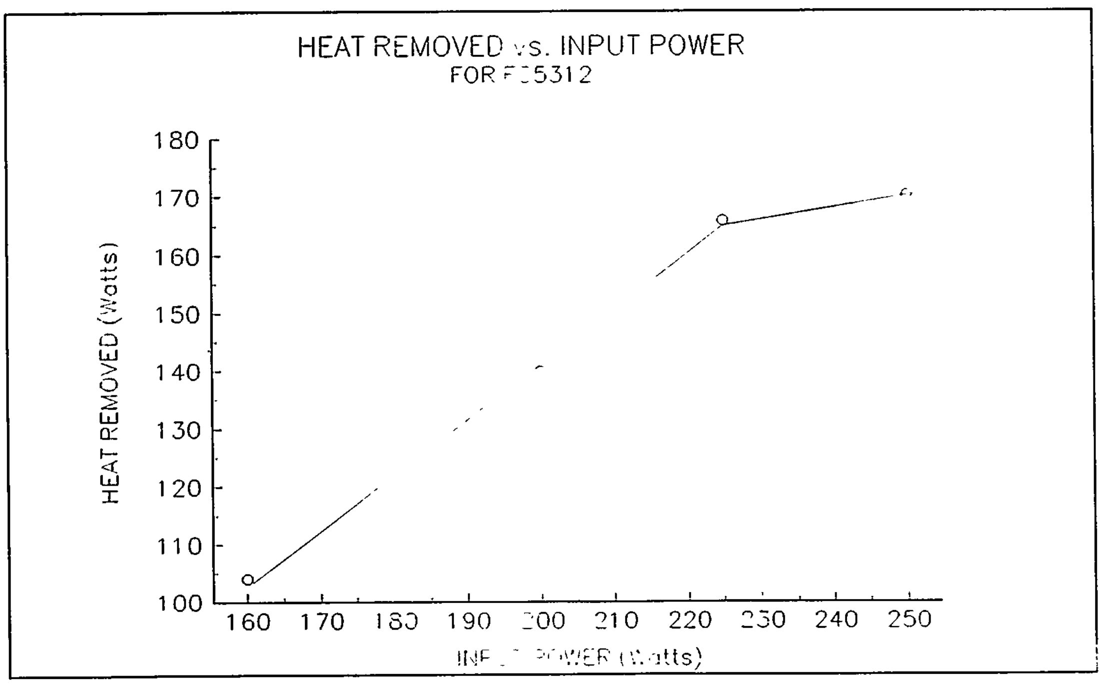



**Figure 5-6.** **Heat Removed in Condenser as a Function of Evaporator Power Input.**

suitable plenum design would incorporate 10 such branch runs embossed into steel sheet stock to transfer battery heat at the required rate. The average evaporator film coefficient was calculated from these experiments to be 735 $W/m^2K$.

### *Cell Design Verification*

#### Cell Fabrication

A very important final activity in the development of the c/S cell is to characterize its electrical safety and service-life performance by testing a statistically significant number of cells. To accomplish this, a final or "prototype" cell design was finalized during March 1995, and cell fabrication was initiated. The cells were designed with a nominal capacity of 30 Ah. The sodium and sulfur seals were the planar TCB seals noted above, and the safety features discussed above were incorporated into the design. From the time of the design finalization until the end of the fiscal year, 99 cells were fabricated.

During the early testing of these cells, two flaws in the cell design were identified. Corrective action was taken as soon as the problem areas were identified. The first of these was the failure during thermal cycling, noted above, of sulfur-side TCB seals fabricated with 5086 aluminum alloy.

The second defect that occurred was contamination of the aluminum seal ring by graphite during the insertion of the Grafoil® washers, which aggravated the problem of cracking in the final closure weld. The cracks were visible only under a microscope and therefore were overlooked during the normal weld inspections. They were noticed only after cells were heated and leakage of cell reactants was observed. Because of delays encountered in getting cells onto test and a test system malfunction that overdischarged the first 10 cells placed on test, 50 of these defective cells were fabricated.

The immediate solution was elimination of the washers in subsequent cells, which, of course, had the potential for altering the safety characteristics of subsequent cells. In future designs, the washers can be easily accommodated by redesigning the aluminum top cap and seal ring so that there is no interference between the washers and the seal ring. In the case of cells that had not been heated, an attempt was made to rework the welds that was successful in most cases. The reworked cells were assigned to be used for safety tests, as they contained all of the improved safety features. If a cell leaked reactants during heat-up or break-in, it was not included in the safety tests.

Out of 99 prototype cells fabricated, 40 cells have been successfully placed on test and two cells await testing. Twenty cells failed during fabrication, and 37 failed (or would have failed had 10 not been overdischarged) during heat-up or early cycling as a result of latent manufacturing defects. Twenty-six of the 57 failures were attributable to final closure weld defects caused by graphite contamination. Twenty-eight failures appear attributable to failure of the TCB in one way or another. Posttest analyses of 12 cells having TCB failures have confirmed fracture of the alpha-alumina as the cause of seal failure in all cases. The remaining failed cells will be examined to ascertain the cause of the failures. Clearly, a substantial effort is still required to fully develop the TCB design and process. This situation has precluded positive support for the viability of the c/S cell (project milestone).

#### Safety Testing

A total of 15 prototype cells were failed intentionally by overcharging at temperature to characterize the safety performance of the cell design. Only one of the 15 cells breached on failure, which is an order of magnitude improvement over the initial safety tests wherein three of five cells breached. Figure 5-7 shows a plot of the maximum temperature attained following failure as a function of the probability of attaining that maximum temperature. The plot shows a distinct bimodality that indicates a design flaw or a lack of control over some aspect of the manufacturing process.

A PTA of the breached cell and several others revealed that the safety tube and the electrolyte are not concentric. In the case of the breached cell, the location of the breach through the side of the safety tube and outer container coincided with the wide side of the annular gap. It is expected that by improving the alignment during the bonding process, further improvements in safety characteristics can be obtained. Some additional improvement can be attained if the tolerances on the outside diameter and straightness of the electrolyte can be tightened. This would allow the annular gap to be reduced even further.

It is also worth noting that, even though the electrolyte failure occurred just below the header, the Grafoil® washers protected the aluminum top cap from burning or corroding. In earlier cells without the graphite, this was not the case. The results of these safety tests represent a significant accomplishment in the c/S development effort.

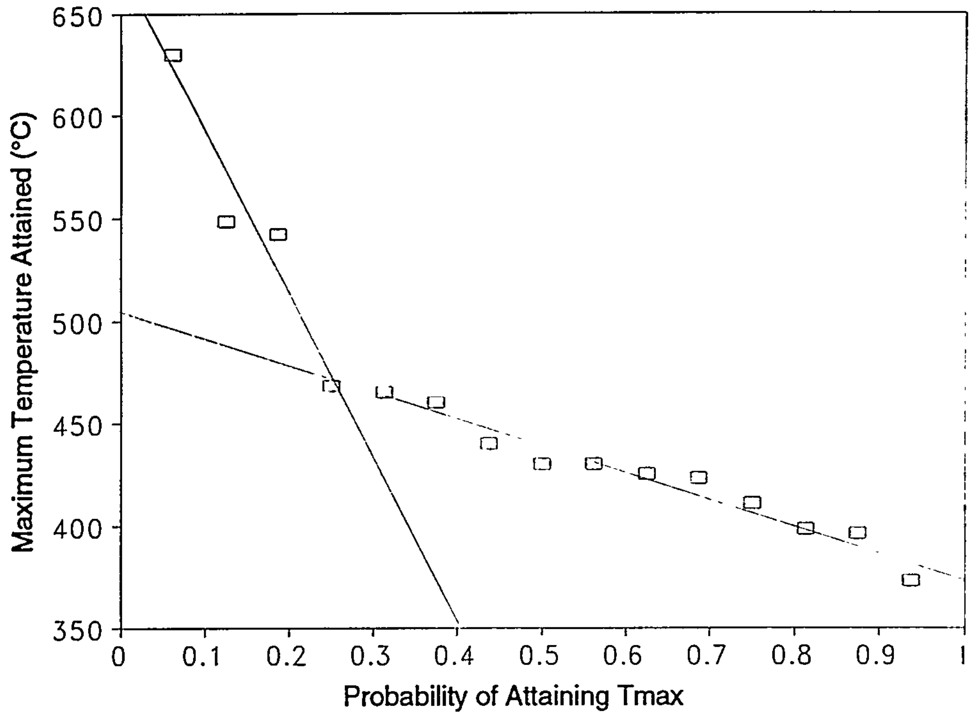



**Figure 5-7.** **Probability of Attaining a Maximum Temperature (in °C) during Safety Testing.**

<u>Performance Testing</u>

Twenty-five prototype cells are presently undergoing life cycle and performance testing. The test data for prototype cells on test are summarized in Table 5-3. In most cases, the cells required between 50 and 70 cycles to break-in and show stable resistances, though in a few cases as many as 100 cycles were required. The average resistance of prototype cells on test with greater than 50 cycles is 13.7 ± 2.7 mΩ.

Of note is that Cell 023, one of the pre-prototype c/S cells built under this contract, remains on test. This cell has completed more than 1720 electrical cycles since October 27, 1992. The majority of cycles were performed under a regime of 7-A discharge and 2-A charge, with 16 to 17 Ah of charge removed each cycle. Cell resistance has ranged between 15 and 17 mWs with an unrecoverable capacity near 28%. During the last 100 or so cycles, the discharge and charge currents were increased to 9 A and 3.6 A, respectively. The usable capacity has decreased to about 15.5 Ah as a consequence of the increased currents.

## Design & Fabrication of UES Module

A 32-VDC, 12-kWh prototype battery was shipped to SNL for testing in February 1994; it was tested through February 1995 and then returned to SPI for PTA. Its design is described in more detail in the two previous UBS Annual Reports. This battery was the first ever designed and assembled by SPI. It incorporated a number of unique design features, including the use of a eutectic salt (thermal energy storage (TES)) to limit temperature rise, a thermally cemented cell TES matrix, a low-cost nonevacuated thermal enclosure, and a plug-and-socket power connector. The initial capacity of the battery was demonstrated to satisfy its 400-Ah rating. Capacity had declined after approximately 150 cycles to 80% of rated capacity because of an inordinate concentration of cell failures in Bank 1. The reason for this is still under investigation and awaits the formal results of the teardown and analysis. The results will be included in the final report. While it is perhaps too early to speculate, it is likely that poor cell manufacturing quality from SPL's Clifton pilot plant and possibly improper drying of the cemented cell matrix before assembly into the battery box contributed to the poor performance.

## Table 5-3. c/S Prototype Cell Testing Summary

| Cell Number | Theoretical Capacity (Ah) | Cycles | Resistance (mΩ) | Unrecoverable Capacity (Percent of Theoretical) |
|---|---|---|---|---|
| 195 | 30.2 | 150 | 11.5 | 12.1 |
| 199 | 29.7 | 198 | 10.5 | 10.1 |
| 202 | 29.5 | 180 | 10.5 | 8.3 |
| 203 | 29.7 | 165 | 10.8 | 7.2 |
| 204 | 30.4 | 185 | 11.5 | 9.0 |
| 205 | 29.3 | 148 | 13.3 | 9.2 |
| 208 | 29.8 | 145 | 13.2 | 8.0 |
| 210 | 29.9 | 157 | 18.8 | 9.0 |
| 211 | 30.2 | 155 | 21.0 | 10.0 |
| 212 | 29.7 | 150 | 13.4 | 11.0 |
| 214 | 29.9 | 145 | 13.1 | 9.7 |
| 215 | 30.1 | 135 | 13.5 | 8.2 |
| 217 | 29.8 | 118 | 14.5 | 10.0 |
| 218 | 29.7 | 120 | 15.0 | 8.2 |
| 220 | 29.5 | 120 | 12.3 | 9.0 |
| 221 | 29.9 | 120 | 16.5 | 15.8 |
| 226 | 28.8 | 85 | 13.4 | 9.0 |
| 227 | 29.0 | 27 | 21.4 | 15.1 |
| 229 | 29.1 | 23 | 17.9 | 15.6 |
| 231 | 29.5 | 36 | 12.3 | 10.3 |
| 232 | 29.5 | 21 | 13.1 | 10.0 |
| 242 | 29.6 | 35 | 21.5 | 8.3 |
| 243 | 29.6 | 43 | 35.1 | 9.0 |
| 246 | 29.5 | 6 | 13.2 | na |
| 247 | 29.1 | 8 | 14.1 | na |

One of the more positive results from battery testing was the thermal performance of the battery during high-rate discharge. The TES salt melted and moderated the temperature rise of the adjacent cells. After some initial interface problems between the battery management system (BMS) and the SNL test system, the BMS performed as planned, tracking the capacity of the battery and limiting recharge.

Following its testing at SNL, the battery was returned to SPI for PTA. The battery has been dismantled and examined. The visual appearance of the battery was quite good. There was no obvious cracking or spalling of the MgO/waterglass coating on the cells or TES capsules. One cell had leaked a small amount of material. Otherwise, no other cell breaches were observed. There were no failures of the instrumentation (thermocouples or voltage probes) within the battery. All of the heater plates were intact, though all four leads (primary as well as backup) on one end heater broke very easily during teardown. The test data were examined to see if there was any evidence that the heater was not functioning near the end of the test period. No such evidence was found, and it was concluded that the heater circuit was continuous during testing. The cell strings were removed from the banks and have been radiographed, but the evaluation of the radiographs has just begun.

### *Full-Scale Battery Plant Design*

The 300-kVA (500-kVA peak)/300-kWh NaS-$P_{ac}$ system design, shown in Figure 5-8, was completed in sufficient detail to support comprehensive cost development. This transportable system is composed of ten 40-kWh sodium/sulfur EV batteries from SPL, mounted in two mirror-imaged structures, shown in Figures 5-9 and 5-10, and integrated with a PCS. The PCS is available from several inverter and UPS manufacturers. Of prime interest was a PCS that offered the capability of having the BMS control function integrated into it. By integrating the BMS function into the PCS controls, the cost burden of individual BMSs could be eliminated.

Figure 5-11 provides the results of a recent survey by SPI of PCS costs as a function of size for systems having similar features for outage protection. The curve is actually composed of price information from discrete size categories (3-5 kVA, 30-50 kVA and 300-500 kVA), with a smooth curve fit between the data. The reason small systems appear to cost so much compared to larger systems is that common elements must appear in all systems the cost of which does not scale linearly with size. However, \$300-235/kW, the price of the larger systems (those in the range of 200-500 kVA), does appear to represent a cost advantage. This fact, coupled with consideration of transportation and of potential utility/customer applications, led to the 1-hr NaS-$P_{ac}$ system design.

