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Utility Battery Storage Systems Program Report for FY94

Paul C. Butler

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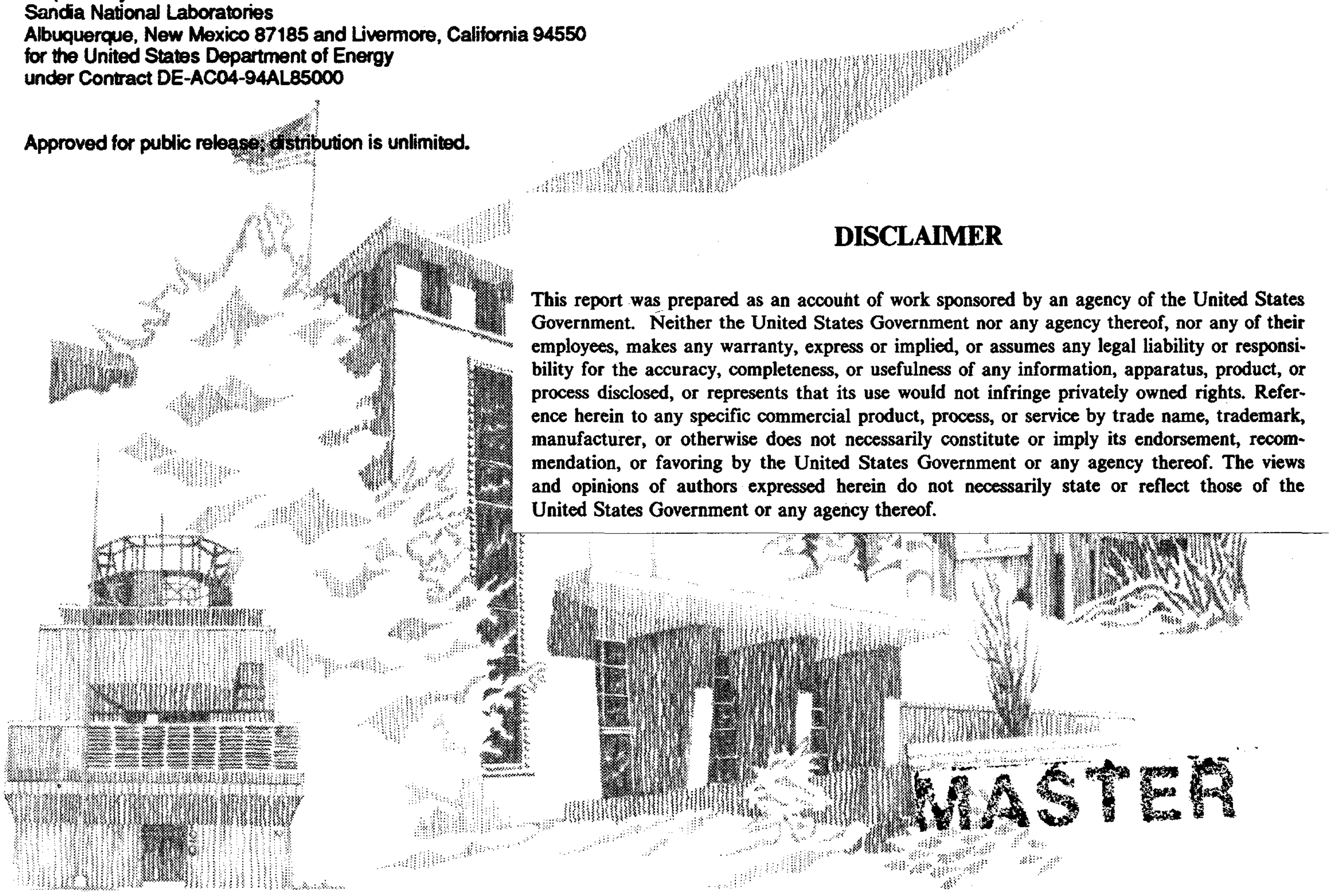

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Utility Battery Storage Systems Program Report for FY94

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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 Energy Management. 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 1994.

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Acronyms and Abbreviations

AML&P	Anchorage Municipal Light & Power
B&W	Babcock and Wilcox
B/C	benefit to cost
BES	battery energy storage
BEST	Battery Energy Storage Test (Facility)
BMS	battery management system
C&D	C&D Charter Power Systems, Inc.
CE	coulombic efficiency
CEA	Chugach Electric Association
CI	constant current
CREST	Center for Renewable Energy Sustainable Technology
c/S	central sulfur
CV	constant voltage
DNA	Defense Nuclear Agency
DOD	depth of discharge
DOE	Department of Energy
EE	energy efficiency
EOC	end of charge
EOD	end of discharge
EOL	end of life
EPRI	Electric Power Research Institute
EV	electric vehicle
FAI	First Article Inspection
F/T	freeze/thaw
FY	fiscal year
GE	General Electric
GNB	GNB Industrial Battery Company
GVEA	Golden Valley Electric Association
IGBT	integrated gate bipolar transistor
IR	internal resistance
JCBGI	Johnson Controls Battery Group, Inc.
LME	liquid metal embrittlement
MGTF	Modular Generation Test Facility
MW	molecular weight
NEMA	National Electrical Manufacturers Association
OEM	Office of Energy Management (DOE)
ORNL	Oak Ridge National Laboratory

PAM	positive active material
PCS	power conversion system
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
PTA	posttest analysis
PTFE	polytetrafluoroethylene
PV	photovoltaic
PVDF	polyvinylidene difluoride
R&D	research and development
REA	Rural Electrification Association
RFP	request for proposal
RFQ	request for quotation
SMUD	Sacramento Municipal Utility District
SMES	superconductive magnetic energy storage
SNL	Sandia National Laboratories
SOC	state of charge
SOW	statement of work
SPI	Silent Power, Incorporated
SPL	Silent Power, Limited
TBS	transportable battery system
TCB	thermal compression bond
TD	Technology Demonstration
TES	thermal energy storage
UBG	Utility Battery Group
UBS	Utility Battery Storage Systems
UES	utility energy storage
UMR	University of Missouri – Rolla
VAR	volt-amp reactive
vpc	volts per cell
VE	voltaic efficiency
VRLA	valve-regulated lead-acid
XPB	extended PB
ZBB	ZBB Technologies, Inc.

1. Executive Summary

Introduction

The Utility Battery Storage Systems (UBS) Program is funded by the U.S. Department of Energy (DOE) Office of Energy Management (OEM), and is conducted by Sandia National Laboratories (SNL). UBS is 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
  - 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 AC Battery at Pacific Gas and Electric (PG&E)
  - Special Evaluation
- Industry Outreach

This report describes the progress made on each program element during FY94. 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, the UBS Program continues 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.

Subsystems Engineering improves the subsystems that make up battery energy storage (BES) systems. The battery subsystem must have lower cost, higher performance, and improved integration with other system components. Consequently, the UBS Program is 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 technology, 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 these 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 $\geq$ 1 hr) and footprint/ portability are important. Relevant applications include renewables, transmission and distribution (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 and to be commercially available around the year 2000. The technologies have different sets of obstacles to overcome because two radically different types of batteries are represented. 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. While both mandate safety first, the UES application must emphasize cost over weight- or volume-based performance requirements. Nevertheless, during the course of this program, external development of any emerging battery technology (e.g., lithium/polymer electrolyte, nickel/metal-hydride) will be closely monitored to determine whether a utility-specific activity is warranted.

For the electrical subsystem, UBS 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 power conversion, control systems, and switch gear, by pursuing design standardization leading to lower manufacturing costs and incorporating advances in power electronics to improve performance.

In the System Integration element, the program develops 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 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 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 FY94 follow. Also included in this chapter are status sheets for the nine FY94 controllable milestones for the UBS Program.

Highlights

Battery Systems Analysis

Opportunities Analysis

Over the last few years, developments in the application and design of BES systems have added a fairly broad base of new information in this emerging technology. At this time, there is a need to pull together this body of information and identify areas where further study is needed to fill in the gaps. Thus, the UBS undertook a major task, the Opportunities Analysis, which was initiated in October 1993, with five specific objectives:

- Identify and rank potential utility applications for BES systems.
- Define application requirements for BES systems.
- Identify the best applications for each UBS battery technology: lead-acid, sodium/sulfur, and zinc/bromine.
- Assess the potential market size and potential benefits of BES to utilities and the nation.
- Establish a standardized cost breakdown for BES systems.

The UBS formed a team consisting of utility representatives, battery and battery system developers, industry consultants, and UBS staff to contribute to the study and review its findings. As the team met and compared available information, it became evident that applications requirements information was available to accomplish most of the study objectives; however, there were large gaps in knowledge relating to market size and national benefits. It was decided that this information would be gathered separately in a follow-on Phase II that will be specifically targeted toward obtaining battery market information.

In the current phase, the study identified 13 potentially feasible applications of BES, broadly classified as (1) generation, (2) T&D, and (3) customer service applications. For each application, the fundamental requirements for the battery system in power, energy capacity, interconnection voltage, power conditioning, expected cycles per year, footprint, and portability were identified. In addition to these individual applications, another set of three multiple (or combined) application groups were also defined, because of the likelihood that BES systems will not be used in a single application mode only. These applications and their requirements were then matched to the three battery technologies under development in the UBS on the basis of the performance characteristics for each technology.

Following the identification of the 13 applications and their requirements, the study developed a set of unique graphical and text description sheets for individual applications. This is a first-of-a-kind attempt at graphically representing the condition on the utility network and the corresponding response by the battery system to compensate or correct it.

The study also reviewed the costs of existing battery projects and noted the inconsistencies in allocating cost to individual subcomponents of the system. These inconsistencies make it difficult to compare the project costs on a component-by-component basis. The study proposed a standardized cost breakdown scheme composed of 10 discrete subsystem components. Adherence to this scheme will eliminate the ambiguity in reporting the costs of future battery system installations.

The potential benefits and market size of BES on a national scale were analyzed. Results indicate a potential benefit of $57 billion through 2010. This estimate is larger than previous SNL study estimates because it includes T&D benefits that were not included in the previous study. However, due to the preliminary nature, the study recommended a Phase II follow-on effort to refine these values through a well-defined market study.

In addition to presenting the range of original information generated during the study, the study report listed the following important conclusions:

- VRLA technology has the potential to optimally or adequately satisfy most of the defined UES applications. The key deficiencies for this technology are energy density and portability. Consequently, in applications where footprint or portability is an important consideration, the VRLA-based systems will be at a disadvantage.
- The advanced batteries (sodium/sulfur and zinc/bromine) favorably complement the near-term VRLA option primarily where higher energy capacity is required (>1 hr) and portability and footprint are important.

SMUD Battery Storage Feasibility Study

The Sacramento Municipal Utility District (SMUD) is cost-sharing a study of the economic feasibility of battery storage in conjunction with new renewable generation through variable-speed wind turbines. The study began in August.

Chugach Electric Feasibility Study

A feasibility study has started at Chugach (Anchorage, Alaska) with participation from the EPRI, Chugach, and the Golden Valley Electric Association (GVEA). Two approaches for the study were proposed and discussed, one was selected, and the kickoff meeting was held in Anchorage in June.

Subsystems Engineering – VRLA

Technology Development – GNB

Battery improvement tasks have progressed during this year. Characterization of the operation of the pressure relief vent presently used in the GNB VRLA battery has shown that performance is repeatable; however, a redesign is needed to adjust to a new preferred operating pressure range. Parameters of the present and alternative vent designs that are most influential to the operating pressure have been determined. Development of an optimized design is continuing. Long-term tests on four groups of cells fabricated with various methods for accommodating positive plate growth are also in progress. At this point, the drop in open-circuit voltage during a stand test has been equivalent for all four groups. Float currents and voltages on another group of samples have also been stable, and all cells are delivering in excess of 100% of rated capacity. A recharge profile has been developed that ensures adequate recharge of a VRLA battery in a typical utility application while minimizing gas evolution and limiting temperature rise to less than 10°C. A timed, constant-current finish for the recharge has been found to meet these goals and can be easily incorporated into control logic. In order to be able to estimate the heat generated by a battery system under a variety of operating conditions, a thermal model has been constructed and validated. The model predicts that the ABSOLYTE IIP battery design will reach higher temperatures during overcharge than the older ABSOLYTE II design. Multiple tasks to reduce the risk of ground faults in utility battery systems have also continued. Evaluations of nonconductive battery trays have shown increased temperatures during cycling and overcharging experiments. Active cooling may be necessary for thermal management if these trays are utilized. Also, the terminal-post seals have been redesigned to eliminate electrolyte leakage, which contributes to ground faults. Samples of the new parts have been received and are being examined for signs of porosity and cracking that could still allow leakage to occur. Cycle-life testing of cells constructed with a positive active material formulation based on a leady oxide is in progress. After 300 cycles, performance has not developed as expected and a boost charge has been provided. Test samples made with leady oxide and the baseline positive material formulation are behaving similarly. Float life tests are also under way.

Phase 2 tasks have also shown progress. Tooling to fabricate and assemble the 2-V modular MSB battery battery design has been manufactured and is being debugged at the manufacturing facility. Prototypes will be available early in 1995. Discharge performance estimates have been verified using identical plates in a 12-V battery module. The advanced LSB design has been modified to solve a seal leakage problem. The integrity of the terminal post seal in the new design has been validated, and permanent tooling has been ordered to produce the battery components. High-rate discharge performance was degraded less than 10% by the design change. Preproduction samples will be available for the LSB early in 1995. Work on the copper negative grid for advanced VRLA batteries has been hampered by a lack of suitable lead-coated copper wire. A test of the concept is in progress with lead-plated copper. The initial evaluation of several alternative positive grid alloys that may extend VRLA battery life has been completed. Accelerated deep-cycle tests showed two of the alternatives approach the capabilities of the standard MFX material used by GNB. The second-stage float-life tests in full-size battery modules have now begun. Studies of positive plate additives and new electrolyte immobilization materials have both progressed very slowly due to difficulty in obtaining the desired materials. Modified glass fiber blends and polymeric materials that could be used as electrolyte absorbants tend to have other properties that make them inappropriate in the battery environment.

A final report summarizing Pacific Gas & Electric (PG&E) efforts to evaluate BES as an option for distributed storage within their network was received early in the year. In this study, PG&E primarily looked at the benefit from deferring substation upgrades that were made necessary by load growth on their system. Four case study sites were analyzed assuming a 1-yr upgrade deferral and the availability of battery systems in the 0.5- to 2.0-MW range. The economic benefits from the deferral were adjusted to account for maintenance and transportation costs for the battery and then expressed as an allowable break-even cost for the battery system. For a 1-MW/2-MWh battery with a design life of 10 yr, this allowable cost was found to be about $700/kW.

An announcement of the availability of a 250-kW/500-kWh battery for a field test at the end of the GNB development program was sent out by the UBG. Responses from utilities and other parties interested in hosting this test have been good. Several of the potential hosts are examining their systems to determine specifics about how the battery could be used and the most appropriate size for the system to be tested. A site selection process will begin early in FY95.

Quantification of the Costs/Benefits of Battery Energy Storage – UMR

A contract has been placed with the University of Missouri - Rolla (UMR) to perform operating cost calculations for a utility system with and without BES. This will be one of the inputs to the economic evaluation of improved battery designs in the GNB contract. UMR has learned how to use DYNASTORE and the program is now fully operational at their site. The first utility that has been studied is an island system and calculations have been carried out for battery applications in the areas of load leveling, spinning reserve, and frequency control. These results were compared to base cases where there was no battery on the system. Significant operating cost savings were found for all these applications, either alone or in combination. A few other unit commitment scenarios are being examined and the sensitivity of the results to factors such as battery size is being checked. The final report on the analysis for this utility system is expected at the end of the first quarter of FY95.

Technology Evaluation – SNL

In December of 1993, SNL received three Type 100A-25 ABSOLYTE IIP modules from GNB for evaluation of the intermediate product. Activities in the first three quarters, and in the early part of the fourth, included ordering test station equipment; converting an existing laboratory into a new test facility; assembling the test station (configuring hardware and implementing software code); and performing checkout tests to ensure proper operation of all related test equipment. Other activities in the fourth quarter included drafting a test plan to define testing of the ABSOLYTE IIP modules. The test plan includes constant-current discharges to measure capacity, area/frequency regulation, spinning reserve, and possibly life cycling using the area/frequency regulation and spinning reserve cycles. Area/frequency regulation and spinning-reserve tests will be similar to those for the PREPA/C&D lead-acid batteries that were performed at SNL in 1992-1994, with power levels scaled to ABSOLYTE IIP ratings. In the last quarter, testing of the ABSOLYTE IIP battery was started. At that time, three consecutive constant-current discharge tests at the 8-hr discharge rate were performed.

Applied Research – SNL

Work on coatings for the rubber plugs in GNB pressure relief valves has been suspended. Initial test results on valves containing samples of the coated plugs did show increased uniformity of the opening pressure, but the vent is now being completely redesigned because of a change in the target pressure range for operation of the battery and because of space constraints on new battery cover designs. The need for coatings cannot be assessed until the configuration of the new pressure relief vent has been defined.

Discussions have been held with GNB as to whether SNL could assist in the evaluation of surface treatments of battery grids for the improvement of battery performance. A statement of work has been agreed upon that makes use of special facilities at SNL to prepare treated grid samples that will then be evaluated by GNB. Materials that are needed for the surface treatment are on order and initial samples are anticipated to be available early in FY95.

Subsystems Engineering – Zinc/Bromine

Technology Development – JCBGI/ZBB

The performance of V-design battery stacks has gradually improved over the course of the contract. Three batteries have completed greater than 500 baseline cycles. Battery V1-79 has completed 951 cycles and is still performing at 69.3% energy efficiency (EE). Recent developments in terminal electrode and cathode layer production have produced a stack, V1-80, with 79.0% EE on baseline cycling and 80.2% EE on cycles without a zinc strip. This battery continues to perform at 77.7% EE after 497 cycles.

A new process for preparing terminal electrodes has demonstrated a 50% reduction in resistance. This corresponds to at least a 1% increase in voltaic efficiency. A high-surface-area bromine electrode has been developed with 2-3 times the surface area of previously prepared electrodes. The surface area of recent electrodes is about 10,000 cm^2/cm^2, as compared to 2000-3500 cm^2/cm^2 for earlier electrodes. An electrode with an even higher surface area of 50,000 cm^2/cm^2 has also been developed, but has not yet been tested in a battery. The higher surface areas are expected to extend the cycle life expectancy of the batteries.

Manufacture of the 100-kWh final deliverable battery is in progress. The design consists of three compartments containing battery modules and a compartment for electrical panels, a scrubber and heat exchanger. These are all contained in a sealed Haz-mat building. Seven 60-cell, 2500-cm^2 stacks have been qualified as potential stacks for the 100-kWh deliverable battery. Each stack achieved 75-77% EE on baseline cycling.

A 60-cell, 2500-cm^2 battery stack achieved greater than 19 kWh when it was discharged over a 3- to 6-hr period. Modifications in the design of the 2500-cm^2 series flow frames have demonstrated improved performance. Energy efficiencies as high as 78% have been observed on baseline cycles for 8-cell stacks. Stacks with 60 cells have achieved 77% EE.

The 2-kWh deliverable battery station was redesigned using a prototype controller with control functions similar to that in the 100-kWh deliverable. The station is presently being tested in the SNL laboratory.

Technology Evaluation – Zinc/Bromine

A prototype 2-kWh, 8-cell zinc/bromine battery was delivered to SNL in August 1994 by JCBGI/ZBB. The battery was placed on test, and a new microprocessor controller was installed. The battery capacity was verified in the initial test and the controller was debugged.

Applied Research – Zinc/Bromine

A final report was prepared that described the synthesis and evaluation of novel complexing agents for zinc/bromine electrolyte. The report was reviewed and is being modified for publication.

Subsystems Engineering – Sodium/ Sulfur

Technology Development – SPI

During the first quarter of the year, activity focused on completing the fabrication of a 12-kWh prototype battery (Task 3). This battery was delivered to SNL on schedule (January 1994) for testing. Since that time, the effort has concentrated on identifying suitable applications for the technology (Task 1) and completing the detailed design of the modular NaS-P_{ac} UES system

(Task 4). This detailed design will serve as the basis for developing system cost estimates. The UES central sulfur (c/S) cell development effort (Task 2) was also continued under a restructured plan. This plan emphasized the work required to ensure the hermeticity of the large-diameter anode (sodium) seal and improvements in cell build yields to allow freeze/thaw (F/T) durability and safety performance to be characterized.

To better communicate with potential customers the advantages of advanced BES, Silent Power made a concerted effort to address utility assemblies at association meetings. This forum has proved to be fruitful in that direct feedback from utility members has been provided relative to some specific customer-side applications. In general, the principal customer-side applications appear to be oriented toward improving power quality and reliability with some interest expressed in peak shaving. Small turnkey power packages with 0.5 to 1.5 MW and 0.5-1 hr of storage appear to be required to satisfy these types of applications.

Utilities have a strong interest in maintaining satisfied customers, especially in the face of deregulation and increased competition. Some utilities have expressed a potential interest in providing energy storage systems to their customers as an option, but the acceptance will depend critically on reliability and cost. The primary cost competition for battery systems appears to be diesel generators at $250-375/kW. The instantaneous response and the environmental benefits of BES systems are the attractive features over such traditional types of spinning equipment. Unfortunately, BES systems have 2-3 times the cost of diesel generators, so the customer benefit per incidence must be significant for the few times per year that the system is needed to protect the operation. The ability to do some peak shaving along the way may help the economics depending on how "peaky" the load is, how high the utility demand charges are, and how much storage is required to ensure that the peak is shaved. Peak shaving opportunities exist, especially in the northeast, that can demonstrate a 20-30% rate of return with a 3-yr payback. The results of the application studies thus far are encouraging, with the caveat that reliability and cost will be major issues for market acceptance.

The detailed design of a 300-kW/1-hr modular NaS-P_{ac} BES system was completed. The system design is based on available 300-kW power conversion system (PCS) design options employing line- and self-commutation. The height and width of the National Electrical Materials Association (NEMA) cabinet are limited to 90 in. (2.29 m) and 84 in. (2.13 m), respectively, to permit maximum transportability. The initial battery design consisted of four separate battery packs, each rated to deliver 75 kW continuously for 1 hr without active cooling. The battery packs were stacked on a supporting steel shelf structure attached immediately behind the PCS. Clearance was established between shelves to permit easy on-site battery replacement using a fork lift.

Each pack included 4800 10-Ah Mk4 sodium/sulfur cells. The cells were surrounded by a self-supporting, nonevacuated, thermal enclosure with self-contained heating elements for maintaining operating conditions within the battery pack. A nearly equivalent number of capsules was intimately bound into the interstitial space between cells with a cement that provided both electrical isolation as well as good thermal transport characteristics. These capsules contained a low-cost latent-heat-storage material to arrest temperature rise during extended discharge periods. This is the first battery design to employ such a passive cooling scheme to extend battery operation, improve overall efficiency, and maximize the reliability of the thermal management system.

In June, RWE GmbH, the parent organization of Silent Power, made the decision to close its Clifton Junction Mk4 cell manufacturing facility in order to concentrate its resources on a new, higher-power cell design, one tailored to the needs of electric vehicles (EVs). A new production facility for this high-power cell is now under construction. This decision presented a major perturbation to the efforts of SPI to use the Clifton Junction product in an intended demonstration of the technology. SPI decided to take the approach of simply using EV batteries to accomplish this same goal. The merits of doing this are immediately evident when seen from the standpoint of volume production (availability) and reduced cost as well as lower battery resistance. By combining an early UES battery market with the potential high-volume EV battery business, the goals of a low-cost BES system can be better and more quickly served.

A new 1-hr NaS-P_{ac} system was then designed that uses 10 standard 40-kWh EV batteries. These are connected 2 series $\times$ 5 parallel, providing 640-VDC input to the 300-kW PCS at full load and requiring 800 VDC at the top of charge. The resistance of the battery system is predicted to be 145 mΩ. The batteries are stacked five high in each of two staggered rows behind the PCS envelope. Adjacent alcoves serve as dedicated electrical cabinets for interconnect cabling, isolation switches, and battery management hardware. The module system weight is nearly 16,000 lb (7250 kg) and measures 7.5 ft tall (2.29 m) $\times$ 7 ft wide (2.13 m) $\times$ 8 ft long (2.44 m). Two NaS-P_{ac} units are easily transportable with a standard trailer.

Preliminary costs for the 1-hr NaS-P_{ac} system are \$630/kW for an annual production volume of 10,000 EV batteries (an early EV market). At maturity (~100,000 batteries/yr), the cost of this system is estimated to drop to \$428/kW. Provided that the system proves to be reliable and that battery replacement can be scheduled to meet a projected 5-yr warranty, the NaS-P_{ac} UES system will compete with diesel and gas turbine generators for the peaking and standby power applications, while offering customers enhanced power quality and reliability.

Technology Evaluation – SNL

Testing of the 12-kWh sodium/sulfur UES battery supplied by SPI began during the latter part of FY94. This battery represents the principal hardware deliverable from the development contract. The UBS Test Plan: SPI Sodium/Sulfur Utility Battery, test plan number UBS/SS-1, revision 1, March 29, 1994, is being followed. The objectives of the testing are (1) to confirm the battery electrical performance ratings, (2) to identify its capability to meet basic cycling requirements associated with several promising candidate UES applications, (3) to gain experience with SPI's integrated battery management system (BMS), and (4) to determine the battery service life using a customer peak-shaving requirement.

The commissioning of the battery and test system operational verification began during the first week of September 1994. The only tests performed during this period were constant current discharge and subsequent recharge. These tests consisted of heating the battery to 330°C under control of the BMS and then performing C/3-100% depth-of-discharge (DOD) cycles with C/9 rate recharges. The electrical interfaces between SNL's tester and SPI's BMS were evaluated during these cycles. The evaluations revealed some interface incompatibilities that required software modifications to both SNL's tester and SPI's BMS.

Subsystems Engineering – SNL Evaluation Lab

Four 12-kW testers from Transistor Devices were purchased by SNL for testing utility battery systems. The charge voltage range of these units is 5-48 V and the maximum charge current is 500 A. On discharge, there are three 4-kW loads in parallel to provide a maximum power rating of 12 kW. The discharge voltage is 5-400 V and the maximum current is 1800 A. The hardware controller and data acquisition system for these testers was developed at SNL and can perform a frequency regulation and spinning-reserve cycle. These testers are also capable of performing constant-current and power charge/discharge cycles.

One of these testers is being used to test a 12-kWh sodium/sulfur utility battery from SPI. A second tester is evaluating a 1200-Ah VRLA utility battery from GNB Industrial Battery Company. The remaining two testers are scheduled to evaluate additional VRLA batteries from GNB.

System Integration

AC Battery Prototype Development – Omnion

During the first three quarters of FY94, the AC Battery prototype was thoroughly and successfully tested at the PG&E Modular Generation Test Facility (MGTF) in San Ramon, California. Characterization testing was completed in March 1994 and life testing to determine the cycle capacity of the battery set began immediately thereafter. Life testing continued until late July 1994 when the system began exhibiting end-of-life symptoms and system operation problems precluded continuation of testing. The equivalent of nearly 100 deep-discharge cycles were completed before the system was shut down for a complete retrofit of the battery complement with the AC Delco AES 2010 utility battery, a low-cost flooded lead-acid battery specifically designed for utility applications. Retrofit is scheduled for completion in February 1995 and testing is scheduled to resume at the MGTF in mid-March 1995.

AC Battery Module Modification and Hybrid Development Project – Omnion

Development of a Hybrid Control System, which will provide for the seamless transfer of load to a storage system, a renewable power source, or a diesel generator, is nearing completion at Omnion. Development of this system is cosponsored by the SNL Storage Batteries and Photovoltaic System Departments. Demonstrations of seamless transfer have been observed during breadboard testing. The development of this system will lead to the further development of an intelligent control system to manage the complete operation of off-grid power generation systems. The Hybrid Control System is scheduled for delivery to the Photovoltaic Systems Evaluation Laboratory at SNL in late March 1995. Testing of the Hybrid Control System will be conducted at the Photovoltaic Systems Evaluation Lab (PSEL) to verify the seamlessness of load transfer over a wide variety of loads in an operational environment. The goal of the development is to allow transfers among selected power sources without interruption or corruption of the power to the load.

System Field Evaluation

PG&E Testing of AC Battery

The AC Battery prototype was delivered to the PG&E MGTF in San Ramon, California, in October 1993 after transport by truck from Omnion Power Engineering Corporation, East Troy, Wisconsin. The unit was readied for testing within 1 week after delivery. Characterization testing was initiated in November 1993 and completed in late March. Following the successful completion of the characterization testing phase, the AC Battery prototype immediately began life-cycle testing. Early in life-cycle testing, it appeared that the system was nearing end-of-life prematurely. Delco Remy and Omnion analyzed test data and determined that the system had been chronically undercharged throughout the test program because of a too-conservative charging algorithm. This resulted in the premature aging of the batteries, which led to degradation in system capacity. Testing continued until the end of July 1994, when life-cycle testing was terminated with nearly 100 deep-discharge cycles completed. Testing is scheduled to resume with the new batteries in mid-March 1995.

Special Evaluation at SNL – PREPA/C&D Lead-Acid Battery

Five more UES cycles were completed on the 12-cell series string being tested at SNL. These included a duplicate baseline experiment starting at 32.2°C (90°F); in addition, four tests were run at the higher turnover rate of 3.0, two starting at 32.2°C and two starting from ambient temperature. All of these tests were completed successfully. Analysis of the temperature data showed no evidence of a significantly higher heat generation rate by the battery when it was operated at the higher capacity turnover rate. During these cycles, a few thermocouples were left in position to measure the uniformity of the wall temperatures in the test chamber and to test the exit air temperatures downstream from the exhaust fan. These measurements continued to indicate a fairly uniform condition. Imaging of the inside of the chamber and the battery surface with an infrared camera also showed reasonably homogeneous temperatures.

Before running the last two UES cycles, the battery was equalized in order to determine if cell voltage spread would be decreased and battery capacity improved. A final battery capacity measurement made at the conclusion of the thermal testing showed a capacity decline that was traced to a disconnected air line to one cell on the electrolyte mixing system. A rough estimate of what the capacity test results would have been in the absence of this problem indicated that equalization probably did not significantly improve the available battery capacity.

The latest temperature data have been fit to a thermal model and the reduced noise levels during the spinning reserve discharge part of the test have led to much better estimates of the battery resistance parameter. In general, the battery heat generation rate and heat transfer coefficient have not had to be changed as a result of fitting the current data. A revised prediction of the temperature rise in the Puerto Rico facility has been made with the model by incorporating more realistic battery operating parameters for the spinning reserve discharge. The maximum estimated temperature rise for the Puerto Rico Electric Power Authority (PREPA) facility occurs during the spinning reserve discharge and reaches 10.1°C (18.2°F) above ambient temperature.

Industry Outreach

Multiyear Program Plan

A multiyear program plan titled "Utility Battery Storage Systems Program Plan - FY 1994-1998" was completed and published in February 1994. Copies of the plan were mailed to a large number of individuals on the program's mailing list, and several hundred additional copies have also been distributed at conferences and utility expositions where the UBS program was represented.

The 46-page, fully illustrated document examines the past and future role of battery energy storage in the electric utility network, the critical issues in the acceptance of this technology by utilities, and an activity-by-activity description of the UBS program aimed at resolving each of the issues. Each of the five elements of the UBS Program, 1) battery systems analysis, 2) subsystems engineering, 3) systems integration, 4) system field evaluation, and 5) industry outreach, are described in detail. The document was the result of an intensive effort by the UBS staff examining every aspect of the existing program against the stated goals and objectives. Consequently, the Plan represents a roadmap for the program activities leading to the realization of the program goals. Drafts of the plan were reviewed internally and by DOE/OEM prior to its final publication.

IEE T&D Exposition

Under the ongoing industry outreach activities, the UBS was showcased in an IEEE T&D Exposition held in Chicago April 11-14, 1994. The weeklong biannual exposition focuses on the latest products and services in T&D and attracts 10,000-12,000 attendees from the utility industry.

The UBS display included posters describing the program, significant events in the evolution of BES in utility applications, and utility applications of BES. Four new brochures were prepared describing specific T&D applications, existing and advanced battery systems, the UBS program, and the AC Battery prototype; a separate brochure describing the UBG was also prepared. All the display posters and brochures have been designed for reuse at future conferences and exhibitions as the opportunity arises.

The AC Battery Corporation displayed a complete container and a module, making this the first time that the AC Battery was publicly displayed to such a large audience. The hardware display was supplemented by brochures and background literature describing the system and its capabilities.

Metlakatla Village Battery Project

Metlakatla Village, situated in southern Alaska, operates a large lumber mill that causes an intermittent spike load on the electric system. The village is supplied by baseload hydro units that do not have the ramping capability to correct the mill's spike. To compensate for this, the village installed a large diesel, which is lightly loaded for the majority of its operating time, resulting in low efficiency and high diesel fuel consumption. The village inquired about battery storage as an option, and detailed presentations on battery technology were made by a joint SNL, GNB, and GE team to the Board of Directors of Metlakatla Power and Light.

Consequently, the Board requested that GNB prepare a formal proposal for a battery system; this proposal was submitted to the village in May. In mid-May, the Village Council voted unanimously to purchase the battery system. However, the village also needs REA approval to proceed further with the battery project. The REA expressed reservations about granting its approval, and DOE and SNL staff met with REA to resolve the issues raised by REA. This meeting was successful in resolving most of the REA concerns about the readiness of BES technology and its applications. The REA wants DOE/SNL to remain involved in an advisory/support role to Metlakatla Village during the course of the project. At present, the village and the GNB/GE team are negotiating acceptable terms for a contract to purchase the system.

Utility Battery Group

The UBG held its regular biannual meetings in November 1993 in San Ramon, California, and May 1994 in Dallas, Texas. UBS staff attended the Steering Committee meeting as well as the general meetings.

The San Ramon meeting showcased the newly installed AC Battery prototype at PG&E's Modular Generation Test Facility in San Ramon. The prototype unit had recently been delivered to PG&E for testing, and at the time of the UBG meeting, it was still in the startup stage.

The Dallas meeting marked an evolutionary milestone for the UBG. At this meeting, the voting members of the Steering Committee passed a resolution allowing nonutility participation in the Steering Committee through an Advisory Group. Until that time, the Steering Committee meetings were open only to the original eight founding utilities of the UBG.

Other Industry Outreach Activities

UBS staff attended and made presentations at the Northeast Electric Utility Battery Conference in Albany, New York. Two presentations were made to the over 125 attendees at this annual meeting, one an overview of the UBS Program, the other a presentation on a recently completed applications analysis done by UBS. Both talks generated many questions, and over 20 requests for more information were received. Of the attendees, more than 24 eastern utilities were represented, with many manufacturers and consultants also present. A key issue raised at the meeting involved the perceived poor reliability of VRLA batteries for utility applications. Since this technology is being developed by UBS for these applications, the perception of poor performance by the industry is significant to future market penetration. To investigate the reliability issue, data presented at the meeting will be reviewed and discussed with the UBS lead-acid battery developer.

DOE/OEM and UBS staff visited PREPA to present the results of the thermal tests performed on the PREPA batteries at SNL and to tour the recently completed 20-MW spinning reserve/frequency regulation battery system. Other issues discussed during the meeting included the 5th International Battery Conference that will be held in Puerto Rico and hosted by PREPA in July 1995.

At the time of the visit, the battery system was in the startup testing phase. Problems that are normally expected during the startup of a complex facility such as the PREPA battery were being resolved by both PREPA staff and the subsystem vendors. This battery system was procured on a piecemeal basis, and the major components were assembled on site by the different vendors. Consequently, the predominant problems encountered were in the controls and integration area. PREPA was aggressively pursuing understanding their root causes, and it was evident that, with this experience, future battery systems installed by PREPA will be acquired on a turnkey basis.

UBS Program Controllable Milestones

Milestone Title:
Deliver AC Battery to PG&E.

Responsible Organization:
Omnion Power Engineering Corp.

Reportable Date:
October 1993

Milestone Status:
Completed October 1993.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

Milestone Title:
Complete preliminary opportunities analysis.

Responsible Organization:
SNL

Reportable Date:
March 1994

Milestone Status:
Completed February 1994.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
A comprehensive final report is being prepared and will be available in November.

Milestone Title:
Deliver JCBGI/ZBB 100-kWh zinc/bromine battery system.

Responsible Organization:
JCBGI

Reportable Date:
October 1994

Milestone Status:
Milestone slipped to October due to funding stretchout/lack of funding in quarter 1 of FY94.

Program Discussion Issues:
Design of 100-kWh system is complete. Fabrication of system components is 50% complete.

Future Reportable Milestones/Schedule:
8-cell deliverable for SNL completed JCBGI tests and shipped to SNL in August.

UBS Program Controllable Milestones

Milestone Title:
Deliver SPI 12-kWh sodium/sulfur battery.

Responsible Organization:
SPI

Reportable Date:
March 1994

Milestone Status:
Completed ahead of schedule (January 1994).

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

Milestone Title:
Deliver GNB intermediate design VRLA battery modules.

Responsible Organization:
GNB

Reportable Date:
December 1993

Milestone Status:
Completed on schedule.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

Milestone Title:
Deliver draft UBS Annual Operating Plan to DOE.

Responsible Organization:
SNL

Reportable Date:
September 1993

Milestone Status:
Completed on schedule.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

UBS Program Controllable Milestones

Milestone Title:
Deliver UBS Multiyear Program Plan to DOE for printing.

Responsible Organization:
SNL

Reportable Date:
October 1993

Milestone Status:
Completed on schedule.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

Milestone Title:
Deliver FY93 UBS Annual Technical Report to DOE.

Responsible Organization:
SNL

Reportable Date:
February 1994

Milestone Status:
Completed on schedule.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

Milestone Title:
Deliver report to DOE on National Benefits of Battery Storage (Gateway Study).

Responsible Organization:
SNL

Reportable Date:
December 1993

Milestone Status:
Completed on schedule.

Program Discussion Issues:
None

Future Reportable Milestones/Schedule:
None

2. Battery Systems Analysis

The Battery Systems Analysis activities are intended 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 include battery storage in their planning scenarios routinely. 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 Studies
2. Feasibility Studies
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 coarse estimate of the battery's benefits-to-cost (B/C) ratio, using as a basis a limited examination of utility-specific operation and financial data. 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 any future BES project and become an essential part of its 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 critically 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 operating conditions, is not included. Finally, a study will be performed to match battery technologies with specific applications.

Tasks/Milestones

FY94 Milestones:

- Complete preliminary Opportunity Analysis (3/94) – completed; comprehensive final report in preparation.
- Initiate Chugach Feasibility Study (6/94)
- Initiate SMUD Feasibility Study (9/94)

Status

Opportunity Analysis

Over the last few years, developments in the application and design of BES systems have added a fairly broad base of new information in this emerging technology. At this time, there is a need to pull together this body of information and identify areas where further study is needed to fill in the gaps. Thus, the UBS undertook a major task, the Opportunities Analysis, which was initiated in October 1993, with five specific objectives:

- Identify and rank potential utility applications for BES systems.
- Define application requirements for BES systems.
- Identify the best applications for each UBS battery technology: lead-acid, sodium/sulfur, and zinc/bromine.
- Assess the potential market size and potential benefits of BES to utilities and the nation.
- Establish a standardized cost breakdown for BES systems.

The scope of the study as defined by these objectives was fairly wide. A team consisting of utility representatives, battery and battery system developers, industry consultants, and SNL staff was formed to contribute to the study and review its findings. As the study team met and compared available information, it was evident that applications and the application requirements information was available to accomplish most of the study objectives; however, there were large gaps in knowledge relating to market size and national benefits. During the course of the study it was decided that this information would be gathered separately in a follow-on Phase II that will be specifically targeted toward obtaining and reporting battery market information.

During Phase I, the study identified 13 potentially *feasible* applications of BES in the electric utility market broadly classified as generation, transmission and distribution, or customer service applications. The fundamental requirements for the battery system to meet the application requirements were identified as power, energy, interconnection voltage, power conditioning system type, expected cycles per year, footprint, and portability (see Table 2-1). However, it is unlikely that battery systems will be used exclusively for an individual application; therefore, a set of three multiple (or combined) application groups and their corresponding requirements were defined, as shown in Table 2-2.

The three battery technologies under development have unique performance characteristics that determine their optimum match with each application. For example, there is an excellent match between VRLA battery system characteristics and the area/frequency regulation requirements. Both sodium/sulfur and zinc/bromine systems could meet the performance requirements, but would not represent an optimal match. On the other hand, sodium/sulfur and zinc/bromine are optimal choices for customer service demand peak reduction, because of their deep-discharge/life characteristics, whereas lead-acid represents a less optimal choice. The complete range of applicability is shown in Table 2-3. When using the information in this table, it is important to note that lead-acid batteries are commercially available today, whereas sodium/sulfur and zinc/bromine batteries have yet to go through a commercial production phase. This disparity in commercial readiness limits a user to lead-acid batteries at the present time; however, the information in Table 2-3 will become more pertinent as sodium/sulfur and zinc/bromine systems become commercially available and the user has the ability to select a battery type that optimally matches the application requirements.

When battery system costs are discussed, there is wide variability in exactly which cost elements are included. Generally, these costs include only three major subsystem costs, including the battery, power conversion subsystem, and auxiliaries. Yet, practical experience in installing battery systems in electric utility networks suggests that there are several other cost components that are omitted or not reported. The study identified 10 discrete cost components and proposed a standardized cost breakdown scheme shown in Table 2-4, which includes a comprehensive costing approach.

Finally, the study developed a set of unique graphical and text description sheets for each of the 13 individual applications, as well as a set of three sheets in similar format for the three combined applications. Figures 2-1 and 2-2 are shown as samples.

The potential benefits and market size of BES in electric utilities were analyzed. Results indicate that this market may be larger than previously reported in an SNL study. That study based market size only on generation and transmission applications, and omitted distribution applications due to a lack of data. In the current study, distribution-related applications were estimated at an additional 4 GW. However, as stated earlier, there is a strong need to quantify these estimates to a higher degree of confidence and accuracy through a well-defined market study, which will be the focus of Phase II of this task.

In addition to presenting the range of original information generated during the study, the study report listed the following important conclusions:

- VRLA technology has the potential to optimally or adequately satisfy most of the defined utility energy storage applications. The key deficiencies for this technology are energy density and portability. Consequently, in applications where footprint or portability is an important consideration, the VRLA-based systems will be at a disadvantage.

Table 2-1. Summary of Applications Requirements

Applications	Aporox. Power (MW)	Approx. Storage (hr)	AC Voltage (kVac)	Converter Type	Cycles Per Year	Footprint (Importance)	Portability (Importance)
Generation Applications							
Spinning Reserve	10-100	0.5	12-138	Line	20-50	Medium	Low
Capacity Deferral	10-100	2-4	12-138	Line	5-100	Medium	Medium
Area/Frequency Regulation	10	<1	12-138	Line	250	Low	Low
Renewables Applications	1	1-4	0.48-12	Line	250	Medium	Low
Load Leveling	100	>4	69-765	Line	250	Medium	Negligible
Transmission and Distribution Applications							
Transmission Line Stability	100	<0.01	69-765	Self	100	Medium	Low
Voltage Regulation	1 (MVAR)	<0.25	12-34.5	Self	250	High	High
Transmission Facility Deferral	10	2-4	12-138	Line	5-20	High	Medium
Distribution Facility Deferral	1	1-3	4-34.5	Line	30	High	High
Customer Service Applications							
Demand Peak Reduction	1	1-2	0.48-12	Line	50-500	High	Low
Transit System Peak Reduction	1	1-2	0.48-2.4	Line	250-500	Medium	Low
Reliability and Power Quality (<1 MW)	0.1	<0.25	0.48	Self	<10	High	Low
Reliability and Power Quality (>1 MW)	1	1-2	0.48-12	Self	<10	High	Low

- The advanced batteries (sodium/sulfur and zinc/bromine) favorably complement the near-term VRLA option primarily where higher energy capacity is required (>1 hr) and footprint and portability are important.

The final report will be distributed by the end of the next reporting period.

SMUD Battery Storage Feasibility Study

SMUD is planning an addition of 300-400 MW of renewable-based generation to its system by the year 2000. As part of that goal, SMUD recently purchased 5 MW of US Windpower variable-speed wind turbines. SMUD is planning additional wind turbine purchases that will total 100 MW in the near future. With this new

Table 2-2. Combined Applications Requirements

Group	Applications	Power* (MW)	Discharge Duration (hr)	Discharge Depth	Discharge Frequency (in a 24-hr period)
I	Spinning Reserve, Area/Frequency Regulation, Load Leveling, Generation Capacity Deferral	10-100	1-3	Shallow (A/F Regulation)	Continuous charge and discharge, 250 weekdays
				Medium (Load Leveling/ Gen. Deferral)	One discharge/charge cycle, 250 weekdays
				Deep (Spinning Reserve)	One discharge/charge cycle, 20-50 days/yr
II	Distribution Facility Deferral, Voltage Regulation	1	1-3	Shallow (Voltage Regulation)	Minimal storage for VAR injection, 250 weekdays
				Medium (Distribution Facility Deferral)	One discharge/charge cycle, less than 30 days/yr
				Deep (Distribution Facility Deferral)	One discharge/charge cycle, less than 30 days/yr
III	Reliability (UPS) Power Quality, Peak Shaving	0.1-1	1-2	Shallow (Power Quality and Reliability)	One discharge/charge cycle, less than 20 days/yr
				Medium (Reliability)	One discharge/charge cycle, less than 20 days/yr
				Deep (Peak Shaving)	One-two charge/discharge cycles, 250 days/yr

* Values in this column reflect order of magnitude of power that combined applications require.

renewable generation, there is potential for deploying substantial battery storage capacity to offset the intermittent availability of the wind and solar generation. In addition to the renewable generation, SMUD also has sites where battery storage can be applied in transmission and distribution applications.

Consequently, SMUD has an active interest in cost-sharing a feasibility study to identify BES benefits. The UBS and SMUD have agreed on the cost-share split, methodology, and statement of work (SOW) for the study. The methodology is similar to the Chugach feasibility methodology, where the benefits of battery storage will be identified, followed by a definition of functional specifications for a battery system. This specification will be released to battery system suppliers as a request for quotation (RFQ). The system prices quoted in the RFQ responses will be used to complete the cost/benefit analysis. The outcome of this evaluation will allow SMUD to determine the economic feasibility of the battery project and commit to a follow-on procurement if there is sufficient justification for purchasing the battery system.

Kickoff of the study was delayed due to reorganization at SMUD. The kickoff meeting of the study was held in late August.

Chugach Electric Association

The joint system study conducted by UBS with the Chugach Electric Association (CEA) in FY91-92 showed strong potential for BES in the Chugach system

Table 2-3. Compatibility of UBS Battery Technologies with Individual Applications*

Applications	VRLA	Sodium/ Sulfur	Zinc/Bromine
Generation Applications			
Spinning Reserve	√	X	X
Capacity Deferral	√	X	√
Area/Frequency Regulation	+	√	√
Renewables	√	+	+
Load Leveling	X	X	X
Transmission and Distribution Applications			
Transmission Line Stability	+	X	X
Voltage Regulation	X	√	√
Transmission Facility Deferral	√	√	+
Distribution Facility Deferral	√	√	+
Customer Service Applications			
Demand Peak Reduction	√	+	+
Transit System Peak Reduction	√	+	√
Reliability and Power Quality (<1 MW)	√	X	X
Reliability and Power Quality (>1 MW)	√	X	X

* + – excellent; √ – adequate, but not optimum; X - poor

for both generation and transmission applications. The results of this study also made other regional utilities aware of the benefits of energy storage for the entire interconnected Alaskan utility system. Encouraged by the study results and the interest of the neighboring utilities, CEA decided to undertake the follow-on, higher-level feasibility study to quantify the economic benefits in greater detail.

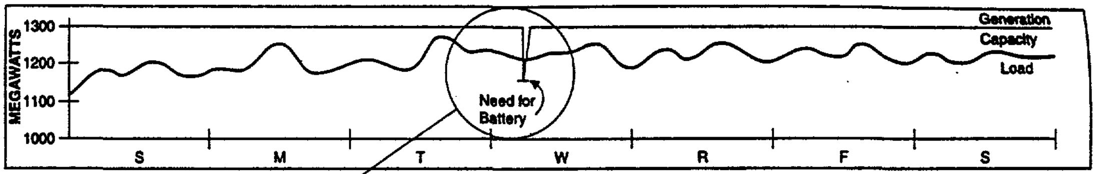
CEA and GVEA, which serves the Fairbanks area, are performing the feasibility study in collaboration with UBS and supported by EPRI through a tailored collaboration project. The study is supported mostly through the tailored collaboration funds, with relatively lower funding support from the UBS program. The feasibility study will quantify the value of BES for both the CEA and GVEA systems by using power flow and production cost models including EPRI's DYNASTORE. A functional specification for the battery system will be developed using these findings and released to battery system suppliers to obtain cost estimates of turnkey systems.

Two separate approaches for the study were proposed. One approach, shown in Figure 2-3a, would require the preparation of a conceptual design with the assistance of an architect/engineer to obtain a cost estimate for the battery system. This cost estimate would then be used in the subsequent economic analysis. At some later time, a separate request for proposal (RFP) would be issued to the battery system vendors. These battery system costs may be quite different from the costs estimated earlier during the study; as has been the case with past projects, if these costs are higher, then the

Table 2-4. Components of Cost for a Utility Battery Storage System

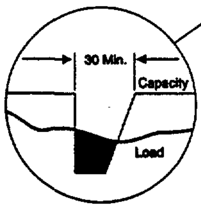
A. AC Source/Load Interface to Battery System	1. New lines to serve installation (e.g., 4, 12, 69 kV) 2. Transformer between utility voltage and battery system AC voltage (e.g., 69 kV; 480 v) 3. Protection Devices (e.g., switches, breakers, fuses)
B. Power Conversion System*	1. AC Switchgear/Disconnect 2. Rectifier/Inverter 3. DC Switchgear/Disconnect 4. Protection Devices (e.g., switches, breakers, fuses)
C. Batteries and Accessories	1. Electrical a. Batteries (cells, tanks, membranes) b. Interconnects c. Protection Devices (e.g., switches, breakers, fuses) d. Chargers 2. Mechanical a. Racking/Physical Support b. Watering/Heating/Air and Fluid Pumping Systems c. Safety Equipment (e.g., ventilation, fire equipment, detectors, respirators, spill troughs)
D. Monitors and Controls*	1. Monitors/diagnostics a. PCS b. Batteries (strings and cells) 2. Controls a. PCS b. Batteries c. Protection Devices
E. Facilities*	1. Foundation and Structure (and associated labor) 2. Materials 3. Lighting/Plumbing 4. Finish Grade/Landscape 5. Access Road 6. Grounding/Cabling 7. HVAC
F. Financing	
G. Transportation*	
H. Taxes	
I. Services	1. Project Management 2. Installation 3. Studies (e.g., relays, harmonic filters) 4. Data Gathering/Trending 5. Permits
J. Operation and Maintenance	1. Service Contract 2. Cell/Fluid Recycling/Replacement 3. Training 4. Inspections

* For the turnkey systems evolving, separate costing of these items may not be necessary. However, these items will be part of the specification upon which turnkey vendors bid.



Generation Capacity and Load on a Randomly Selected Week with a Generation Capacity Interruption

Spinning Reserve

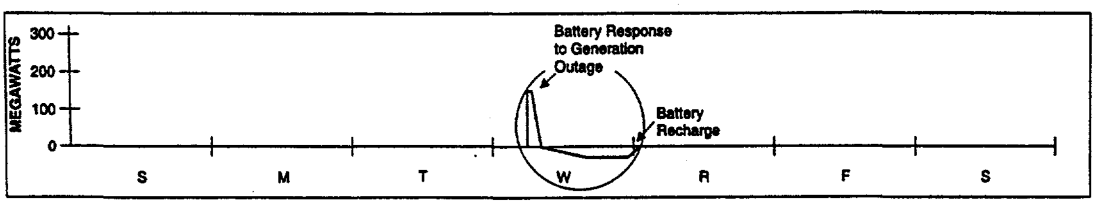


If an electrical generating unit fails, the utility that operates it must draw power from other sources to prevent interruption of service to customers. In an island utility, the available reserve power must equal the power output of the largest generating unit in operation. Both island utilities and grid-connected utilities use thermal power plants and combustion turbines (CTs) to provide reserve power. However, the generators must be "spinning" to provide an instantaneous response.

Cold thermal power plants require hours, and CTs require about half-an-hour to get generators spinning. Consequently, utilities operate thermal plants and CTs at less-than-full capacity to have generators spinning and ready to provide reserve power.

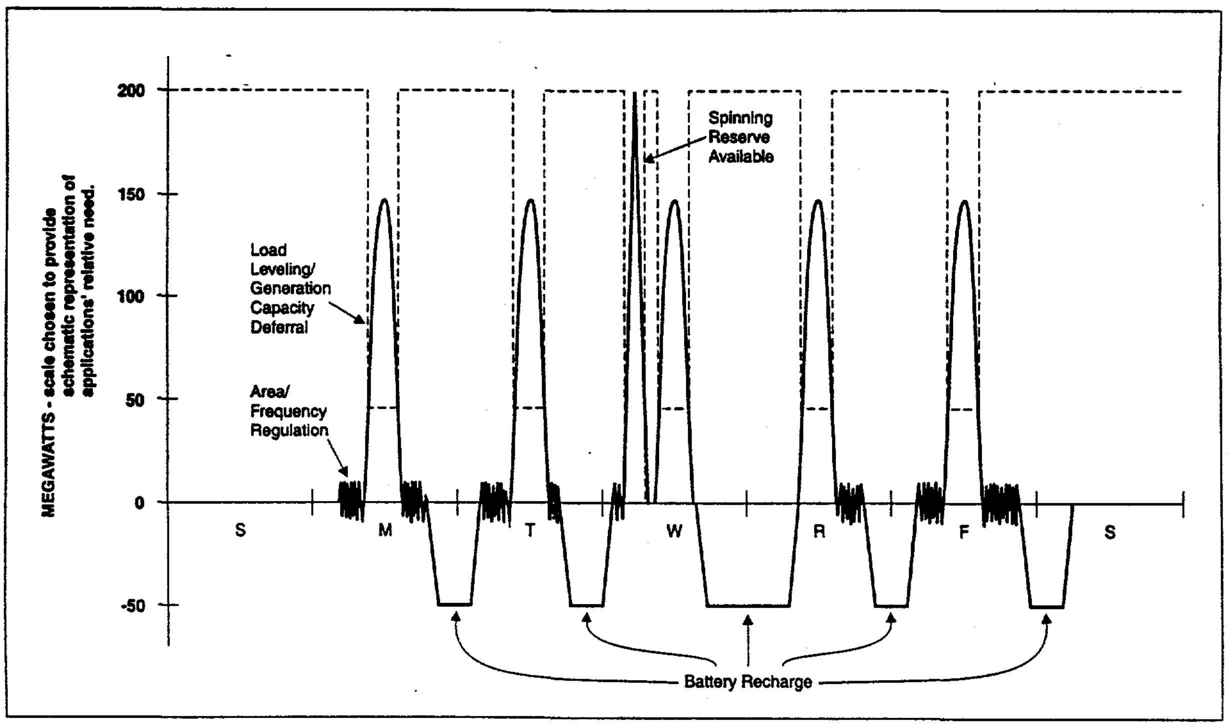
Battery energy storage can help utilities maintain spinning reserve, reduce or eliminate the need for supplemental power from CTs, and free thermal plants to generate at full capacity (and greater efficiency and economy). Battery systems designed for spinning reserve must replace generation units that fail, and provide power until the utility brings other sources of power on line or repairs the failed unit. Therefore, battery systems for spinning reserve must provide power in ranges of 10s and 100s of megawatts for time periods of 30 minutes. Generation outages that require spinning reserve occur about 20 to 50 times per year. These outages occur randomly.

The figure at the top of the page illustrates the generation capacity of a utility on a typical week in which a significant failure occurs; the balloon shows the detail of the capacity loss and the gradual return of the utility's generating capacity. The figure at the bottom of the page shows the battery system response to the utility need; the positive peak in the graph is the battery discharging to meet load demand; the negative peak is the battery recharge time during off-peak hours.



Battery System Operation to Prevent Interruption of Service During Generation Capacity Outage.

Figure 2-1. Spinning Reserve Application Description



Utilities that have simultaneous need for Load Leveling and Generation Capacity Deferral will size batteries appropriately. At times when the battery provides Spinning Reserve, other applications will not be available to the utility.

Figure 2-2. Battery System Flexibility for Combined Application I: Spinning Reserve, Load Leveling Generation Capacity Deferral, and Area and Frequency Regulation

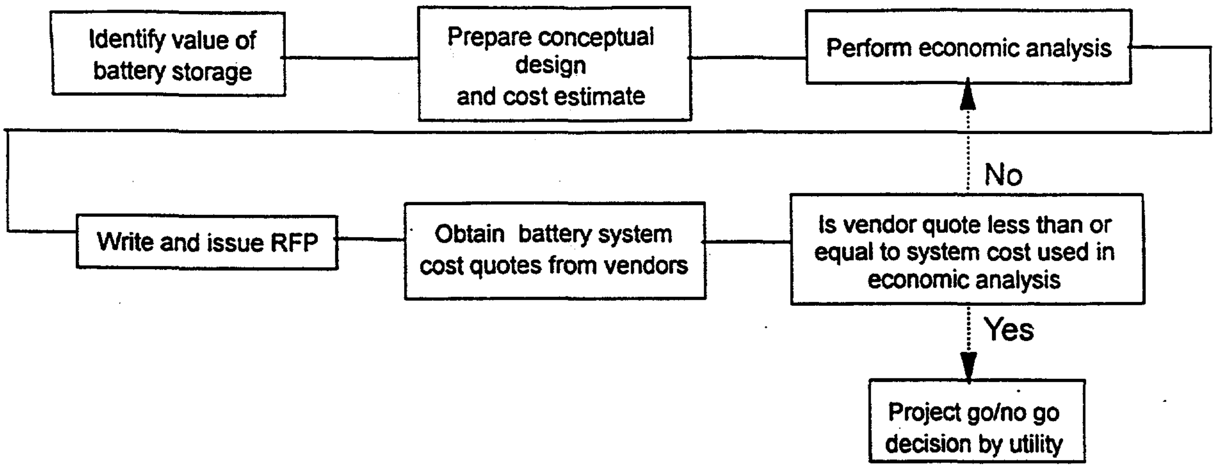


Figure 2-3a. Study Methodology

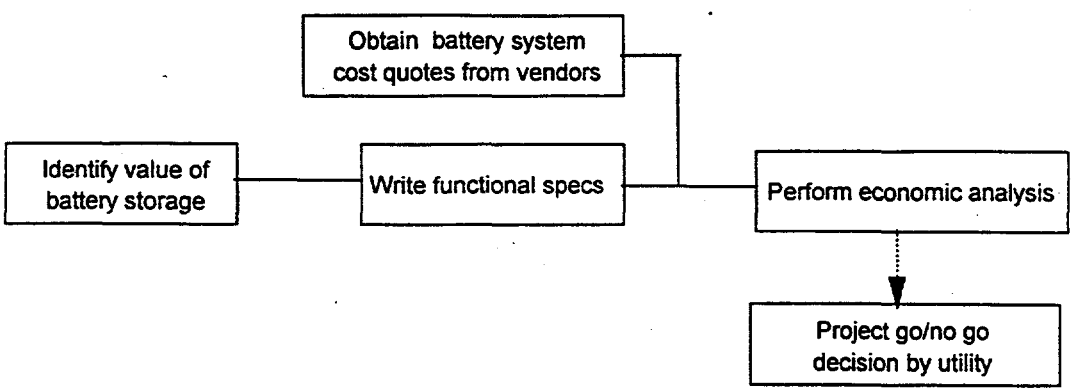


Figure 2-3b. Alternate Methodology

economic analysis has to be repeated to verify the feasibility of the battery project under the new cost scenario.

The alternate approach (Figure 2-3b), the one recommended by UBS personnel, would first identify the value of battery storage benefits for the host utility system. The results would then be used to prepare a functional specification for the battery system that would then be released to battery system vendors through an RFP process to obtain price quotations for the battery system. The system costs obtained would then be used for the battery project feasibility analysis. This approach eliminates the need by the utility to create a conceptual design of the battery system to estimate the battery system cost, a design that may or may not be comparable to the battery system design proposed by the vendors.

The latter approach reduces the cost and manpower burden of the feasibility study upon the host utility and allows the battery system vendors greater flexibility in proposing a battery system that is best matched to the application requirements and in backing it with a performance warranty. After CEA indicated a preference for the latter approach, an SOW was finalized (in mid-June 1994) and a kickoff meeting was held in Anchorage to officially mark the commencement of the feasibility study.

Anchorage Municipal Light and Power (AML&P) held a review meeting in May for the 30-MW/60-MWsec superconductive magnetic energy storage (SMES) Project planned for Anchorage, Alaska. The meeting was attended by UBS staff, CEA, EPRI, Oak Ridge National Laboratory (ORNL), and Babcock and Wilcox (B&W), which is the SMES system supplier. The analytical feasibility study for the project was performed by ORNL as one of five utility-specific system studies performed for SMES applications under a Defense Nuclear Agency (DNA) contract. The ORNL study determined that the SMES system could displace 30 MW of spinning reserve currently provided to AML&P by the Bradley Lake hydro plant. The SMES system hardware development will be cost shared by B&W, the federal government (through a Technology Reinvestment Project grant), and AML&P.

Because of the close proximity of the proposed SMES unit and the battery system that could be installed on the CEA system, there is a strong need to coordinate the studies and design of these two units. Both the SMES and the battery system will attempt to capture similar spinning-reserve benefits that not only affect their individual economic feasibility but also raise concerns about system stability due to the inherent quick response capability of each system. CEA and AML&P understand the implications of implementing these two projects and have agreed to coordinate the review meetings in a manner such that there will be maximum exchange of information during the study and design phases of each project.

3. Subsystems Engineering – Valve-Regulated Lead-Acid

The lead-acid battery has been in existence for over 100 yr and has found use 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 and the relatively low cost of its materials and components, and the generally "user-friendly" characteristics of this battery system. This is true from its manufacture, through its operating lifetime, and to its disposal and reclamation for reuse in new lead-acid batteries. The lead-acid battery has the opportunity to also 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 lifetime uncertainty, understanding of how to apply battery systems, operating inexperience, maintenance, system reliability, and 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 concentrate future lead-acid developmental efforts in BES on VRLA batteries, which are inherently 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, and real-time experience with VRLA batteries, while increasing, is considered insufficient at present by the utility industry to remove skepticism regarding VRLA cycle life. The experience gathered from earlier demonstration installations (BEWAG, Crescent Electric, and the Chino plants for example), has generated positive reactions from the utility community. However, all of these demonstrations used flooded-electrolyte lead-acid batteries, and there is a reluctance to immediately translate these 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 Laboratory have provided a good start. Data from the Utility Battery Storage Systems Program will help to further allay the concerns of the utility industry. A final major market related barrier to implementation of large-scale BES systems is their perceived high initial cost. While improvements in battery performance should help to reduce costs, a better understanding of the benefits derived from using batteries could offset some of their high initial cost.

The lead-acid battery subsystems engineering project therefore 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, together with utility companies, the benefits of these improvements in specific utility applications for which battery system requirements have been defined. To ensure that appropriate issues are identified, two operating utilities are participating in the project. SNL supports the GNB contract work by evaluating the performance of battery modules furnished at several stages during the contract and is also carrying out material development and characterization studies on selected battery components.

Technology Development – GNB

Tasks/Milestones

The GNB effort in this contract is comprised of three tasks. Task 1, which is still under way, is a two-phase activity that is intended to improve the performance and reliability of VRLA batteries through changes in battery design, materials, and manufacturing techniques. 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. To ensure that the VRLA battery designs developed meet the needs of utilities, two utility companies were included on the project team so that the battery designers at GNB could obtain firsthand input about battery storage requirements in their respective utility networks. Task 2 has been led by UMR and has required extensive participation by the 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 developed in Task 1 and to incorporate the improved VRLA battery systems into the economic model developed during Task 2. Task 3 is just beginning and UMR is using the DYNASTORE computer program to calculate the operating cost savings from incorporating different BES configurations on 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 lead-acid batteries at a cost equal to or lower than that of these competing designs. All this must be accomplished without sacrificing the inherent advantages available from the VRLA technology. The technical efforts in this first phase have been focused on performance issues such as vent valve reliability, thermal management, charging profiles, positive plate behavior and ground fault prevention, all of which have been perceived by the utility industry as critical barriers to the widespread implementation of VRLA battery systems. An additional objective was to improve the consistency of cell performance by manufacturing process enhancements.

In the second phase 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. Manufacturing processes that improve consistency and control costs will be evaluated and implemented where appropriate.

These various improvements in the VRLA technology will be incorporated into products in stages and, in some cases, the intent of the incorporated changes will be to produce designs that address the needs of specific utility applications. Figure 3-1 shows a flow chart of the product designations anticipated as a result of this development process. ABSOLYTE II was an existing product marketed for telecommunications and other standby power applications. Some of the improvements in Task 1, Phase 1, have been incorporated into the ABSOLYTE IIP, which is an intermediate product. Commercial production of the ABSOLYTE IIP commenced during the first quarter of 1993.

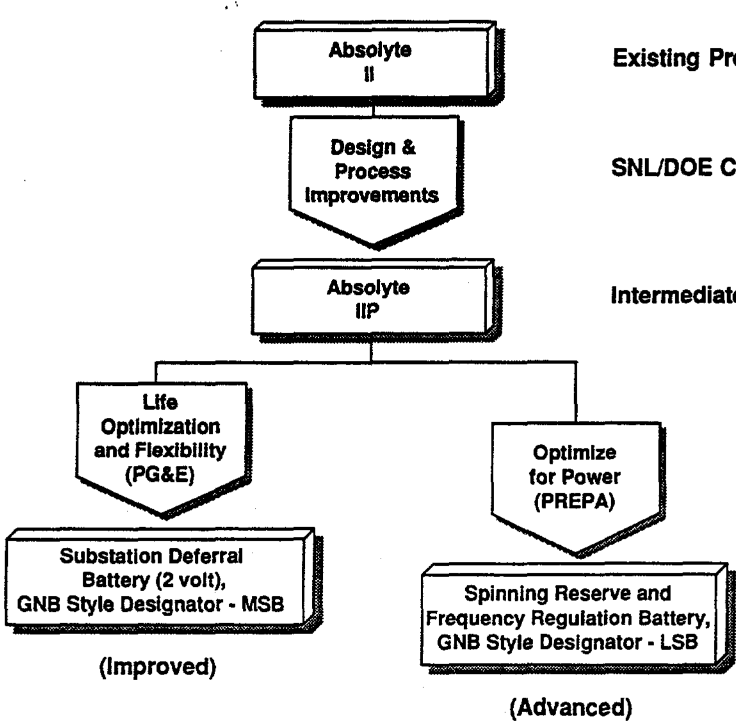


Figure 3-1. Flow Chart of Product Designations Anticipated during VRLA Battery Development Process

The MSB product will contain many of the enhancements developed during Task 1, Phase 1, and is designated as an "improved" design. The MSB is optimized for a set of life, performance, and installation flexibility requirements as recommended by PG&E, a host utility participating in this project. Prototypes of this particular MSB design will be available early in 1995. The LSB product will incorporate technology developed during Phase 2 of Task 1, and is therefore called an "advanced" design. The LSB design is optimized for the power needed in spinning reserve and frequency regulation applications as anticipated by PREPA, the second host utility participating in this project. The advanced-design LSB VRLA battery modules are scheduled to become available for site demonstrations in the second half of 1995.

FY 94 Milestones:

- Deliver GNB intermediate-design VRLA battery modules (12/93) - completed
- Furnish additional coated plug samples for vent valve tests (2/94) [canceled due to program direction change]
- Complete DYNASTORE calculations on first utility system (2/94) [rescheduled to 12/94 because of delay in placing contract]

Status

Task 1/ Phase 1. VRLA Battery Improvements

Vent Valve Reliability

VRLA batteries operate on the "oxygen cycle" wherein oxygen gas generated during charge at the positive plate is recombined on the negative plate. As such, some positive internal pressure must be anticipated during the operation of a VRLA battery. The containers for VRLA batteries are typically made of an acid-resistant plastic, and are not capable of withstanding extremely high internal operating pressures. This is particularly true for large capacity VRLA batteries where the large, thin-walled plastic jars deform relatively easily. For this reason, these large VRLA batteries are often assembled into stronger metal structures to prevent deformation even at the relatively low internal pressures that normally exist during VRLA battery operation.

The pressure relief vent incorporated into the design of all VRLA battery designs is provided as a safety device to allow excess gases built up during periods of high rate charging or overcharging to be vented to the ambient atmosphere. Because the VRLA battery does operate with some positive internal pressure, the vent must stay closed during normal operation. If the vent opens at too low of a pressure, unnecessary quantities of oxygen and/or hydrogen gas will be allowed to vent from the cell, causing loss of water from the electrolyte and potentially resulting in cell "dry-out" and eventual failure. If the vent opens at too high a pressure, the plastic cell case can deform, leading to stresses at the seals and joints that can cause them to deteriorate and potentially develop leaks. A further requirement for the vent valve assembly is to prevent the ingress of oxygen from the surrounding environment to the cell, which will accelerate the rate of self discharge of the VRLA battery by reacting with the charged negative plates.

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.

Testing was completed during the year demonstrating the consistency of operation of this vent design over a 500-hr period during which the vent was forced to operate by excessively overcharging the sample VRLA batteries. The data from these tests showed that:

1. The ABSOLYTE pressure relief vent maintained the internal pressure of the cell below 7 psig, even though oxygen and hydrogen gas were continuously generated in the cell under these test conditions in quantities greater than what would realistically be expected under normal operation.
2. The pressure relief vents resealed well above an "open vent condition," thus maintaining a positive internal pressure relative to the ambient and preventing any outside gas from entering the cell and affecting the balance of the electrochemical reactions.
3. The pressure relief vent operated reliably over the entire test period, accumulating more venting operations than would be expected over a VRLA battery's lifetime under normal operating conditions.

However, testing completed as part of another task within this contract indicated that a more aggressive charging regime would be required to completely recharge a VRLA battery from a relatively low state of charge in the typical overnight time period available for battery uses in conjunction with a utility network. The charge profile that GNB developed to achieve recharge within the time allocated required that the battery operate at slightly higher pressures than the present ones, which are designed to minimize the amount of gas vented from these cells. The preferred vent operating pressure for this reduced-time recharge was in the range of 5 to 10 psig. The pressure relief vent presently used on GNB's ABSOLYTE VRLA cell operates in the range of 3 to 7 psig.

The technical approach taken to shift to the desired pressure range was to first identify those parameters in the present pressure relief vent design and its assembly that were most influential to its operational pressure relief value. A Taguchi-type set of experiments was designed and completed to identify the primary parameters. The experiment showed that the vent opening pressure was most closely correlated to the assembly process, particularly the distance by which the assembly is compressed during welding and the weld time itself. Using adjusted assembly criteria, a group of 88 sample pressure relief vents were assembled and tested. A total of 88.6% of these vents operated at between 5 and 10 psig, and 99.6% of the vents operated within the range of 5 to 11 psig. With additional adjustments to the assembly process, pressure relief vents operating in the desired range could be consistently produced. Samples have been assembled using these process parameters, and are awaiting accelerated operational life testing, as described previously.

Furthermore, since GNB is considering a redesign of the ABSOLYTE cell cover to improve the reliability of the terminal post seals, the evaluation of other pressure relief vent designs that require less space on the cell/battery cover was undertaken. One of these vent designs is an "umbrella" configuration. Once again, it was important to determine the factors that influence vent operating pressure for this design. It was determined that seat thickness and vent seal diameter were the two primary factors. A Taguchi analysis indicated that seat thickness had a contribution factor of 84.3% while the seat diameter contribution factor was 7.75%.

Tooling inserts were fabricated to manufacture battery covers with various vent valve seat thicknesses and opening diameters. Variations of seat thicknesses between 0.08 and 0.135 in. and seat opening diameters between 0.225 and 0.240 in. were fabricated and tested. Pressure relief points were measured for each of the experimental matrix combinations. The results confirmed that seat thickness is the most significant variable affecting the opening pressure of this vent. Seat opening diameter had very little influence on vent operating pressure. The plot of vent opening pressure versus vent seat thickness is shown in Figure 3-2.