The projected price of the 1-hr NaS-$P_{ac}$ system is \$189,000 (\$630/kW or \$630/kWh), assuming annual battery production levels of 400 MWh (combined EV and stationary markets) and annual sales of 10 systems. The battery price was determined from detailed manufacturing price development by SPL for its 40-kWh EV sodium/sulfur batteries at the stated volume. The battery subsystem portion of the price amounts to 59%, including support structure, enclosure, and DC electrical components. The PCS is capable of four-quadrant operation with a total harmonic distortion of less than 5% (non-linear loads) and with a 95% efficiency at rated load. It includes phone-home features for status and service checks along with event storage and waveform capture for diagnostics. The system's operational interface is user-friendly and flexible, i.e., the system can be programmed from the front panel to be dispatchable by time, operator signal, or custom load management algorithm.

With an increase in annual battery sales volume by a factor of 10 (combined EV and stationary markets), the 1-hr system price is expected to drop to \$128,400 (\$428/kW or \$428/kWh). This price reduction includes the effect of improvements in the PCS and, especially, in battery manufacturing.

Having completed the design of the 300-kVA/300-kWh NaS-$P_{ac}$ system for utility and utility customer applications, SPI has embarked on a smaller 30-kVA (50-kVA peak) version that can be used as a near-term, proof-of-concept design. The rationale for the selection of a relatively small system was based on limited battery manufacturing capability at SPL, utilization of available EV batteries from SPL, and the desire to minimize risk while maximizing knowledge gain in attempting to integrate the DC and AC subsystems. The proposed system uses two series-connected EV batteries that provide a DC voltage range of 312-400 VDC (end of discharge to top of charge). The 28-kWh batteries together will permit the system to be discharged continuously for nearly 2 hr. In addition, as shown in Figure 5-12, fitting in a space 3 ft (W) × 3-1/2 ft (H) × 4-1/2 ft (L), the system size approximates that of a large residential heat pump. With a power capability of 30-50 kVA, the system can potentially be used with renewable power systems for power backup and/or to provide peak-shaving opportunities for commercial businesses.

SPI has recently completed construction of a detailed mock-up of the system design. The purpose of the mock-up is to check the design fit-up and to verify

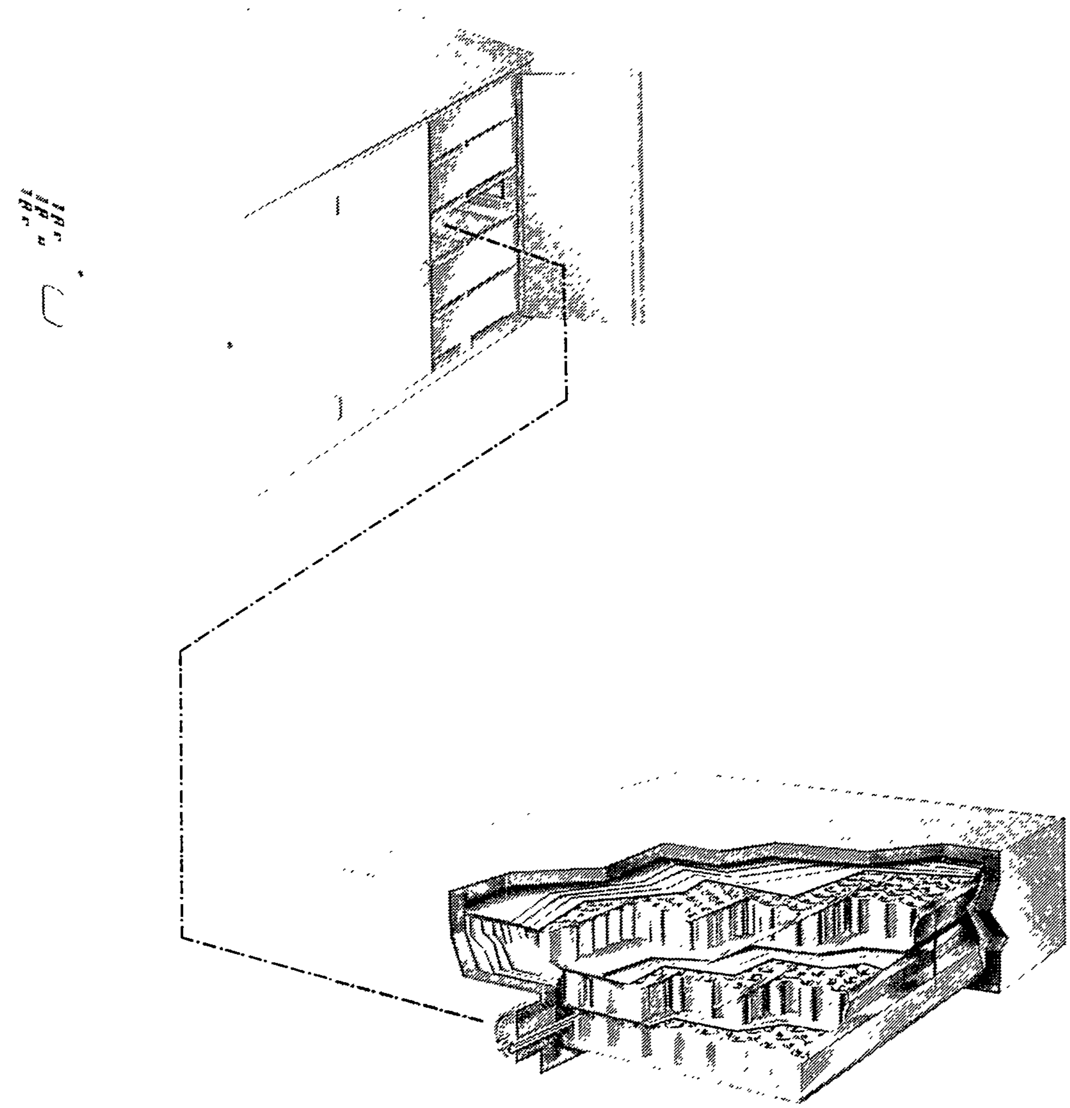


Figure 5-8. Artist's Depiction of Integrated NaS-$P_{ac}$ System and Cutaway View of 40-kWh Subbattery Module.

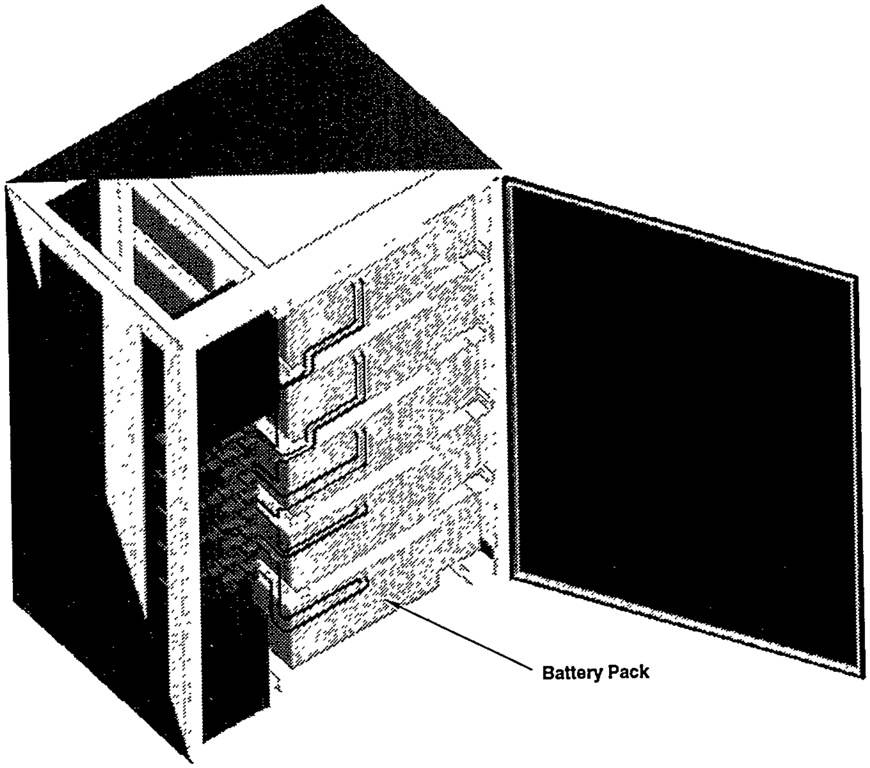



**Figure 5-9.** **Artist's Depiction of Left Side of the NaS-$P_{ac}$ DC Subsystem Twin Structures.**

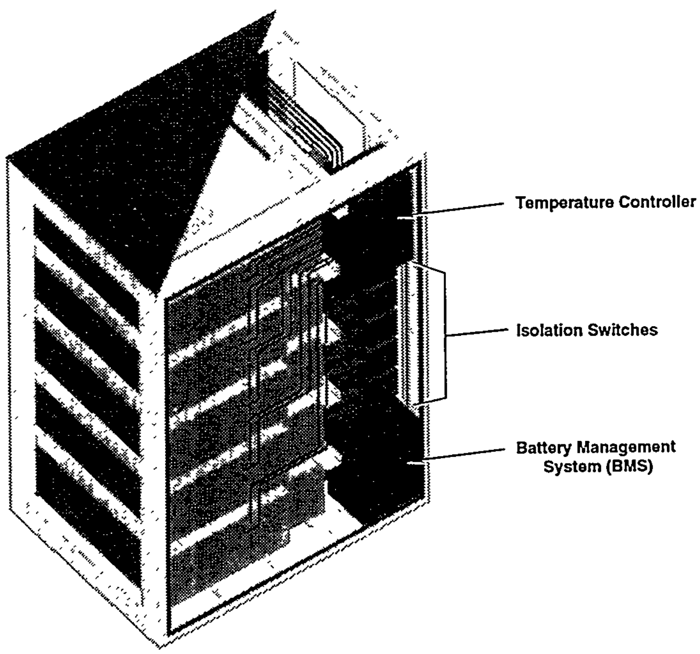



**Figure 5-10.** **Artist's Depiction of Right Side of the NaS-$P_{ac}$ DC Subsystem Twin Structures.**

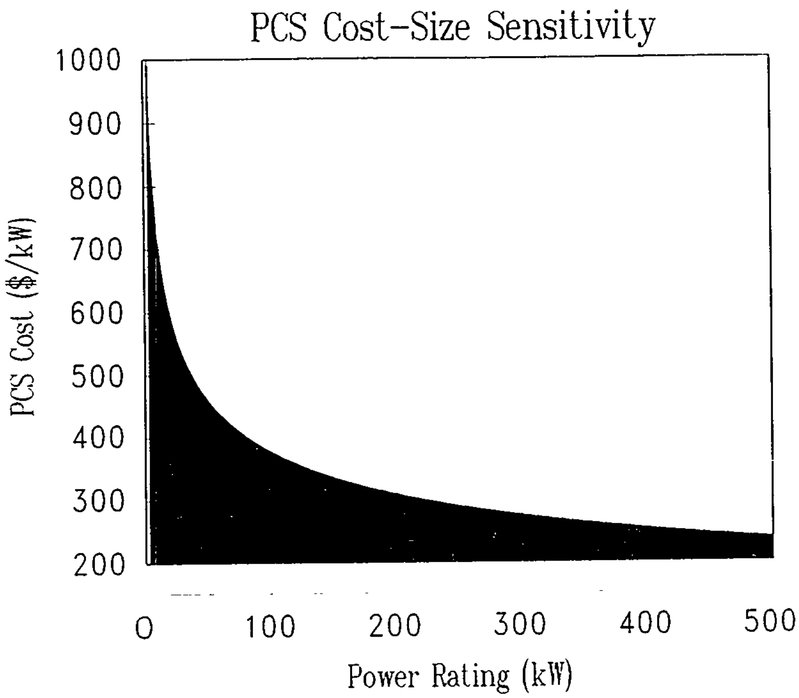



**Figure 5-11. Effect of System Power Rating on PCS Cost.**

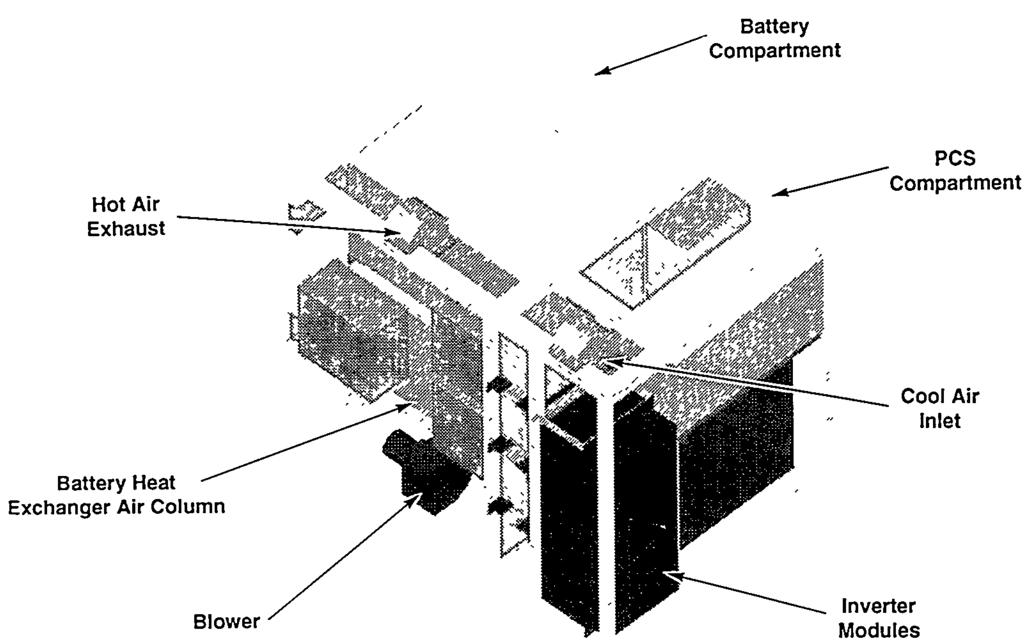



**Figure 5-12. Artist's Depiction of 30-kW, 2-hr Prototype System.**

the performance of the proposed air cooling system, which uses a single blower located at the base of the battery column.

## Applied Research – SNL

SNL has continued an effort to develop prototype thermal fuses for sodium/sulfur batteries. Thermal fusing addresses a concern that individual cell failures generating electrical shorts could lead to catastrophic failure of a battery. The objective of this task is to demonstrate the feasibility of a fuse concept for use in this battery system. Cast metal fuses appear able to satisfy a list of initial requirements obtained from SPL. This work is nearing completion and was transferred to the UBS Program earlier in the year.

The only pure material with a melting point near the correct fusing range for a sodium/sulfur battery is zinc, with a melting point of 419.5°C. However, this melting point is too low by a slight amount, and zinc also has the disadvantage of oxidizing very rapidly as it fuses. In a fuse, the oxide shell that forms on the surface of the molten zinc prevents the drop from falling off the leads, and the electrical circuit therefore remains unbroken. Possible solutions to this problem are to devise a way of protecting the surface of the zinc from oxidation or redesigning the prototype fuses so that the oxide cannot hold the liquid drop in place. Although these approaches are feasible, another solution that might also allow the fusing temperature to be moved closer to 450°C would be to identify an alternative fuse material that has less tendency to oxidize.

In prior work this year, several more trial fuses were cast from an alloy that has a melting point of about 445°C. These samples were cast in a glove box with an argon atmosphere to avoid forming any oxide during the fabrication process, and the gap between the fuse leads was widened from 5 mm to 10 mm to make it easier for the molten drop to fall. When two of these fuses were heated in air, an open electrical circuit was obtained, although the fuse material still showed some tendency to cling to the ends of the electrical leads. In a third test, a fuse that had been cast from the same material in air was held at 400°C for an hour before the temperature was increased above the melting point. This sample also had the narrower, 5-mm gap. An open circuit was not obtained in this case. It was concluded that further investigation was needed to determine the minimum gap width for reliable operation of this type of fuse.

The carbon mold that was used to fabricate previous trial fuses was designed to form samples with a 5-mm gap between the ends of the fuse leads. By cutting each of the nickel leads 2.5 mm shorter, the gap could be increased to 10 mm, although the length of lead buried in the fuse material was correspondingly decreased. Initial fusing test results indicated that evaluation of gaps wider than 10 mm would be required, and it was felt that the original mold could not be used above this limit. A new mold has therefore been constructed so that the minimum gap necessary for the various alloys of interest for the thermal fuse can be determined. As shown in Figure 5-13, the new mold has several improvements not present in the original version. It has two 2.5-mm spacers that, in combination with the shortened leads used before, allow the formation of various gap widths of from 10 to 20 mm. The new mold also has improved hold-down plates to prevent the leads from moving while the fuses are being cast. Samples of metal alloys that gave promising results with fuses cast in the old mold are being formulated and characterized so that prototype fuses with the wider gaps can be prepared and tested.

## Test and Evaluation – SNL

During FY94, a 12-kWh UES sodium/sulfur battery was delivered to SNL by SPI for testing. The battery was the principal hardware deliverable from the development contract with SPI. The formal test plan, named "SPI Sodium/Sulfur Utility Battery" (March 29, 1994), was followed as closely as possible. The objectives of the testing were (1) to confirm the battery electrical performance ratings, (2) to identify its ability to meet basic cycling requirements associated with several promising candidate UES applications, (3) to gain experience with SPI's integrated BMS, and (4) to determine the battery service life using a preferred customer peak-shaving requirement.

The commissioning of the battery and test system operational verification began during the first week of September 1994. The initial tests performed on the battery were C/3 100% DOD cycles with C/9 recharges. The electrical interfaces between SNL's tester and SPI's BMS were evaluated in October, after which they underwent constant-current C/3 test cycles. Figures 5-14 and 5-15 show examples of typical cycles. The capacity of the battery started declining in November 1994. Data analysis indicated that some string failures probably had occurred. Testing continued through December 1994 using C/3 80% DOD cycles while a determination was being made as to which banks were affected by possible string failures.

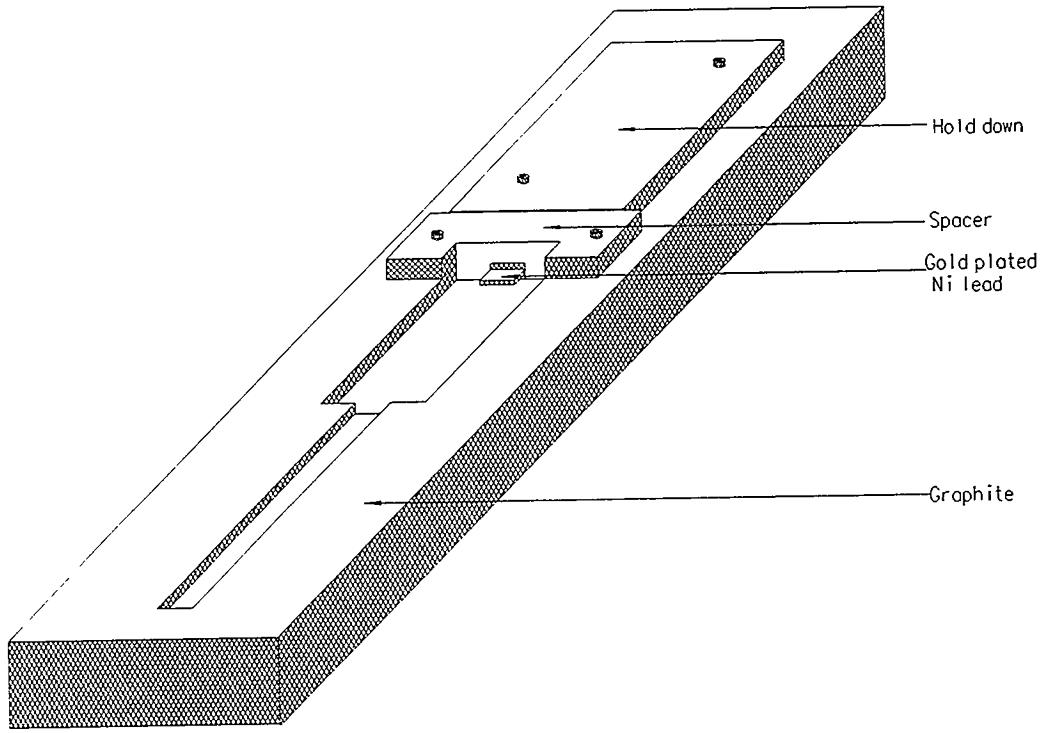



Figure 5-13. Modified Mold for Casting Prototype Thermal Fuses.

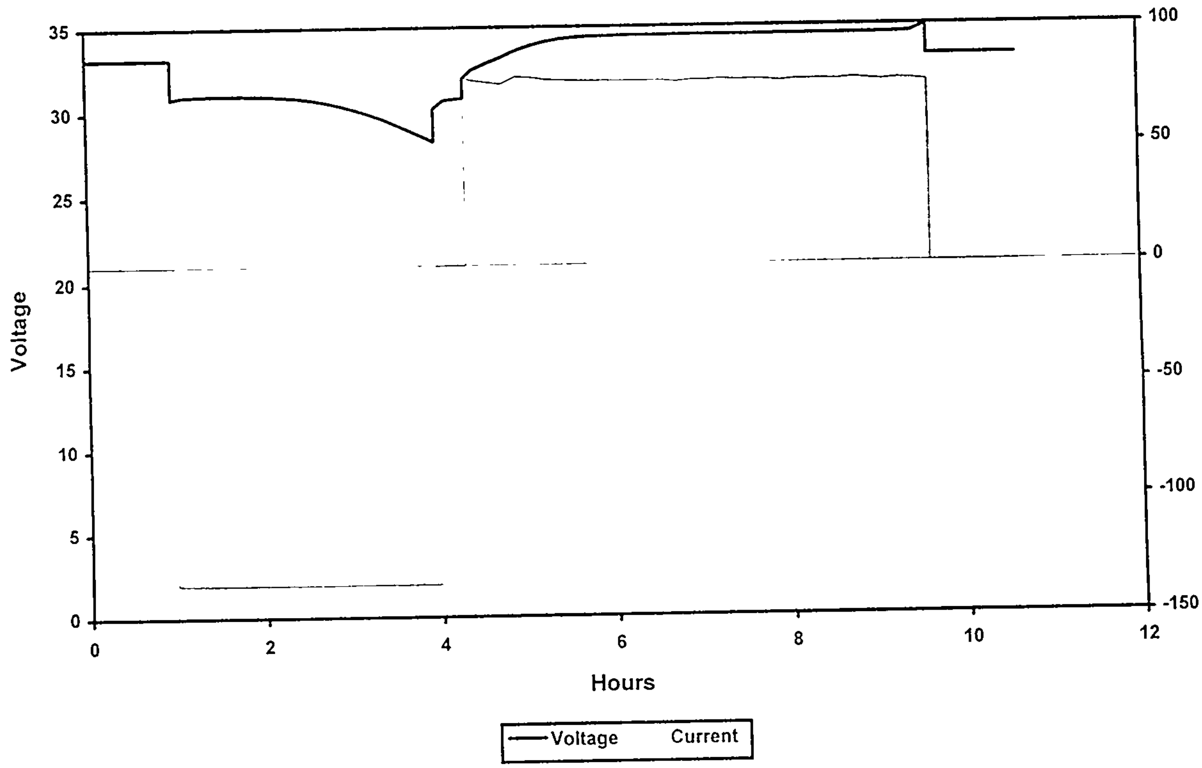



Figure 5-14. ID615: Cycle 69, Constant Current.

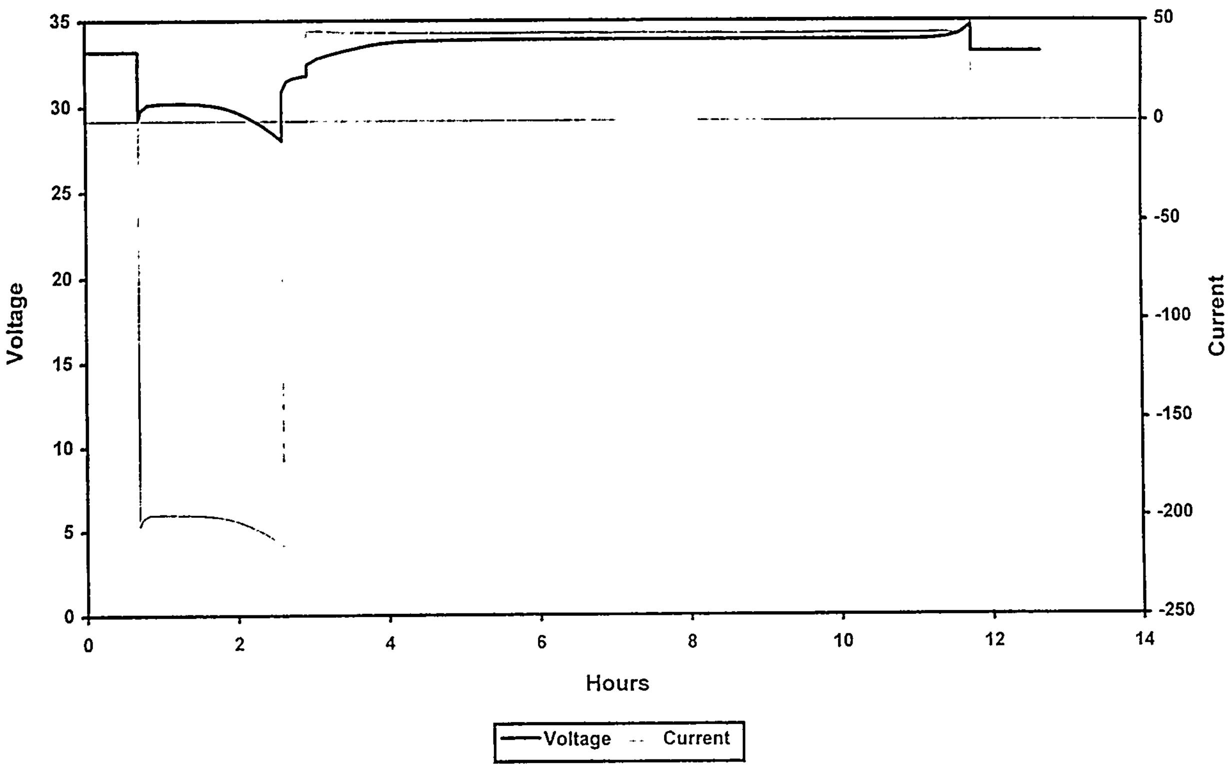



**Figure 5-15. ID615: Cycle 53, Constant Power.**

At the beginning of January 1995, the battery had completed 114 cycles and had a BMS calculated capacity of 353 Ah, down from the rated capacity of 400 Ah. There was a concern that an internal short might have developed within Bank 1. To check for an internal short, Bank 1 was discharged into the single-phase (variable-voltage) region, and open-circuit voltage was monitored over a weekend. A small leakage current of 42 mA was detected that was found to be caused by the power supplies within the tester. The power supplies were disconnected during open-circuit monitoring and individual bank charging to eliminate the drain on the battery.

The banks were charged individually, and another series of tests was performed during the first week of February 1995. On Cycle 124, Bank 1 was discharged to 7.2 V, and the open-circuit voltage was monitored on all four banks. A step in the voltage monitor curve was observed. Figure 5-16 shows the occurrence of this step approximately 30 hr after the end of discharge. This step in the voltage monitor curve corresponds to a 6-W load and indicates that something was happening within Bank 1. Figures 5-17 through 5-19 show the voltage monitor curves for Banks 2 through 4, which are normal. Additional tests were performed to verify the Bank 1 voltage changes.

The calculated capacity of the battery was 327 Ah for Cycle 124. As testing continued, the capacity continued to fluctuate and drop. Table 5-4 summarizes the calculated capacity for Cycles 124 through 133.

Battery testing was discontinued on February 20, 1995, with a calculated capacity of 296 Ah after 133 cycles. The BMS was fully operational, and a significant amount of experience was obtained in the use of the system. The other objectives of the testing (the application-specific and extended-life-cycle portions) were not completed because of the premature failure of Bank 1. The battery was shipped to SPI in Salt Lake City for PTA.