The relationship between vent seat thickness and vent opening pressure is nonlinear, as shown in Figure 3-2. Furthermore, at seat thicknesses above 0.11 in., it became extremely difficult to insert the molded umbrella vent valve, and opening pressures were not repeatable. From these data, it has been determined that providing a pressure relief venting system that operates consistently in the 5 to 10 psig range may not be feasible using the existing molded umbrella vent. This task will require further investigation.

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 grid lead 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 density change, the grid structure deforms and commonly undergoes what is referred to in the battery industry as "plate growth." The plate will attempt 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 alloy experiences (i.e., surface corrosion versus intergranular corrosion) and the actual length of the grid. 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 positive active material 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 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 GNB's R&D efforts have determined that the annualized corrosion rate for the MFX alloy, when maintained at 25°C and at a float voltage of 2.25 vpc, is 1.8 mils per year. 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 reaction that evenly corrodes the lead grid surface. This type of corrosion results in the least amount of grid growth. In comparison, intergranular penetration corrosion results in a greater amount of corrosion derived grid growth.

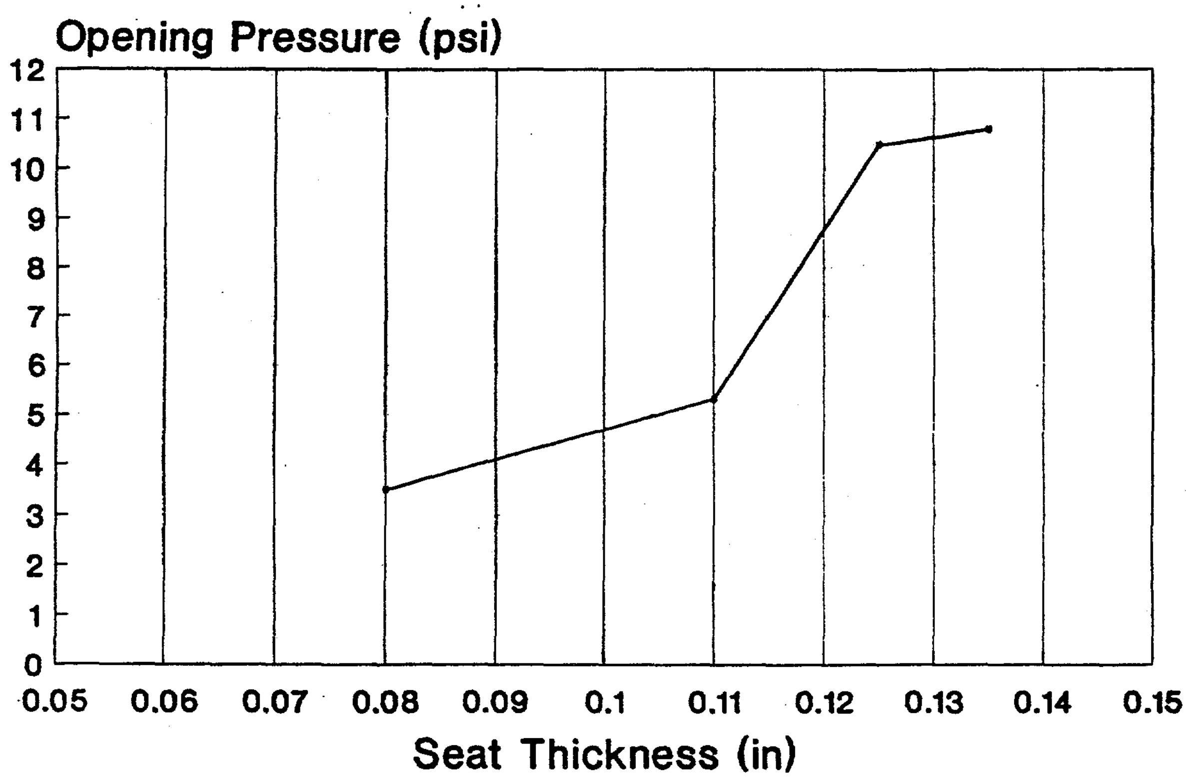


Figure 3-2. Umbrella Vent Valve Opening Pressure as a Function of Seat Thickness

Although the MFX alloy affords a good deal of 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 designed to collapse as the positive grid grows and hence accommodate its growth.

Several sample lots of cells varying the method of protection from positive grid growth have been fabricated and have started on long-term testing. The test lots include the following:

1. Positive plates fitted with a collapsible boot; only the positive plates are wrapped with separator material (Test Group CW).
2. Positive plates fitted with a collapsible boot; both positive and negative plates are wrapped with separator material (Test Group C).
3. Positive plates fitted with the standard design boot; only the positive plates are wrapped with separator material (Test Group S).
4. No boots fitted onto the positive plates; only the positive plates are wrapped with separator material (Test Group N).

Cells from each test group have started on an open circuit stand and a float charge test at both room temperature and 60°C temperature-accelerated conditions. The float charge samples are connected in a series string and are being charged at a nominal 2.30 vpc.

The samples on open-circuit stand at room temperature have completed 26 weeks of test. The open-circuit voltages (OCVs) of all four test groups have dropped approximately 17 mV over the test period. The average OCV for the group has dropped from 2.135 V to 2.118 V. The slope of the curve of open circuit voltage versus time is equivalent for all four groups.

The samples being tested under open circuit, "no load" conditions at 60°C have completed 30 days of test. Average voltage has decayed from 2.147 V to 2.085 V, a loss of approximately 62 mV over the period of the test. As observed in the room-temperature open-circuit test, voltage decay with time is following the same slope for all four of the test groups.

The room-temperature float samples have completed nine months on test. A capacity check was completed recently on the samples and all cells delivered in excess of 100% of rated capacity. The cells on the 60°C float test have completed 30 days of test. All cells on these float tests are exhibiting stable and consistent on-charge voltages, varying only slightly from the average voltage applied to their series strings.

The float current for the room temperature samples has stabilized at about 476 mA and that of the 60°C test cells at 5.2 A. Applying the Arrhenius relationship, which doubles float current for each 10°C rise in temperature, predicts that float current at the elevated temperature condition should be approximately 11 times that at room temperature. This is what has been measured.

These tests are continuing and capacity discharges will be completed in the near future on all test samples to assess their ability to retain capacity under the test conditions.

Thermal Management And Charging Analysis

Elevated temperature has a deleterious effect on the life of any lead-acid battery. In flooded-electrolyte types, the reduction in life is due to the acceleration of positive grid corrosion. In VRLA batteries, in addition to the acceleration of the grid corrosion process, it is suspected that elevated operating temperatures may also induce failures due to accelerated loss of water by gassing and diffusion through the container material and the pressure relief vent valve.

In addition to the heat generation mechanisms associated with the operation of any battery that include (1) the resistive heating effects during discharge, (2) the heat released due to the chemical and electrochemical reactions on charge, coupled with the resistive heating effects during charge, and (3) miscellaneous heating effects from polarization and the grid corrosion reactions, VRLA batteries have one additional significant heat generating source. This is the oxygen recombination reaction occurring at the negative plate during overcharge.

Normally, heat is dissipated in a lead-acid cell by (1) conduction through the cell materials, particularly the lead in the grids, straps and terminal posts, (2) convection from the surface of the battery and its components to the surrounding air, (3) a small amount of radiation, but only if the temperature differential is large, and (4) evaporative cooling caused by the gases being vented from the battery. Being a starved-electrolyte system, VRLA batteries have a lower heat capacity than equivalent flooded-electrolyte batteries, have no internal convection, and have the additional mechanism for heat generation mentioned above. These conditions increase the likelihood of thermal instability and the prospect for thermal runaway.

Earlier in this project, GNB demonstrated how its ABSOLYTE VRLA cells assembled in their modular steel trays can tolerate overcharge at voltages significantly higher than those recommended for normal operation without experiencing thermal runaway. Furthermore, GNB developed a recharge profile that assured adequate recharge of a deeply discharged VRLA battery in less than 8 hr while causing a temperature rise of less than 10°C in the battery and minimizing any gas evolution to provide 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.

The initial in-rush 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. The charge profile using these parameters can recharge a battery from an 80% depth of discharge in approximately 7 hr with an observed 9°C temperature rise and no gas emissions.

In discussions with the utility partners in the project, it was determined that a model to estimate the amount of heat a battery system would generate under a variety of operating conditions would be needed to project building ventilation and cooling requirements. The model has been constructed and validated against an actual ABSOLYTE battery stack with excellent agreement.

As a result of using the thermal model to predict battery temperature under continuous overcharge conditions, an unusual relationship between battery configuration and temperature rise was accidentally encountered. Two different battery configurations were being considered for a typical UES installation. One battery was based on the original ABSOLYTE II design and the other was based on the ABSOLYTE IIP design, which has an improved volumetric energy density. Both battery modules had an energy storage capacity of approximately 6.5 kWh. The thermal model predicted that the ABSOLYTE IIP design would reach a higher temperature on continuous overcharge than the model based on the older ABSOLYTE II design.

This finding highlights the fact that increasing energy density (Wh/volume) of a battery for a utility application may be attractive from a facility space standpoint; but the facility may then require more rigorous thermal management to ensure proper conditions for optimum operation and lifetime of the battery.

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 a serious safety risk to operators and utility personnel. Furthermore, ground faults can lead to premature failure of a portion of the battery because some of the battery charging voltage can bypass the cells between the ground fault point and the facility ground.

GNB's approach to eliminating the risk of ground faults in BES systems involves five levels of redundancy:

1. Improvements to the electrolyte filling process to ensure that cells are not overfilled causing an excess of free liquid electrolyte in the cell. GNB's solution to this challenge was the implementation of a computer-controlled "fill-by-weight" process.
2. Improvements to the heat-sealing process by which the cell jar and cover are sealed together. In response to this challenge, GNB optimized a redundant bead smoothing and jar/cover sealing process to ensure leak tightness.
3. Improvements in leak detection capabilities of testing performed at the factory to ensure seal integrity. GNB's solution was the implementation of an advanced helium-leak-detection system that detects microholes four times smaller than the ones through which sulfuric acid electrolyte can leak.
4. Identification and evaluation of alternative nonconductive battery tray materials. GNB has fabricated and is evaluating a plastic battery tray. Thermal management will be a greater challenge using this plastic tray, but auxiliary cooling fans incorporated into the tray package could overcome this deficiency.
5. Modifications to the terminal post design to prevent damage to the plastic-to-lead seals during manufacture and assembly. This task has taken on greater importance because manufacturing improvements implemented as a result of this project task (items 1-3) have left terminal-post seal leaks as the major contributor to factory failures as identified by the in-plant leak-detection testing.

The present ABSOLYTE terminal post design is based on a copper-inserted 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 that could affect the integrity of the seal between the lead bushing and the plastic cover.

An improved welding process was introduced into the manufacturing procedure; however, a residual percentage of failures due to terminal post leaks persisted. The approach to resolving these complications while retaining the advantages of a copper-inserted terminal connection was to redesign the post assembly and the cover to permit more lead to be cast around the inserted copper piece. This change will minimize the amount of heat required to make the weld to the lead bushing and thus avoid overheating the seal between the lead bushing and the plastic cell cover. The proposed design is compared with the design presently used in the ABSOLYTE cell in Figure 3-3.

Detailed evaluations of the individual parts used in the present terminal design indicated that porosity in the die cast bushings, porosity in the lead surrounding the copper insert of the terminal post, and degradation of the bond at the copper-to-lead interface were the primary paths through which sulfuric acid travels to create leaks. More significant is the fact that these causes often do not appear as electrolyte leakage paths until some time (months to years) after the battery has been placed into service. Even the most sophisticated of leak-detection tests cannot identify these potential leakage paths before exposure to acid and time create the path. GNB's approach to solving this problem is to design the parts to minimize porosity and inclusions that could subsequently lead to electrolyte leakage paths.

A particular cell size has been selected and detailed designs have been completed for a new cover incorporating the proposed design features. The design revisions require that a new cover mold and new bushing and terminal-post molds be fabricated. Samples of the bushing and terminal post have been received and have been examined for indications of included porosity, cracking, or alloy knit lines, all of which could allow electrolyte to creep and eventually leak.

Positive Active Material

The positive electrode active material has a significant effect in determining the life of a lead-acid battery. The positive plate in a lead-acid battery is considered to be the "workhorse" plate because the positive active material undergoes much greater crystal structure and

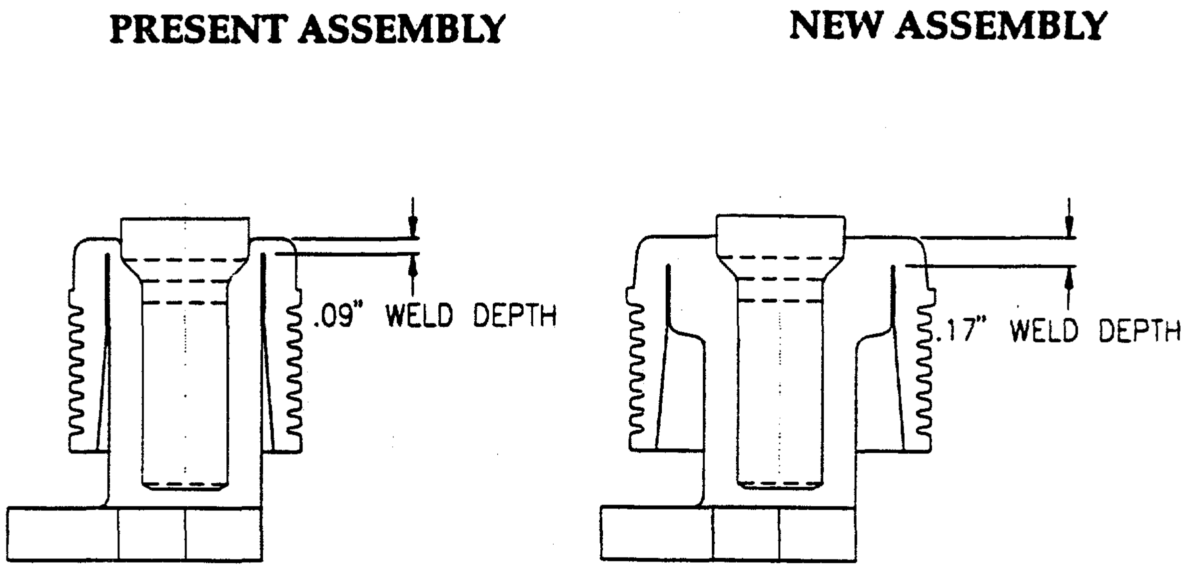


Figure 3-3. Present and New Designs for a VRLA Cell Terminal Post Assembly

morphology changes than the negative active materials during discharge/charge cycling. The objective of this project task is to determine the paste formulation, paste mixing, and plate curing process parameters needed to achieve material structures that exhibit optimized performance and lifetime.

GNB is evaluating the use of a "leady-oxide" material for use in the positive electrode to improve battery lifetime under the severe discharge/recharge cycling conditions expected in utility BES system applications. A series of paste-mixing and plate-curing experiments has been completed and a group of cells has been constructed using optimized processing parameters for the leady-oxide formulation in the positive electrode.

Cycle-life testing of these cells has started with the samples being discharged to 100% depth of discharge at the C/5 discharge rate. Periodically, the samples are tested at their C/8 rate as a comparison to their rated performance. Although the test units have completed over 300 cycles, performance for both the leady-oxide group and the red-lead-oxide samples representing the current design has not developed as anticipated. Capacity has continued to hover near 80% of rated performance.

A change in the recharge profile used in the cycle tests resulted in a short term improvement, but battery capacity soon returned to near 80% of rated performance. Recently, one of the samples was equipped with a reference electrode, and, surprisingly, the negative electrode was the electrode limiting the capacity of the battery. The battery was provided with a boost charge at an elevated charge voltage to recover the negative electrodes, and has since been returned to the cycle test.

In addition to the cycle tests, a temperature-accelerated float-life test has been started. After one month of test at 80°C, the test samples were capacity tested, and all delivered in excess of 100% of rated capacity.

Task 1/Phase 2. VRLA Battery Advancements

Cell Design

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

Intermediate Design (ABSOLYTE IIP)

The intermediate design product developed under this task has been introduced as a commercially available product.

2-V Modular Battery (MSB)

Based on discussions with one of the host utilities in this project, the need for a modular battery suitable for "portable" applications was identified. Critical characteristics included minimum space and weight, and flexibility of installation. To obtain these features, a reduction in operational lifetime to 5-10 yr was deemed necessary and acceptable.

GNB developed a design based on a medium-sized modular battery package (approximately the size of a Group 27 automotive battery). The module, however, would be a 2-V unit that would be connected in series/parallel configurations to achieve the desired voltage and capacity. The modular approach would increase the flexibility of installation and would permit easy replacement of modules during the operational lifetime of the battery system. The design would allow utilities to minimize their initial investment while evaluating BES in their network. In addition, this approach could be used where temporary, seasonal, or short-term conditions exist that could be resolved using BES.

Tooling to fabricate the case and cover parts for this 2-V MSB battery design is being fabricated and first parts have been produced off of the molds. First Article Inspections (FAIs) of these parts are being completed. In addition to these parts tools, the tooling necessary to fabricate and assemble this design on the manufacturing line at GNB's Columbus, Georgia manufacturing facility is being debugged during off-shift times at the plant.

Both discharge performance estimates and recharge capabilities for the 2-V modular MSB battery design have been verified with a 12-V battery module that uses the identical plates planned for this battery.

Advanced Design (LSB)

Present ABSOLYTE batteries are designed to provide the sustained discharges typical of energy storage systems. These batteries offer significant reductions in battery footprint, space, and weight when compared to conventional flooded-electrolyte lead-acid batteries. A battery that has been optimized specifically for high power applications, such as power 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 concept for this battery was completed and prototype cells were fabricated. Initial performance testing indicated that the LSB design could provide as much as a 66% capacity improvement over the ABSOLYTE IIP design at the 15-min discharge rate. The prototypes, however, highlighted several process and assembly issues that had to be resolved before the design could be considered to be reliable enough for utility applications. These included leakage at the jar-to-cover heat seal and at the interface between the cover and the terminal bushings.

The primary cause for the jar-to-cover heat seal leakage was determined to be the poor heat-sealing characteristics of the plastic used to mold the cell's components. This issue was readily resolved by changing to a polypropylene copolymer that had much better heat sealing characteristics. The terminal post sealing issues were more difficult to resolve.

After extensive evaluation and study of the terminal-post design and the component construction, it was decided that the initial proposed design would invariably have sealing difficulties. A decision was reached to redesign the terminal ends of the cell using a more conventional approach that allowed the plates in the cell element to be connected to a terminal-post strap similar to that used in conventional battery constructions. The reason for this was that bonding the individual plates to the current collector in the original design required a significant amount of heat to accomplish simply because there was so much lead that had to be bonded. This excess quantity of heat would certainly do damage to any plastic material when the terminal strap was welded to the insert-molded bushing in the cover. The revised design bonds the plates to the strap using a conventional cast-on-strap process, the strap having a terminal post. This terminal post is subsequently welded to a bushing that is insert-molded into the cover. This approach drastically reduces the heat needed to complete the final terminal post weld, and the potential for heat damage to the plastic is similarly reduced.

This change was a radical departure from the original proposed design, and most of the component tooling needed to be replaced, as well as most of the process and assembly tooling. In addition, several new pieces of equipment would be required to complete the design and implement it into manufacture. Because of the high cost of tooling, it was decided to first build several prototype cells using parts produced from "soft" tooling. These prototype cells were fabricated and tested to validate the integrity of the terminal-post seal. The validation tests were successful, and approval was obtained to proceed in obtaining permanent tooling.

Using these prototype samples, electrical tests were also conducted to determine the effect these design changes would have on cell resistance and high-rate discharge performance. Actual performance reduction was less than 10% compared to that of the original LSB design. Test results are provided in Figure 3-4. These discharge rates are still very respectable and will provide the highest high-current discharge performance per battery weight and volume of any known lead-acid battery with equivalent life expectations. Plans are for preproduction samples of the redesigned LSB cell being available by the first quarter of 1995.

Copper Negative Grid

Historically, lead has been used as the grid material for the negative plate. The principal considerations in the selection of a lead alloy to be used as the negative plate grid are over-potential characteristics and strength; corrosion resistance is not a major consideration. Lead is a poor electrical conductor and other materials, copper for example, with higher conductivities 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, a 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 utilizes 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, primarily because of the lack of availability of a suitable lead-coated copper wire.

To test the concept however, GNB plans to fabricate negative electrode frames using lead-plated copper wires. Although plated copper wire is probably not an acceptable approach to achieve long life in a lead-acid battery, its use would be acceptable to determine relative electrical performance improvements potentially available from using the copper negative grid concept. Appropriately sized copper wire has been received and has been sent out to be plated with a thick coating of lead. A prototype mold is being fabricated to mold electrode frames with copper wires inserted at the proper locations.

Positive Plate Design

Three of the most basic factors that limit a lead-acid cell's cycle and float life are positive grid corrosion, damaging changes in the positive active material (PAM) structure, and the formation of passivating films at the PAM-to-grid interface. This task explores changes in the positive grid alloy to lower positive grid corrosion, and the potential benefits of PAM additives to improve PAM stability and utilization.

PERFORMANCE IN WATTS PER CELL

	CELL TYPE			
RATE	LSB600	LSB800	LSB1000	LSB1340
5 MIN.	980	1400	1590	1920
10 MIN.	710	970	1190	1510
15 MIN.	570	760	970	1230
20 MIN.	470	630	820	1020
30 MIN.	350	480	630	730
60 MIN.	220	280	360	450

Figure 3-4. Performance Ratings (Watts) for Prototypes of the Redesigned Advanced LSB Battery.

Positive Grid Alloys

Selection of a positive grid alloy requires the evaluation of corrosion resistance, grid growth, tensile strength, and gassing characteristics. The behavior of the alloy in a cell also needs to be studied to establish cycle and float performance and oxygen recombination efficiency when it is used in a VRLA design. GNB utilizes its patented MFX alloy in the positive grid of its ABSOLYTE batteries. This alloy corrodes by a uniform surface erosion process that allows GNB to reliably predict a 20-yr lifetime for the ABSOLYTE IIP cell at 25°C in a float charge application. The objective of this project is to evaluate other lead alloy compositions that corrode at slower rates than the MFX alloy, which may extend the overall lifetime of a battery in a utility application.

GNB has completed the initial evaluation of several alternative alloy compositions in comparison to the MFX alloy. The first series of evaluation tests included an accelerated cycle test in which cells assembled with plate grids made from each of the alloys were deeply discharged at a low discharge rate and recharged with a significant amount of overcharge in order to provide accelerated-life test conditions. Although the MFX alloy provided the best deep-cycle performance of the group tested, two of the test alloys are approaching the capabilities of the MFX alloy.

The second stage of this task is now under way. The test vehicle configuration has been changed from hand-built laboratory cells to full size, 12-V, Group-27 battery modules. These battery samples were assembled in GNB's Columbus, Georgia manufacturing facility using standard production equipment and were fully characterized before being placed on accelerated life tests. This accelerated test is a float-life test. Battery modules have been placed into heated water baths and are receiving a constant voltage charge. The modules are still in their first charge period, after which they will be capacity tested and have selected samples removed from them for grid corrosion analysis.

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 will allow an increase in the active material porosity and, therefore, permit an increase in active material utilization and capacity without sacrificing cycle lifetime.

Based on a study of the literature of available additive materials, tin dioxide, fluoridated tin dioxide, a fluorocarbon polymer (polytetrafluoroethylene (PTFE) or polyvinylidene difluoride (PVDF)), and a conductive titanium suboxide ceramic were selected for further investigation.

This project has made little progress since its inception because the materials identified in the literature are not readily available as commercial products. It appears that the cited researchers not only examined the additive's effects in battery positive active material, but also provided the tested additives by preparing or synthesizing the materials themselves. The few sources that GNB has been able to identify have been extremely reluctant to provide appropriate materials, and GNB does not have the resources to prepare these additives internally.

GNB is aware of projects being conducted in participation with university laboratories to investigate the role of additives similar to those identified by GNB in providing stabilized positive active material structure for lead-acid batteries designed for EV applications. Considering the difficulties GNB has had in obtaining materials to conduct this part of the project, GNB recommends following the progress of these research projects to identify specific materials and to assess their effect on improving PAM stability in deep cycling applications.

Electrolyte Immobilization

The present ABSOLYTE design utilizes an absorbent fiberglass mat that serves as a plate separator as well as the means of electrolyte immobilization. By and large, this glass mat has worked very well; however, there are some disadvantages. The most important disadvantage of this material is cost, which is the primary reason for the higher cost of VRLA cells compared to flooded lead-acid battery designs. Another limitation is the wicking height of liquid in the glass mat, which limits overall cell height, as installed, to 24 in. or less. The objective of this task is to investigate lower-cost alternatives to the fiberglass mat presently used in VRLA cells. These investigations involve the evaluation of vendor-supplied samples and the performance testing of cells containing materials that have passed initial screening tests.

There are only a few suppliers of the type of fiberglass mat that is usable in VRLA cells; and of these few, there was only one manufacturer who was willing to undertake a development effort to identify and produce an alternative material. GNB has been working with this vendor to establish product requirements and to evaluate samples provided. The current material is a nonwoven fabric made from a specific blend of glass fibers with varying fiber diameters. The nature of the glass surface, as well as the blend ratio of fiber diameters, imparts the wicking characteristics observed in the final separator mat. The glass fiber blend also affects the physical strength of the material.

GNB's supplier has been looking at alternative blends that utilize more of the larger glass fibers to reduce cost; however, these materials have had reduced wicking, absorption, and strength capabilities. Synthetic materials are also being investigated, but most plastics that can survive in a sulfuric acid environment (such as polyethylene or polypropylene) also have extremely poor wetting characteristics. Consequently, progress on this particular task has also been very slow, and results have been limited. GNB will continue to evaluate materials as they become available from our vendor for VRLA battery separators.

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 systems requirements and to conduct economic analyses relating to battery systems as part of their utility equipment portfolio. UMR assisted by developing system specifications for these applications and also developed several conceptual plant layouts to meet the requirements using various battery types being developed by GNB for BES installations. Most of this work was completed during the 1993 fiscal year reporting period.

A final report summarizing PG&E's efforts in the definition of BES system requirements within its network was completed and has been submitted during this year. The PG&E objective was to evaluate energy storage as an option for distributed storage within the network. The battery would be used at substation sites to shave peak load from the substation feeder during peak demand periods. This mode of operation would defer the need to upgrade the substation transformer as well as contribute to reducing the overall system peak.

In their study, PG&E evaluated the economic benefit of using a "transportable" grid-connected battery system. The primary benefit that was analyzed arises from the deferral of costly substation capital investments at locations that are anticipated to experience demand overloads. A secondary benefit was the generation capacity value of dispatching the battery system on-peak.

Hourly loads at four case study sites were analyzed and battery systems in the 0.5- to 2.0-MW range were modeled to verify the technical viability of deferring substation and distribution capacity increases. Based upon battery dispatch modeling consistent with the case studies, peak load reductions and capacity deferrals were estimated for the four sites.

Substation upgrade cost estimates were used in the economic analysis to assign a typical deferral value over the life of the battery system. These economic benefits, adjusted to account for costs of maintaining and transporting the system, were evaluated over the life of the system, and a present worth was calculated as an estimate of the allowable break-even capital cost of the battery.

By deferring one substation upgrade per year, a 1-MW, 2-hr transportable battery system (TBS) with a design lifetime of 10 yr could be economically justified at a cost of about $700/kW.

Final Battery Deliverable for Field Test

A moderate-sized battery will be furnished by GNB for a field test at the conclusion of its development program. The approximate size of this battery will be 250 kW/500 kWh. It is now expected to be available during the summer of 1995. Due to a slip in the schedule for production of the advanced LSB battery, the field test deliverable will be either the ABSOLYTE IIP, which is currently in production, or the 2-V MSB modular battery, depending on the particular application at the chosen field test site. The balance of the battery system, including the PCS, controls, and building, will be the responsibility of the host. During the spring of 1994, an announcement of the availability of this battery was sent out by the UBG to its general mailing list. Approximately 10 inquiries were received in response to this mailing, and 4 serious contenders to host the field test have developed. Several of the sites are studying load profiles on their systems to better define the usage the battery would see and to more accurately estimate the minimum battery system size that would be appropriate for their application. The site selection process will conclude in the first part of 1995 with the placement of a contract to carry out the field test.

Quantification of Costs/Benefits of Battery Energy Storage – UMR

This task was activated during the year by placing a contract with UMR from SNL to use the DYNASTORE computer program to calculate utility operating costs with and without BES on the system. Operating costs are one portion of the cost/benefit picture and will be combined with battery developer cost estimates and utility benefit projections that have been done to show that battery improvements are economically justified. The first utility analyzed by UMR was a medium-sized island system since they had already acquired much of the system data needed for the operating cost study.

UMR has learned how to use the DYNASTORE program and helped to debug a beta-test version of the software. After the program was fully operational, input parameters were entered for the island utility and utility operating costs were calculated for a 2-yr time period, 1996-1997, using estimated peak loads for these 2 yr. The generation mix for this utility is primarily derived from oil-fired steam, and total generation capacity exceeds the estimated peak load by about 33%. Three applications for BES were examined on this system: (1) spinning reserve, (2) load leveling, and (3) frequency control. The applications were evaluated both singly and in combinations. A total of 200 MW was assumed to be available from batteries, compared to 3,783 MW of conventional generation capacity on this system. Typical results for the calculated operating cost savings are shown in Table 3-1. The greatest savings are derived from the spinning reserve application where, in the absence of the battery, higher-cost generation units would have to be put on line to cover the reserve requirement. However, significant operating cost benefits are available from all of these applications. It appears that the savings from load leveling and frequency control are probably similar.

These preliminary results are being examined to check for inconsistencies that may have appeared when a new version of the program was issued in July 1994. Other unit commitment scenarios and battery applications are also being reviewed to determine if calculations should be done for any of those cases. The results are not believed to be particularly sensitive to the relative amount of BES compared to total system generation capacity in this situation, but some additional calculations may also be done with different battery sizes to verify that this is true.

Technology Evaluation – SNL

In the latter part of the first quarter of FY94, three Type 100A-25 ABSOLYTE IIP modules were received from GNB for evaluation of the intermediate design. Each 6-V unit has a rated nominal capacity of 1200 Ah at the C/8 discharge rate to an end-of-discharge voltage of 5.25 V (1.75 vpc). Also during this period, test station equipment necessary to carry out the evaluation was ordered.

In the second quarter, the test station equipment was delivered. Assembly of it, however, awaited remodeling of an existing laboratory, which did not begin until the onset of the third quarter.

Table 3-1. Summary of Operating Cost Savings for Selected Battery Energy Storage Applications

Battery Application	Savings ($K) 1996	Savings ($K) 1997
No frequency control engaged:		
Spinning reserve only	14,250	26,014
Load leveling only	11,774	23,247
Frequency control using base and cycling generating units:		
Load leveling and spinning reserve	11,874	23,232
Load leveling and frequency control	11,214	20,114
Spinning reserve and frequency control	13,029	22,061

In the latter part of the third quarter, remodeling of the new test facility was completed, and hardware for the test station was assembled. Also, at that time, the ABSOLYTE IIP modules were moved into the facility, strapped in a series configuration, and connected to the test station. A picture of the test station and the ABSOLYTE IIP battery is shown in Figure 3-5.

During the fourth quarter of FY94, all related test station equipment was checked for proper operation, and the controllers programmed. Also during this period, a draft test plan was written to define testing of the three series-connected modules. The objectives of testing this battery were identified as follows: (1) confirm electrical performance ratings, (2) evaluate the battery's capability to meet area/frequency regulation and spinning-reserve requirements for utility energy storage (UES) applications, and (3) possibly determine the service life of the battery while using area/frequency regulation and spinning-reserve cycles. The decision of whether or not to pursue the last objective will be made after completing the first and second objectives. Note, the area/frequency regulation and spinning reserve tests will be similar to those for the PREPA/C&D lead-acid batteries that were performed at SNL in 1992-1994, with power levels scaled to ABSOLYTE IIP ratings. Details of PREPA/C&D battery test procedures are covered in the "Utility Battery Storage Systems Program Report for FY93," SAND93-3899.

Testing to confirm electrical performance ratings commenced in late September. Initially, an equalizing charge was given to the battery as described in the ABSOLYTE IIP Installation and Operating Instructions. Since the battery was in storage for more than 6 mo, the instructions called for a constant-voltage charge at a level of 21.15 V (2.35 vpc) until the charging current tapered to a stable level, which was defined as no further reduction for 3 hr. This was followed by 12 hr of charging at this stabilized current level. The in-rush current was limited to 300 A. The current level at the end of the equalizing charge was 6.26 A. Following the equalizing charge, three consecutive 150-A constant-current discharge tests were performed to compare measured amp-hour and kilowatt-hour capacities with rated capacities for the ABSOLYTE IIP. The rated capacities are 1200 Ah and 21 kWh at an 8-hr discharge rate to a cut-off voltage of 15.75 V (1.75 vpc). The measured discharges yielded 1180, 1202, and 1195 Ah, and 20.9, 21.4, and 21.3 kWh, respectively. Recharges were accomplished in two steps. First, an in-rush current of 300 A was delivered to the battery until a charging voltage of

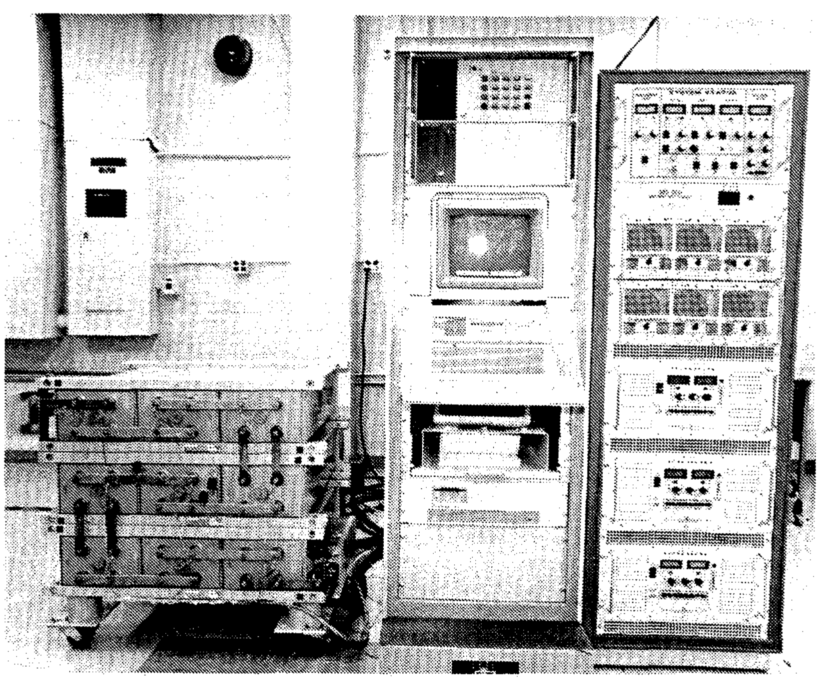


Figure 3-5. Test Station and ABSOLYTE IIP Battery

21.15 V (2.35 vpc) was reached. Then, the charging voltage was fixed, and the current allowed to taper until 107% of the Ah capacity removed during the previous discharge was returned to the battery. Subsequent to each of the recharges, the battery was allowed to rest at open circuit for 2 hr before proceeding to the following discharge.

One cell (cell 3) consistently reached the average cut-off voltage of 1.75 vpc before the other eight cells on each of the three discharges, causing the string voltage of the battery to reach the 15.75-V cut-off limit sooner, consequently lowering the measured Ah and kWh capacities. At the 15.75-V cut-off limit, this particular cell was at 1.64 V on the first discharge, 1.56 V on the second, and 1.49 V on the third.

Temperature data were also recorded for the three discharge/recharge tests. Four type-k thermocouples were mounted on the battery at the following locations, with reference to Figure 3-6: one against the right side of cell 8; one at the middle of the top side of the steel case of Module B; one against the right side of cell 5; and one against the upper left corner of cell 5. These locations are given with respect to facing the terminal side of the battery cells, and describe thermocouple placement in terms of x- and y-coordinates. In terms of the z-coordinate, each thermocouple was placed midway back along the battery case. Table 3-2 shows temperature increase results from the start-of-charge to the end-of-charge (EOC) for each of the three recharges. The external temperature at the right side of cell 5 was assumed to best represent internal cell temperatures, since it is closest to the center of the entire battery; therefore, the data shown in Table 3-2 are that produced by this thermocouple.