The PTA of the UES battery was performed by SNL and SPI personnel during August 1995. The battery was disassembled down to individual four-cell strings. There was no breaching or bulging of any of the cell cases, and only two possible seal leaks were observed. The instrumentation and heater assemblies were intact. There was no obvious physical evidence of what caused the Bank 1 reduced capacity during testing. X-rays of the individual strings will be performed to determine what, if any, internal damage exists within the cells.

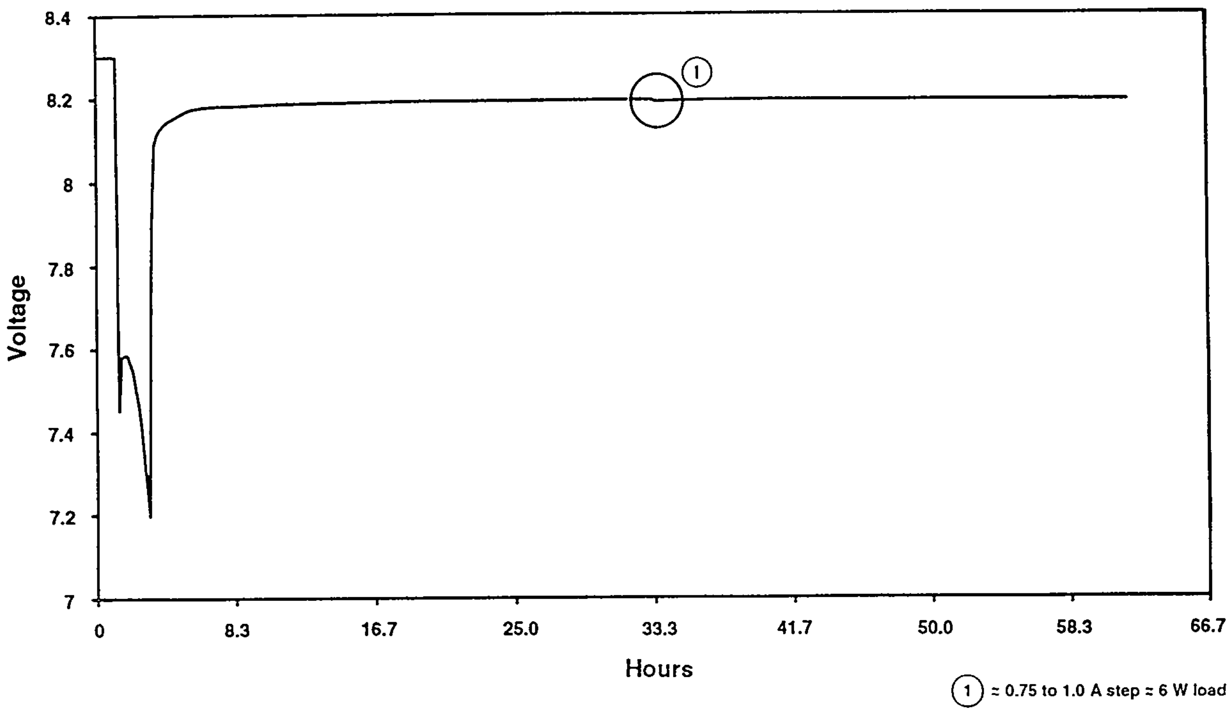



Figure 5-16. Cycle 124 Discharge and Hold, Bank 1 Open-Circuit Voltage Monitor (note drop in voltage level, = 6-W load).

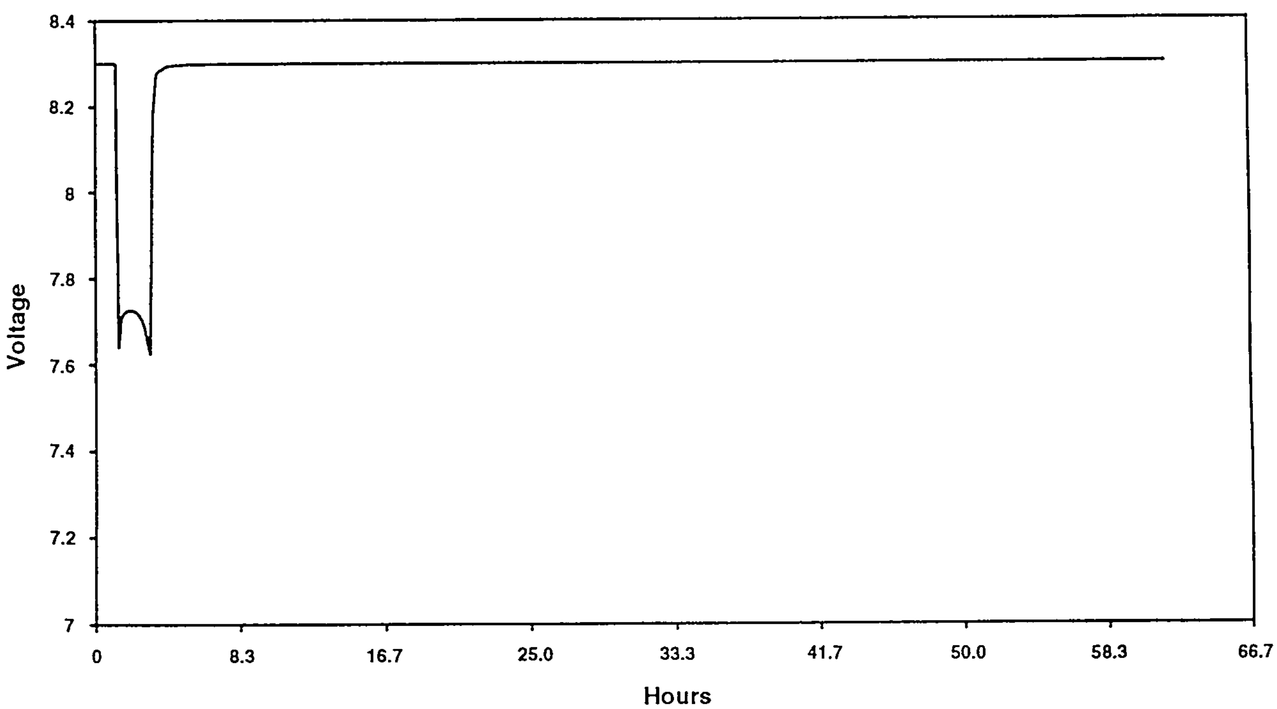



Figure 5-17. Cycle 124, Bank 2 Open-Circuit Voltage Monitor.

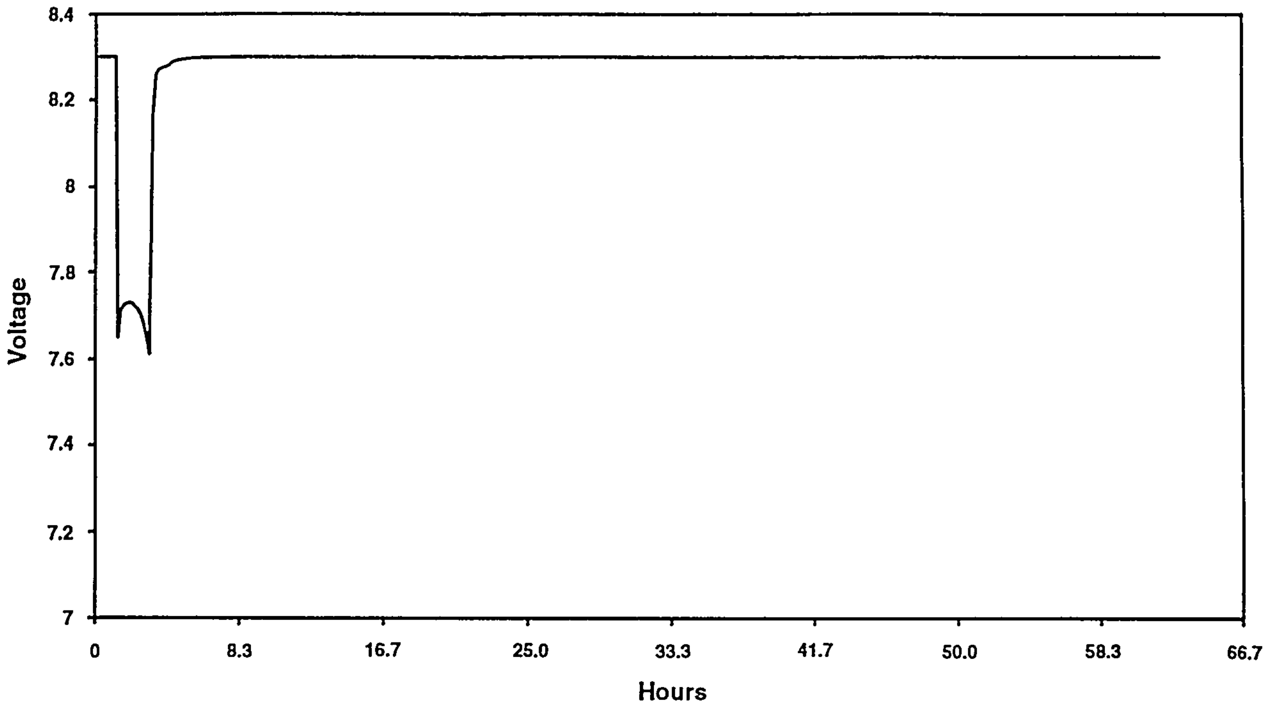



**Figure 5-18. Cycle 124, Bank 3 Open-Circuit Voltage Monitor.**

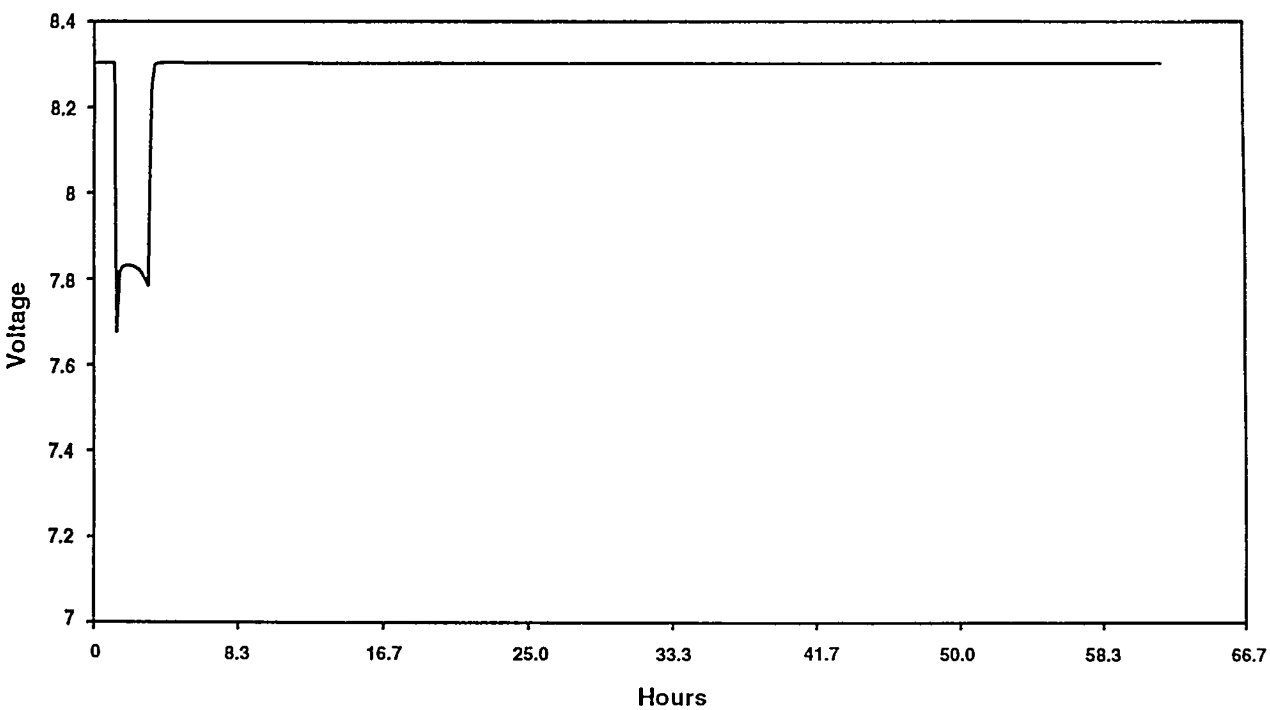



**Figure 5-19. Cycle 124, Bank 4 Open-Circuit Voltage Monitor.**

## Table 5-4. Cycle Number vs. Calculated Capacity for the SPI 12-kWh Utility Battery

| SNL Cycle No. | Calculated Capacity (Ah) |
|---|---|
| 124 | 327 |
| 125 | 298 |
| 126 | 307 |
| 127 | 313 |
| 128 | 292 |
| 129 | 298 |
| 130 | 294 |
| 131 | 299 |
| 132 | 295 |
| 133 | 296 |

# 6. System Integration

The System Integration element is aimed at developing totally integrated BES systems. The objective is to develop several battery system designs that can meet the various application requirements in the utility operating environment. A modular system design approach is being promoted in all UBS system engineering and system integration activities to reduce production costs. Initiatives addressing the use of BES systems in power quality systems, hybrid generation systems, renewable energy systems, and transportable multi-megawatt systems are currently in progress.

## Hybrid System Controller and PCS Development Project – Omnion

In FY94, under a project jointly sponsored by the UBS and Photovoltaic Programs Departments, a contract was placed with Omnion Power Engineering Corporation of East Troy, Wisconsin, to design and develop a hybrid PCS (one that operates as either a voltage or current source) and power management control system that will provide seamless transfer among various power sources available to the system. Although the system is designed around a battery storage device, a PV source, and a DG, the controls are designed to be generic in nature, allowing a variety of different battery types to be used as the storage source and various power generation sources, such as wind turbines and PV arrays, to be used to provide a renewable power source to the hybrid system. A DG is needed as a backup power source for when the battery is depleted and requires charging and the renewable resource is not available. A primary goal for the design is to enable power to be selected and switched among the sources with no effect on the load. In other words, the load would not be subject to power fluctuations during the selection and switching process.

The hybrid PCS will be designed to operate as either a voltage source or a current source. In the voltage source mode, the hybrid controller will establish the line frequency in a self-commutating mode and operate as a generator using either the renewable resource or the battery as a power source. In the current source mode, the PCS will self-commutate and synchronize to the DG line frequency and supply power to supplement the output of the DG. This mode will be useful in the event the DG cannot supply the full load required and additional power is needed. This supplemental power will be provided from either the renewable source or the battery.