Future activities include finalizing the test plan after soliciting input from GNB, and pursuing the objectives listed in the test plan, with the next one being to confirm capacity ratings of the ABSOLYTE IIP intermediate design at 2-hr and 20-hr discharge rates.

Applied Research – SNL

Sandia has been supporting the development of improved pressure relief valves for VRLA batteries by supplying coated samples of the molded rubber plug in the valve assembly to GNB for testing. Because coated plugs should be less subject to chemical attack by the battery electrolyte, they would be less prone to stick to the valve seat, and therefore may operate more repeatably than uncoated plugs. Early test results did show more uniform opening pressures for valves containing coated plugs. However, GNB has begun evaluating other vent valve designs because of a shift in the desired pressure range for valve operation and because of concerns about the space required for the compressed rubber cylinder relief vent on the cover of the advanced battery designs. Since a totally different valve concept could be implemented as a result of this work, evaluation of coatings for the rubber cylinders has been suspended.

During FY94, discussions were begun as to whether SNL could assist GNB in the evaluation of surface treatments for battery grids as a method of improving lead-acid battery performance. SNL has personnel and facilities to perform various surface treatment processes that may be beneficial. An initial approach for this study was agreed upon and a work proposal has been drafted. Specific powder compounds necessary to do the surface treatments are now on order, and a few different sizes of grids have been received at SNL from GNB. SNL plans to treat the initial grid samples and then return them to GNB for evaluation. The first sur-

Table 3-2. Temperature Rise Data During Recharges

Cycle #	Temperature at Start of Charge	Peak Temperature	Temperature Rise
6	30.5°C	40.2°C	9.7°C
7	33.8°C	45.0°C	11.2°C
8	33.7°C	43.9°C	10.2°C

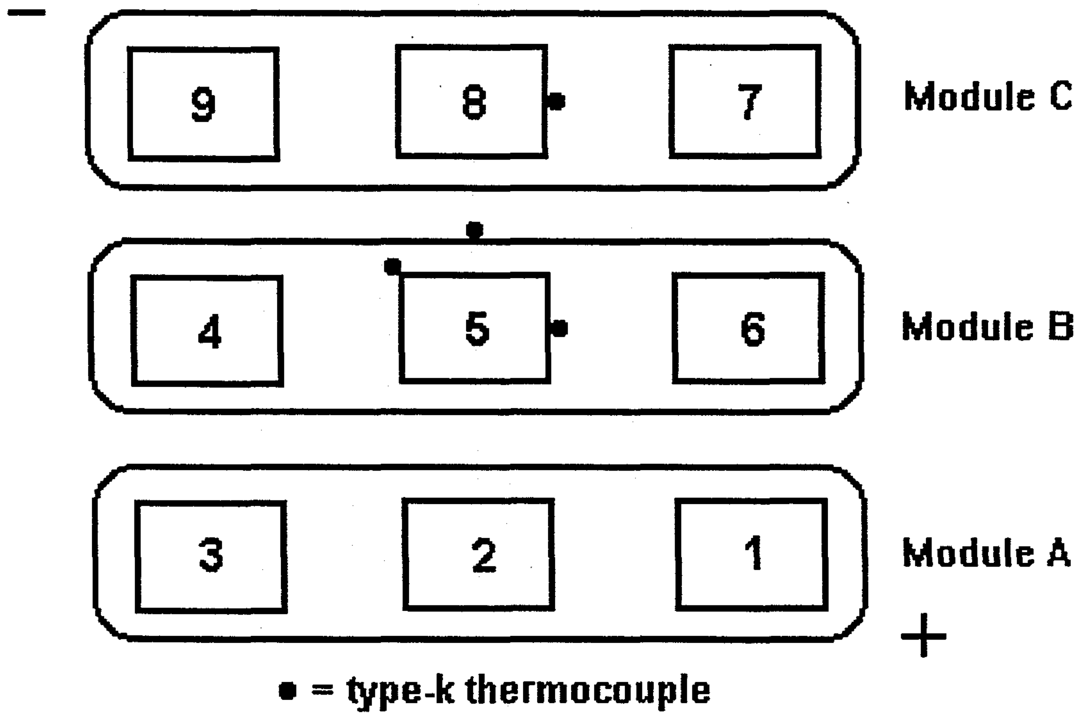


Figure 3-6. Thermocouple Placement on Module and Cells of ABSOLYTE IIP Battery

face treatment trials are expected to be carried out early in FY95 if the supplies on order arrive as scheduled. If the initial treatments meet expectations, then other variations of the process will be studied, and, at some point, enough grids will be treated for battery-level performance testing to be carried out.

4. Subsystems Engineering – Zinc/Bromine

The zinc/bromine battery differs from conventional batteries in that the electrolyte is circulated and stored external to the battery stack. The system consists of battery stacks, electrolyte storage reservoirs, and an electrolyte circulation system. The flowing electrolyte is necessary to ensure uniform zinc plating, to separate the reactive bromine from the electroplated zinc in the battery stack, and to improve the thermal management of the system. The main advantages of the zinc/bromine system are the high specific energy (70-80 Wh/kg), ambient temperature operation, low-cost materials, and simple manufacturing techniques.

A bipolar electrode design is used to increase the specific energy of the system. During charge, zinc is electroplated on the anode, and bromine is formed at the cathode. A complexing agent is used to lower the reactivity and vapor pressure of the elemental bromine, which reduces the self-discharge of the battery and significantly improves the safety of the system. 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 stack, 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:	$QBr^- + nBr_2 \rightarrow Q(Br_2)_nBr^-$ 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 microporous silica-filled polyethylene, which allows ions to transfer from one side of the cell to the other. Each electrode and separator is 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 and placed between glass-filled polyethylene end blocks to form a hermetically 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 stacks is about three times the operating pressure.

Technology Development – JCBGI/ZBB

Tasks

The zinc/bromine battery development contract is being cost shared by the industrial partners. At the end of FY94, JCBGI sold the zinc/bromine technology to ZBB. Continuity in the contract was possible because ZBB hired several JCBGI employees working on the contract.

The objectives of this contract are to design, fabricate, evaluate, and optimize a zinc/bromine battery system suitable for electric utilities. The soundness of the battery technology was demonstrated during Phase 1 of the contract. In Phase 2, new larger cell stacks, designed for an electric utility battery, are being developed, while core technology research is continuing. 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. Based on the results of this testing and utility interest, larger systems may be tested in the future.

Status

During the course of this contract, major improvements have been made in raw material properties and manufacturing techniques; this has resulted in reduced leaks and increased battery performance.

Battery Testing

The V-design battery stacks (1170 cm^2) were originally developed to demonstrate the feasibility of the vibration welding process for sealing the battery stacks. These stacks are being used for long-term cycle life testing. As shown in Table 4-1, V-design battery

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	951	74.0	76.0
V1-80*	2/94	497	78.4	79.0

* Denotes Test in Progress

builds have exhibited significant improvements in performance and cycle life since the beginning of the contract. The end of life is considered to be when the energy efficiency declines by more than 10% from the peak value for that battery stack.

Batteries V1-53 to V1-57 were manufactured early in the contract and gave an average 71.8% energy efficiency and an average cycle life of 290 cycles before the performance degraded by more than 10% from the peak value.

A lower-resistance carbon plastic electrode was developed and tested in batteries V1-72 to V1-77. Battery V1-76 gave slightly higher energy efficiency than the others primarily due to the use of silver screen as opposed to copper screen as the current collector in the terminal electrodes. These batteries had an average cycle life of 447 cycles and an average energy efficiency of 74.6%.

Battery V1-79 was manufactured with the same carbon plastic as the previous batteries, but the cathode activation-layer pressing parameters were optimized. The battery is still performing with less than 10% degradation in performance after 951 baseline cycles.

Battery V1-80 was manufactured with low-resistance terminal electrodes and a very-high-surface-area carbon activation layer. The terminal electrodes had about 50% lower resistance than previously prepared electrodes, and the surface area of the cathode layer was about three times higher than for those used in battery V1-79. These improvements demonstrated higher energy efficiencies and are expected to extend the life of the battery. Battery V1-80 continues to perform at about 78% after 497 cycles.

The performance of several of the V-design, 1170-cm^2 battery stacks is described in the following section.

Eight Cell, 1170-cm^2 Stacks

<u>V1-72 (1-kWh)</u>

Battery V1-72 was the first V-design battery stack to complete more than 500 cycles (see Figure 4-1). The battery was performing at 88.4% coulombic, 79.1% voltaic, and 70.0% energy efficiencies after 504 cycles. At this point, the second-phase solenoid valve became inoperable during a series of six consecutive baseline cycles. Because of the valve remaining closed, only

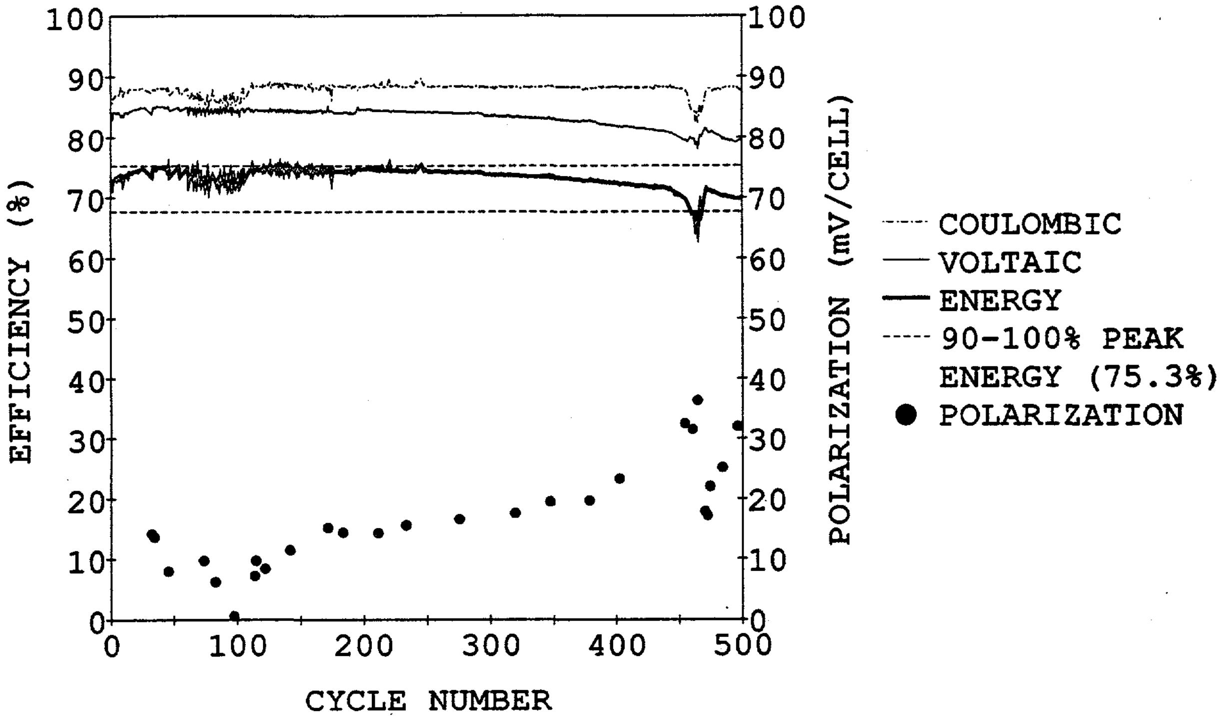


Figure 4-1. V1-72 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)

aqueous-phase electrolyte could be circulated during the discharge portion of the cycle. The battery became severely overcharged, since it could only be partially discharged during each of the six cycles. It was taken off test because a small leak developed from the anode terminal stud connection.

V1-76 (1-kWh)

The energy efficiency of battery V1-76 had declined by more than 10% after 325 cycles. A number of attempts were made to bring the performance of this battery back into the 10% degradation range without much success, as seen in Figure 4-2. The battery was taken off test after completing 414 cycles. The efficiencies for the final cycle were 85.9% coulombic, 76.8% voltaic, and 66.0% energy efficiencies with 7.3% transport and 6.7% residual inefficiencies. The efficiencies fluctuated a great deal over the last 50 cycles, so testing was discontinued. The battery failed because of high electrochemical polarization and an increase in internal resistance.

V1-77 (1-kWh)

After completing 517 cycles, the performance of battery V1-77 had declined by more than 10% from the peak energy efficiency of 76.7%. The final cycle gave 84.0% coulombic, 80.6% voltaic, and 67.7% energy efficiencies. Figure 4-3 is a plot of baseline cycle efficiencies for battery V1-77. This battery failed because of high electrochemical polarization and an increase in internal resistance.

During the charge portion of cycle 454, a cooling water line broke and filled the spill containment tray, completely submerging the pumps. The pumps became inoperable, and the battery remained partially charged until the stack could be drained and transferred to another test station. This pump failure did not appear to irreversibly damage the battery, but it may have caused the battery performance to deteriorate more rapidly than expected.

V1-78 (1-kWh)

Twenty-one baseline cycles were run on battery V1-78 with very consistent results. The cycle efficiencies averaged 89.6% coulombic, 85.6% voltaic, and 76.7% energy, with 5.4% transport and 5.0% residual inefficiencies. It was removed from testing and was going to be sent to SNL for testing. Figure 4-4 is a graph of the cycle efficiencies for battery V1-78.

The battery was placed back on test after being on the shelf for more than a year. A lower-cost electrolyte

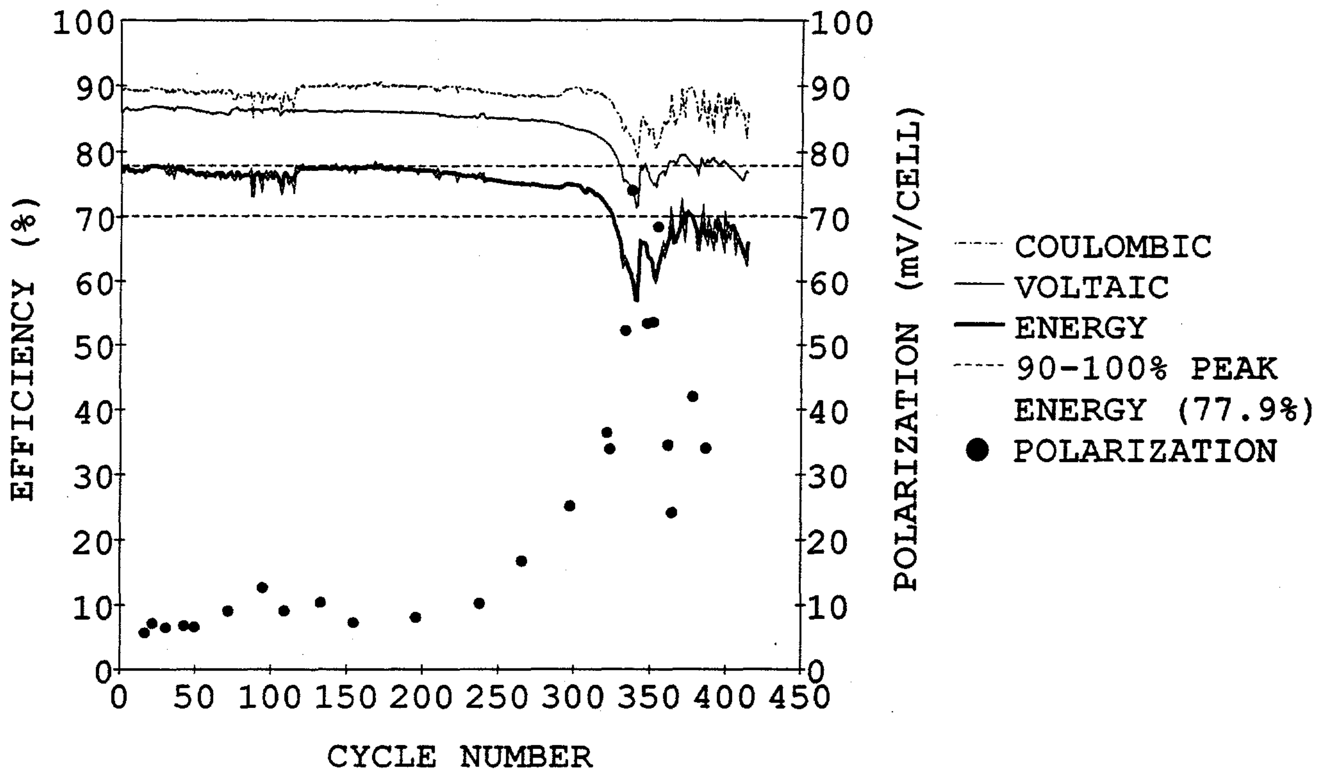


Figure 4-2. **V1-76 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)**

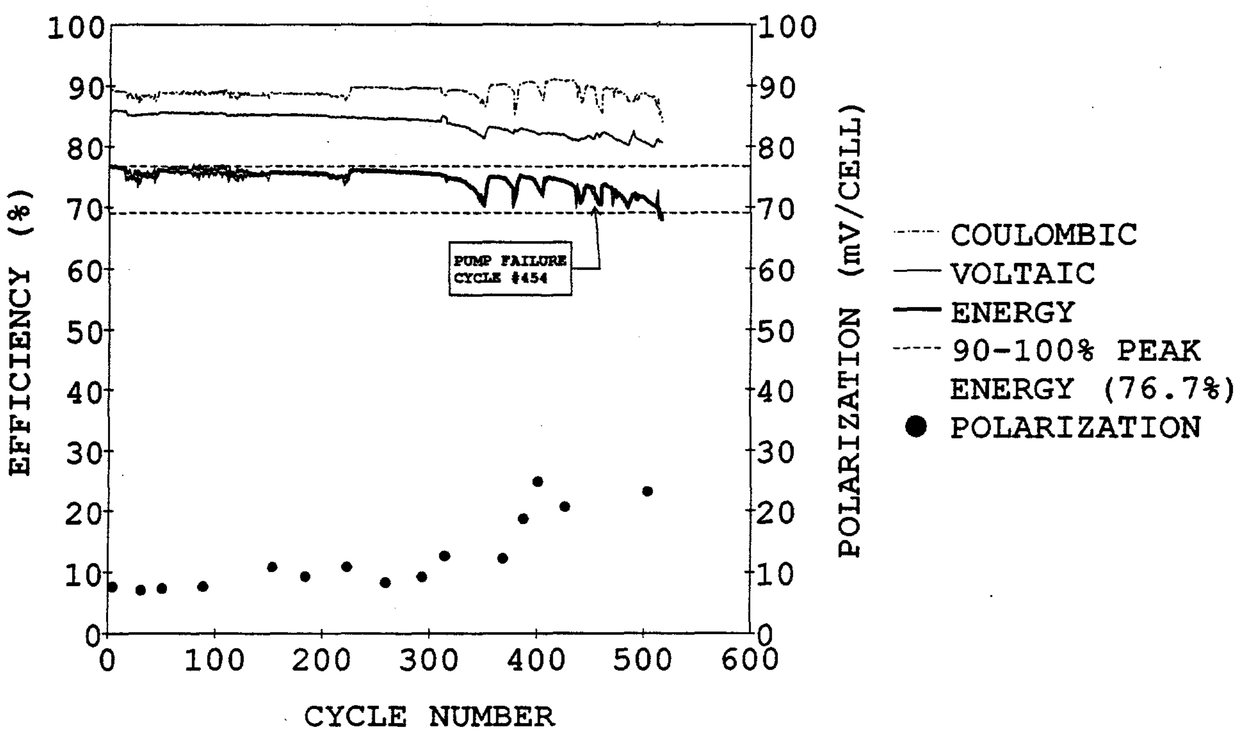


Figure 4-3. **V1-77 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)**

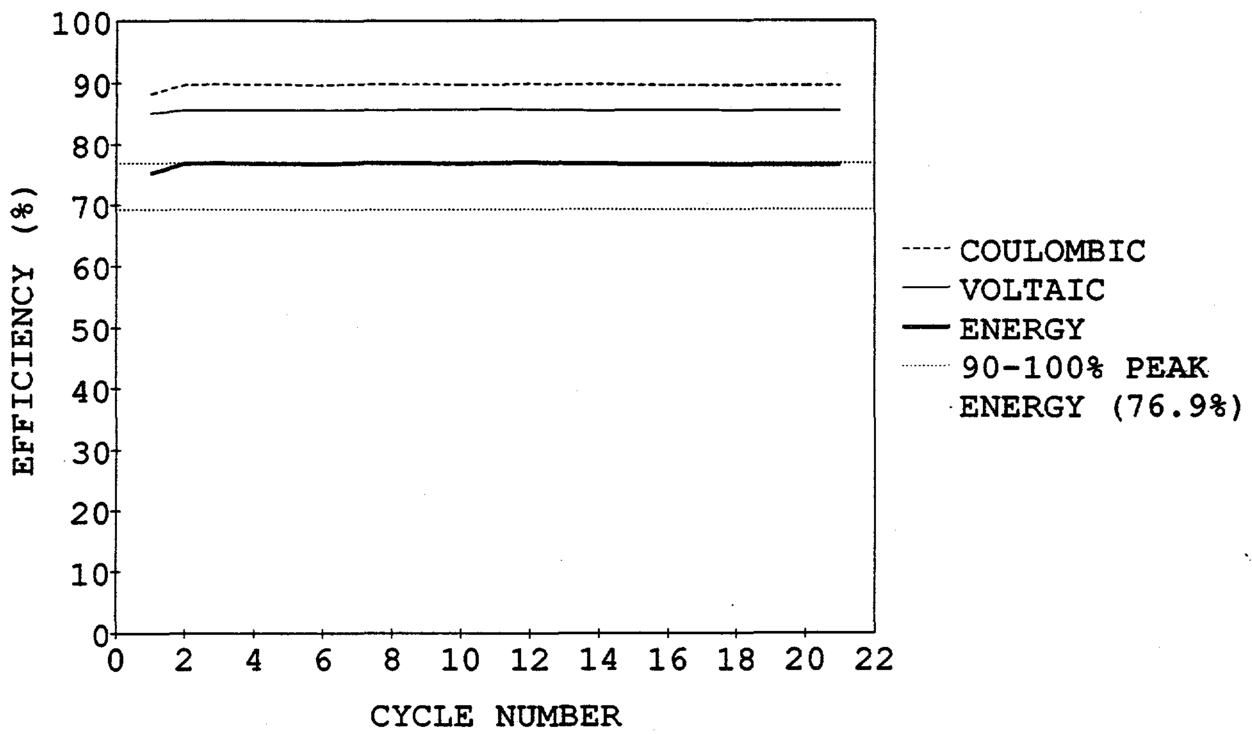


Figure 4-4. V1-78 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)

was being tested, but the battery gave poor performance. When torn down, some of the separators were observed to have cracks near the bottom of the stack. It appears that the separators may have dried out and cracked while the battery was not in operation, which probably caused the poor performance.

V1-79 (1-kWh)

Battery V1-79 is the first V-design battery stack to complete more than 900 baseline cycles with no leaks and less than 10% degradation in performance. Figure 4-5 shows that the battery is currently performing at 88.1% coulombic efficiency, 79.6% voltaic efficiency, and 69.3% energy efficiency after 951 cycles. The energy efficiency is still greater than 91% of the peak value of 76.0% and the stack continues to provide greater than 1.1 kWh on baseline cycles.

V1-80 (1-kWh)

Battery V1-80 has completed 497 cycles, with the most recent baseline cycle giving 91.1% coulombic, 85.3% voltaic and 77.7% energy efficiencies (see Figure 4-6). This battery was manufactured using low-resistance terminal electrodes and a cathode activation layer with a very high electrochemical surface area. The surface area of the bipolar electrodes is about three times higher than for the electrodes used in battery V1-79. This increase in surface area gave very low polarization and is also expected to extend the cycle life of the battery. The performance of this stack has declined by less than 2% from the peak energy efficiency of 79.0%.

V1-81 (1-kWh)

Battery V1-81 was assembled to qualify an experimental manufacturing technique. The bipolar electrodes were the same as those used in battery V1-80, but the terminal electrodes were prepared using the original manufacturing technique, which gives higher resistance. The battery had completed 334 cycles with very little decline in efficiencies, but the following cycle showed a rapid decline in coulombic efficiency, as shown in Figure 4-7. The battery completed a total of 343 cycles with the final cycle giving 79.9% coulombic, 82.0% voltaic, and 65.6% energy efficiencies with 11.1% transport and 9.0% residual losses. Teardown of this battery stack showed rough plating on the anode terminal electrode but no sign of any internal weld failures. The poor plating indicates probable poor electrolyte flow distribution in the anode terminal electrode cell.

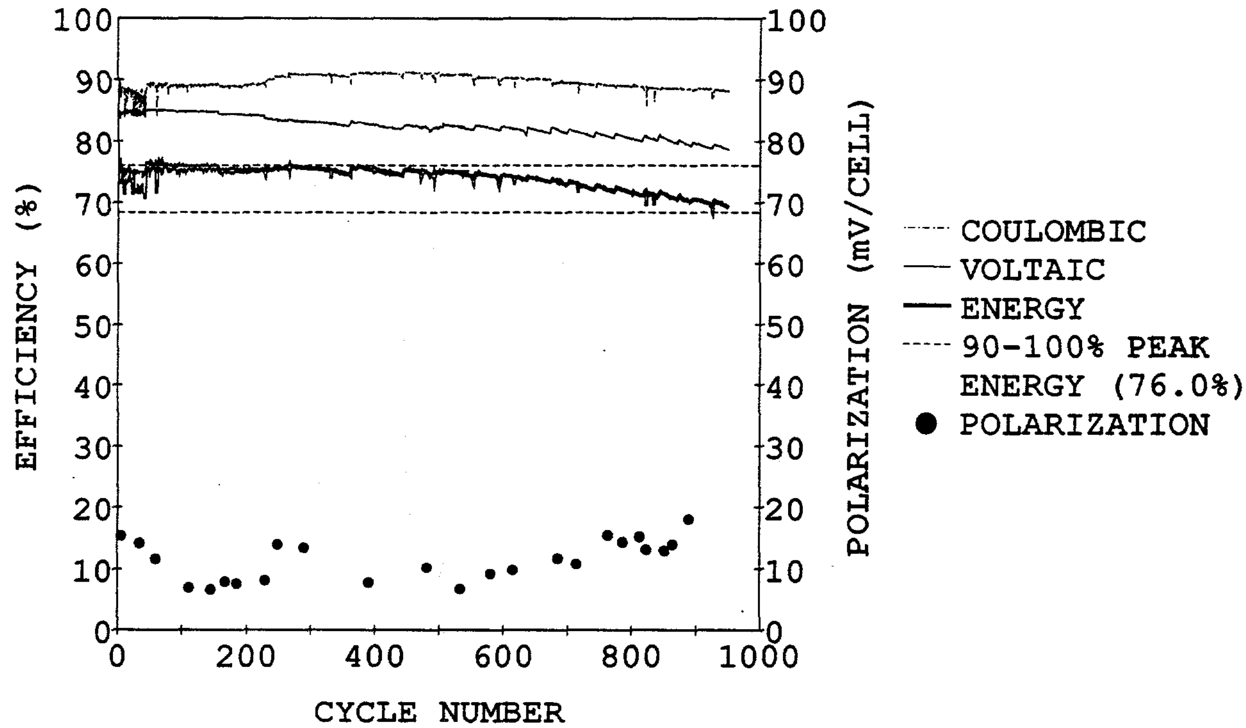


Figure 4-5. V1-79 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)

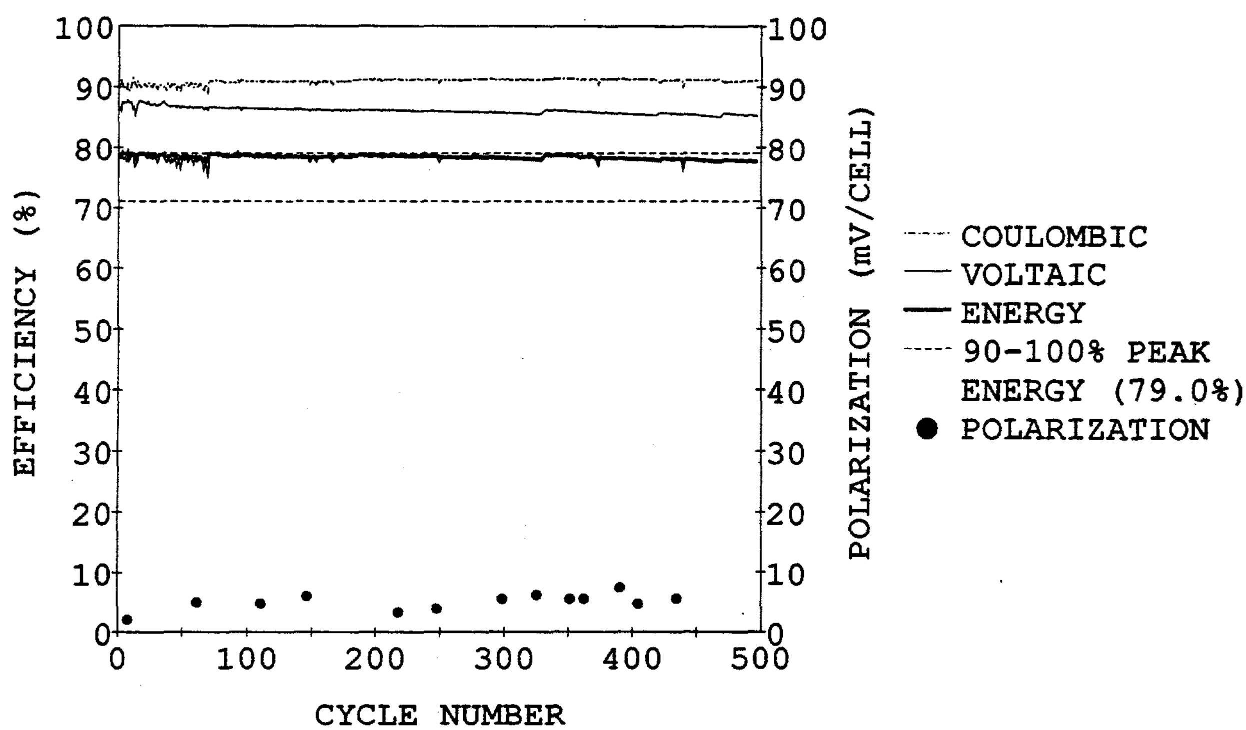


Figure 4-6. V1-80 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)

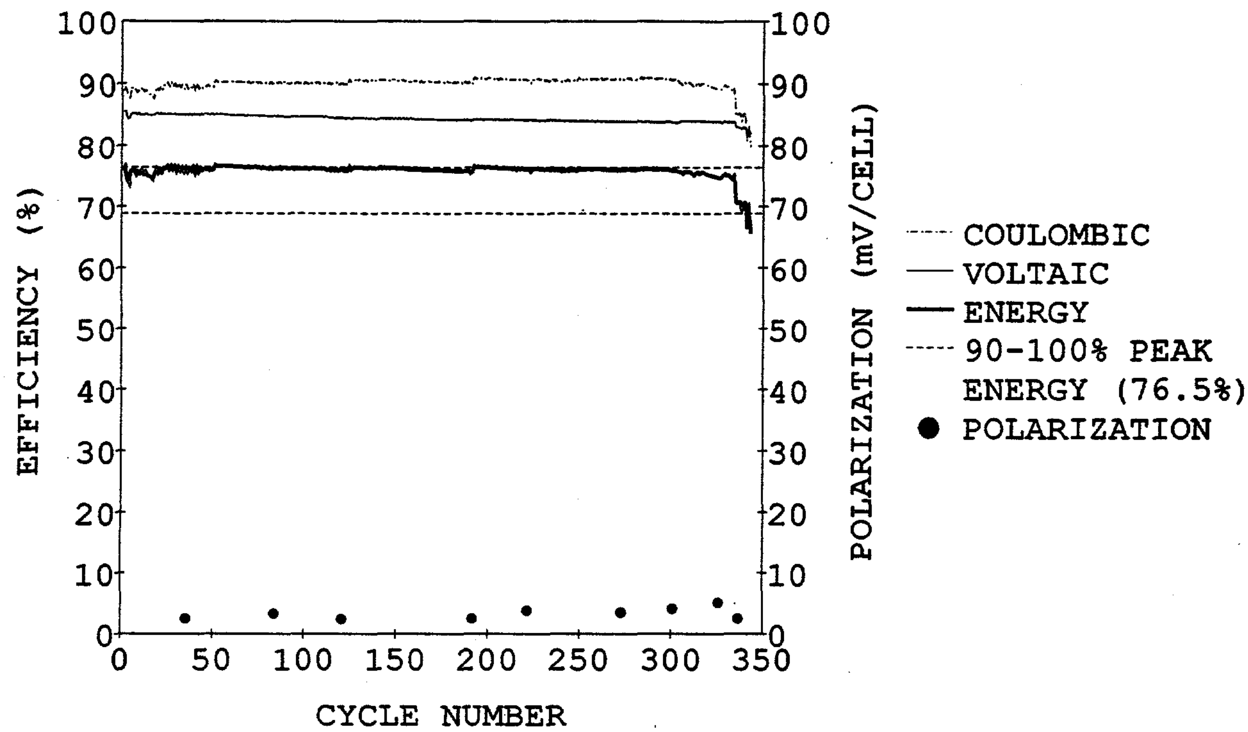


Figure 4-7. V1-81 Baseline Cycle Efficiencies (1-kWh, 8-cell battery stack)

Eight Cell, 2500-cm² Battery Stacks

The size of the battery stack was increased from 1170 cm² to 2500 cm² to reduce the part count and to lower the cost of the battery. The channels and diverters of the 2500 cm² flow frame were designed to minimize shunt currents and to improve the flow of electrolyte across the face of the electrodes.

The 1170-cm² stack contained metal inserts in the end block to provide dimensional stability. The 2500-cm² design uses a 100% glass-filled plastic end-block design, which eliminates the need for the metal inserts and improves the recyclability of the battery stack.

The 2500-cm² series battery stacks are being developed as the building block for large utility battery systems. Battery stacks with eight cells were manufactured to demonstrate the design of the larger flow frames. A number of flow-frame and end-block design iterations were completed over a 7-mo period. Once adequate performance was achieved from 8-cell stacks, 60-cell stacks were produced. Details on the performance of individual 8-cell, 2500-series stacks are given in the following sections.

V25-01-08 (2-kWh)

Battery V25-01-08 was cycled 10 times and demonstrated inconsistent performance. The energy efficiencies for this battery ranged from 10.7% to 64.9%. Some of the charge cycles had voltages below the open-circuit voltage of the battery, indicating a probable internal short.

Two leaks were observed from the battery stack. One was on the top near the center cells of the stack on the anode right side. The other was at the bottom left side near the anode terminal electrode. The reasons for the leaks appeared to be sink marks, which have since been eliminated during the injection molding process.

The zinc plating was very smooth; therefore, the poor performance of this battery indicated poor flow of the catholyte second phase across the face of the electrodes. Cross sections of the flow channels showed that some of the vanes were not completely welded, which caused an uneven distribution of the catholyte across the electrode surface. The flow frames were modified to eliminate this problem.

V25-02-08 (2-kWh)

The performance of battery V25-02-08 declined by more than 10% in energy efficiency after only seven cycles, as shown in Figure 4-8. Initially the battery performed well (76.1% energy efficiency), but the efficiencies after nine cycles were 74.2% coulombic, 84.6% voltaic, and 62.8% energy. Small leaks were observed from both the bottom and the top of the stack. The leaks appeared to be coming from between the first frame and the end block. Also, by the end of cycling, a small amount of complexed-phase bromine was observed in the anolyte reservoir.

The battery was torn down at 80% depth of discharge. The terminal anode on the left side of the stack had very little zinc, which indicates that complexed bromine was getting into this cell. The flow channels, especially near the manifolds, showed some incomplete welds. These appeared to be in regions of the flow frame where the plastic was thin. The welding process deforms these areas slightly, causing incomplete contact of the weld beads. A solution to this problem was initiated, and new flow frames and endblocks were produced.

V25-03-08 (2-kWh)

Battery V25-03-08 had some external leaks when the battery was water tested. Because of this, it was never cycled with electrolyte.

V25-04-08 (2-kWh)

Battery V25-04-08 gave consistent performance with about 74.5% energy efficiency for the first 10 cycles, as shown in Figure 4-9. It was then placed on the 2-kWh deliverable station to demonstrate the controller and station design. The performance of the stack on the deliverable station was fairly good, about 89.5% coulombic efficiency, but the voltaic efficiency was low, about 82-83%, which was attributed to a problem with the cycling unit. This battery was tested on the deliverable station until 20 cycles were completed.

V25-05-08 (2-kWh)

Figure 4-10 shows that battery V25-05-08 had consistent performance until the coulombic efficiency dropped dramatically during cycle 11. Teardown of this battery stack showed a failure of the center weld between the end block and the first flow frame. The failure was attributed to warpage of the end block, which

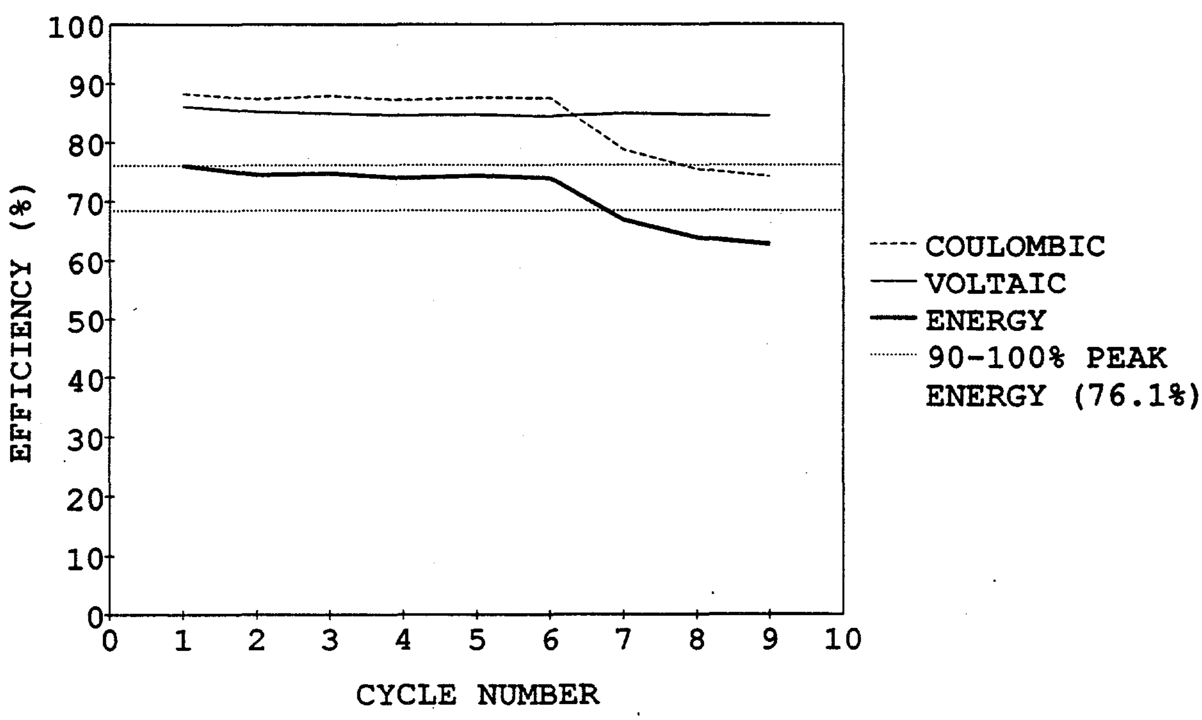


Figure 4-8. V25-02-08 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack)

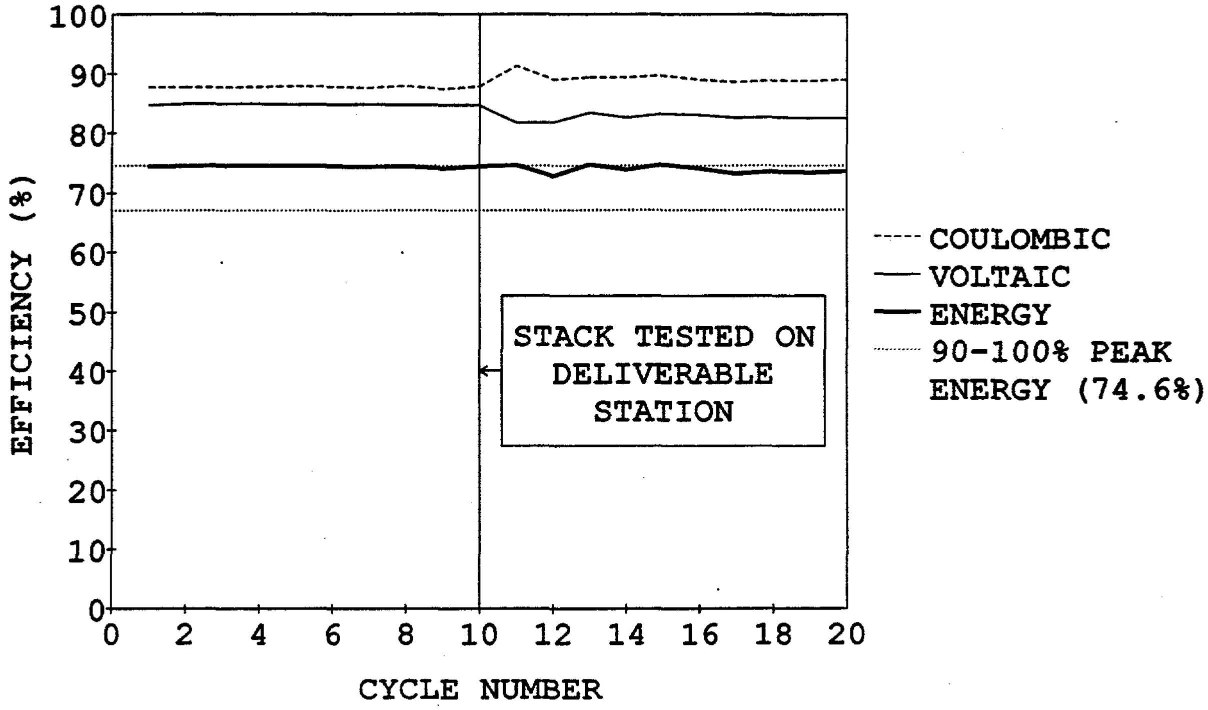


Figure 4-9. V25-04-08 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack)

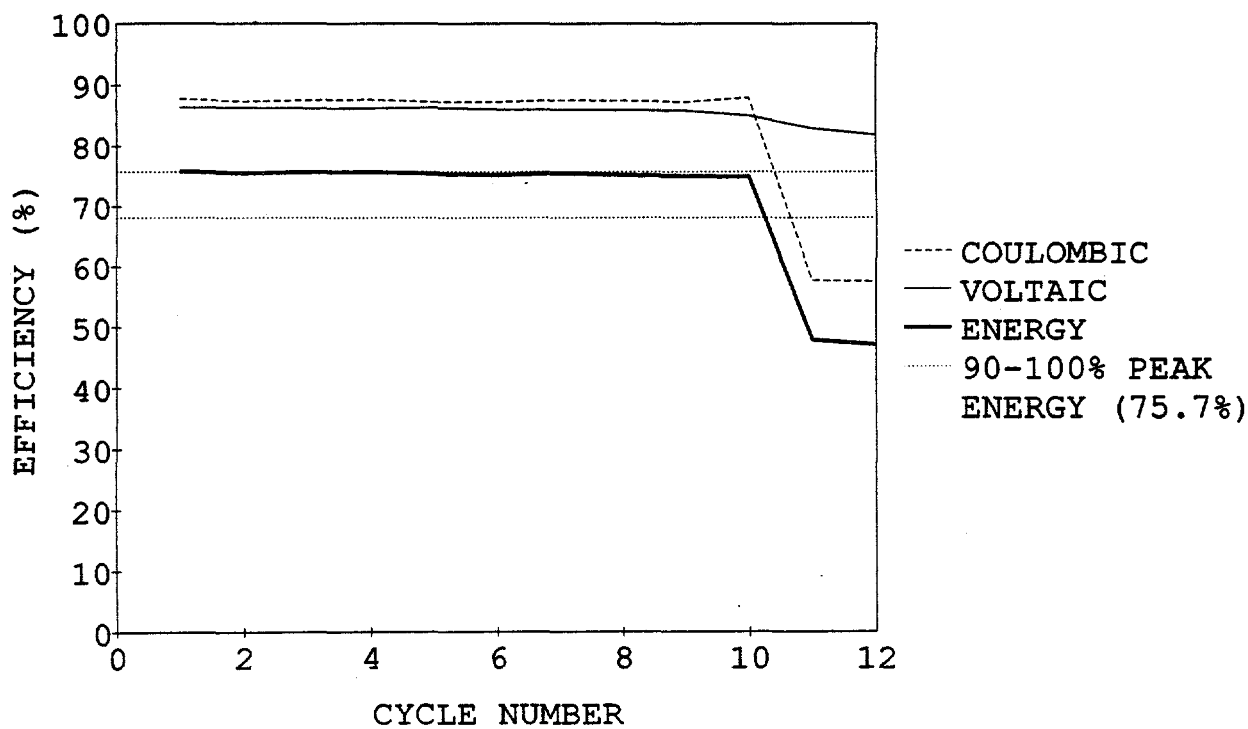


Figure 4-10. V25-05-08 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack)

caused a weak weld at the center of the stack. Additional gates were added to the end block injection mold, which reduced warpage and eliminated the center weld failure problem.

V25-06-08 (2-kWh)

Problems with the first 2500-series battery stacks included poor distribution of complexed phase over the face of the electrode, and electrolyte crossing over between flow frames. Battery V25-06-08 was the first 2500-series battery stack to be manufactured using the flow frames that were modified to eliminate these problems.

Flow rates needed to obtain optimum performance for the 2500-cm^2 battery stacks were determined using this battery stack. The battery consistently gave about 76-77% energy efficiency over the first 26 cycles, as shown in Figure 4-11. During a set of six consecutive baseline cycles, the anolyte reservoir cracked, causing all of the electrolyte to drain from the reservoir. Following this, complexed-phase bromine was observed in the anolyte, and the battery was taken off test.

V25-07-08 (2-kWh)

Several welding problems were encountered during the manufacture of battery V25-07-08. Initial results gave greater than 77% energy efficiency, but the performance varied considerably from one cycle to the next. This battery was used for no-strip cycle testing, which will be described later.

During cycle 18, complexed bromine was observed in the anolyte reservoir, indicating cross flow between cells. Teardown of this stack showed that the center weld between the cathode end block and the first frame had failed. This is the probable reason for the inconsistent performance of this battery stack. Changes were implemented to reduce the warpage of the end block, which appears to have eliminated the problem.

V25-10-08 (2-kWh)

Battery V25-10-08 completed 20 cycles with very consistent performance. The last cycle gave 89.2% coulombic, 85.8% voltaic, and 76.5% energy efficiencies. This stack is presently being tested at SNL with the 2-kWh deliverable battery station. Figure 4-12 is a plot of cycle efficiencies for battery V25-10-08. The last four cycles are the results of testing on the deliverable station at SNL.

V25-12-08 (2-kWh)

Battery V25-12-08 was cycled seven times with inconsistent results. The battery was torn down at 50%

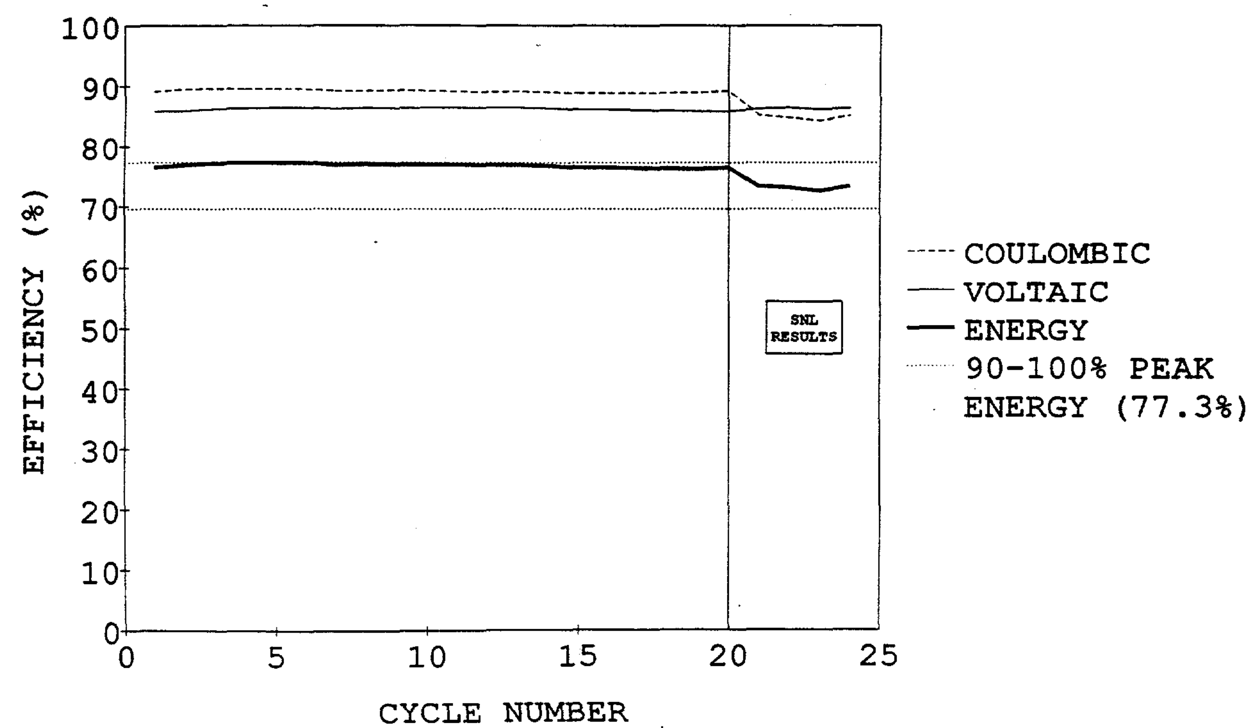


Figure 4-11. V25-06-08 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack)

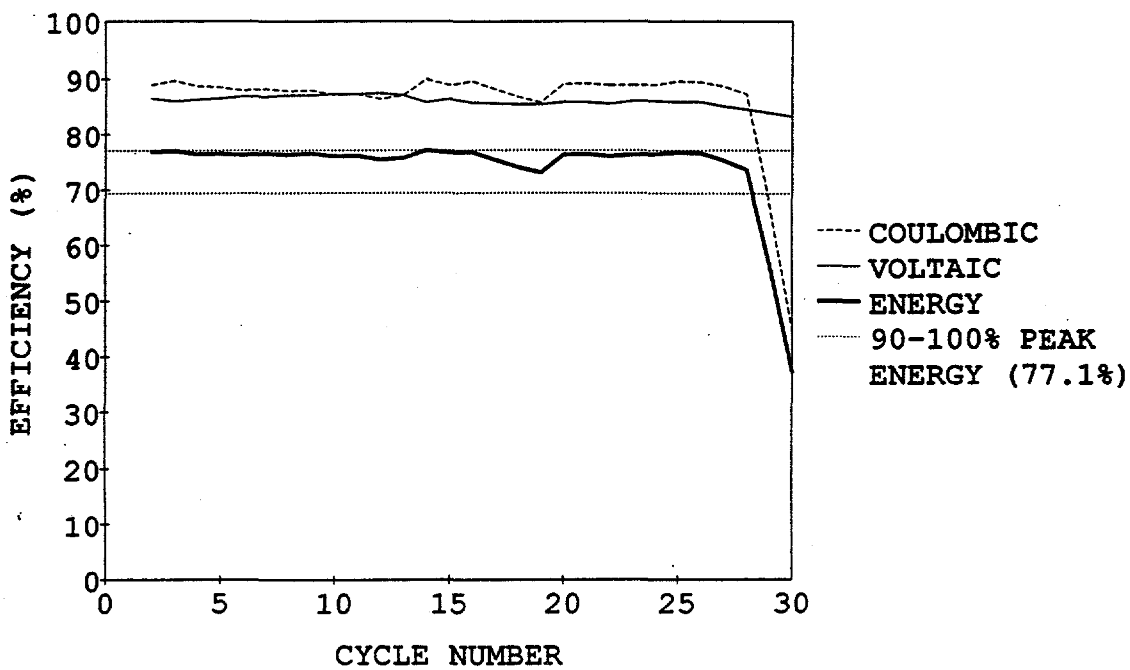


Figure 4-12. V25-10-08 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack)

depth of discharge and was found to have good zinc plating except for the first bipolar electrode next to the cathode terminal electrode. This electrode had a large bare area with no zinc and other areas with a large number of dendrites. This electrode frame was overwelded, which apparently restricted the flow in the first cell.

V25-13-08 (2-kWh)

Battery V25-13-08 performed consistently over the first 20 cycles, with energy efficiencies of about 78%, as shown in Figure 4-13. This battery was taken off test when a bromine stain on the bottom of the stack was observed. Since the stack was performing well, it was used to compare bromine complexing agents. Results of the complexing agent testing are given later.

Following cycling, the stack was milled apart to locate the source of the leak. One frame near the center of the stack was found to have an incomplete weld near the catholyte manifold that allowed bromine to escape from the flow channel to a dead space near the outside of the stack. This was the site of the bromine stain, but the problem did not appear to adversely affect the performance of the battery.

60-Cell, 2500-cm² Stacks

The 60-cell, 2500-series battery stack will be the building block of large utility battery systems. The 100-kWh deliverable battery will contain six of these battery stacks. Battery stacks were qualified by running 5 to 10 baseline cycles; then the stacks were taken off test until the modules for the 100-kWh deliverable battery were completed. The peak efficiencies for each stack are given in Table 4-2.

Other Test Results

Polarization and IR Testing

Polarization and IR losses are compared for 8-cell, 1170-cm² battery stacks in Figures 4-14 and 4-15, respectively. Figure 4-14 shows that the polarization for earlier batteries (V1-54 and V1-76) began to increase rapidly at about 250 cycles, but not for the most recent battery builds. Battery V1-80 gave the lowest polarization over the first 450 cycles because of the development of a large-surface-area cathode activation layer.

Figure 4-15 shows that recent stacks are much lower in resistance than earlier battery stacks (i.e.,

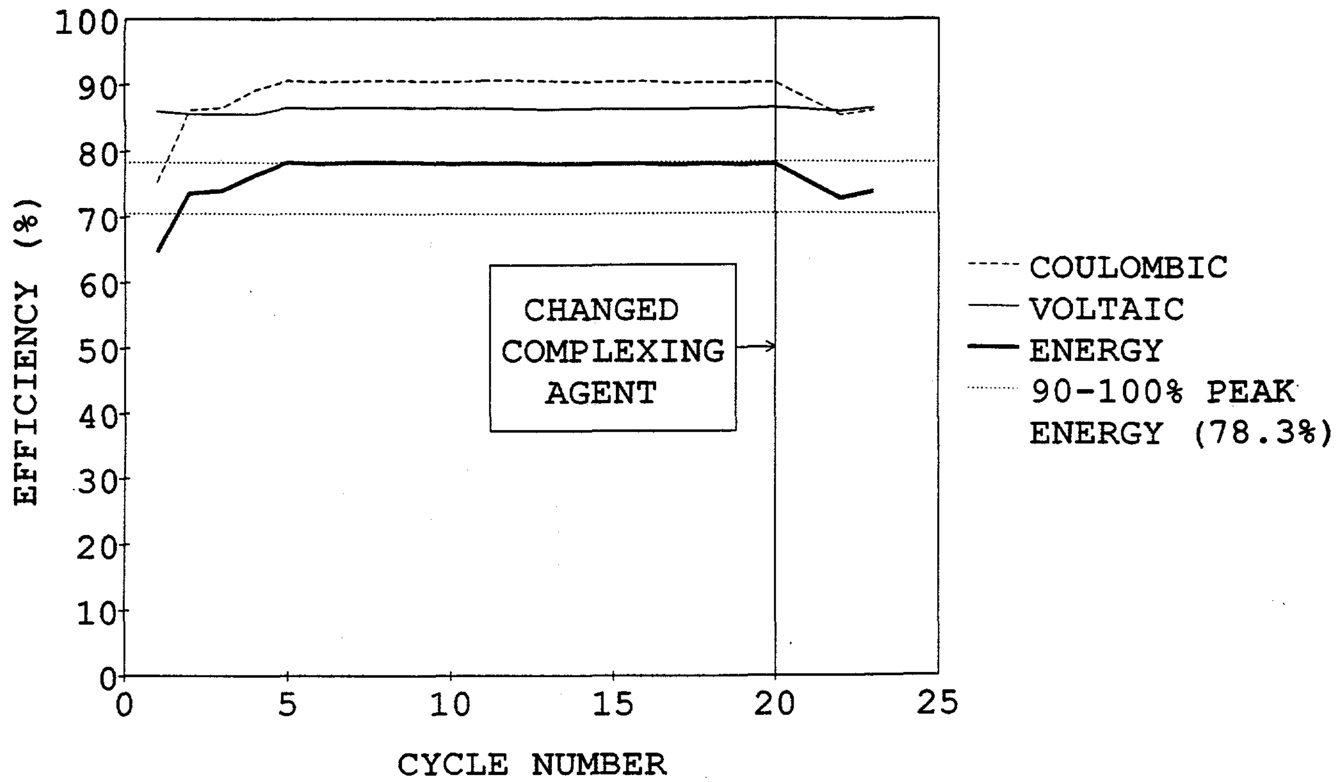


Figure 4-13. V25-13-08 Baseline Cycle Efficiencies (2-kWh, 8-cell battery stack)

Table 4-2. Performance of 60-Cell, 2500-cm^2 Stacks

Battery Number	Coulombic Efficiency (%)	Voltaic Efficiency (%)	Energy Efficiency (%)	Transport Losses (%)	Residual Losses (%)
V25-09-60	87.1	83.8	73.0	6.9	6.0
V25-11-60	89.6	85.9	77.0	6.9	3.6
V25-14-60	84.3	85.4	72.0	10.6	5.1
V25-15-60	89.0	86.1	76.6	6.9	4.1
V25-16-60	88.8	86.5	76.8	7.3	3.9
V25-19-60	87.1	86.3	75.2	8.4	4.5
V25-20-60	88.0	86.8	76.4	9.5	3.8
V25-21-60	86.0	86.1	74.1	9.6	4.4
V25-22-60	86.3	87.4	75.4	10.3	3.5
V25-23-60	86.2	87.5	75.4	10.1	3.8

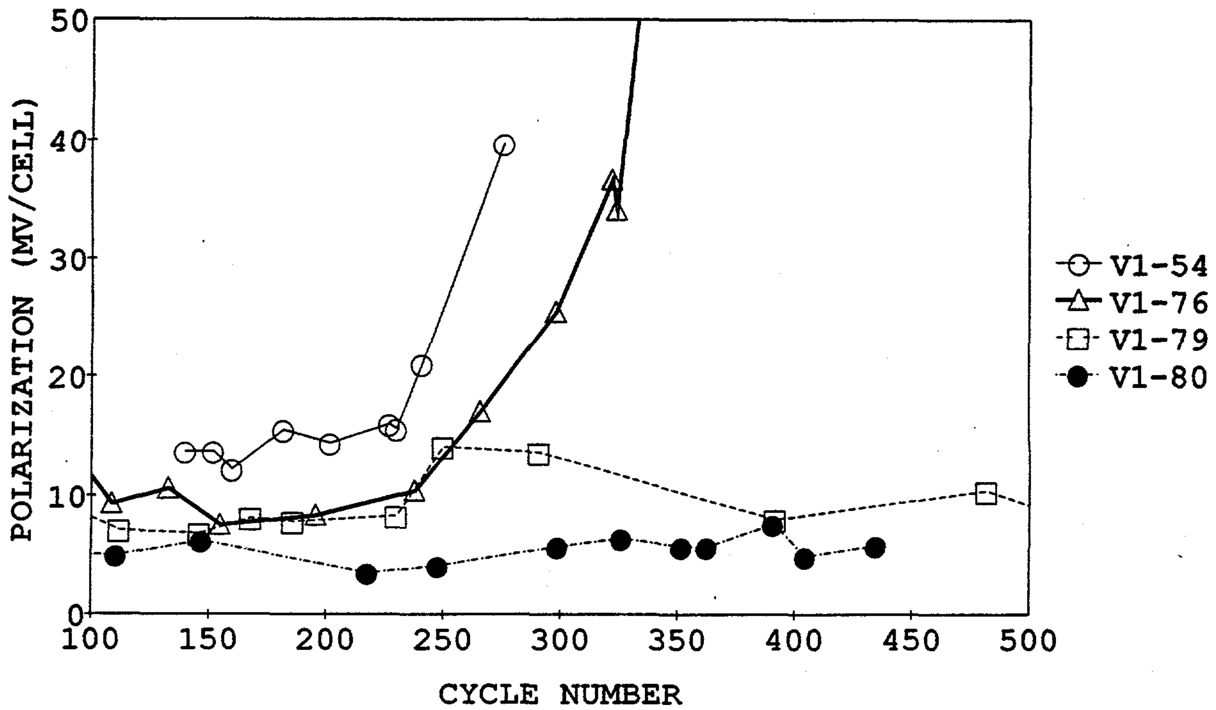


Figure 4-14. Polarization vs. Cycle Number for 8-Cell, 1170-cm^2 Stacks

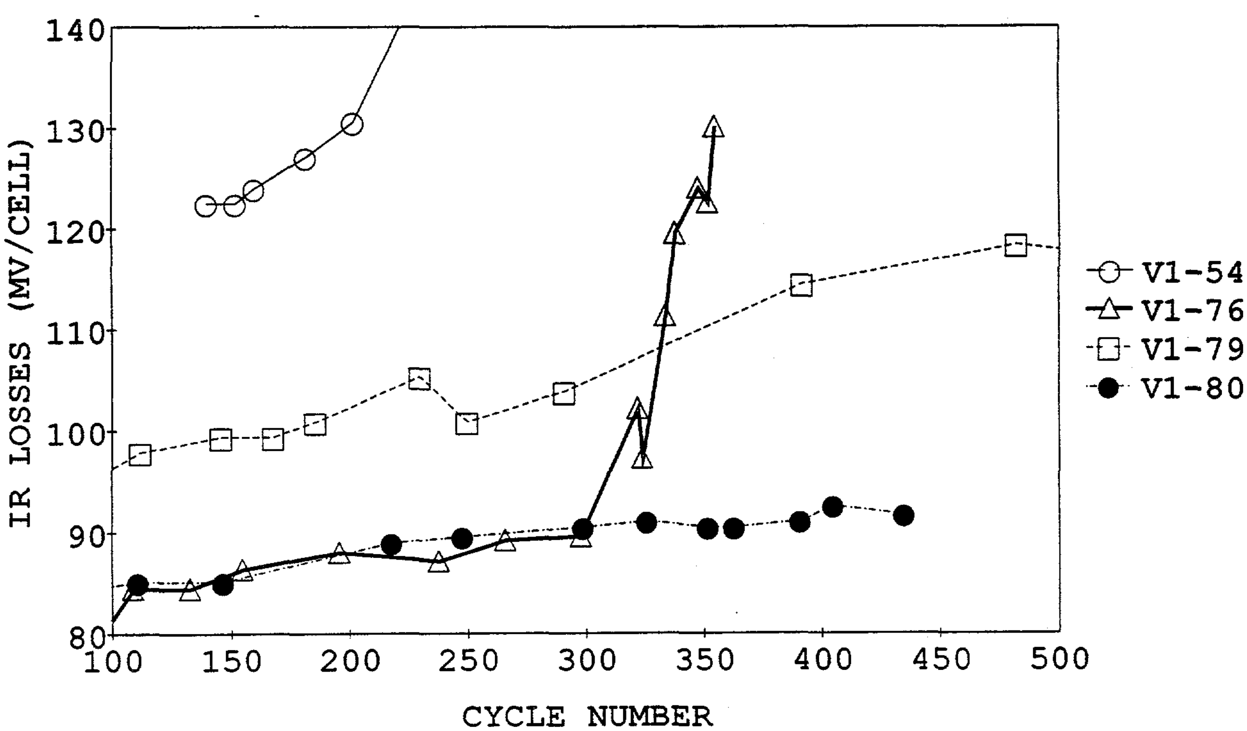


Figure 4-15. IR Losses vs. Cycle Number for 8-Cell, 1170-cm^2 Stacks

V1-54). This is because of the development of a low-resistance carbon plastic electrode material. Batteries V1-76 and V1-80 gave very low IR losses because of the development of low-resistance terminal electrodes. The modifications incorporated into battery V1-80, low-resistance carbon plastic, a high-surface-area cathode layer, and improved terminal electrode manufacturing techniques, have demonstrated improved battery performance over the first 450 baseline cycles.

The polarization and IR losses of an 1170-cm^2 battery stack were also measured during a standard discharge cycle. The rapid decline in voltage near the end of discharge is associated with an increase in battery polarization, as shown in Figure 4-16. The IR losses appear to increase nearly linearly during discharge, but the polarization increases more rapidly near the end of discharge. The increase in polarization is from a reduction in the amount of bromine available for reaction and the nonuniform dissolution of zinc from the anode.

No-Strip Cycling

After discharging the zinc/bromine battery to 1.0 vpc, it is usually completely stripped of any residual zinc by connecting the battery across a resistor. This is done to ensure that there is a smooth electrode surface at the beginning of each cycle for the deposition of zinc.

Although it is recommended, the battery does not have to be stripped following every cycle. The time needed to completely strip the battery may not be available in all cases, and the capacity remaining in the battery prior to stripping can be utilized as usable energy during the following cycle.

Results of six consecutive cycles without stripping are compared to baseline cycle efficiencies in Table 4-3 for batteries V1-80 and V1-81. The average efficiencies did not increase as much as for previously tested batteries, but this is due to the small amount of residual losses observed during baseline cycling for these two battery stacks. Earlier battery stacks gave 5-6% residual losses on baseline cycling.

One other interesting characteristic of these two batteries is that the energy efficiencies increased on each cycle up to cycle 5 for V1-81 and cycle 6 for V1-80. Previous battery stacks achieved the maximum efficiencies on the second cycle of the set and declined on each successive cycle, as shown in Figure 4-17.

Results from no-strip cycling performed on a 2500-cm^2 battery stack are given in Table 4-4. The second cycle of the no-strip set experienced an increase in coulombic efficiency as anticipated, but the efficiencies dropped off rapidly on each successive cycle. The efficiencies for a properly performing battery stack should

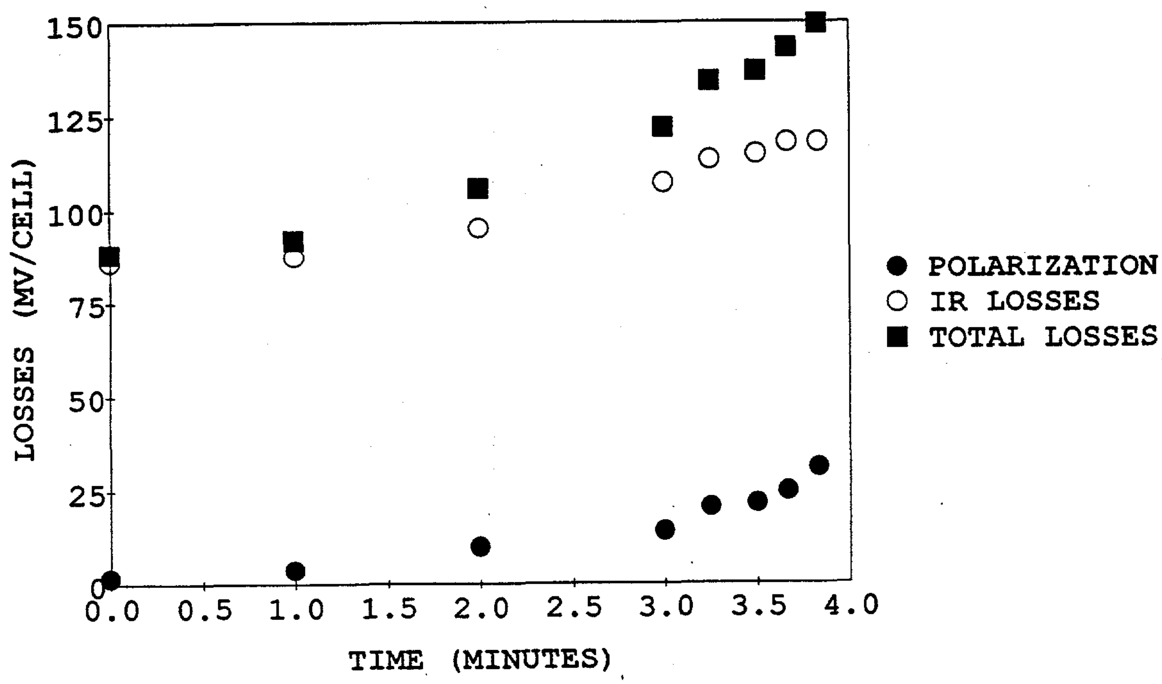


Figure 4-16. Polarization and IR Losses During Discharge after Cycle 165 (V1-80, 1-kWh, 8-cell battery stack)

Table 4-3. Average of Six No-Strip Cycles Compared to Baseline Cycle Results

Cycling Regime	Coulombic (%)	Voltaic (%)	Energy (%)	Transport (%)	Residual (%)
Battery V1-80					
Baseline	90.7	86.5	78.5	6.1	3.2
No-strip	91.9	86.8	79.8	6.4	1.7
Battery V1-81					
Baseline	90.3	84.8	76.6	5.8	3.9
No-strip	91.6	85.3	78.6	6.6	1.8

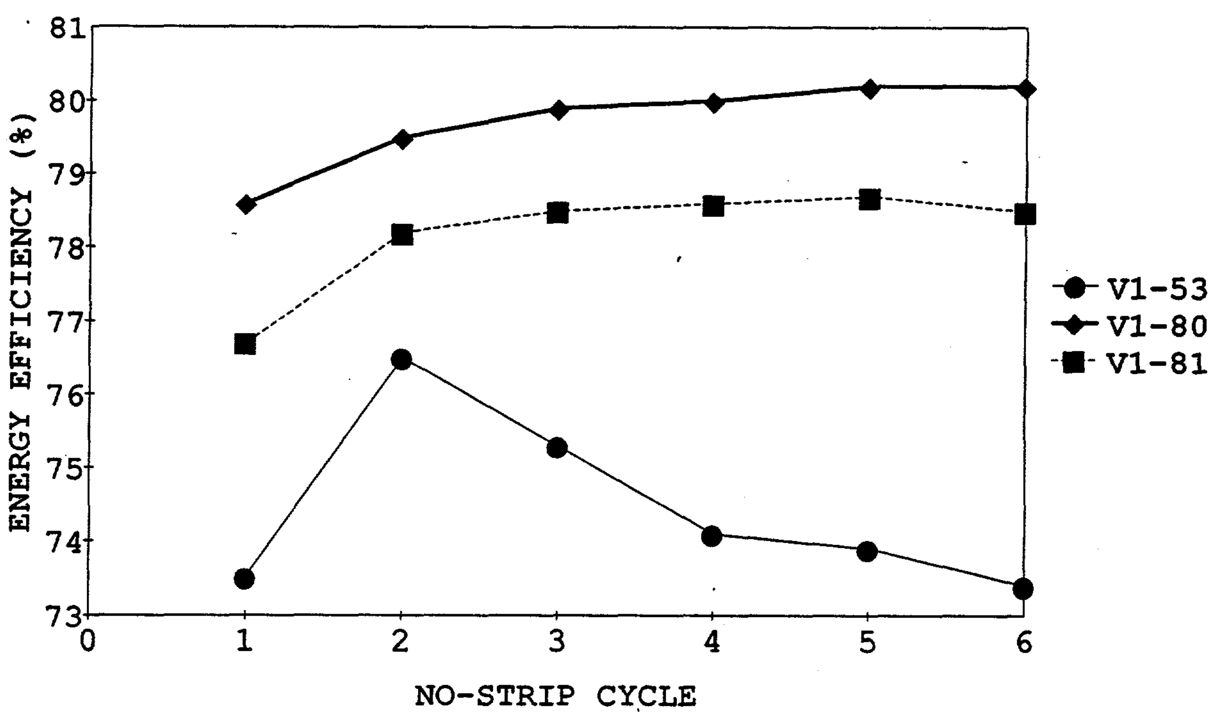


Figure 4-17. Comparison of No-Strip Cycling for 8-Cell, V-Design Battery Stacks

level off following the second cycle of a no-strip sequence. These results are similar to results observed for early V-design, 1170-cm^2 battery stacks and apparently result from poor electrolyte flow distribution. This battery stack did have a center weld failure that may have caused poor flow. Because of the inconsistent results, the test will be performed again on a new battery stack.