The successful completion of the development of the hybrid power management system is expected to lead to the development of a "smart controller." This controller will evaluate the operational environment and make decisions as to the most efficient source of power by checking the status of the various power sources. The ultimate goal of the development effort is to provide a turnkey control solution for future off-grid power systems that will operate autonomously, with minimal operator intervention.

Field testing of the hybrid PCS and power management system will be conducted at the SNL PSEL.

### Tasks/Milestones

A contract was placed with Omnion Power Engineering of East Troy, Wisconsin, to modify an SNL-owned AC Battery module so that it would operate as both a voltage and current source and provide seamless transfer between power sources consisting of a renewable source (PVs), a storage device (battery), and a DG.

FY95 Milestones:

- Demonstrate seamless transfer capabilities of Hybrid System (1/95) – completed 1/95.
- Deliver modified AC Battery module to SNL for PV/Hybrid demonstration (3/95) – completed.
- Identify a field test candidate for the controller (9/95) – rescheduled to 6/96.

### Status

During the first quarter of FY95, fabrication and checkout of the Hybrid System Controller and PCS was completed at Omnion Power Systems. However, early in the second quarter, a design modification was proposed to reduce the system input DC levels to less than 600 VDC. The purpose of the revised specification was to bring the system into compliance with the 600 VDC limitations imposed by the National Electrical Code, which levies special requirements on systems that operate above 600 VDC. The impact on the overall performance of the hybrid PCS and controller was expected to be minimal. The modifications were completed in early

February. Although the DC range for the PCS was revised downward to operate in the 325-588 VDC range, the lower voltages did not result in a derating of the system, which continues to be rated at 31 kW.

Witness testing of the operational hybrid PCS and power management system was conducted by Omnion engineers in the presence of SNL battery and PVs representatives. Under various load conditions and power ranges, seamless transfer among the various sources with only minor aberrations in the voltage waveform was observed. The inconsequential aberrations were not of sufficient magnitude to cause any problems for a sensitive load. All functions of the power management controller were successfully demonstrated using an AC Battery module battery string, a PV-simulation DC voltage source, and a 75-kW DG. As a result of the successful completion of the witness testing, the system was accepted for field testing at SNL; however, several minor hardware fabrication tasks remained to be completed before delivery to SNL. The Hybrid System Controller and PCS was shipped to the SNL PSEL in early April 1995.

Using installation documentation provided by Omnion Power Engineering Corporation, the Hybrid System Controller was successfully interconnected with PSEL resources consisting of a 750-kWh battery, an 85-kW DG, and a 15-kW PV array. Loads were provided by a 3-phase grid interconnection and various reactive and resistive components. Robert Schneider of Omnion was present for the shakedown tests, which were completed successfully. Shakedown testing consisted of the demonstration of all functional modes specified in the SOW. Following the shakedown tests, the Hybrid System was extensively tested to verify the seamless transfer among the various energy sources under a broad range of load power factors and magnitudes. In all cases, the Hybrid System successfully transferred between the sources with no disruption of power to the loads.

Following characterization testing at the SNL PSEL, the Hybrid System was integrated with a Daystar fuzzy-logic controller to determine the performance of both the Hybrid System and controller in a simulated operational environment. The system was set up to supply power to a load by cycling among the energy sources and selecting the most efficient source as determined by the fuzzy-logic controller. The controller monitored several system parameters, such as insulation levels for PV availability, load demands, and battery SOC, in determining which energy source would be activated to support the load. Several weeks of testing and debugging of the fuzzy-logic controller software yielded useful data on how the system would function in a simulated operational environment, although additional testing is necessary to fully evaluate this controller. This testing was completed in May 1995, and the system was placed into storage in June 1995. A complete report is being prepared by the PSEL test team. Release of the final report is expected in the first quarter of FY96.

The seamless transfer among energy sources is of major importance for off-grid applications, which require a continuous and reliable electric energy source. The successful demonstration of this functionality in the Hybrid System is indeed noteworthy. Many off-grid applications can benefit from this type of automated controller. Through the use of the fuzzy-logic controller, the most efficient source, whether it is batteries, diesel, or a renewable source (PV or wind generation), can be activated to support the loads. Use of this type of system will result in reductions both in diesel run-time and in the use of renewable resources, with the battery providing the dispatchability of energy initially generated by the most efficient source.

## 250-kW Bridge Development Project – Omnion

The first requirement for the development of the AC Battery PQ2000, a power quality management BES system, is to design, fabricate, and test a 250-kW bridge that is to be used on each of the eight modules to convert DC to a 60-Hz AC source. In putting development of the PQ2000 on the fast track, the development of the 250-kW bridge is considered the item with the longest lead time and the highest risk. The purpose of this development is to design, fabricate, and test a three-phase, 82-kW-per-phase bridge and control firmware for the PQ2000. This effort will identify the components needed to handle the thermal buildup in the bridge components.

The PQ2000 design goal is to operate each of the eight modules at 250 kW for a period of up to 10 sec to arrive at an aggregated 2-MW output power. Thermal considerations for the short energy burst constitute the primary driver for the design; however, the target for the final design will be to provide 2 MW of power for up to 25 sec.

### Tasks/Milestones

A task order was placed with Omnion late in the last quarter of FY94 to design, fabricate, and test the 250-kW bridge for the PQ2000 development effort.

FY95 Milestones:

- Complete the design of a 10-sec, 250-kW bridge (1/95) – completed 1/95.
- Complete testing of 250-kW bridge (6/95) – completed 8/95.

## Status

A Preliminary Design Review for the 250-kW bridge was held at Omnion on September 23, 1994. At that meeting, a preliminary design specification was reviewed and full-scale development was initiated. Development continued at a fast pace throughout the first quarter of FY95. Development of a single-phase bridge was completed, and testing began in January. Goals of the testing were to determine the correct design of the snubber circuit and select the most reliable IGBT for the bridge in order to minimize the effects of the high current surge transients. Both goals were realized, and testing continued to yield information on the ultimate performance capabilities for the bridge. At the end of the second quarter, full-power tests were being conducted to determine the thermal limits for the system. The design team revised the run-time targets to 90 sec in an attempt to enhance the robustness of the design and expand the capabilities of the complete system. The design specification remains at 10 sec.

It was demonstrated during testing that all bridge components were capable of operating for at least 60 sec at full power. Extension of the run time to the 90-sec target was limited by the thermal response of the reactors. A new reactor design will eliminate this problem. The new reactors will remove the run time restrictions, and the target duration time should move toward the 90-sec run time design goal.

During the third quarter, after receiving redesigned filter chokes, the complete 3-phase, 250-kW bridge and associated electronics were assembled and checked out. Figure 6-1 is a photograph of the test setup of the 250-kW bridge in the Omnion fabrication and test facility. Early in the test program, overheating problems in the redesigned PCS output filter chokes were noted again, delaying full-power testing until after delivery of new chokes in late July. Final design and fabrication of the PCS control boards was completed while waiting for the new filter chokes.

Full-power testing of the bridge and PCS was completed in mid-August 1995. Although the initial design specification called for a 10-sec operating period, each power component of the complete bridge was tested for an operating period of 90 sec at full power to ensure that sufficient thermal margin was available after final assembly of the packaged system. All power components passed the 90-sec thermal bench test. The 250-kW bridge development project was successfully completed during the fourth quarter of FY95.

# AC Battery Follow-On Tasks – Omnion

Several important tasks were not completed following delivery of the AC Battery PM250 prototype because of funding limitations in the original contract. Several contracts were placed with Omnion Power Engineering to complete these tasks. One contract was placed to support maintenance requirements of the PM250 during field testing at San Ramon, California, during FY94 quarters 3 and 4 and FY95 quarters 1 and 2. The purpose of this contract is to provide field engineering support and repair materials for hardware failures and maintenance during the characterization and life testing of the PM250 prototype. A second contract was placed to complete the final report and cost projections for the AC Battery prototype development program. The purpose of this contract is to complete the documentation for the AC Battery project.

## Tasks/Milestones

- Provide on-site repair services during PM250 prototype field testing (as required, FY95, quarters 1 and 2) – completed.
- Complete and deliver the AC Battery Project Final Report (6/95) – rescheduled to 3/96.
- Complete and deliver the AC Battery Component Cost Analysis Report (6/95) – rescheduled to 3/96.
- Complete AC Battery PM250 retrofit (9/95) – rescheduled to 4/96.

## Status

The AC Battery maintenance contract with Omnion expired in early April. Responsibility for all follow-on maintenance of the AC Battery PM250 Prototype was delegated to AC Battery Corporation, East Troy, Wisconsin. After placement of the AC Battery maintenance contract, AC Battery Corporation assumed responsibility for coordinating the AC Battery retrofit activities in progress at Delphi Energy Systems, Indianapolis, Indi-

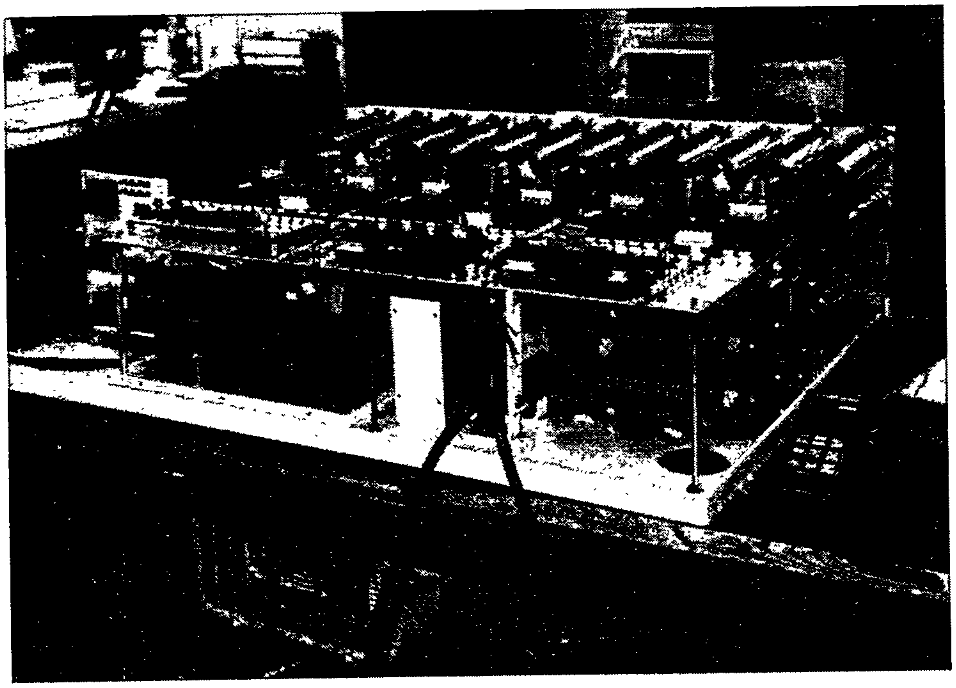


**Figure 6-1. PQ2000 250-kW Bridge Undergoing Bench Testing at Omnion.**

ana. Omnion continues in a consultant role in support of the AC Battery Test Program.

After the PM250 modules were shipped to Delphi Energy Systems, Indianapolis, Indiana, the decision was made to retrofit the modules with Delco 2000 batteries while the new Delco AES 2010 battery was undergoing Delco acceptance testing. SNL requested that the complement of control computers be shipped to Delphi so that the Delphi AC Battery PM250 system could be operated using the PG&E Win-SCADA control program. PG&E agreed and, after the system was successfully integrated with the Delphi Container, cycle testing resumed. Because of interference caused by the intense activity on the PQ2000 module development and battery selection, the AES 2010 acceptance testing was delayed until late in the fourth quarter, and resumption of testing of the retrofitted PM250 at PG&E will be rescheduled for the third quarter of FY96.

Little progress was made during the year on the AC Battery follow-on contract, which called for the completion of the AC Battery Project Final Report and the AC Battery Component Cost Analysis Report, as most of Omnion's resources were dedicated to the development of the 250-kW bridge and PQ2000 container design and fabrication. With the completion of the PQ2000 projects, Omnion will again concentrate on completing this important documentation. Delivery of these reports has been rescheduled for the second quarter of FY96.

## DOE Cooperative Agreement for PQ2000 Development – Omnion

In the last quarter of FY94, a Cooperative Agreement was placed by DOE/Office of Utility Technologies (OUT) through DOE/AL with Omnion Power Engineering Corporation of East Troy, Wisconsin. SNL was tasked by DOE/OUT with providing a Technical Advisor to assist DOE/AL in managing the development of the AC Battery PQ2000, a 2-MW, 10-sec BES system. The project is jointly sponsored by PG&E, DOE/OUT, SNL, the State of Wisconsin, Omnion Power Engineering Corp., and AC Battery Corporation. The PQ2000 is a power quality BES system functioning as a voltage source to provide ride-through capability for over 95% of the power quality problems experienced by utility customers. An additional capability to be designed into the system is a control capability that will activate a backup generator for providing power in the event the utility power loss is more than 10 sec in duration.

The two areas of highest risk for the project have been identified as the development of the 250-kW bridge (status reported above) and the acquisition of a 2-MW static automatic transfer switch (SATS) required to control the PQ2000/utility interface. Omnion was tasked with identifying and selecting the vendor for the static switch by the end of the second quarter FY95.

Following factory testing, the PQ2000 will be moved to PG&E for field testing. After approximately six weeks of testing at the PG&E MGTF, plans call for additional field testing to take place after the installation of the PQ2000 at a PG&E customer site.

## Tasks/Milestones

- Preliminary Design Review (1/95) – completed 1/95.
- Selection of vendor for static switch (3/95) – completed 4/95.
- Completion of factory testing (9/95) – rescheduled to 1/96.

## Status

Early in the first quarter of FY95, work began at Omnion on the Cooperative Agreement placed by DOE/AL to support the design, fabrication, and testing of the first AC Battery PQ2000. The first meeting of the PQ2000 Design Team was held in Milwaukee in early January 1995. At this meeting, the preliminary design review was conducted and the initial schedule for development of the PQ2000 was presented. Under this schedule, PQ2000 development would be completed in less than 1 yr. Although the schedule was extremely aggressive, the Team agreed that the delivery of the first PQ2000 could be made during the first quarter of FY96.