Multiple Stack Testing

The performance of two 60-cell, 2500-cm^2 battery stacks hydraulically connected in parallel is compared

Table 4-4. No-Strip Cycle Performance for Battery V25-07-08

Cycle Number	Coulombic Efficiency (%)	Voltaic Efficiency (%)	Energy Efficiency (%)
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

to the performance of a single stack in Table 4-5. The comparison is made at a zinc loading of 60 mAh/cm^2 because the reservoir could not hold enough electrolyte to obtain a full loading for the two-stack configuration. The two stacks gave the same efficiencies as a single stack that was charged to 60 mAh/cm^2, and are expected to give similar energy efficiencies of 76-77% on a full charge.

High-Rate Discharge

The results of discharging a 60-cell, 2500-cm^2 battery stack at different rates are given in Table 4-6. The results demonstrate that the battery produces 19 kWh of energy for discharges lasting 3 hr or more. For discharges of less than 3 hr, the energy output decreases significantly. The results at the higher-rate discharges may be low since the amount of complexed second phase delivered to the battery stack during discharge was limited by the station design. Results might have been better if the amount of complexed bromine circulated during discharge was increased. Table 4-6 also shows that it is much more difficult to control the temperature once the battery is discharged at the higher rates. All cycles began charging at a temperature of about 25°C.

Initial Bromine Concentration

Recent battery stacks have required more bromine than previous builds because of the increased surface area of the cathode activation layer. It has also been found that a slight excess of bromine can be beneficial to the performance of the battery. Figures 4-6 and 4-7 show that the efficiencies for batteries V1-80 and V1-81 were very inconsistent early in life, but adding 0.1% excess bromine significantly improved the consistency from one cycle to the next. The slight excess of bromine also reduced the amount of time needed to strip the battery following discharge.

Materials Development

Terminal Electrode Development

Terminal electrodes are prepared by imbedding a metal screen between two layers of conductive carbon plastic. The metal screen is necessary to uniformly dis-

Table 4-5. Battery Stack Performance (60-Cell, 2500-cm^2 Stacks)

Number of Stacks	Zinc Loading (mAh/cm^2)	Coulombic Efficiency (%)	Voltaic Efficiency (%)	Energy Efficiency (%)
1	90	89.1	86.1	76.6
1	60	86.9	85.9	74.7
2	60	87.0	85.9	74.7

Table 4-6. Effect of Discharge Rate on Performance for a 60-Cell, 2500-cm² Battery Stack

Discharge Current (A)	Discharge Time (hr)	Maximum Temperature (°C)	Energy Output (kWh)
35.5	5.61	30.6	19.83
42.8	4.67	31.6	19.71
53.3	3.75	33.2	19.43
71.2	2.82	35.0	19.15
104.9	1.87	39.5	17.86
209.9	0.83	50.9	13.54

tribute the current in the x-y plane of the terminal electrode. In the past, the resistance from the electrical connection to the face of the electrode was found to be higher than predicted, indicating high resistance at the plastic/metal interface. A new method of preparing terminal electrodes was developed that reduced the resistance from the copper stud connection to the face of the electrode by about 50%, from 0.5 Ω to 0.25 Ω. This reduction in terminal electrode resistance resulted in about a 2% increase in battery stack voltaic efficiency.

Cathode Activation Layer Development

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

A high-surface-area cathode layer has been developed and is presently being tested in battery V1-80. These bromine electrodes had high surface areas of 10,000 cm^2/cm^2, as compared to the 2000 to 3500 cm^2/cm^2 used 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. This cathode layer has demonstrated very good performance over the first 450 cycles for battery V1-80.

Another type of cathode layer, which has an electrochemical surface area of about 50,000 cm^2/cm^2, has also been developed, but it has not yet been tested in a battery.

Battery Design and Manufacturing

2500-cm² Battery Stack Design

Several problems were discovered after the post-mortem analysis of the 2500-series battery stacks. 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 process. Poor quality welds in the area where weld beads cross a flow channel on the adjacent frame were improved by adding additional weld beads in this area.

Scaling up from 8 cells to 60 cells 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 during the manufacture of 60-cell stacks. 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.

Table 4-7. 100-kWh Battery Specifications

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

2-kWh Battery Station Design

The 2-kWh station was designed as a prototype for each of the 33-kWh modules to be used in the 100 kWh deliverable. The battery stack contains eight cells with an electrode area of 2500 cm^2. Directly coupled pumps/motors to circulate electrolyte were tested but displayed seal failure resulting in corrosion of the motor. Therefore, magnetically coupled pumps have been installed to eliminate this failure mechanism. The 2-kWh station pumps and reservoirs have been equipped with vertically mounted centrifugal pumps mounted inside of a recessed area in the cover of the electrolyte reservoirs. This was done to keep most of the plumbing inside the reservoirs and to eliminate the need to prime the pumps. A microprocessor controller, similar to the ones used for the 100-kWh battery, is used to coordinate the operation and safety of the system. More details on the controller are given later.

100-kWh Battery Station Design

The original 100-kWh deliverable station proposal consisted of six battery stacks, two electrolyte reservoirs, and a support structure. The statement of work of the contract has since been changed to require delivery of a self-contained, stand-alone peak shaving system to be connected to the utility grid at PG&E. The three-module configuration was selected to test series and parallel arrangements of the battery modules. Details of the 100-kWh battery design are given in the following section.

The demonstration peak shaving unit consists of a 100-kWh stand-alone system housed in a portable chemical storage vault. It contains three 33-kWh battery modules, each consisting of two 60-cell, 2500-cm^2 battery stacks hydraulically and electrically 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.

Each module is supported by a steel frame, with the reservoirs inserted into the frame and the two battery stacks located between the reservoirs. The stacks are attached to the frame by steel cords. The steel frame is coated with epoxy, and the cords are covered with plastic to eliminate corrosion.

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 needed to circulate both the catholyte aqueous and complexed bromine phases. Brushless DC centrifugal motors run the pumps and are located in the containers such that the inlet to the pump is located slightly below the liquid level in the reservoir. This eliminates the need to prime the pumps and limits the amount of electrolyte that could be lost in the case of a leak. Most of the reservoir plumbing is made of fused kynar and is located inside the reservoirs to minimize leakage from the system. Any leakage from this plumbing would be contained inside the reservoirs.

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

Liquid-level sensors are inserted into the top of each reservoir. The sensors are accurate to 0.25 in. and supply data to the battery controller. The data are used to maintain constant electrolyte levels in each reservoir by adjusting pump speeds. The sensors are also used to indicate electrolyte and coolant leaks by reading low or high levels on both sensors at the same time. Leak sensing wires are also located in the module spill tray and each reservoir pump area. They will indicate small leaks of electrolyte into either location.

A dry module will weigh more than 700 lb, and over 1800 lb when filled with electrolyte. Forklift provisions have been made for transporting the modules. 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 system is designed to sustain a 200-A discharge at an average 273 V for 2 hr. Heat exchangers, a bromine scrubber, and electrical panels are located in an isolated quadrant in the building. The building contains a spill containment sump in addition to those for the individual modules. Additional safety devices in the building include bromine and hydrogen sensors and an accelerometer for earthquake detection. Seismic zone 4 design requirements apply to the station as well as the Haz-mat building.

The 100-kWh system will be designed such that batteries can be put in parallel or series configurations. Each module has an open-circuit voltage of 109 V. The battery system specifications are given in Table 4-7.

Battery Controller

Each battery module is monitored and operated by a programmable logic controller (PLC). Each PLC has 2 KB of user memory and is capable of data acquisition through a full-duplex RS232C serial port. Each PLC monitors module voltage, stack current, currents for each motor, and electrolyte liquid levels in each reservoir.

The microprocessor controller coordinates the overall operation and safety of the system. It also monitors a number of potentially hazardous conditions to the system and its surroundings. Some of these conditions include electrolyte or coolant leaks, earthquakes, high levels of bromine or hydrogen, high indoor temperatures, and manual emergency stops. When one of these conditions arises, the controller will completely shut down the system.

Technology Evaluation – SNL

Evaluation of 8-Cell Stack

One of the deliverables from the utility battery contract with JCBGI/ZBB was a 2-kWh, 8-cell battery. A major change from previous batteries tested at SNL was that the flow frame size was increased from 1200 cm^2 to 2500 cm^2. The testing goals for this battery are to determine cycle life under baseline, no-strip, and simulated utility profile conditions.

Prior to delivering the battery to SNL, 20 full cycles, at a zinc loading of 90 mAh/cm^2, were run at JCBGI. The cycling regime used by JCBGI is listed below. The results are shown on Figure 4-12 and indicate that the battery performed well at JCBGI. This regime is also being followed by 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 should be stripped of zinc at regular intervals. This procedure 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 battery, a 1-Ω, 600-watt resistor was used.

This battery was delivered to SNL in August 1994. A representative from JCBGI accompanied the zinc/bromine battery and set up the system using the JCBGI controller designed for this test. Figure 4-18 is a photograph of this battery showing the 8-cell stack and reservoirs. During the initial cycling period, an electrolyte leak was discovered. This leak was located around the "O"-ring where the catholyte pump enters the reservoir. The reservoir section of the battery was returned to JCBGI for repair. In early September, the reservoir was returned to SNL, and attempts were made to start the testing; however, due to considerable noise in the second-phase pump, the reservoir was again shipped back to JCBGI. It was discovered that the pump noise problem was due to air being trapped around the pump.

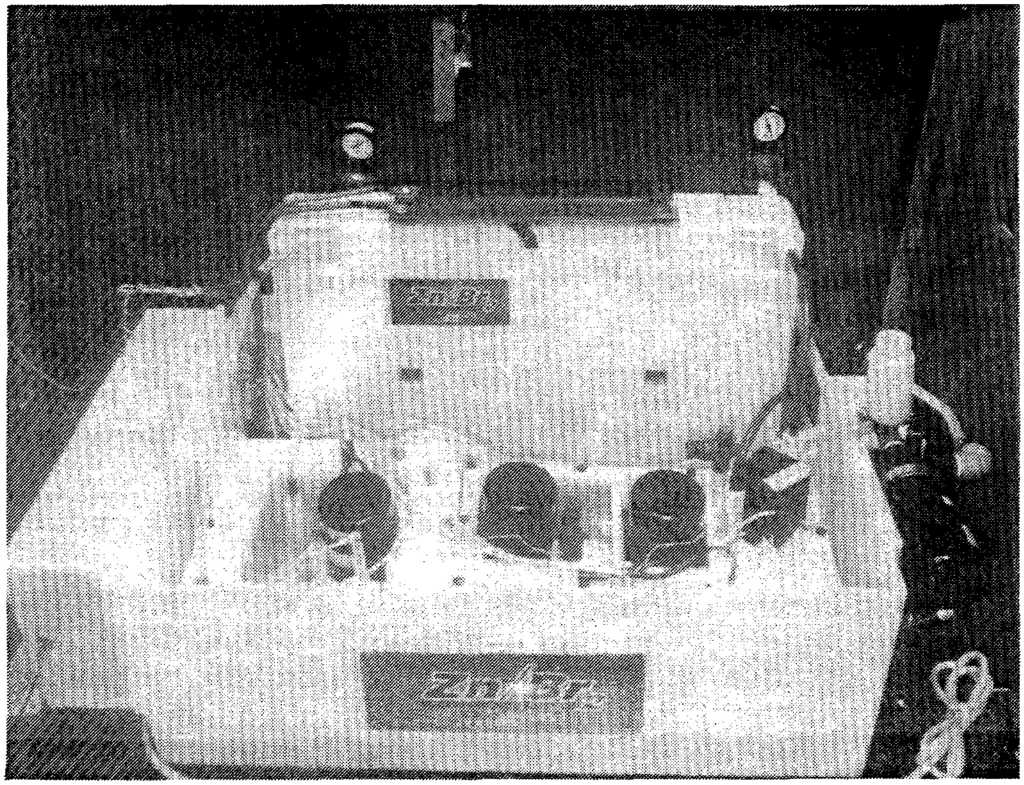


Figure 4-18. Photograph of 2-kWh Zinc/Bromine Battery

To correct this problem, valves were added at the catholyte and second-phase pumps to allow the air to be bled from the pumps. The battery was returned to SNL on September 27, and testing was again started. Preliminary results indicate that SNL is getting approximately 3% less coulombic and energy efficiency than JCBGI.

5. Subsystems Engineering – Sodium/Sulfur

The sodium/sulfur technology is being developed for UES applications primarily because of its excellent energy density (low footprint), potential for relatively low cost (capital and maintenance), and capability for easy transport. These characteristics allow sodium/sulfur to better satisfy those UES applications that place importance on footprint and portability compared with conventional lead-acid options. This opportunity is optimum when an energy/power ratio greater than 1 is required. Other benefits of this technology include the ability to accommodate multiple applications with a single battery plant and insensitivity to changes in ambient conditions. System analyses performed to date indicate that sodium/sulfur battery systems can be used in many utility battery-storage applications. Customer and transit system peak reduction, renewables, and deferral of distribution facilities have been determined to be among the best applications for this technology.

The overall goal of this UBS Program subelement is to ensure that a viable sodium/sulfur technology will be available for utility applications such that the markets that will be or are being served by conventional battery technologies will be enhanced. The actual development process is following a structured and phased strategy. The phases specific to this program are as follows: (1) component engineering that permitted the construction of effective and safe battery modules, in turn allowing the sodium/sulfur concept to be proved (1985-1990); (2) preliminary battery engineering and design for a single load-leveling application that demonstrated the advantages of the technology (1989-1990); (3) iteration of component engineering to resolve specific utility-battery feasibility issues and identify long-term development requirements (1991-1993); (4) conceptual battery engineering to provide the basis for entering into relatively expensive battery-system level engineering development and demonstration (1993-1995); (5) prototype battery engineering to qualify the production processes and final product configuration (1996-1998); and (6) product engineering to scale up production to commercial levels and satisfy institutional and regulatory requirements (1998-2000). A very important part of the two latter phases involves the comprehensive evaluation and demonstration of complete battery systems at customer locations.

Technology Development – SPI

Tasks

The development of the UES sodium/sulfur technology was continued past the component engineering and preliminary battery engineering steps for two reasons: (1) during the last few years utility systems analyses have shown a true need for advanced battery storage and (2) the benefits of the sodium/sulfur technology in these applications became recognized and substantiated. Based on the status of the technology, a 4-yr, $3.1M contract was placed in mid-1991 with SPI to complete the activities described in Phases 3 and 4 in the preceding paragraph. In this contract, relevant utility applications are being identified, specific cell and battery hardware are being developed, preliminary engineering of utility battery modules is being completed, and, finally, a full-scale integrated battery system concept is being designed. An integral part of this work is the definition of battery requirements, an activity that with increased involvement of the utility industry is progressing (see Chapter 2). The continued need to reduce capital 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 both under intended and accident situations, and, ultimately, on reclamation.

It is relevant that development of the sodium/sulfur technology for mobile applications at SPI's sister organization, Silent Power, Limited (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 in this effort. Work under this project is focusing solely on the specific needs of UES applications.

The tasks that are being performed under the Silent Power, Inc. contract include the following:

1. UES Application Assessment
2. UES Cell and Battery Component Development
3. Preliminary Engineering of UES Modules
4. Full-Scale Battery Plant Design

The remainder of this section contains a description of the results obtained during FY94.

Status

Task 1. UES Application Assessment

SPI participated in the first phase of the UBS Program Opportunities Analysis, which assessed the requirements and benefits of utility and customer applications for advanced lead-acid, sodium/sulfur, and zinc/bromine UES systems. The modular sodium/sulfur technology tends to fit most beneficially into the smaller 1-2 MW class of applications, which have storage time requirements of 1 hr or more and require fairly regular utilization. Because of its excellent energy density (25 kWh/m^3 and 41 Wh/kg for the rated system), the NaS-P_{ac} sodium/sulfur system offers distinct footprint and portability advantages over lead-acid. The pure applications that tend to best fit the benefits offered by sodium/sulfur were identified as distribution facility deferral, customer reliability and peak shaving, and storage for renewables.

In practice, a NaS-P_{ac} system may need to fulfill more than one function. For example, it could be used to improve power quality to a customer, thus eliminating the havoc that short outage periods create on sensitive process equipment while also shaving peak loads as a form of demand-side management. The net benefit to the customer includes material and labor savings for the few times per year that a utility may interrupt service, and the monthly savings from shaving the demand. The latter has been shown to offer a 20-30% rate of return, depending on how "peaky" the load is, the utility demand charges, and the energy storage required to guarantee that the peak is shaved.

Issues relating to heat loss as a parasitic and power limitation factor, which have tended to restrict some of the utility applications for sodium/sulfur, have changed with the substitution of high-power EV batteries in the NaS-P_{ac} system (see Task 4). With a heat loss less than 4-W/kWh in its stacked stationary setting, the heat loss is no different than self-discharge is to lead-acid batteries. Because sodium/sulfur batteries have no self-discharge characteristic other than thermal loss, those applications demanding power less frequently may now be viable candidates for this technology. In fact, there is a significant advantage to outdoor deployment of the NaS-P_{ac} system over other technologies because the low-heat-loss thermal enclosure required for sodium sulfur makes the battery insensitive to outside ambient conditions. Thus, whether the system is located outdoors in Alaska or in Puerto Rico, there is little difference in the loss of power or capacity of the battery.

The new cell proposed for use in these batteries was designed to provide acceleration power to midterm electric vehicles. It has a power-to-energy ratio of 2, a factor of 1.5 × its predecessor. With this understanding, the customer reliability application can now be served with the new NaS-P_{ac} system solely on its own merits (instead of attempting to enhance the benefit with peak shaving). The NaS-P_{ac} system can be designed with a self-commutated inverter expressly to eliminate poor quality utility power (noise, occasional low voltage, power interruptions, and/or lightning strikes). The system can also provide power factor correction that either sources or sinks volt-amp reactivities (VARs) as required. This is an area that can provide utility customer savings, since most power bills include a charge for power factors below 95%.

To stimulate utility interest in BES, SPI has talked directly with East Coast utilities about BES and their plans regarding distributed generation and maintaining customer-side satisfaction in the face of deregulation. The northeast, in particular, has the highest rates in the nation, which makes it a target for BES demonstrations and eventual sales. The most fruitful approach has been presentations at utility association meetings, such as those sponsored by the Allegheny Electric Cooperative and the Pennsylvania Electric Association, to name a few local organizations. Here, a wider audience of utility participants hears about BES; they can ask questions and follow up with their own situation. So far, SPI has found this to be the best forum for getting the word out on BES. Most participants are not well-informed about current and future BES products.

For BES reliability-peak shaving opportunities, it seems reasonable to concentrate on the needs of light industry, commercial facilities and strategic public facilities. Heavy industries tend to generate their own power; to have the clout to negotiate with utilities for the best rates; to have more than one utility feeding them; to have implemented their own demand-side management plans; and to have their own dedicated backup/peaking generators that they service with their own personnel. Light industry and commercial establishments, on the other hand, have little clout in negotiating more favorable rates and are constrained from purchasing rotating equipment because of ordinances and restrictions on leased properties; furthermore, they can least afford the maintenance on such equipment. The message that the BES systems suppliers must impart to their prospective clients is that the BES system is no more intrusive than a transformer sitting on their premises.

Public power utilities are also candidates for peak shaving. They are just as susceptible to coincident peak demand billing as industrial or commercial customers. Most public power utilities simply buy power from local utilities and turn around and sell it to their public constituency. BES, strategically placed, can serve to reduce the peak-billed demand, allowing the generating utility to dispatch the power from the BES system coincident with the utility's peak. The end result is more efficient operation at the generating utility and demand savings passed along to the served public.

The best opportunity for entering a customer-side market is in conjunction with a utility and specifically with the direct involvement of a customer applications engineer. For these types of applications, the utility may want to retain ownership of the equipment and offer it as an optional service to its customers. This situation would also allow the utility some control over the power dispatch. If the customer attains or perceives a substantial benefit with an acceptable payback period, they may desire to have their own dedicated piece of equipment, similar in their case to a transformer.

A typical BES opportunity in industry is in the area of molding and extruding, including both plastics and metals. Any process whose output requires precise control and in which the control is susceptible to utility server power quality will be a good candidate for BES systems. As an example, a plastic bottle extruder has three process lines that produce 50,000 bottles/hr. A typical plant might draw 1-2 MW. If there is a power glitch, the process controls are affected, which can scrap the entire run as out of spec. If the outage is sufficiently long, power is lost to the conveyor, as well as the quartz heaters, which allows the plastic to solidify along the line. It can take two shifts to strip the solidified plastic out of the line and return the line to production. The extruder might loose $30-40K in material alone per incidence, not to mention the labor. It only takes a few occurrences until the extruder begins to turn his ire toward the utility and threatens to move the facility or limit his production plans, in order to find a better utility server. A half hour of storage appears to be a suitable duration to allow the line an orderly shutdown. Assuming 1.2 MW of installed BES backup power and a low volume (early market) cost for the BES system of $600/kW, it would take six such occurrences per year to provide a 3-yr payback for this investment. In a mature market, it is reasonable to expect that the BES system cost would be reduced sufficiently to allow less than a 2-yr payback. Note that the economics are based strictly on the customer-derived benefit of having BES backup power in place, rather than on any peak shaving opportunity.

Task 2. UES Cell & Battery Development

Most of the program funding has been allocated to the hardware development embodied in this task. The series of activities that constitutes Task 2 includes the original NaS-P_{ac} battery design activity, the development of a dedicated UES cell with test support, and battery component development.

Task 2.1 Preliminary UES Battery Design

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-commutated converter, in which the maximum battery voltage is limited to 500 VDC. The battery was designed to fit behind the 7.5-ft height and 7-ft width dimensions of the available PCS. The overall package, with 1- or 2-hr BES options, was designed to be easily transportable by truck and could be contained in a standard seabox.

Task 2.2.1 Cell Component Development

The cell configuration chosen to be ideal for UES applications is a c/S cell designed around SPL's XPB electrolyte. The c/S configuration was chosen over the traditional central sodium design because of its potential for long service life, as demonstrated by a similar cell configuration (the Technology Demonstration [TD] cell) designed and tested at SPL. Having the cathode 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 while preserving its long life. The major changes relative to the TD design were the use of planar thermocompression bond (TCB) metal-to-ceramic seals rather than tapered radial TCB seals and the incorporation of the sodium reservoir in the area surrounding the safety tube instead of locating it underneath the cell. The current c/S cell design is shown schematically in Figure 5-1.

During the past year, the primary effort under this task focused on resolving a sodium seal freeze/thaw problem. Further development of a modified sodium filling method and sulfur seal has been pursued.

<u>Sodium Seal Development</u>

In the previous (FY93) UBS Annual Report, it was reported that a problem existed with failure of the

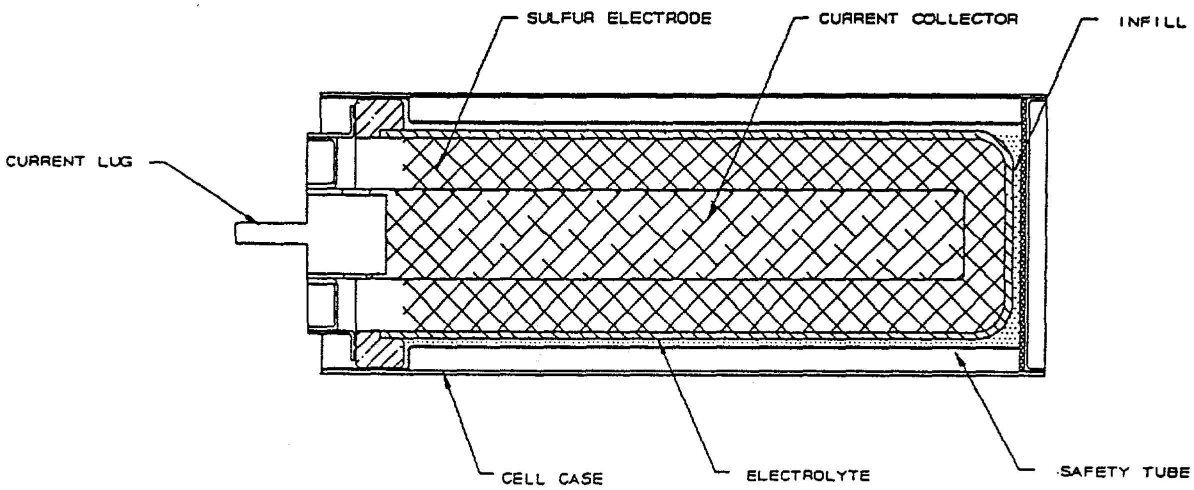


Figure 5-1. c/S Cell Configuration

sodium-side seal during initial heat-up of cells and during subsequent thermal cycles. It has been observed that approximately 10-20% of cells fail during the initial heat-up to operating temperature. The cell failure is manifested by sodium leaking from the sodium seal, pooling in the well created by the safety tube and outer container and eventually shorting the cell. That the cell has become short-circuited becomes evident at temperatures usually ranging from 280° to 310°C. In some cases, the sodium has ignited and melted or burned through the cathode cap, occasionally causing additional damage to the cell, such as fracture of the electrolyte. Posttest analyses (PTAs) of failed cells has shown that the failure of the sodium seal occurs at the interface between the aluminum gasket and the alpha-alumina header.

Liquid Metal Embrittlement

An initial investigation into possible causes of the problem suggested that liquid metal embrittlement (LME) of aluminum by liquid sodium could be responsible for the seal failures. Certainly the three elements required for LME are present: stress, the presence of an embrittling liquid metal, and a metal that can be embrittled. If LME is the cause, it should be possible to eliminate the failures by eliminating any of these three elements. Thermal compression bonded seal assemblies which were thermally cycled without sodium between room temperature and 350°C for 10 cycles showed no loss of hermeticity in helium leak tests.

In order to further quantify the magnitude of the LME problem and establish a comparative database of bond strengths, a series of mechanical tests of seal assemblies is being conducted. The TCB seal samples were made by bonding seal rings made from Kovar, chromized mild steel, and 410 stainless steel to alpha-alumina headers with 6061 aluminum alloy gaskets using standard bonding jigs and thermal conditions. The resultant seal strength is determined by axially loading the joints on an Instron machine until failure occurs. Five samples each are being tested at room temperature in air, at 120°C in sodium, and at 330°C in sodium. The samples being tested in sodium are loaded, one at a time, into the fixture shown in Figure 5-2 with enough sodium added to completely submerge the seal in sodium when it melts. Loading is done in a controlled-atmosphere glove box, and standard vacuum hardware is used for the seals on the fixture so as to minimize the possibility of oxygen contamination of the sodium. The results of the strength tests completed to date are shown in Table 5-1.

The data in Table 5-1 for seals with chromized mild steel show a minimum in strength at a temperature just above the melting point of the embrittling metal, a result that is consistent with an LME mechanism. The tests of the remaining seal types will be completed during the coming quarter.

Given that LME is responsible for the sodium-side seal failures, solving the problem should be a matter of

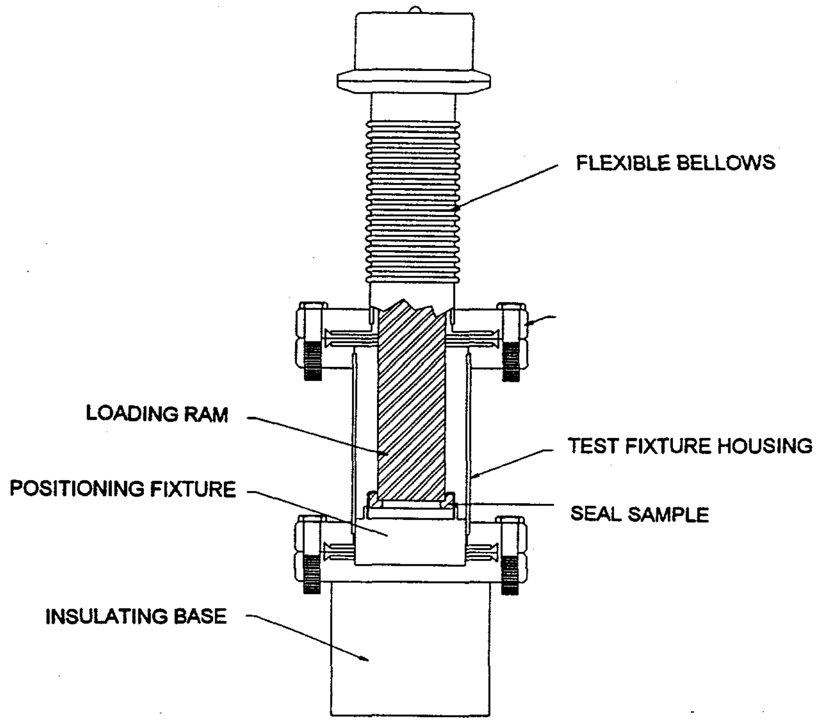


Figure 5-2. Strength Test Fixture

Table 5-1. Thermal Compression Bond (Seal) Strength

Seal Type	23°C, in Air (MPa)	330°C, in Sodium (MPa)	120°C, in Sodium (MPa)
Chromized Mild Steel	14.0 ± 2.8	13.9 ± 2.5	8.2 ± 0.7
Nitrided 410 SS	12.4 ± 1.3	13.5 ± 2.7	NC*
Kovar	9.3 ± 2.4	16.6 ± 3.3	NC

* Test not completed.

removing one of the three conditions required for LME to occur, that is, keeping sodium away from the seal, removing or altering the configuration of the stress on the seal, or using as the interlayer in the seal a metal that is not subject to LME.

Seal Modification Trials

A number of approaches are being or have been taken to resolve the sodium seal freeze/thaw failure problem. As noted above, completely eliminating any one of the three conditions required for LME should eliminate the seal failures. Several alternatives to each of the three conditions are being pursued.

Seal Stress Reduction or Reconfiguration - Modifications to the baseline design intended to reduce the thermal stresses on the seal have included changing the alloy of the metal seal member from chromized mild steel to Kovar or nitrided 410 stainless steel; increasing the thickness of the aluminum interlayer; reducing the thickness of the metal seal member; and detaching the safety tube from the seal element. Reducing the thickness of the metal seal member may also assist in keeping sodium away from the aluminum interlayer. Of these, changing to Kovar or 410 stainless steel in combination with detaching the safety tube from the seal member appear to have resulted in marginal improvement of the seal's durability during thermal cycling. Tests have not yet been conducted to isolate the alloy change from the safety tube detachment.

Work on another approach to resolving the problem has recently been initiated. This approach consists of modifying the entire sodium seal configuration to a tapered circumferential seal such as was used in the original TD cell. In this configuration, the outside diameter of the alumina header is ground with a slight degree taper. A sealing ring made from Inconel 600 with a mating taper and an aluminum alloy interlayer ring are pressed onto the alumina header at an elevated temperature, bonding the ring to the circumference of the header. As the assembly cools, the aluminum interlayer becomes compressed between the seal ring and the header because of the higher TCE of the Inconel. With this configuration, the stresses in the aluminum interlayer are always compressive, and shearing of the aluminum interlayer during thermal cycling is eliminated.

Though this approach is expected to be less cost-effective than use of the planar baseline seal design, it may provide sufficient seal durability to permit testing that can confirm that c/S cells do not have an electrolyte freeze/thaw failure problem, and to allow c/S cell safety to be effectively characterized.

Reduction of the Susceptibility of the Bonding Alloy to LME - The first approach in this category was to make brazed metal-to-alumina seals. Though it was recognized that brazed seals could never be cost-effective in a commercial cell, it was expected that cells could be produced in which safety and electrolyte freeze/thaw durability could be tested. The most readily used brazing fillers, copper/silver alloys, were tried, and hermetic seals could be produced using them. However, the silver phase of the filler was rapidly dissolved by liquid sodium, resulting in seal lives insufficiently long to permit freeze/thaw or safety testing. Several nonsilvers bearing alloys were also tried, but their effective use required facilities and expertise beyond those immediately available at Silent Power. The effort was abandoned in favor of other approaches that are believed to be within the scope of capability and that would more likely be applicable in commercial cells.

The second approach in this category is to change the aluminum alloy (6061 is the baseline alloy) used for bonding while maintaining the baseline geometry. Alloy 5086 was selected for trial because it is a non-heat-treatable alloy and has a eutectic temperature similar to that of 6061. Hermetic seals were produced under bonding conditions that were the same as those in use for 6061 alloy. However, there was no improvement in the freeze/thaw durability of the seals.

The third approach in this group is to use an aluminum-silicon eutectic alloy and a modified bonding process (higher pressure and lower temperature). This approach, described in German Patent No. DE 43 01 927 A1 (issued to NGK Insulator), reportedly produced seals with greater resistance to general sodium attack, though its freeze/thaw durability was not discussed in the patent. To date, a number of hermetic seals have been fabricated for mechanical testing. Additionally, one cell has been fabricated and is currently on test.

Elimination of Sodium Contact with the Bonding Alloy - The final solution to eliminating the LME of the sodium seal is to completely eliminate contact between liquid sodium and the seal. The approach being taken is to coat the seals with a material that is not wetted by sodium. Materials and components have been ordered, but no seals have yet been fabricated or tested.

Task 2.2.2 Battery Component Development

Many battery-level components were successfully developed and incorporated into the 12-kWh prototype battery delivered to SNL for testing. These included:

- A low-cost, nonevacuated, thermal enclosure offering excellent temperature uniformity;
- Inexpensive passive thermal management system utilizing latent heat storage materials to arrest cell temperature rise during sustained discharge and to maximize system energy efficiency;
- A thermally conductive, but electrically insulating, cement for binding cells and salt capsules together in a tight array;
- A special dedicated battery management system that eliminated reliance on calculating open-circuit voltage, using instead a more straightforward (Ah) accounting;
- A quick push-pull plug for handling the full battery current to the load, which facilitates easy maintenance/replacement.

The battery component development task has recently extended the eutectic mixture consideration to salts with lower melting temperatures. This is in keeping with the intent of lowering the operating temperature of cells to minimize corrosion and extend useful life. Experimental salt capsules have been filled and tested to verify performance. With the small addition of NaCl to the LiCl/KCl, the ternary mixture melting point is reduced by 5°C to 350°C with a latent heat of 52.5 cal/gm (220 kJ/kg) (see Figure 5-3). Essentially, there is no change from the latent heat of fusion of the LiCl-KCl binary salt, while the material cost is slightly lower. This eutectic is therefore a promising candidate for future passively cooled battery designs.

Task 2.2.3 Cell Design Verification

Cell Performance Testing

Cell Life Testing - Cell 023, with a theoretical capacity of 29 Ah, has been cycling since October 28, 1992. In that time, it has completed over 1350 cycles. Currently, the cell is discharging at a 7-A rate, and charging at a 2-A rate. It is being discharged to a cutoff voltage of 1.78 (1.90 VOC), and charged to a cutoff voltage of 2.3.

Within the previously mentioned voltage limit boundaries, 17 Ah are typically being removed and added, with a corresponding resistance of 13 - 14 mΩ at the beginning of charge and an end-of-discharge resistance of 15-16 mΩ. Calculations of rate of change indicate that resistance is increasing at the rate of about 3 mΩ per 1000 cycles. Plots of the cell resistance and depth of discharge as functions of cycle number are shown in Figures 5-4 and 5-5, respectively.

Cell 023 has been discharging to 80 percent of theoretical capacity (based on an open circuit voltage of 1.9 V, 1 hr after the end of discharge). Statistical analysis shows that the unrecoverable capacity (f1) has been increasing at 3.9 percent per 1000 cycles. This translates to a loss of capacity of 1.14 Ah per 1000 cycles.

Analysis of the number of watt hours returned to the cell during a 2-A charge divided by the watt-hours the cell delivered during a 7-A discharge indicates a loss in energy efficiency of only 0.78% over the course of the 600 cycles during which that particular charge and discharge testing was performed.

TiN-Coated Current Collectors - Four cells (096, 097, 098, and 099) with TiN-coated current collectors (sputtered on aluminum by Applied Modular Power Systems, Inc., Ann Arbor, Michigan) were assembled and placed on test. Cells 098 and 099 were assembled with three segments of glassed nickel wire to prevent undesirable recharge polarization.