The second meeting of the PQ2000 Design Team was held in April 1995 at PG&E headquarters in San Francisco, California. At that meeting, Delphi Energy Systems reported that a standard production battery, the Delco 1150, had been identified for potential use in the PQ2000 and was undergoing testing for suitability in the PQ2000 operating environment. Delphi also reported that the July 1995 delivery of the eight PQ2000 modules with the full battery complement was on schedule. Omnion announced that PDI of Sandston, Virginia, a company with broad experience in SATS technology, has been selected to design and fabricate the 2-MW SATS for the PQ2000. The selection of PDI was considered a major milestone for the successful delivery of the SATS by August 1995.

The final meeting of the PQ2000 Design Team was held in early August at Omnion in East Troy, Wisconsin. The purpose of the meeting was to review progress to date and to resolve several technical issues that had the potential to jeopardize the schedule. A primary decision reached at the meeting was to postpone the development of the DG startup control unit as it was expected to extend the schedule for 3-6 mo. A second issue that concerned the team was a request, made in response to test results up to that time, to extend the run time to 20-30 sec. The team decided to stay with the original 10-sec specification. Following the formal phase of the meeting, a half-power test of the 250-kW bridge was observed by the Design Team. Omnion and AC Battery conducted tours for the design team of the area where the PQ2000 container (Figure 6-2) was undergoing final assembly at Omnion and, at AC Battery Corporation, of the area where the modules, complete with their battery complement (Figure 6-3), were awaiting bridge installation.

The scheduled time for factory testing of the PQ2000 has slipped to late in the first quarter of FY96. Several factors are responsible for the delay. One, the delivery of the SATS shown in Figure 6-4 slipped nearly 2 mo because of component acquisition problems experienced by PDI. The delay was also caused, in part, by the extended period for final testing of the 250-kW bridge. There were also delays in the receipt of several critical components needed for final bridge assembly and in the design of the printed circuit boards for the 250-kW bridge control circuits. At the end of FY95, witness testing and customer acceptance was scheduled for December 28, 1995.

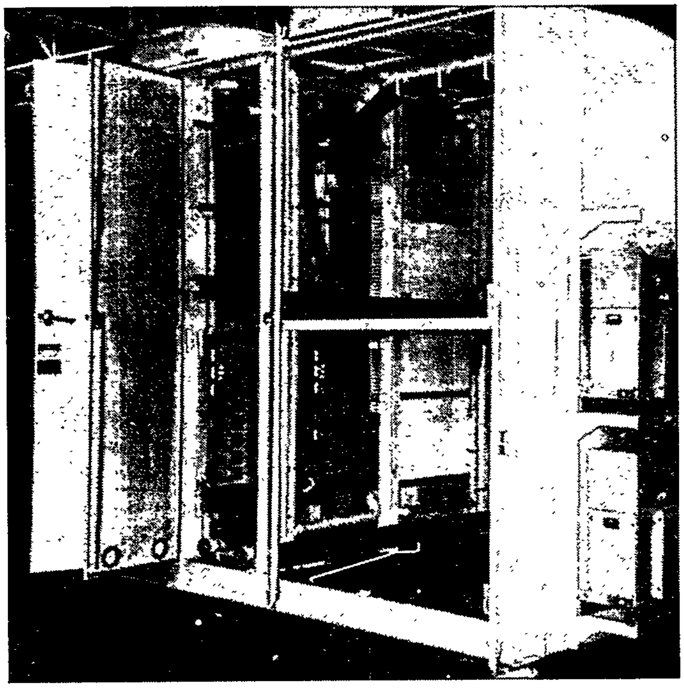


**Figure 6-2. PQ2000 Container during Final Assembly at Omnion.**

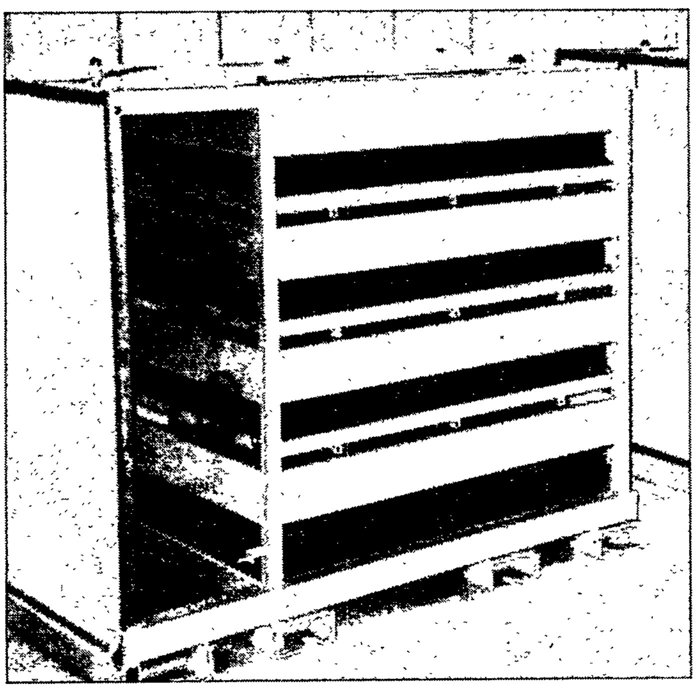


**Figure 6-3. PQ2000 Module with a Full Complement of 48 Batteries.**

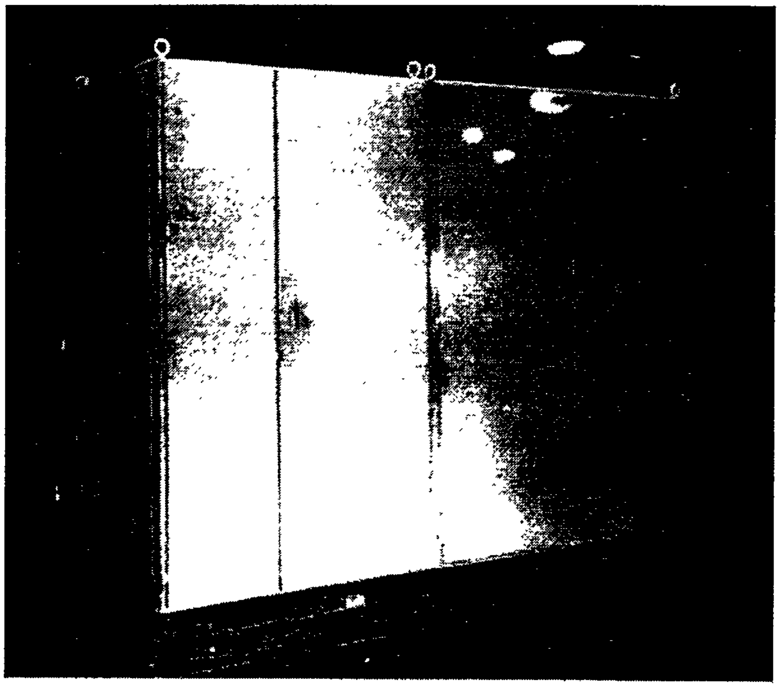


**Figure 6-4. SATS Ready for Shipping from PDI to AC Battery Facilities.**

# 7. System Field Evaluation

In the System Field Evaluation element, the qualification of hardware incorporating the prototype design and associated manufacturing methods represents the final step of engineering development. The process involves the characterization of performance, maintenance requirements, and reliability of integrated systems at relevant utility sites. Current field evaluation programs include life testing of the AC Battery PM250, field testing of the AC Battery PQ2000 (development jointly sponsored by PG&E, DOE/OUT, the State of Wisconsin, and AC Battery Corporation), testing of the Hybrid System Controller and PCS, and the zinc/bromine BES system.

## Testing of Hybrid System Controller and PCS – SNL

Testing of the Hybrid System Controller and PCS was performed at the PSEL at SNL. A PV source, a battery storage system, and a DG were used as the primary power sources for testing the controller. Tests evaluated the seamless power transfer capability of the controller in a highly reactive load environment up to the full 31-kW power rating of the PCS. Also evaluated was the overall system performance, including power quality, electromagnetic interference (EMI), and capabilities for managing the off-grid power requirements. An intelligent control system was used to test the system in a stand-alone operational environment consisting of a PV array, a battery storage system, and a DG. The goals of this test are twofold. The first goal was to evaluate the operation of the Hybrid controller under an automatic external controller to determine the capability of the controller to operate effectively in a totally hands-off environment. The second goal was to evaluate the performance of a fuzzy-logic intelligent control system and its capability to effectively automate a multisource, off-grid power system.

### Tasks/Milestones

- Complete initial testing at the SNL PSEL (5/95) – completed.

### Status

The Hybrid System Controller and PCS was delivered to the PSEL in early April 1995. Figure 7-1 is a photograph of the Hybrid System Controller installed in the PSEL. The PSEL is capable of providing all the inputs and loads that the hybrid system controller was designed to manage. The Hybrid Controller was subsequently interconnected to existing PSEL resources consisting of a 750-kWh battery, an 85-kW DG, and a 15-kW PV array. Loads were provided by a 3-phase grid interconnection, and various reactive and resistive components were provided for power factor testing. Test plans included shakedown testing, characterization testing (testing the hybrid controller in highly reactive load conditions to evaluate the effect of stressful loads on the seamless switching capability), and simulated operational testing, including implementing a controller that provided intelligent decisions on the optimal source to activate based on the availability of PV power and the SOC of the battery. A controller manufactured by Day Star was available at the PSEL for this phase of testing.

Shakedown testing, consisting of the demonstration of all functional modes specified in the SOW, was completed successfully. Following the shakedown tests, the Hybrid System was extensively tested to verify the seamless transfer among the various energy sources under a broad range of load power factors and magnitudes. In all cases, the Hybrid System successfully transferred between the sources with no interruption or corruption of power to the loads. While the system was under test, complete autonomy of the system was maintained, with the various sources operating interactively to supply power and charge batteries as commanded by the controller.

The seamless transfer among energy sources is of major importance for off-grid applications, which require a continuous and reliable electrical energy source. The successful demonstration of this functionality in the Hybrid System is indeed noteworthy. Many off-grid applications can benefit from an automated controller. Implementation of this type of system in an operational environment should result in more efficient use of DGs for load support and battery charging, where they can be operated at near 100% capacity. When available, renewable resources would operate as the primary energy source, with the battery providing system stability by stiffening up the mini-grid.

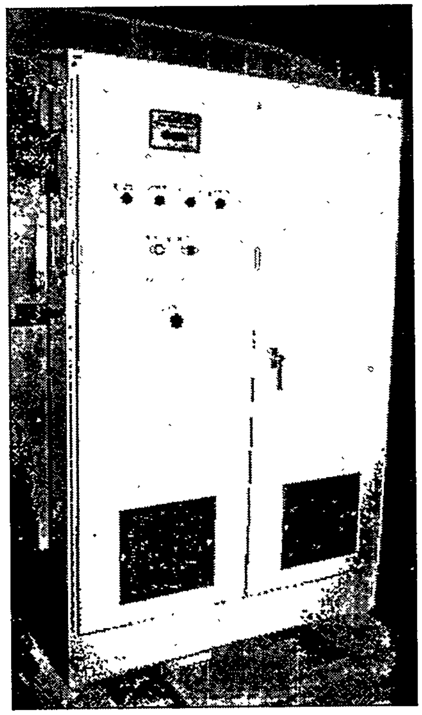


**Figure 7-1. Hybrid System Controller Installed at the SNL Photovoltaic Evaluation Laboratory.**

After completion of characterization tests, the Hybrid System Controller and PCS was interfaced with a fuzzy-logic controller to test the feasibility of using this type of controller in an automated hybrid system. Initial results indicated that this type of controller has high potential in a hybrid environment.

Testing of the fuzzy-logic controlled environment was terminated in early June, and the system was placed in temporary storage with plans to resume testing in FY96. A formal report on the results of the testing is expected to be published by the PSEL test team in late FY95.

Future test plans include operating the system in a field environment under the control of a fuzzy-logic controller to demonstrate the fully automated capabilities of the system in supplying reliable, high-quality power in an off-grid environment.

## Testing of AC Battery PM250 – PG&E

In FY93, a cost-shared contract was placed by SNL with PG&E of San Ramon, California, to test the AC Battery PM250 prototype then under development by Omnion Power Engineering Corporation. Testing of the PM250 was planned at the PG&E MGTF, a unique test facility owned and operated by PG&E where pre-commercial prototypes of various utility-generation sources can be tested in a controlled environment.

Following completion of characterization testing in March 1994, the PM250 was tested in a cycling mode until July 1994, when the batteries began to exhibit end-of-life performance characteristics. The PM250 Test Team decided to withdraw the unit from further testing until the batteries were replaced with the AES 2010 production battery developed by AC Delco Systems. Following retrofit of the complete battery complement, scheduled for completion by AC Delco Systems in the second quarter of FY96, the PM250 will be returned to PG&E so that they may continue with their test plan for the life testing of the PM250. Plans are for testing to resume during the third quarter of FY96.

### Tasks/Milestones

- Complete testing of AES 2010 retrofitted modules at AC Delco Systems (1/95) – rescheduled to 4/96.
- Complete restart testing of PM250 at San Ramon, California (2/95) – rescheduled to 6/96.

- Resume life testing of PM250 (3/95) – rescheduled to 8/96.

## Status

Throughout FY95, testing of the AC Battery Prototype PM250 at PG&E was on hold as retrofit activities continued on the eight modules at Delphi Energy Systems. After removal from the container in August 1994, the eight modules were shipped to Delphi Energy Systems, Indianapolis, Indiana, where the original Delco 2000 batteries were removed and replaced with a revised design, the Delco AES 2010 battery, which was specifically designed for the AC Battery deep-cycle application. During final testing of the new batteries, several manufacturing defects were discovered that required several months of evaluation before testing with the new battery could proceed. Consequently, the modules were loaded with a fresh complement of Delco 2000 batteries and cycling was initiated in the Delphi container in Indianapolis. During the testing period, the Delco charge algorithm was refined, and several control software problems were corrected. At the end of FY95, the eight modules had been cycled more than 150 times and the system still exhibited full capacity during benchmark tests. Manufacturing problems for the AES 2010 were corrected in late summer, and plans were formulated to complete the retrofit in the second quarter of FY96.

Life cycle testing of the PM250 Prototype with the new AES 2010 batteries will resume at the PG&E MGTF during the third quarter of FY96 as soon as the PQ2000 vacates the test pad.