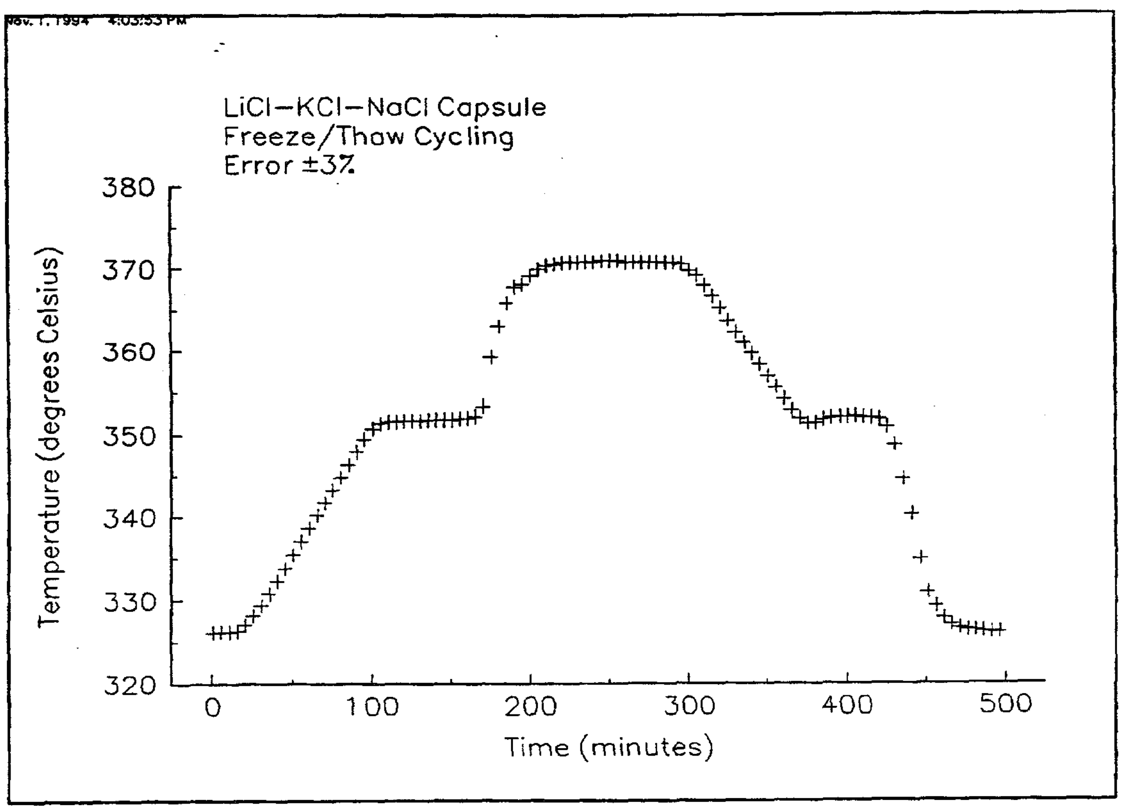


Figure 5-3. Thermal Behavior of KCl-LiCl-NaCl Eutectic Salt for Battery Energy Storage

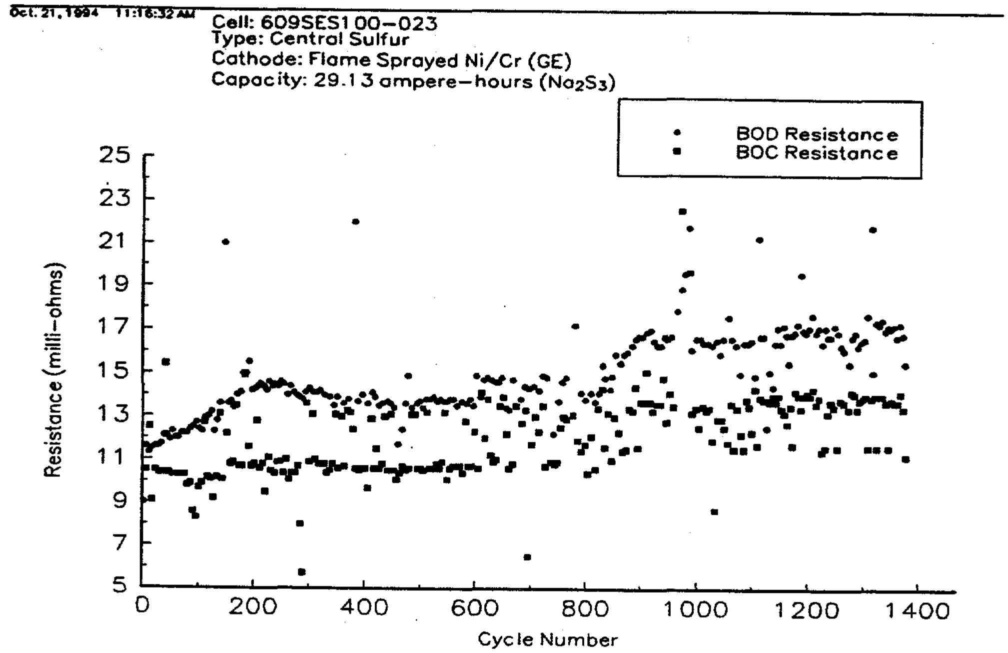


Figure 5-4. Cell Resistance vs. Cycle Number for Cell 023

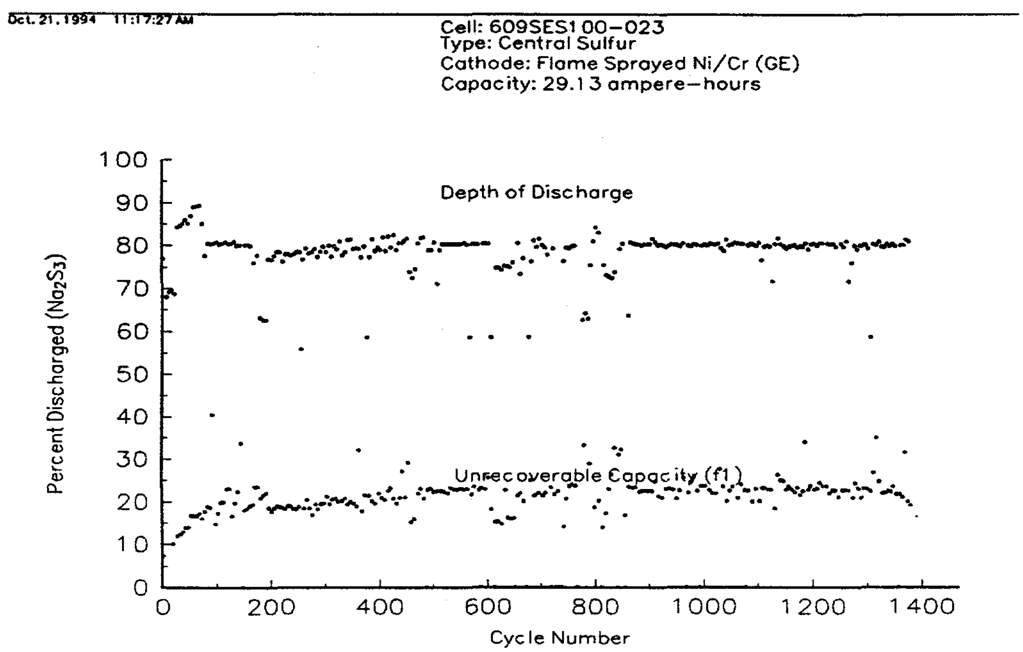


Figure 5-5. Depth of Discharge and f1 vs. Cycle Number for Cell 023

Cells 097 and 099 completed more than 120 cycles, but both performed poorly, with high resistance and poor recharge characteristics. In both cases, the initial resistance was high but decreased until about cycle 115, at which point the resistance in both cells abruptly increased and cycling was no longer possible. A plot of cell resistance vs. cycle number for cell 099 is shown in Figure 5-6. Plots of the depth of discharge and f1 are shown in Figure 5-7. PTA results showed that the TiN coating had been severely corroded by sodium polysulfides. In both cells, greater than 75% of the coating was spalled from the current collector. Cell 098 failed during heat-up caused by a sodium seal failure. Cell 096 failed after 51 cycles at the top of charge because of fracture of the electrolyte or of the alpha-alumina-to-beta"-alumina seal.

Freeze/Thaw Testing

Freeze/thaw testing of cells fabricated with alternate seal materials and modified seal/safety tube designs has been completed. The results, summarized in Table 5-2, are quite encouraging. Though three cells failed as a result of sodium seal failures during freeze/thaw, they withstood as many or more thermal cycles than any other cells tested under this program. Until now, cells with the baseline design, chromized mild steel seal rings with integral safety tubes, have exhibited a 10-20% failure rate upon initial heat-up. The failure rate during subsequent freeze/thaw cycles has been even higher, with no cell having survived more than four heat-ups, including the initial heat-up.

It is also notable that no electrolyte failures occurred during thermal cycling. The electrolyte in cell 092 failed during electrical cycling and not during thermal cycling. That there were no electrolyte failures is a very positive result and suggests that previous concerns regarding electrolyte durability in c/S cells may be unjustified.

Task 3. Design & Fabrication of UES Module

Fabrication of the 12-kWh, 400-Ah, sodium-sulfur UES prototype battery was completed as planned at the end of January 1994 at the Silent Power Salt Lake City facility and shipped to SNL for testing.

The UES battery, shown in Figure 5-8, was installed and commissioned at the SNL facility in Albuquerque and has been operating since September 9, 1994. It has completed more than 44 constant-current discharge (C/3) cycles to a depth of discharge of

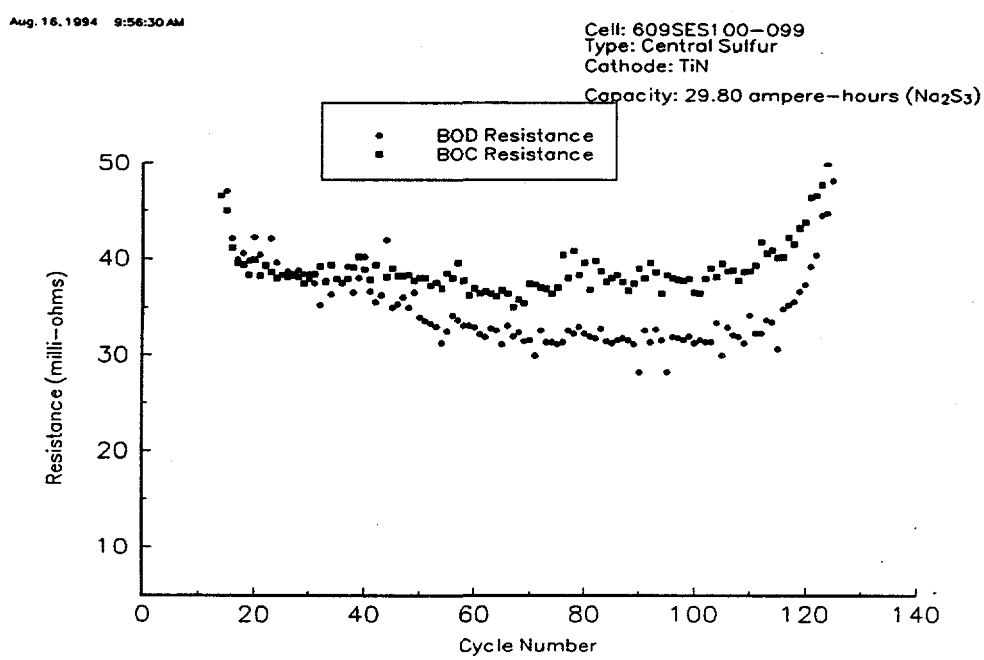


Figure 5-6. Cell Resistance for Cell 099

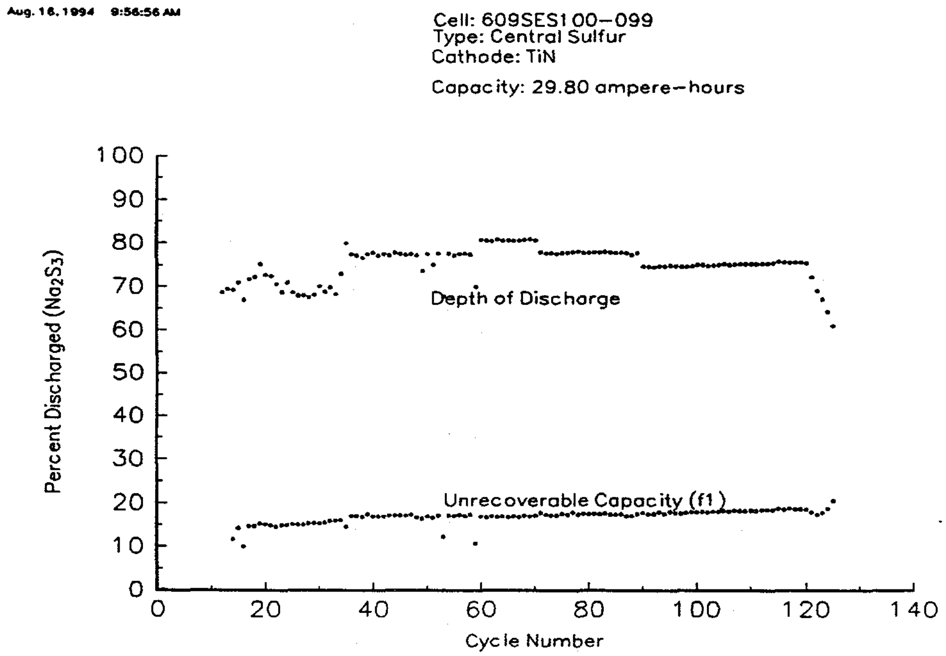


Figure 5-7. Depth of Discharge and Unrecoverable Capacity for Cell 099

Table 5-2. Sodium Seal Freeze/Thaw Test Results

Cell #	Seal Ring	F/T Cycles Survived	Failure Location, Mode
-091	Nitrided 410	7	Na seal, freeze/thaw
-092	Nitrided 410	1	Electrolyte, top of charge
-093	Nitrided 410	4	Na seal, freeze/thaw
-094	Kovar	4	Na seal, freeze/thaw
-095	Kovar	3	Current lug braze joint, cycling

408 Ah. The unrecoverable capacity has stabilized near 11% with a maximum usable capacity of 460 Ah (to 1.9 VOC). It was known from bank qualification testing prior to battery assembly that two cell strings were faulty at the time the battery was shipped from Salt Lake City. However, the usable capacity of 460 Ah indicates that no additional strings failed during shipment or during heat-up.

After completing 6 cycles, the bank resistances ranged from 3.2 to 3.4 mΩ for a total battery resistance of 13.1 mΩ. This is in good agreement with the expected battery resistance of 12.9 mΩ.

Surface temperature measurements at various points on the exposed exterior of the battery average 44.5°C, which is consistent with a heat loss through the

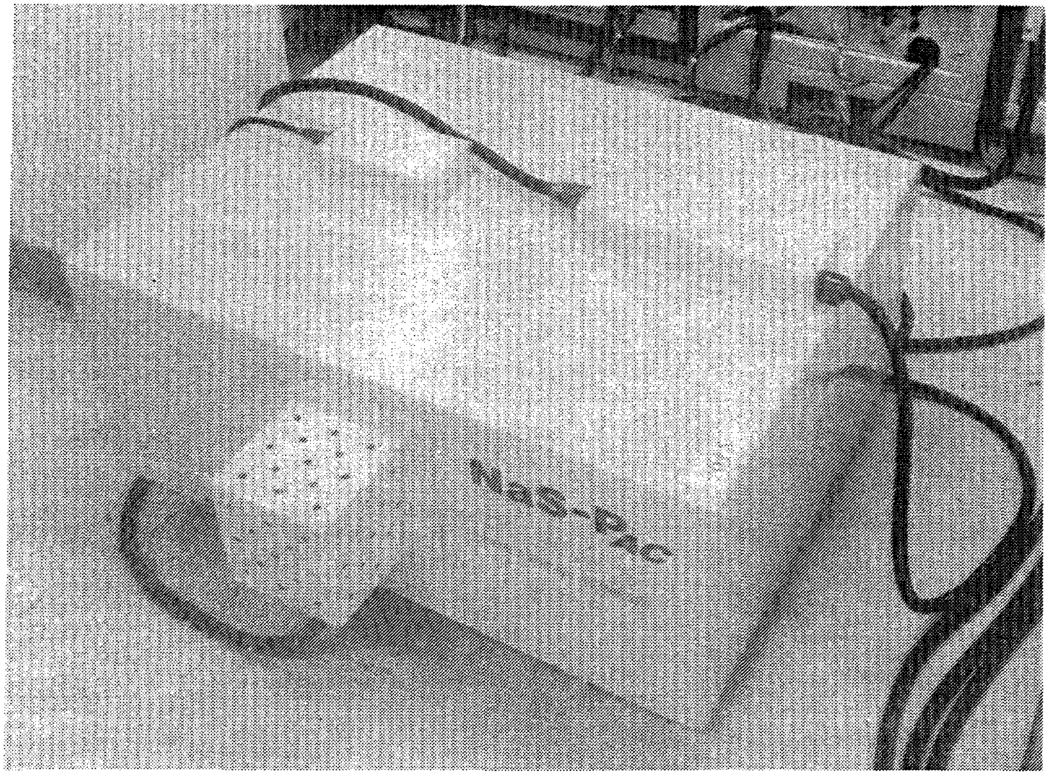


Figure 5-8. 12-kWh Sodium/Sulfur UES Battery Being Tested at SNL

insulation of 230 W. The mean thermal conductivity of the insulation is .050 W/m°C.

This task is essentially complete; however, Silent Power will continue to monitor, advise, and support the ongoing testing at SNL.

Task 4. Full-Scale Battery Plant Design

The original NaS-P_{ac} BES system design was based on the use of 125-VDC, 75-kWh battery packs. The design of these batteries was similar to that of the 12-kWh prototype battery (Task 3). The intention, however, was to replace, at the appropriate time, the small 10-Ah Mk4 cells manufactured in Clifton, UK, with the 35-Ah cell that is being developed in Task 2 specifically to achieve long life for a UES market. Battery packs, then, would be composed of two tightly bound cell layers, each experiencing equivalent thermal conditions. The thermal energy storage (TES) capsules, cemented into the interstitial space between in-line cells, would provide the passive cooling mechanism required to limit cell temperature rise during sustained discharge. The perceived benefits of this design included fewer cells and TES capsules and improved thermal uniformity in a passive design that utilized a simple non-evacuated thermal enclosure. The end result was a battery design that offered lower cost and no maintenance over a 5-yr warranted life.

For any near-term demonstrations, the reality of cell production capability was such that only the smaller Mk4 cells would be available. On this basis, SPI concentrated on a BES system design utilizing these smaller cells. Figure 5-9 is a cutaway view of the 75-kWh battery pack proposed for the NaS-P_{ac} BES system. It is composed of 12 series banks of 80 parallel 5-cell series strings, arranged as shown in the planform view in Figure 5-10. The battery capacity was derated by 22% to allow cells to fail over time without creating a need to replace the batteries.

The 1-hr NaS-P_{ac} BES system design is composed of a 300-kW PCS, either line-commutated or self-commutated, depending on the requirements of the application, four 75-kWh battery packs, a support structure for the batteries, and electrical control and interface equipment. Figure 5-11 depicts this system with a door open for battery access. The entire system weight is 16,300 lb (7400 kg) and measures 90 in. H × 84 in. W × 112 in. L (2.3 m × 2.1 m × 2.8 m). Battery packs are

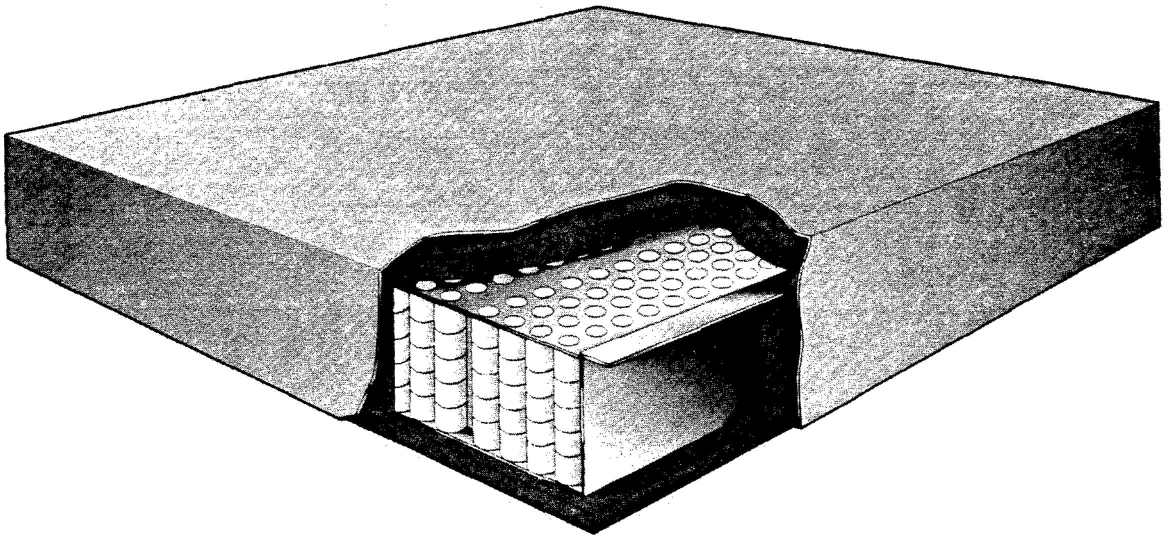


Figure 5-9. Cutaway View of a 75-kWh Battery Pack Design for the NaS-P_{ac} System

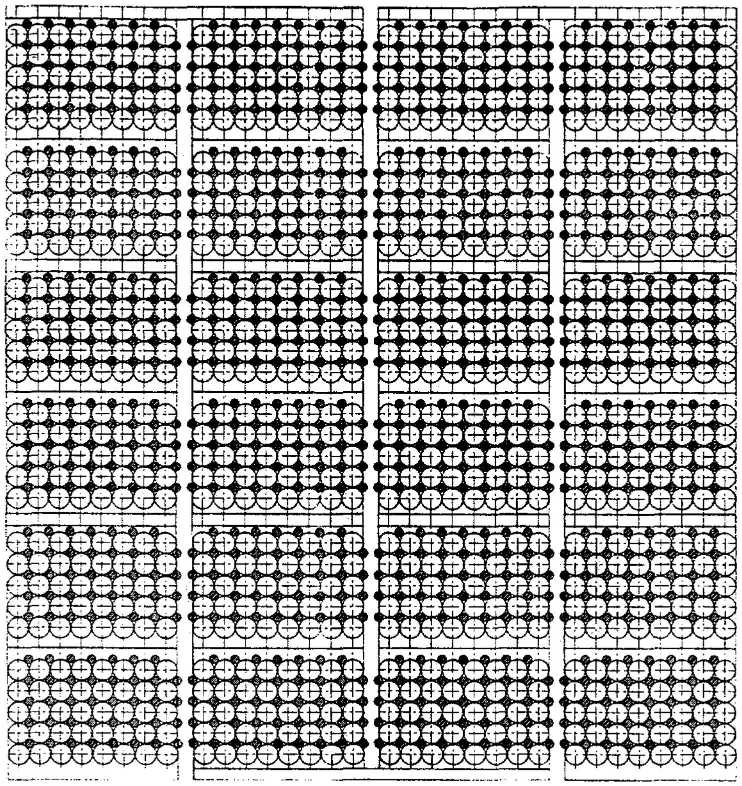


Figure 5-10. Plan View of the 75-kWh Battery Pack Design

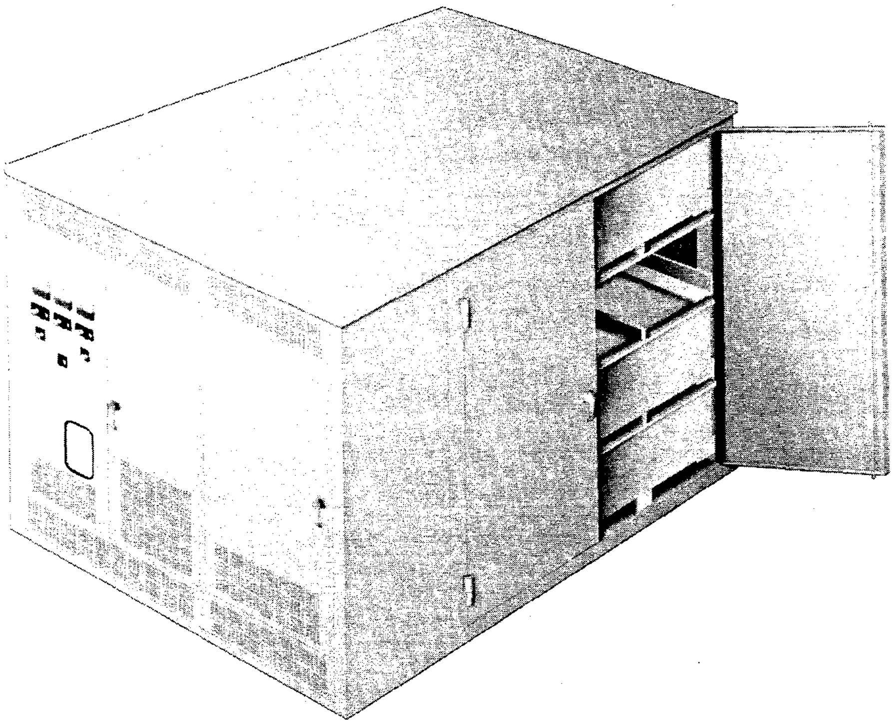


Figure 5-11. 300-kWh/1-hr NaS-P_{ac} System Shown with Battery Access

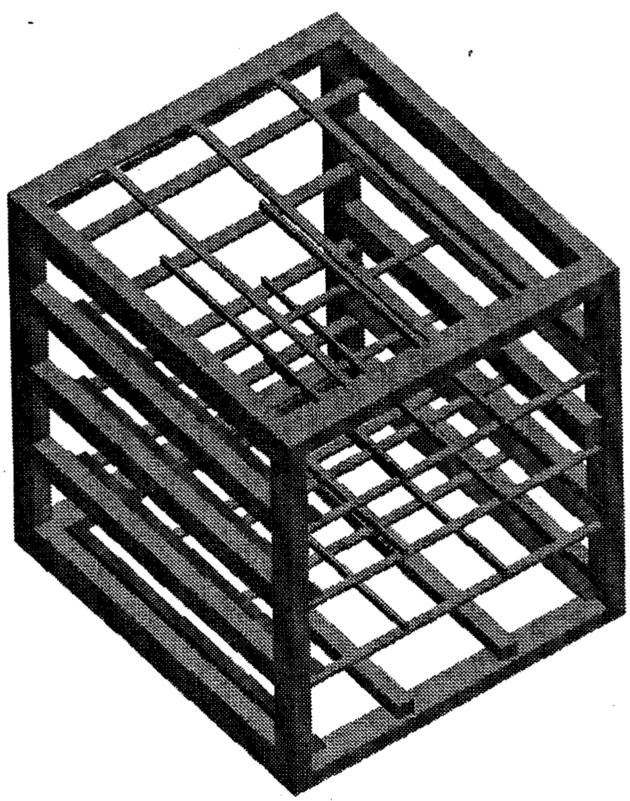


Figure 5-12. NaS-P_{ac} Battery Structural Support Design

inserted and replaced with a fork lift. The steel structure, shown in Figure 5-12, was designed to facilitate this operation. Detailed engineering drawings were produced and sent out for quotations to support the system cost development and weight tally.

The opposite side of the unit, shown in Figure 5-13, houses the electrical and electronic equipment. This includes the power cabling for battery interconnection and connection to/from the PCS, manual switches for isolating each of the batteries, and a BMS and its associated interface boxes. The BMS is responsible for maintaining battery temperature and for providing status signals to the PCS for charge/discharge. It also retains a record of battery operation for diagnostic downloading. The DC and AC switchgear were included as part of the PCS specification. A multiplexed version of the BMS delivered to SNL is expected to provide control to each of the four batteries supplied as part of the 1-hr system.

Recently, Silent Power's parent organization made a strategic decision to concentrate its resources on the manufacture of a new high-power cell, driven principally by the need for improved EV acceleration. As part of this focus, the decision was made to close the Clifton pilot plant that produced the Mk4 cell. SPI decided to piggyback the NaS-P_{ac} UES battery design on the emerging EV market and thereby increase demand for the product and more quickly reduce cost. By utilizing standard 40-kWh EV batteries as a building block, an effective NaS-P_{ac} BES system could be designed that would meet the needs of UES markets by the year 2000.

In addition to having a more powerful battery available, a number of significant benefits can be realized, starting with access to a complete battery detailed manufacturing cost study. In stationary applications, there is an opportunity to reduce the cost further by allocating one BMS to the control of several batteries. The parasitic loss from maintaining temperature for an EV battery can be considerably lower in the stationary application, since battery plan areas in a stacked array experience little heat loss. Finally, these batteries have their own cooling system to handle periods of sustained hill climb, etc., which can serve as a design basis for sustained power capabilities in UES applications.

For the 1-hr NaS-P_{ac} BES system design, 10 EV batteries will be utilized, connected 2 series × 5 parallel. The operating voltage window extends from 800 VDC at the top of charge to 640 VDC to the end of discharge. The actual voltage, however, is amenable to the needs of the PCS, but the voltage window is fixed by the battery characteristics. In Figure 5-14, consideration was given

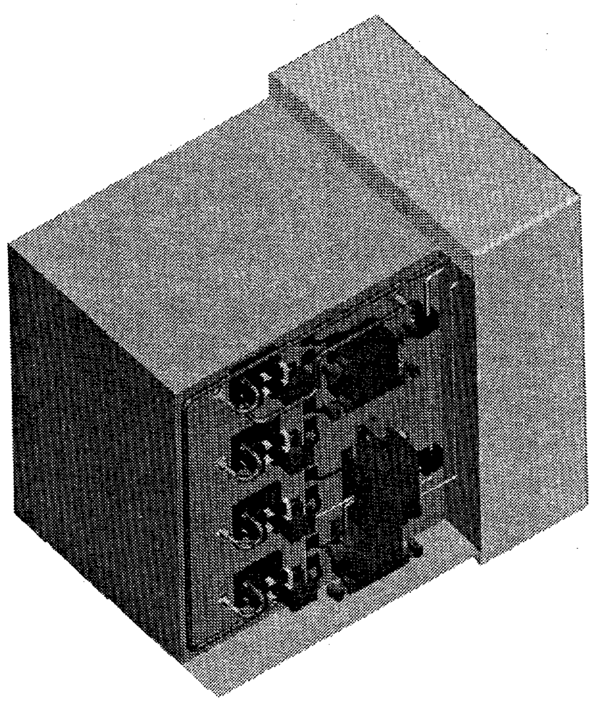


Figure 5-13. Electrical/Electronic Compartment of the NaS-P_{ac} System

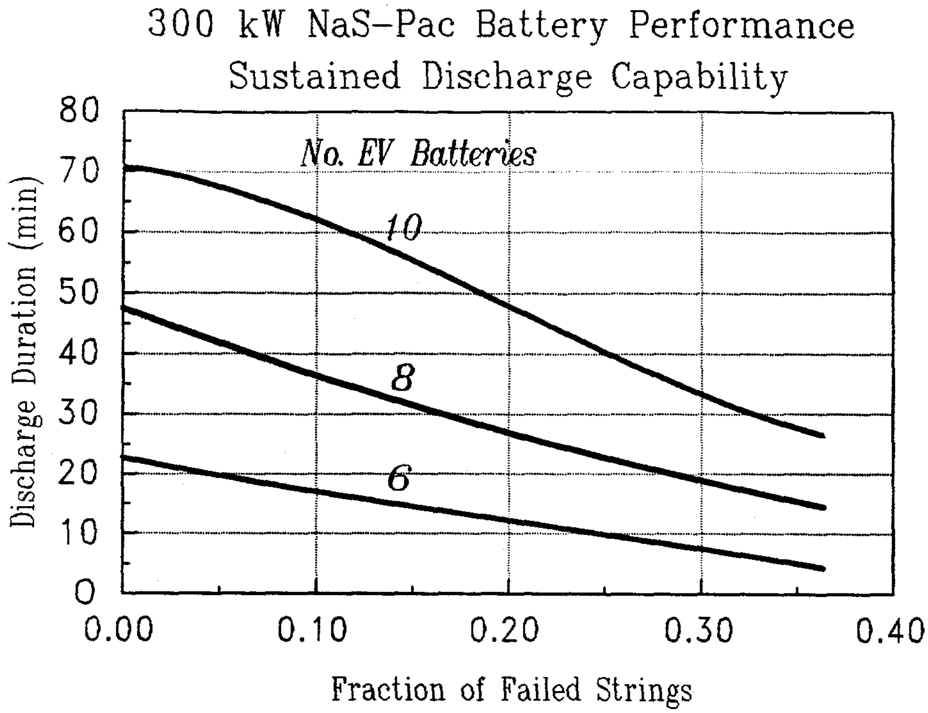


Figure 5-14. Battery System Performance Degradation with Cell Failures

to the influence of cell failures on battery performance as a function of number of EV batteries utilized in a 300-kW NaS-P_{ac} design. In general, 1-hr, 1/2-hr, and 15-min ratings can be developed using 10, 8, and 6 EV batteries, respectively. Capacity utilization, however, diminishes with applications below 1 hr. The only solution to extending discharge in these cases is to develop a more effective cooling system. While this is a worthwhile goal, for the time being only the 1-hr system is being pursued under this contract.

A preliminary support structure for the 10 EV batteries is shown in Figure 5-15. To distribute the weight more evenly, battery stacks are staggered in each of two rows behind the PCS envelope. The alcoves created in the staggered configuration become useful space for mounting the electrical and electronic equipment. The overall length of this new design is actually 16% less than the original design.

Preliminary system cost, given in ($/kW), is summarized in Table 5-3 as a function of market size. The PCS portion of these costs was received from quotations based on integrated gate bipolar resistor (IGBT) switched line-commutated products meeting IEEE-519 with a few enhancements.

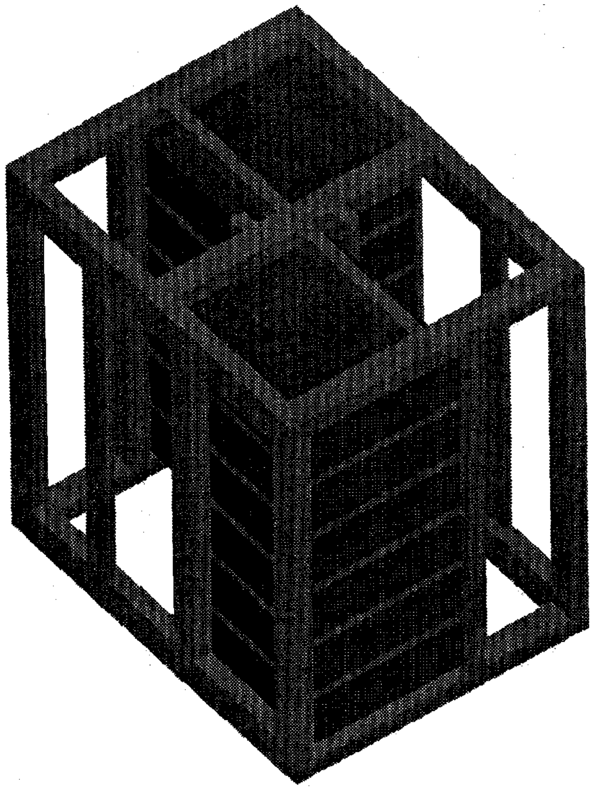


Figure 5-15. Preliminary Layout of EV Batteries Incorporated into the NaS-P_{ac} Modular System

Table 5-3. Estimated Sodium/Sulfur System Cost

EV/UES Market	Duration (hr)	# Battery Packs	Price ($/kW)
Near Term	1	10	630
	2	20	1030
Mature	1	10	428
	2	20	672

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 the UBS system engineering and system integration activities to reduce production costs as well as one-of-a-kind engineering and design costs. Omnion Power Engineering is under contract to develop the AC Battery. PG&E is the host utility to field-test the first AC Battery prototype container.

AC Battery Development – Omnion

The AC Battery is a patented, modular battery system concept proposed by Omnion Power Engineering. The concept embodies several of the design features that are desirable for utility operations. It offers redundancy at several levels, ease of maintenance, portability, and unattended remote operation. It also relies on mass-manufacturing production techniques to realize the maximum potential for reducing the cost of battery energy systems. Upon completion of a successful development phase, the AC Battery will be able to meet application requirements in the 250-kW to 3-MW size range.