# Testing of AC Battery PQ2000 – PG&E

SNL has been tasked with technical oversight in support of a DOE/OUT and DOE/AL cooperative agreement for the development and testing of the AC Battery PQ2000. Following factory testing at Omnion Power Engineering Corporation of East Troy, Wisconsin, the PQ2000 will be tested at the PG&E MGTF in San Ramon, California. PG&E will develop a formal test plan for all testing to be completed at the MGTF. The purpose of testing at PG&E will be to verify that the system operates at published specifications following transport of the system from East Troy. Following testing at the MGTF, the PQ2000 will be installed at a PG&E customer site for field testing in an operational environment. Throughout the test period, SNL will maintain technical oversight for the entire test program.

## Tasks/Milestones

Note: All milestones are managed by DOE/AL.

- Complete MGTF PQ2000 Test Plan (6/95) – completed 9/95.

## Status

At the PQ2000 design team meeting held in April 1995 in San Francisco, California, PG&E accepted responsibility for the development of a comprehensive test plan for PQ2000 field testing at the PG&E MGTF. The draft PQ2000 Field Test Plan was presented at the August 1995 PQ2000 design team meeting for initial review. General agreement was reached on the draft test plan presented by PG&E. The Design Team requested that PG&E and Omnion proceed with the development of a factory acceptance test plan, which should be ready by November 1995.

# Testing of Zinc/Bromine Factory-Integrated Battery System – PG&E

## Tasks/Milestones

The major task of the contract in FY95 was follows:

- Complete a mutually agreed upon test plan with ZBB – completed 9/95.

## Status

PG&E has been working with ZBB to develop safety plans and operating manuals for the system and to provide the documentation necessary for approval of on-site acceptance testing at PG&E. The necessary documentation has been completed and approval was given to begin on-site acceptance testing.

# 8. Industry Outreach

The Industry Outreach element of the UBS program seeks to communicate the benefits of battery storage systems to electric utilities and industrial users. Utility-scale BES has the potential to make its users more competitive in world markets. A primary cost component of production is electric power, but the loss of electric power to a production process is an expense that is not usually addressed because it is difficult to measure the economic impact. However, most electric power experts agree that the cost is very large and means to minimize power interruptions should be taken as a major step to keep the U.S. manufacturing sector competitive in world markets. BES systems appear ideally suited as a method of reducing power interruptions. Instantaneous response is the key characteristic of BES systems, and that characteristic is required to avoid power interruptions caused by frequency and voltage problems. Power quality and reliability are currently important production issues, not only in the U.S. but worldwide.

Both the economic and the power quality benefits that accrue to users of utility-scale BES systems have recently been documented. PREPA has been successfully operating a 20-MW facility since 1994. The economic and technical success of this system has resulted in a decision to augment the 20-MW system with an additional 80 MW. The PREPA success is an excellent case study because it involves an island, without outside events influencing the case results. In short, the PREPA experience proves that BES systems work.

Power outages, voltage spikes and sags, and frequency irregularities trigger cascading detrimental and costly work stoppages. The large utility-scale BES systems developed by the UBS program, properly applied, have the potential to reduce 95% of the power/voltage/frequency irregularities that cause production interruptions. This could represent a major manufacturing cost reduction in the U.S., resulting in making the U.S. significantly more cost competitive in all levels of production. The opportunity and the means to effect these cost saving needs to be communicated to U.S. industry and electric utility companies.

A major element of the FY95 Industry Outreach effort was taking the message of BES benefits to trade shows, conventions, and exhibitions. The targeted audience was utility executives, engineers, and the manufacturing sector. Five major electric utility and power-related events were attended during the year. These events were attended by more than 15,000 people interested in the electric power industry. UBS personnel chaired sessions, presented papers, and participated in the exhibits. Literature and brochures summarizing the UBS Program and communicating the benefits were distributed. The major theme presented at the exhibitions was that BES systems could save utilities and their customers money. The exhibitions emphasized not only reduced operating costs for the utilities but the much more important cost avoidance to manufacturing customers resulting from not having production interruptions.

The UBS Program also develops, hosts, and supports forums in which ideas are shared, information is exchanged, and cooperative/cost-shared projects with the private sector are initiated. These forums create opportunities to leverage limited government and private sector resources in joint projects that can expedite the early commercial introduction of battery storage systems. UBS' personnel attend and participate in various utility conventions, symposia, and expositions to illustrate the multiple benefits of battery storage. At the expositions, the DOE/SNL/UBS booth has posters that highlight the program structure and industrial partnerships as well as the program history. The posters are designed to encourage questions from and discussion with the exposition participants. Past and current electric utility participant/partners are listed. At the personal level, informal discussions are held, questions are answered, UBS literature is handed out, and requests for additional information are taken.

Following is a brief description of the trade shows and expositions in which UBS representatives participated. Figures 8-1 through 8-6 show scenes from some of these trade shows and exhibitions and depict a few of the UBS Program display materials.

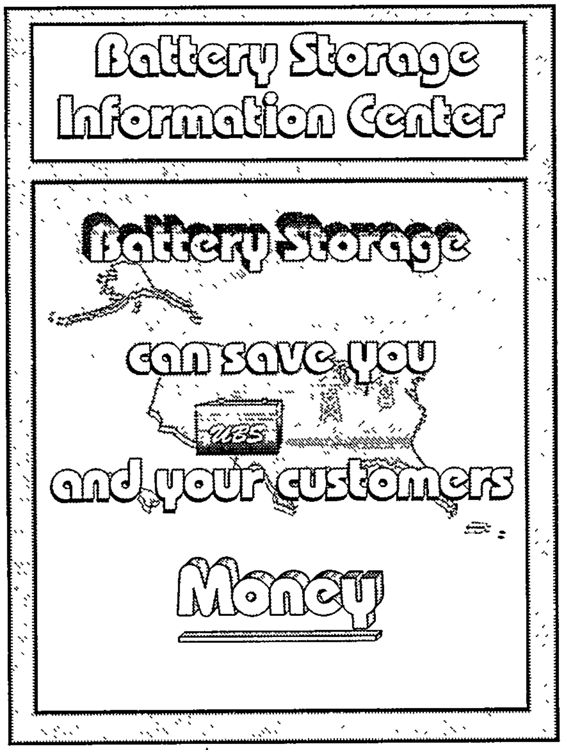



**Figure 8-1.** **UBS Poster.**

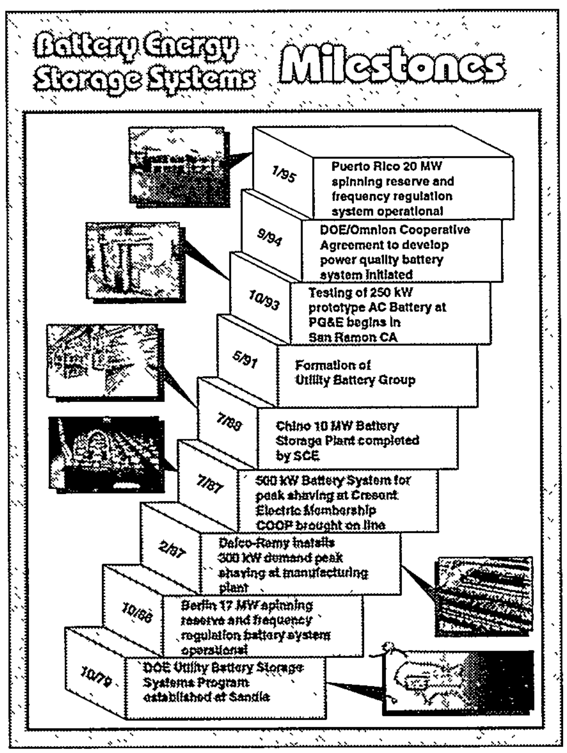



**Figure 8-2.** **Poster Depicting BES System Milestones.**

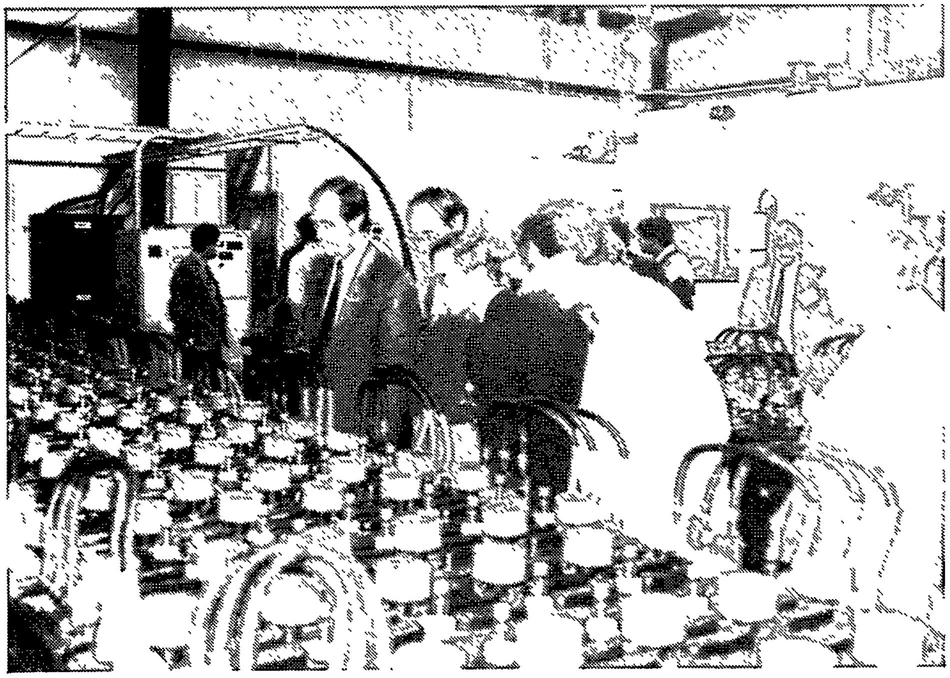


**Figure 8-3. At the Crescent Co-op.**

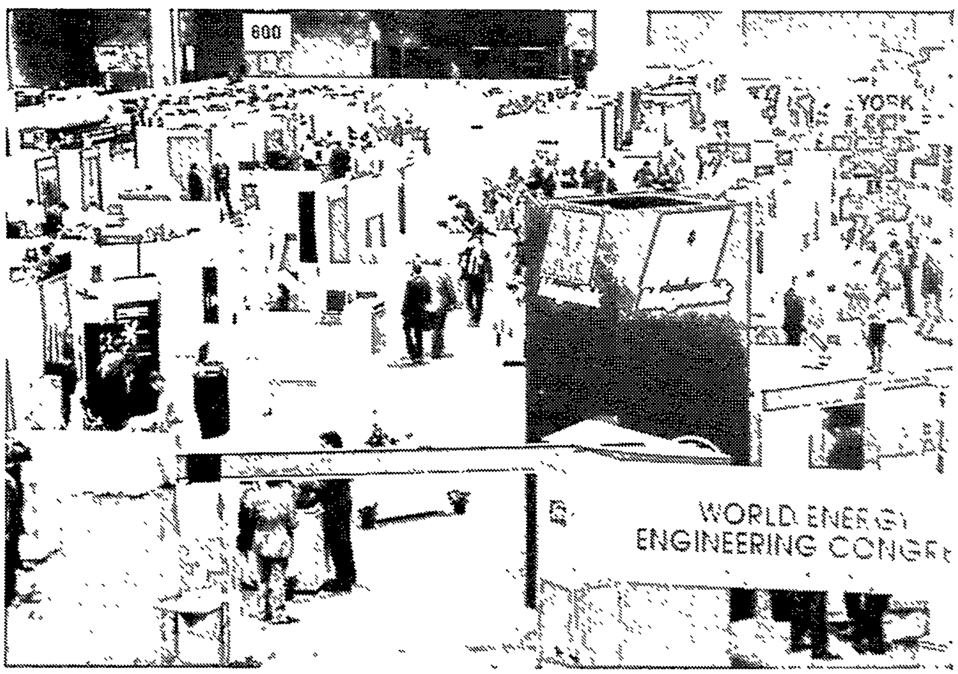



**Figure 8-4. Trade Show Exhibition.**

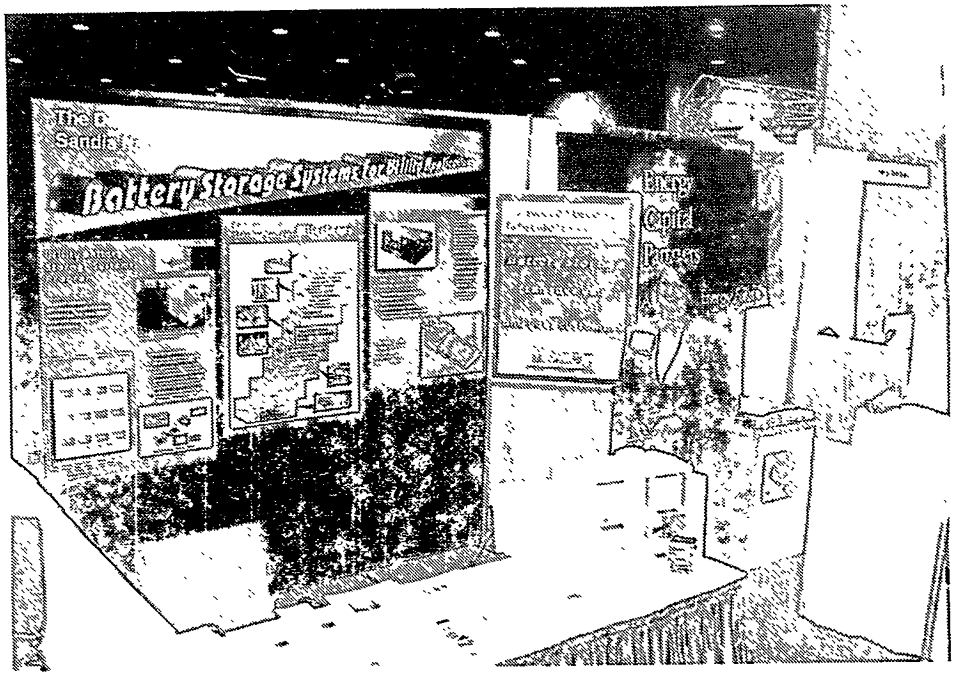


Figure 8-5. UBS Booth.

## Third International Conference on Power Quality: End-Use Applications and Perspectives, PQA '94 – Amsterdam, The Netherlands – October 22-28, 1994

The International Conference on Power Quality is held each year and is an exchange forum for discussion of power quality issues and methods used to mitigate power quality problems. This year's conference attracted more than 300 power utility professionals from more than 30 countries. During the conference, over 40 papers were presented covering power quality topics of broad interest to the European Common Market countries, North America, Africa, Eastern Europe, and the Far East. Garth P. Corey, a UBS Program staff member, attended this conference, which focused on gathering information on power quality issues that are experienced worldwide and on determining if solutions to these issues are currently available or are under development in other nations. He also presented a paper, titled "Development of a 2-MW, 10-Sec Battery System," on the development of the AC Battery PQ2000 currently in progress under the sponsorship of a partnership consisting of a U.S. Utility, the DOE, SNL, the state of Wisconsin, and Omnion Power Engineering Corporation. The paper was received with a high level of interest.

Also during the conference, interest was expressed by A.W. van der Weegen, Research Program Manager for Electricity Distribution at KEMA (a Dutch organization in Arnhem, the Netherlands, analagous to EPRI), in forming an association with SNL, perhaps with EPRI as a partner, to pursue development of mitigation techniques to solve power quality problems. He will attempt to generate the necessary support from KEMA and EPRI and, if he is successful, further discussions will be scheduled.

## Eighth Meeting of the UBG – Baltimore – November 1994

The Eighth Meeting of the UBG was held in Baltimore in November 1994 with an attendance of more than 80 participants from industry. The one-and-a-half-day agenda included technical presentations and a tour of the Delmarva PV/AC Battery demonstration site. The UBS Annual Review was held in conjunction with this meeting.

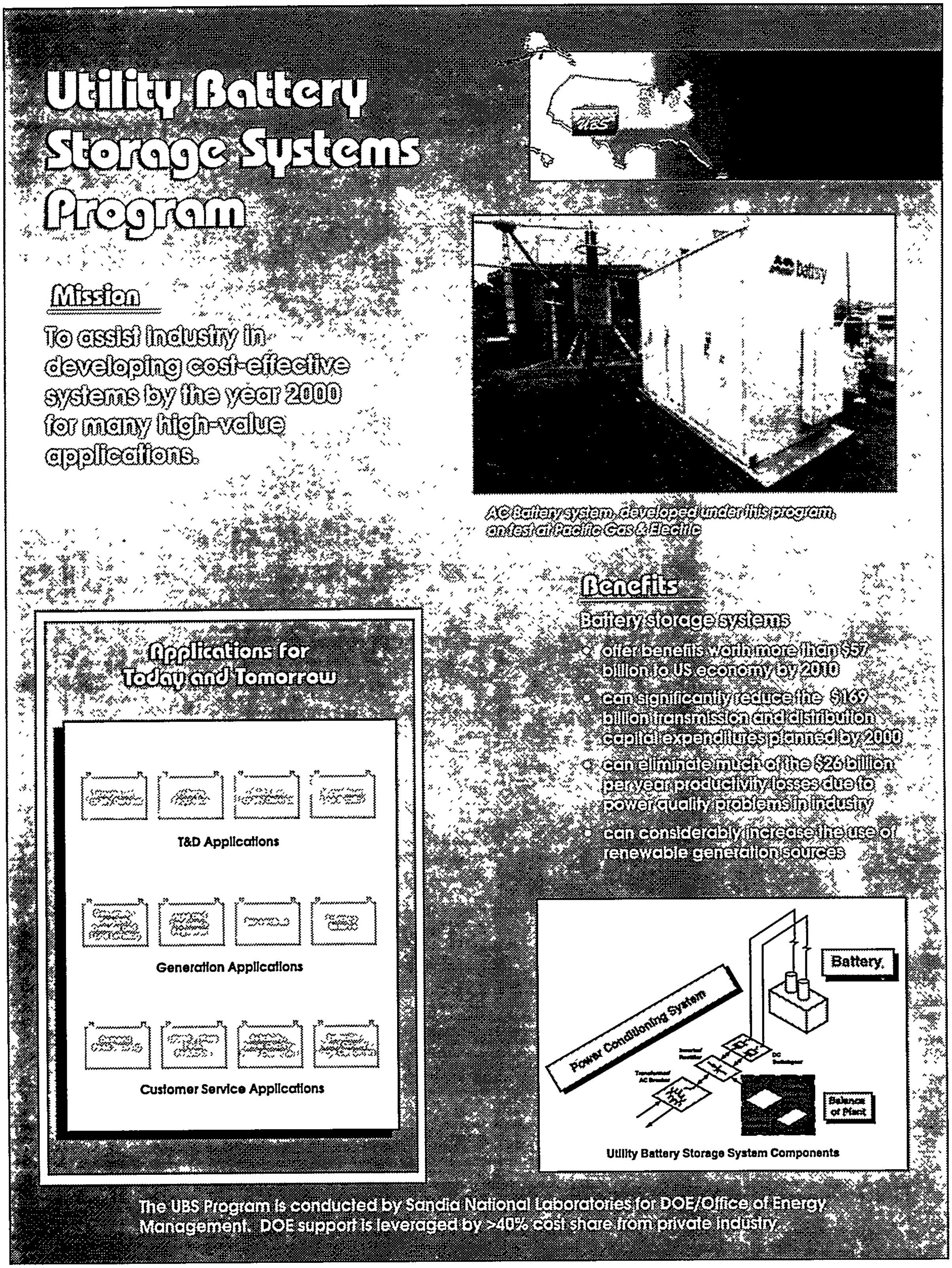



**Figure 8-6. Poster Depicting Mission, Benefits, and Applications of BES Systems.**

## DA/DSM – San Jose – January 23-27, 1995

The Design Automation/Demand-Side Management (DA/DSM) Conference and Exposition was held in San Jose, California. The UBS Program sponsored a panel session (Jon Hurwitch, Energetics; Hank Zaininger, ZECO; Chieu Nguyen, GPU; Bob Flemming, AC Battery). A booth was donated to the UBS program by the conference organizers. The booth display focused on utility applications of BES. Through these activities, utility manufacturing representatives learned about the UBS Program, the state of battery storage system technology, and its various applications. Using as a basis the responses received, a database of contacts from the conference was initiated; several of those contacts have maintained active communication with the UBS and have begun participation in the UBG.

## NRECA – Orlando – February 25-28, 1995

The NRECA 1995 Conference Exhibition was held in Orlando, Florida. UBS Programs personnel (and volunteer co-op representative Chuck Ward of Oglethorpe Power Corporation) staffed the booth. Contact was made with a cross-section of the nation's rural electric co-ops. The UBS staff published a special handout that highlighted BES systems applications at four co-ops: Crescent Electric Membership Cooperative, Oglethorpe Power Corporation, Metlakatla Power and Light, and CEA. The handout showed how BES systems were projected to overcome large load swings at Metlakatla, how a BES system could provide spinning reserve and reduce load shedding at CEA, how Oglethorpe will employ a portable BES system, the AC Battery PQ2000, to ride through voltage sags and momentary outages, and how Crescent has been using a BES system for demand peak shaving for over 9 yr. One day of the exhibition was dedicated to technical staff and one day was dedicated to upper management. During these focus days, each group was able to learn about the facets of BES that are most relevant to them. Co-op executives and engineers were added to the database. Several of those contacts are considering membership in the UBG. Follow-on activities have been initiated.

## Globalcon/RETSIE – San Francisco – April 18-20, 1995

The Globalcon/RETSIE/Exposition in San Francisco, California afforded UBS staff an opportunity to sponsor a panel session (Garth Corey, SNL; Paula Taylor, Energetics; Ben Norris, PG&E; Hank Zaininger, ZECO; Bob Flemming, AC Battery) and booth that focused on utility applications of BES that tie in with renewable generation sources. This symposium was attended by over 5,000 participants. At this conference, on the 20th anniversary of Earth Day, UBS staff contacted utility and manufacturing representatives as well as regulators. Discussions focused on the UBS Program, and the state of BES technology and its applications (especially as they relate to T&D and renewables penetration). The UBS added to its database of conference contacts; several of those contacts began active communication with the UBS and began participating in the UBG.

## IEEC – Richmond – August 16-17, 1995

The IEEC/Facilities Management and Maintenance Expo (FMME) Conference and Exhibition in Richmond had over 2,500 participants. The UBS sponsored a booth that focused on utility applications of BES. At the conference, UBS staff contacted utility and manufacturing representatives, as well as numerous representatives from military bases, that are involved in renewable generation projects to ensure system reliability. Through these contacts, the UBS added to its database; follow-on activities with military renewables projects are a possible outcome of this interaction; several contacts began active communication with the UBS and hope to participate in the UBG.

## PowerSystems World International – Long Beach – September 13-15, 1995

PowerSystems World International Conference/Exhibition was held in Long Beach, California, September 13-15, 1995. The emphasis was on systems and subsystems designed to make the systems approach a reality. Systems such as BES that support power reliability and quality were a major focus of this trade show, and therefore BES fit well within the context and was well received. One of the six "tracks" of the conference was titled "Battery Systems Engineering Forum." Two of the other tracks were on the subject of power quality. Large-scale BES developed in the UBS program fit into these forums well.

## Ninth Meeting of the UBG and the Fifth International Conference on Batteries for UES

The Ninth Meeting of the UBG was held in conjunction with the Fifth International Conference on Batteries for UES In San Juan, Puerto Rico, in July 1995. These meetings were held concurrently and were hosted by the PREPA. San Juan was chosen for the conference site because PREPA had just inaugurated a 20-MW Battery Storage Plant for spinning reserve, frequency control and voltage regulation. Whereas the economic and technical feasibility of BES systems has been shown in various parts of the world by demonstration plants later converted to commercial plants, the PREPA battery facility is the first plant to be developed as a commercially ready plant from its inception. After more than 1 yr of operation, the PREPA 20-MW BES system is a financial success for the utility. What is more important, however, is that power outages to the customers have been reduced significantly. This is a major boost to the manufacturing entities in Puerto Rico straining to compete in the world market. The Industry Outreach goal is to communicate successes such as the one in Puerto Rico so that the rest of America can achieve similar lower overall production costs and thereby create more employment.

The Fifth International Conference's agenda was to provide a forum for the discussion of recent developments and future trends in the theory, design, manufacture, application, monitoring, and operations of BES systems for electric utility companies and their customers. This conference was sponsored by EPRI, New Energy Development Organization (NEDO), and BEWAG.

# Appendix: Presentations and Publications

## Presentations

A.A. Akhil, "Battery Systems Analysis," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

A.A. Akhil, "Industry Outreach," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

A.A. Akhil, "20-MW PREPA Battery System," Eighth Meeting of the Utility Battery Group, Baltimore, MD, November 9-10, 1994.

J. Braithwaite and N. Clark, "Battery Subsystems Engineering," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

P. Butler, "The DOE Utility Battery Storage Systems Program Plan," Ninth Meeting of the Utility Battery Group, San Juan, Puerto Rico, July 17, 1995.

J. Cooley, "Energy Storage Systems for the Interconnected Rail Belt of Alaska," Eighth Meeting of the Utility Battery Group, Baltimore, MD, November 9-10, 1994.

G.P. Corey, "Development of a 2-MW, 10-Second Battery System," Third International Conference on Power Quality: End-Use Applications and Perspectives, PQA '94, Amsterdam, The Netherlands, October 22-28, 1994.

G.P. Corey, "System Integration and Evaluation," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

G.P. Corey, "Development and Testing of the AC Battery," Annual Battery Conference, California State University, Long Beach, CA, January 13, 1995.

G.P. Corey, "Overview of the U.S. Department of Energy Utility Battery Storage Systems Program Utility Scale Battery Projects," Georgia Institute of Technology Energy Committee, Atlanta, GA, January 26, 1995.

G.P. Corey, "Electrical Energy Storage Systems and Utility Scale Storage Projects," Renewable Energy Electric Technologies Assessment Roundtable, Houston, TX, February 10, 1995.

G.P. Corey, Session on "Battery Energy Storage: Timely Solutions for Public Utility, Renewables, and Hybrid Storage Problems," RETSIE Competitive Advantage '95, San Francisco, CA, April 19-20, 1995.

P. Eidler, "Zinc/Bromine Battery Development," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

R. Jungst, "PREPA Battery Testing at SNL," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

S. Klassen, "Applied Research Projects," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

A.A. Koenig, "NaS-$P_{ac}$: A Compact Energy Storage Device for Utilities," Fifth International Battery Energy Storage Conference, San Juan, Puerto Rico, July 1995.

A.A. Koenig, "Sodium/Sulfur Battery Development," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

H. Meyer, "AC Battery Development," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

B. Norris, "AC Battery Testing at PG&E," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

B. Norris, "Utility-Scale Battery Demonstration," Eighth Meeting of the Utility Battery Group, Baltimore, MD, November 9-10, 1994.

J. Szymborski, "VRLA Battery Development," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

P. Taylor, "Opportunities Analysis," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

R. Winter, "PG&E Battery Application Study," UBS Program Contractor's Conference, Baltimore, MD, November 8, 1994.

## Publications

P. Butler, *Battery Energy Storage for Utility Applications: Phase I – Opportunities Analysis*, Sandia Report, SAND94-2605, October 1994.

P. Butler and P. Taylor, *Opportunities for Battery Energy Storage in the Electric Utility Industry: Phase I Results of an Analysis of an Electric Utility Battery Energy Storage Program.* Fifth International Battery Energy Storage Conference, San Juan, Puerto Rico, July 1995.

G.P. Corey, *Development and Testing of the AC Battery*, Tenth Annual Battery Conference on Applications and Advances, California State University, Long Beach, CA, January 13, 1995.

A.A. Koenig, *NaS-$P_{ac}$: A Compact Energy Storage Device for Utilities*, Fifth International Battery Energy Storage Conference, San Juan, Puerto Rico, July 1995.

A.A. Koenig, *NaS-$P_{ac}$ System for Industrial Applications, Workshop: Summer Study on Electrical Efficiency in Industry.* American Council for an Energy Efficient Economy, Grand Island, NY, August 1995.

P.J. Lex and P.A. Eidler, *Demonstration of a 100 kWh Peak Shaving Zinc/Bromine Utility Battery*, Proceedings of the 5th International Conference, "Batteries for Utility Energy Storage," San Juan, Puerto Rico, July 1995.

P. Taylor, "Spinning Reserve in Puerto Rico Doesn't Spin—It's a Battery," *Electrical World*, April 1995.

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Calpine Corp.
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CREST
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Solar Energy Research & Education Foundation
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