In its present operational form, the AC Battery is a 250-kW/167-kWh BES system packaged in a factory-integrated container. Each container houses up to eight "modules" that contain the batteries as well as an on-board power conversion system. This enables the modules to accept AC power and convert it to DC to charge the batteries. In the discharge mode, the DC output of the batteries is converted to AC power that is aggregated from all the modules to equal the rated power capacity of the container.

At present, the AC Battery is a fully functional demonstration prototype undergoing testing at the PG&E Company Modular Generation Test Facility in San Ramon, California. Characterization testing is scheduled for completion during the first quarter of FY94. Following characterization testing, the AC Battery will continue to be tested in daily operational cycles to determine the end of life (EOL) for the batteries. EOL has been defined as the condition in which the AC Battery container can no longer deliver power to 80% DOD without shutting down, due to reaching the module minimum string voltage of 504 VDC for any module. Testing with the present set of batteries is expected to be completed during the third or fourth quarter of FY94. After the EOL point has been identified, the unit will continue to be tested to determine the behavior of battery strings beyond their useful life. After completion of all currently planned testing with the present set of batteries, options for follow-on testing of other battery sets will be considered.

Tasks/Milestones

A follow-on contract was issued to Omnion early in 1994 to perform the following tasks that were not completed under the original AC Battery contract:

1. Production Cost Estimate – A study to estimate the cost of producing the commercial design of the AC Battery assuming various rates of production. Identify changes in design that might be necessary for economic manufacturability at higher production rates.

2. Final Report for AC Battery Development – Report on the design and development activities that led to the completion of the AC Battery project.

3. AC Battery Module – Assemble, test, and deliver one stand-alone AC Battery Module for testing at SNL.

A new contract was also placed with Omnion in FY94 to modify an AC Battery Module to operate either as a voltage source in a stand-alone environment or as a current source in a peak-shaving environment. Controls will be developed to allow seamless transition among utility power sources in a hybrid configuration consisting of a photovoltaic array, a diesel generator, and the AC Battery module.

FY94 Milestones:

- Deliver AC Battery to PG&E (10/93) – completed
- Deliver AC Battery module to SNL (11/93) [because of lack of funding, not completed on original contract; milestone rescheduled to FY95 in accordance with new contract]

- Deliver modified AC Battery module to SNL for PV/Hybrid demonstration (5/94) [rescheduled to FY95 because of delay in contract placement]

Status

This has been an especially chaotic year for system integration activities in utility scale battery systems and related projects. The year began with the successful completion of the AC Battery Prototype unit and delivery of the system to PG&E in October 1993. After the typical startup difficulties related to fielding new equipment and getting prototypes operational, the AC Battery Prototype began characterization testing in December 1993. A contract was placed with Omnion to provide field engineering and maintenance support for the PG&E testing activities. Dave Porter and Roger Troyer made several trips to PG&E to correct AC Battery system deficiencies discovered early in the testing program. The Test Team expected to find some deficiencies as the unit was moved to PG&E following an incomplete factory testing program. The nature of the problems discovered at PG&E were such that they would have been discovered and corrected at the factory if the factory test program had been allowed to continue to its planned completion. However, because of the importance of getting this first-of-its-kind, transportable utility scale battery into the field for testing, the SNL project manager, Garth Corey, opted to curtail factory testing and have the system shakedown testing completed at PG&E.

As characterization testing neared completion, Module 6 behavior became very erratic and unreliable; all other modules were performing per specifications. The Test Team decided to replace Module 6 with a spare module (SNL Module #1) which was available at Omnion. The swap-out of the module would also provide proof-of-concept for the field maintainability of the AC Battery Container. The swap-out was completed without incident and the bad Module 6 was returned to Omnion for diagnostics. The container was restarted immediately after the swap-out and resumed operation with no further problems. Characterization testing was completed in March 1994, and life testing began immediately using a PG&E-developed discharge profile. Life testing continued until mid-June, when many batteries and most modules were beginning to show mild to severe EOL symptoms.

With the container batteries rapidly nearing end-of-life, a meeting of the AC Battery Test Team was held at PG&E in mid-June to address the future of the AC Battery Prototype testing program. Because of the problems encountered during characterization testing, the batteries were exposed to many abusive situations and, in addition, were chronically undercharged because of flaws in the charging algorithm that were not discovered until after the unit entered the life testing phase. At the meeting, AC Delco proposed to retrofit the container with a complete set of AC Delco AES 2010 batteries. The purpose of the retrofit was to install an improved battery, the battery slated for the production versions of the AC Battery, and to acquire life data on the production configuration of the AC Battery. The AC Battery testing shutdown was scheduled to take place in late July or sooner if the container was unable to continue cycling because of battery failures.

After completing a total of nearly 100 deep discharge cycles during characterization and life testing, the AC Battery prototype ceased testing operations on August 8, 1994. Following shutdown, the modules were removed from the container and shipped to the AC Delco Systems plant in Indianapolis, Indiana for removal of the spent batteries and replacement with AC Delco AES 2010 batteries. All retrofit and factory testing operations are scheduled for completion in early January 1995. Following the retrofit and final checkout, the modules will be shipped back to PG&E in mid-February for reinstallation in the container. Life cycle testing of the new set of AES 2010 batteries is scheduled to begin in mid-March 1995.

Work continued on the AC Battery follow-on contract tasks which include a production cost estimate and the final report for the AC Battery development program. This effort is expected to be completed in the second quarter FY95 with the delivery of the Production Cost Estimate Report and Final AC Battery Development Report.

Tasks related to the delivery of the two SNL AC Battery Modules evolved into two separate projects as needs were identified during the year. The first AC Battery Module project was to convert one of the modules to operate as a voltage source in a stand-alone hybrid environment. Discussion of this project can be found in the AC Battery Module Modification for the Hybrid Development Project section of this report. The second AC Battery Module was earmarked for use at the Center for Renewable Energy Sustainable Technology (CREST) project sponsored by the Solar Energy Research and Education Foundation. Plans are underway to design an environmentally sound, transparent enclosure in which to place the module for public view and operation in the CREST building currently undergoing renovation in Washington, DC. The purpose of the CREST facility is to provide information and hands-on demonstrations of renewable and storage technologies to inform and educate government officials and the general public on the benefits of these technologies.

AC Battery Module Modification for the Hybrid Development Project – Omnion

Tasks

Under a project jointly sponsored by SNL's Storage Batteries and the Photovoltaic Systems Departments, a contract was placed during the second quarter of FY94 with Omnion Power Engineering Corporation of East Troy, Wisconsin, to design and develop a hybrid power conditioning system and related controls that would provide seamless transfer among various power sources available to the unit. Although the system was to be designed around a stacked lead-acid battery storage source, a photovoltaic (PV) source, and a diesel generator source, the controls were to be designed to be generic in nature, allowing different battery types to be used as storage sources and various renewables such as wind turbines and PV arrays to be used to provide power to the hybrid system. 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 successful completion of the development of the hybrid system is expected to lead to the development of a "smart controller" that will evaluate the operational environment and make decisions as to the most efficient source of power on the basis of the status of the various power sources. The ultimate goal of the development effort will be to provide a turnkey control solution for future off-grid power systems.

Status

On April 21, 1994, Russell Bonn (Dept. 6218) and Garth Corey (Dept. 2225), both of SNL, and Hans Meyer, Dave Porter, and Bob Schneider of Omnion conducted a preliminary design review for the Hybrid Development Project. At this meeting, the design specification (Omnion Document #900734) and project schedule were reviewed. A decision was made to deviate from the standard AC Battery Module structure so that a more efficient topology could be applied. A final design was selected that will provide a fully enclosed cabinet containing all the power electronics and controls with interfaces to the various sources available external to the cabinet. The power conversion system will provide the capability of producing up to 31 kW of continuous power as a voltage source with power provided by either a storage source or a renewable source. In addition, the power conversion system will have the capability to operate as a current source to act as a peak-shaving device in the event the diesel generator is unable to support the total operational load. An RS-232 communications channel will be provided to allow external commands from the system operator to be processed and to give the system the ability to provide the control functions necessary to switch the system seamlessly among the power sources as requested by the operator.

In June 1994, a critical design review was held at Omnion to review the final design of the hybrid control system. The purpose of the meeting was to review the system design with the intent of releasing the design to fabrication. Several design changes were proposed, reviewed, and accepted, and the design was released to fabrication. In the original design, the photovoltaic array was to share the high voltage DC bus with the storage system. Because of the potential to overcharge the batteries when the PV array was supporting the load, the design was modified to insert DC-DC conversion on the input side of the PV system to manage the voltage level on the shared DC bus. DC voltages would then be maintained so that the batteries would not be subjected to DC voltage levels that could overcharge the battery string.

Near the end of FY94, the first seamless power transfer was observed during witness testing of the breadboard design at Omnion. Various loads were applied and the unit was commanded to switch between the diesel generator and the storage system. A typical operational scenario and switching test sequence is as follows:

- PV off-line and diesel generator off-line and shut down.
- Battery storage system providing 20 kW power to the load as a voltage source.
- System commanded to go to the diesel generation mode.
- Diesel generator started by the control system.
- Conversion by the power conversion system establishes frequency synchronization with the diesel generator.
- Control by the power conversion system transfers load to the diesel generator and then shuts down as a voltage source.

At this point, the battery storage unit could be placed on charge and the diesel would charge the system and also support the load until the battery string was fully recharged. At that point the above scenario could be reversed, that is, the operator would issue a command to the system for the battery storage system to assume the load and the system would seamlessly activate the power conditioning system for the storage system and shut down the diesel generator.

Many different switching scenarios were tested at various load levels using a PV simulation source, a battery storage unit, and a diesel generator. There were no voltage waveform aberrations noted during the switching activity going either from or to the various power sources. Additional testing is planned using a variety of load scenarios to determine the system performance to be expected when the system is used in a highly reactive (capacitive or inductive) environment.

Delivery of the system to SNL is expected late in the first quarter FY95. Comprehensive field testing of the completed hybrid system is scheduled to be performed at the Photovoltaic Systems Evaluation Laboratory at SNL starting during the second quarter FY95.

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. Two key activities have been initiated in this program element and their progress is reported here.

PG&E – Testing of AC Battery

In FY93, a cost-shared contract was placed by Sandia with PG&E of San Ramon, California to test the AC Battery prototype being developed by Omnion Power Engineering Corporation. The PG&E MGTF is a unique test facility, owned and operated by PG&E, where pre-commercial prototypes of various utility equipment can be tested in a controlled environment under simulated utility operating conditions. The MGTF provides an ideal test facility in which to test the AC Battery prototype.

Under the scope of the SNL contract, PG&E developed a test plan for the AC Battery prototype for various operating modes. PG&E also developed a control interface to operate the AC Battery using the same communications protocol as used in other PG&E system control environments. In addition to purely operational testing, PG&E also evaluated the maintainability of the system under simulated field conditions.

Tasks/Milestones

Tasks for PG&E AC Battery Field Testing and Evaluation are as follows:

1. System Startup – Install the AC Battery on the MGTF test pad, connect to the MGTF grid system, perform safety and operational tests, and prepare the AC Battery for characterization testing.

2. Characterization Testing – Prepare an AC Battery Test Plan for review and approval by the AC Battery Test Team. Perform all tests as specified by the PG&E AC Battery Test Plan. Analyze test data; prepare and publish a report on the results of the characterization test program.

3. Life Testing – After completion of characterization testing, continue to cycle the AC Battery through typical utility-type discharge/charge applications until it can no longer meet the 80% DOD specification before modules go off-line as they reach specified minimum DC levels for the module strings.

Status

In the first quarter of FY94, following an uneventful truck transport from East Troy, Wisconsin to the San Francisco Bay Area in California, the AC Battery prototype was delivered to the PG&E MGTF in San Ramon. Off-loading from the truck and installation at the MGTF was completed in one day. Following initial installation, several days were dedicated to performing a series of safety and operational checks prior to powering the AC Battery up for the first time in a field environment. In early November, the system completed the initial checkout phase and was connected to the MGTF grid to begin characterization testing.

Characterization testing began with a baseline benchmark capacity test to determine the test program startup capacity and to compare the results to an identical test conducted at the factory prior to shipment. The system exhibited slightly higher capacity than the final factory test. This was a very important test as the life performance of the system is to be based on the system capacity as defined in this test. The system delivered 167 kW for 1 hr, 13 min; specifications require the system to deliver 167 kW for 1 hr to meet requirements. Characterization testing continued with the goal of proving the functionality of the AC Battery in an operational environment. Tests were performed to determine the range of operations the AC Battery could support from VAR compensation to islanding management. In all cases, the AC Battery met or exceeded the design specification for the system. A document has been prepared by PG&E reporting on all aspects of the AC Battery prototype characterization testing program. This PG&E report will be available during the second quarter of FY95.

A key activity of the testing program was to validate the maintainability of the AC Battery in the field environment. Early in the testing program, evaluation of the test data indicated that two batteries in one module may have failed. To evaluate field maintenance concepts, the faulty module was removed, unstacked, and two faulty batteries were identified and replaced (an additional battery, a control, was also removed for comparison). The module was reassembled, tested, and reinserted into the AC Battery container, where it resumed operation; the testing program then continued. The total time that the AC Battery was off-line was less than 4 hr, proving one aspect of the field maintainability concept for the system.

As characterization testing progressed, Module 6 began to exhibit erratic behavior and a marked degradation in capacity. A meeting of the Test Team resulted in the decision to replace the erratic module with a partially assembled Sandia spare module that was in temporary storage at Omnion and available as a replacement unit. Final assembly of the spare module was performed at Omnion, a successful preshipment checkout was conducted, and the spare module was shipped to PG&E ready for immediate installation. During the week of April 25, 1994, the unit was received by PG&E and readied for installation. The entire module swap-out activity required less than 4 hr, after which the container was ready to power up. Prior to putting the unit back on the MGTF grid, a number of safety checks were successfully completed, and the container was restored to operational status. During the first test sequence, the new Module 6 exhibited none of the old symptoms of the old Module 6, and PTA indicated a substantial increase in capacity for the module, as would be expected for a new module.

Several conclusions may be drawn from the information obtained through this exercise. First, the ease of execution of field maintenance operations was proven in that a replacement module was transported to the site, off-loaded, and swapped with the defective unit, and the AC Battery was restored to full operations in less than half a day. The modular design for the system was responsible for the ease in which this operation was planned and executed.

Several system operations problems were identified and solved during characterization testing with the help of engineering staff support from Omnion. Throughout the characterization testing program, the Test Team was very active in evaluating system performance and making recommendations to the Omnion engineering team, who were very effective in implementing fixes to solve operational problems. Characterization testing was completed in late March 1994.

Life cycle testing began immediately following the module swap-out and was scheduled to continue until the AC Battery exhibited end-of-life symptoms. End of life would be reached when the AC Battery could no longer deliver 80% of rated capacity. At the end of the characterization testing phase and as the system entered life cycle testing, PG&E, Omnion, and Delco Remy analysts noted that the overall system exhibited a significant degradation in energy capacity. Batteries removed from Module 6 exhibited a substantial stratification and sulfating characteristic, indicating that the batteries had been severely undercharged during their operational life in Module 6. Delco Remy battery engineers determined that, because of the operation of the charging algorithm, the entire system had been exposed to a chronic undercharged condition. A meeting of the Test Team was held at PG&E on June 14, 1994, to assess the situation and make recommendations as to how to proceed with the testing program. After several hours of very productive, open discussions, the Test Team made several conclusions and recommendations. The Test Team recommended that testing of the current battery set continue so that as much data as possible on the failure mode of battery strings could be gathered as the batteries and strings began to fail in the operational environment. A further Test Team recommendation was to remove all the Delco 2000 batteries from the system, replace them with AES 2010s, and proceed with life testing for the system so that the life-cycle test outcome would be based on the results from testing the actual battery type that is to be used in the production version of the AC Battery. Delco Remy agreed to replace the battery set with the new batteries as soon as the AC Battery unit was taken off testing.

In an attempt to select the most meaningful test termination point, criteria were established that would define the situation in which the unit would be shut down for retrofit of the new battery set. It was determined that, when the container could no longer deliver 167 kW for 1 hr, or on July 31, 1994, the system would be shut down for retrofit. Testing of the AC Battery prototype ended on August 8, 1994, and the modules were prepared for shipment to the AC Delco Systems facilities in Indianapolis, Indiana.

During the retrofit period, several minor modifications were scheduled for the system, but the consensus of the Test Team was to make only minimal changes to avoid troubleshooting when the system resumed testing with the life-cycle test program. Retrofit, including module checkout at the AC Delco plant, was expected to take up to six months to complete. Testing is scheduled to resume in the second quarter of FY95.

Special Evaluation at SNL - PREPA/C&D Lead-Acid Battery

Task/Milestone

Testing of the 12 C&D Charter Power Systems, Inc. (C&D) flooded lead-acid cells of the same type that PREPA is installing in its 20-MW BES system is now complete. This PREPA facility contains 6000 of these cells configured in six parallel strings. Each cell has a nominal 2000-Ah capacity. The BES system will be used to provide frequency regulation and spinning reserve for the PREPA system. The main objective of the tests at SNL is to assess the thermal load that will be imposed on the battery facility during normal operation of the BES system. If the results indicate that the cooling system has been undersized, then adjustments can be made before operation of the facility begins.

FY94 Milestone:

- Complete PREPA battery thermal tests (12/93) – completed

Status

This test program was completed during the first part of the fiscal year. Activity during the first quarter focused on repeating some of the battery cycling experiments where the portion of the cycle representing a spinning reserve discharge failed to run as long as requested at the full power levels selected. This behavior was believed to be related to the high ambient temperatures experienced during the summer in the laboratory used to house the battery cycler. Outdoor temperatures had cooled enough by the start of FY94 that thermal data could again be recorded for UES cycles running at full power all the way through. Several experiments were also carried out in the first quarter using higher battery power levels during the frequency regulation part of the cycle to determine if a higher turnover rate of the battery capacity would result in a noticeably higher thermal power being given off by the cells. During the second quarter, the final experiments at the higher turnover rate were completed and the simulations of the thermal behavior of the battery at the Puerto Rico facility were finalized. Measurements of the battery capacity and the cell dimensions were also obtained at the conclusion of the test program.

A replicate UES test starting at 37.8°C (100°F) was run at the end of FY93 because of experimental difficulties in one of the earlier trials at these same conditions. When the data from this repeat experiment were inspected, it was found that the spinning reserve part of the cycle had run all the way through, suggesting that ambient temperatures had dropped enough by that time for our test equipment to run the complete cycle at the power levels selected. After the success of the test starting at 37.8°C, the only one of the three starting conditions where thermal data had not been recorded for a full power spinning reserve discharge was 32.2°C (90°F). The chamber temperature was therefore lowered to 32.2°C to collect thermal data on one more UES cycle at that temperature. This cycle could also be used as a baseline for thermal measurements made with the battery running at a higher capacity turnover rate. The duplicate test ran normally, including the spinning reserve portion. Battery electrolyte temperature rose from an average of 32.1°C (89.8°F) to a maximum of 37.9°C (100.2°F) during frequency regulation and increased to 39.3°C (102.8°F) during the spinning reserve discharge. These upper level temperatures were slightly cooler than the values found in earlier experiments beginning at 32.2°C, probably due to the cooler laboratory air being pulled into the chamber.

All of the UES cycles run up to this point were done with battery power levels chosen near to values that were derived from an analysis of PREPA operating data by United Engineers and Constructors (now Raytheon Engineers and Constructors). These power settings produce over 24 hr a capacity turnover of 2.55 times the rated battery capacity. It was believed by PREPA that some possibility exists that slightly higher turnover rates could be observed occasionally during actual operation of the BES facility, so a few UES cycles were carried out at a turnover of 3.0 to determine if this would have a significant effect on the thermal load. Table 7-1 compares the original and the adjusted power levels that were used for this test. Only the two lower power settings were increased because the high-level recharge power was already limited by the rate at which the battery could be recharged near the top of the 72-92% state-of-charge window used to run frequency regulation in these tests. Since the high level recharge power could not be increased, the high level discharge power was also left the same in order to not further shorten the time between intermediate charge sessions. Two UES tests were run using these operating parameters and a nominal starting temperature of 32.2°C. The first trial began at 31.4°C (88.6°F), and in that trial the battery electrolyte reached a maximum of 37.0°C (98.6°F) during frequency regulation. The peak electrolyte temperature during the spinning reserve test was 39.7°C (103.4°F). These values are comparable to those in the preceding test at the lower turnover rate. The second high-turnover test began at an average 31.8°C (89.2°F), reached a maximum of 37.3°C (99.1°F) in one cell during fre-

Table 7-1. Battery Power Settings for Frequency Regulation during a UES Cycle

	Original Power (kW)		Adjusted Power (kW)	
Frequency Shift	Charge	Discharge	Charge	Discharge
High	18.2	20	18.2	20
Medium	12	12	14.5	14.5
Low	4	4	5	5
Turnover Rate		2.55		3.03

quency regulation, and peaked at 39.8°C (103.6°F) in two cells during the spinning reserve part of the test. These results essentially duplicated the first higher-rate experiment.

For all of the tests during this fiscal year, the thermocouples in the test chamber were left in the same positions that they had been placed in for the final UES trial run at 37.8°C that was done at the end of FY93. In that experiment, some of the thermocouples that had been on the exterior of the battery were moved to the chamber walls and the exhaust vent line. The purpose of this move was to verify that the interior wall temperature in the chamber was fairly uniform and to see if the measurement of the exit air temperature that was being used in the data analysis was really a maximum value. During the latest UES cycles, the three interior wall temperatures were very close together most of the time, showing that the battery is radiating heat to a fairly uniform surface. The original thermocouple measuring the temperature of the exit air just before the exhaust fan consistently read slightly warmer temperatures than a second thermocouple placed downstream in the duct. Therefore there has been no indication that the location of the exit air temperature measurement should be moved.

In order to further verify the relative uniformity of the temperature of the surfaces in this experiment, an infrared camera was used to make a visual record of the interior chamber walls and the battery while a UES frequency regulation cycle was running with the heating panels set for a 32.2°C initial operating condition. A nonreflective, black paint was applied on some areas to reduce the reflected thermal image of the heating panels for this record. This investigation allowed a more detailed examination of the interior wall temperature variation to be made, and, again, the results indicated a very uniform condition. The surface of the battery was also relatively homogeneous in temperature, typically only varying by 3-4°C over one of the large sides of a cell. It was noted that the ends of the battery were a few degrees cooler than the sides facing the heating panels. This correlates with the lower electrolyte temperatures for the end cells in the battery stack. The end of the stack also more prominently showed a slightly warmer band at the top of the cells, above the level of the electrolyte. This difference was only on the order of 1-2°C. A videotape has been made that shows these results.

As discussed in the annual report for FY93, electrical capacity measurements on the battery have dropped slightly from the maximum values found just before the start of the thermal measurements. One possible reason for this slight capacity drop was that the battery needed to be equalized, although the voltage spread among the cells at the end of a refreshing charge procedure was still within the ±50 mV specified by the manufacturer. Because an equalization had not been carried out since the beginning of the thermal testing, it was decided to perform this procedure at the end of the first quarter, before a two-week break in testing at the end of the year. The string voltage was set at 28.7 V (2.39 vpc) for the equalization. After a charging period of 48 hr, there was a spread of 66 mV in the individual cell voltages and one cell (number 7) was still 48 mV below the string average at that point. Although this voltage spread was greater than after the original battery equalization, charging was terminated because of the long time period already spent and the fact that the voltage for cell 7 did meet the manufacturer's specification of being within 50 mV of the string average. Cell 7 has been among the lowest in voltage during recent refreshing charges, but had not been singled out on the basis of its performance before.

Two UES experiments starting at ambient temperature were run at the beginning of the second quarter. The purpose of this was twofold: we wanted to cycle the battery a few times after the equalization before remeasuring the capacity, and, also, we wanted to see if the effect of a higher turnover rate on heat generation by the battery might be more apparent under conditions where the heater panels were off. Part of the heat that must be rejected by the battery comes from the heater panels, and a small increase in the internal heat generation could be hidden by a larger amount of heat from the panels at higher chamber temperatures. The two experiments ran normally with a complete spinning reserve test at full power in both trials. The first experiment started with the battery relatively cool, since no activity had occurred at the test facility for approximately two weeks at the end of 1993. The second UES cycle was started immediately after the completion of the refreshing charge for the first one so that the battery was already hot. No ramp up to the equilibrium operating temperature during frequency regulation was observed in that case. The first UES cycle began at an average battery electrolyte temperature of 19.8°C (67.7°F) and reached a maximum of 33.3°C (92.0°F) during frequency regulation. The maximum temperature during the spinning reserve test was 35.8°C (96.4°F). In the second trial, the average starting electrolyte temperature was 32.1°C (89.8°F) and the battery actually cooled slightly at the beginning of the test. The maximum level temperature during frequency regulation was 33.2°C (91.8°F), and the maximum during the spinning reserve discharge was 35.7°C (96.3°F). These values reproduced those in the first run quite well and are slightly higher than the 29.6 to 30.4°C maximum temperatures observed during frequency regulation in earlier ambient temperature tests at a lower turnover rate.

A standard, constant-current capacity test (800-A, 21-V cutoff for the string) was carried out to determine whether any battery capacity had been recovered by equalizing at the end of the first quarter. The measured capacity, corrected to 25°C, was 2033 Ah. This was lower than the last determination before the battery was equalized (~2200 Ah) and was also slightly less than the lowest value found previously for this system, which was 2073 Ah (average of results from two discharges). A review of the individual cell voltage data recorded during the capacity test revealed that the voltage of cell number 3 had declined to 0.94 V when the discharge was terminated. The average voltage of the other 11 cells in the string was still 1.81 V at that point. Shortly after the capacity test was completed, it was discovered that the air line to cell 3 was disconnected so that the electrolyte in that cell was not being mixed. This was also probably true during the capacity test. Measurements of sulfuric acid density showed that the electrolyte in cell 3 was stratified and this is almost certainly responsible for its apparent low capacity in the test. The capacity test was not repeated after the air line was reattached, but if the voltage of cell 3 had remained similar to the others in the string, it is estimated that an additional 10-15 min of discharge would have been obtained. This would have increased the capacity of the string to about 2200 Ah, and indicates that the recent equalization probably did not increase the overall battery capacity very much.

Dimensional measurements of the cells were also repeated at this time to compare with the dimensions that were found at the start of the thermal property experiments. Cell widths were recorded both parallel and perpendicular to the battery plates at several heights on the jars. All of these values were identical with the original ones, indicating there was no observable bulging of the battery jars. There has also been no observable shedding of active material from the plates to the bottom of the cells.

The same variable heat sink formulation of the thermal model that was used for the rest of the data was applied to these more recent data sets. During the frequency regulation part of the test, the battery is assumed to be generating heat at a constant rate. This is reasonable, in spite of the rapid cycling of the battery between charge and discharge in this mode of operation, because of the long thermal time constant of the cells. The assumption of a constant heat generation rate is not valid during the spinning reserve discharge while the current is ramping linearly down to zero. For that portion of the test, the heat generation rate is calculated from the square of the battery current times a constant electrical resistance parameter. The derived thermal powers, electrical resistances, and heat transfer coefficients for the battery can be combined with known air flow rates to predict the thermal response of the battery in the Puerto Rico facility.

Two fitting parameters are used for the frequency regulation portion of the data. The first (A/B) is the thermal time constant of the cells and the second (Q/B) is the steady-state temperature difference between the cells and the heat sink temperature. In the past, the numerical optimization routine used could easily determine the thermal time constant from the data and the same was true for all but one of these data sets. The value found for A/B was on the order of 8 hr, in agreement with results from earlier experiments. However, when the same procedure was tried on the last data set, where the batteries were in a preheated condition, unrealistic time constants were typically obtained. This data set was the only one that failed to give reasonable time constants. While it is possible that another factor such as a larger amount of noise in the data could have been responsible for this behavior, this experiment is unique in beginning from a completely preheated condition. For this one case, the time constant was fixed at 8 hr, and the normal optimization routine was used to find the corresponding temperature difference.

Table 7-2 lists the parameters obtained from fitting the frequency regulation part of all of the UES cycles that were run. These values have been converted to heat transfer coefficients, h, and thermal powers, Q, in Table 7-3 by using the physical properties of the cells. Some improved agreement between results for tests carried out under similar conditions has been obtained by removing early time data that were incorrectly included in the prior analysis, but differences still remain. However, the matches are good enough that only average values are shown in Tables 7-2 and 7-3. At least two data sets were collected for all conditions. The general trends noted in earlier reports have continued. Heat transfer coefficients were larger for the end cells in the battery array since they can reject heat more easily to the environment. All of the cells were generating approximately 20 W of thermal power during frequency regulation. The results at higher temperatures were more scattered, so it is not clear in those cases whether the thermal power generated was exactly the same each time; the averages, however, were very similar. Two tests run with the battery off showed that the cells picked up heat from the chamber heaters being used to create the 32.2 or 37.8°C environment. This increased the apparent thermal power rejected by the battery when it was cycled at those temperatures, but when the thermal power was corrected for this factor, all tests at the 2.55 turnover rate showed a consistent heat generation rate, as expected. The values in Table 7-3 have not been corrected for the heater power. Experiments carried out at the higher turnover rate of 3.0 did not give a significantly larger Q.

Spinning reserve data from the recent tests were also fit to the same model. A battery resistance was obtained from the second fit parameter (Q/B). In this analysis, the first parameter (A/B) was always fixed at 8 hr because the duration of the spinning reserve test was too short to determine the relatively long thermal time constant. The reported electrical resistance is fairly insensitive to the exact time constant used. Table 7-4 lists the individual cell resistances calculated from all the data sets for the six cells that were fitted with thermocouples. Previous data reduction efforts were hampered so much by noise in the temperature data that only results from averaged temperatures were reported. Recent data have been much more consistent so that fits of the individual cell temperature traces have been possible. However, some of the calculated resistance values from earlier spinning reserve test data are still considered less reliable because of noise. The suspect results are shown in Table 7-4 in boldface type and have not been included in the averages. Most of the resistances are somewhat lower than the values shown in previous reports that were derived from averaged temperature data, but they agree well with resistances calcu-

Table 7-2. Fit Parameters Obtained for PREPA Battery Thermal Data Collected during Frequency Regulation

Test Conditions T(°C), Turnover	End Cells		Center Cells	
	A/B, Std. Dev. (hr)	Q/B, Std. Dev. (°C)	A/B, Std. Dev. (hr)	Q/B, Std. Dev. (°C)
Ambient, 2.55	6.42 (0.38)	2.80 (0.22)	7.75 (0.37)	4.32 (0.33)
32.2, 2.55	5.52 (1.29)	2.89 (0.41)	7.82 (1.40)	4.62 (0.32)
32.2, Battery Off	10.7 (2.10)	0.50 (0.16)	12.9 (0.72)	0.65 (0.19)
37.8, 2.55	5.78 (0.98)	2.90 (0.69)	7.88 (1.28)	5.03 (0.49)
37.8, Battery Off	11.2 (1.76)	0.30 (3.2)	7.47 (0.31)	1.10 (0.61)
Ambient, 3.0	7.45 (0.85)	3.20 (0.23)	8.65 (0.97)	5.12 (0.65)
32.2, 3.0	7.83 (1.25)	2.75 (0.15)	8.60 (1.22)	4.63 (0.68)

Table 7-3. Reduced Thermal Data from PREPA Battery Frequency Regulation Cycling

Test Conditions T(°C), Turnover	End Cells		Center Cells	
	h, Std. Dev. (W/m^2-°C)	Q, Std. Dev. (W)	h, Std. Dev. (W/m^2-°C)	Q, Std. Dev. (W)
Ambient, 2.55	6.40 (0.42)	16.8 (1.6)	5.27 (0.24)	21.0 (1.7)
32.2, 2.55	7.72 (2.02)	20.5 (4.5)	5.48 (1.20)	22.9 (3.6)
32.2, Battery Off	4.47 (0.15)	2.0 (0.7)	3.27 (0.15)	1.9 (0.6)
37.8, 2.55	7.27 (1.13)	19.2 (5.1)	5.28 (0.79)	25.0 (5.3)
37.8, Battery Off	3.67 (0.60)	0 (11.2)	5.47 (0.25)	5.3 (3.2)
Ambient, 3.0	5.55 (0.70)	16.5 (1.4)	4.77 (0.52)	22.7 (3.0)
32.2, 3.0	5.33 (0.83)	13.7 (2.0)	4.87 (0.69)	20.8 (4.8)

Table 7-4. Cell Electrical Resistances Calculated from Fits of the Spinning Reserve Thermal Data

Test Date	Temp (°C)	R (Ohms × 10^6)						
		Cell 2	Cell 3	Cell 5	Cell 7	Cell 8	Cell 10	Average
5/28/93	Ambient	110	150	150	170	130	90	133
1/3/94	Ambient	140	150	140	130	140	150	142
1/7/94	Ambient	110	160	120	130	100	130	125
7/14/93	32.2	**160**	230	150	**190**	**200**	190	190
7/21/93	32.2	**120**	200	**170**	200	**220**	180	193
7/26/93	32.2	150	170	130	170	160	170	158
11/9/93	32.2	120	120	130	150	140	130	132
11/29/93	32.2	130	130	130	150	150	140	138
12/6/93	32.2	120	160	130	130	140	140	137
6/25/93	37.8	110	150	150	190	**10**	130	146
9/15/93	37.8	110	170	130	150	130	110	133

lated from the battery current and voltage data recorded during frequency regulation cycling. Overall, there is very little difference among the average values obtained from tests starting at different chamber temperatures. The noise in earlier data was probably responsible for a trend in resistance with temperature that was originally suggested.

Thermal energy balances were performed for the frequency regulation portion of the tests. The net thermal power can be calculated according to the following equation:

$$Q_{net} = Q_{heater} + Q_{battery} - Q_{air} - Q_{chamber\ wall}$$

Ideally, if the experimental measurements are consistent, the net power should be zero. However, some of the estimates for the terms in the net thermal power equation are only approximate. For example, it has already been noted that the cell thermal power also contains some of the heater thermal power in the elevated temperature tests. In fact, the power balance is better in general for the tests where the heaters were off. Although the calculated net thermal powers were not zero, values found were relatively small compared to the other quantities in the equation, indicating that these estimated powers are generally correct. The model that has been used to analyze these data is a fairly simple one that assumes a single time constant can be used to describe the thermal transient of each cell in the battery. When the variation in the local environment around each cell and the thermal resistance within each cell are large enough, a single time constant is probably not completely adequate to describe the process. This was demonstrated by analyzing a data set with and without the initial hours of data. When this was done, the first parameter, A/B, changed significantly while Q/B remained nearly invariant. Any transients associated with shorter system time constants have died away by the time the truncated data set begins. Unfortunately, the calculated thermal power is a function of both parameters. This demonstrates that some of the scatter seen in our results is due to the approximate nature of the model. That being said, the parameters derived in the analysis are fairly consistent and seem to have reasonable values, so predictions from them should be useful. A more complex model is probably not necessary at this point, and the data needed to determine the parameters are not available.

Finally, a revised prediction of the thermal response of the Puerto Rico battery system has been made and compared to a prediction for the 12-cell string in a test at SNL. The same values have been used for the thermal power produced by the battery during frequency regulation as in the original prediction (20 W), and the same heat-transfer coefficients have also been retained. However, in the spinning reserve part of the test, the Puerto Rico current has been increased to account for the higher battery power projected for the actual operating condition (1867 A) compared to what could be tested for the 12-cell string (1400 A). The time has also been adjusted back to the 15 min at constant power and 15-min linear ramp to zero power that was specified for Puerto Rico. In light of the results of the fits of the recent data sets, the electrical resistance parameter has been reduced to 150×10^{-6} ohms per cell for these simulations. Figure 7-1 shows the resulting temperature plots for both the Puerto Rico facility and the SNL tests. The SNL spinning reserve test simulation has been left at a 1400-A current and with segment lengths of 20 min in order to agree with the way the tests were run in Albuquerque. Temperatures during a 110-hr period of operation in frequency regulation mode remain lower in the Puerto Rico facility simulation because of the increased airflow rate per cell. The temperature increase during the spinning reserve discharge was greater in the Puerto Rico case since the battery electrical power is larger. However, because the time period is shorter and the temperature at the start of the spinning reserve discharge is lower in Puerto Rico, the maximum temperature reached was similar in the two cases. At SNL, the maximum temperature rise predicted was 10.6°C above ambient and at Puerto Rico the corresponding rise was 10.1°C.

This completes the experimental thermal testing and data analysis portion of the project. All of the results have been shown to PREPA and C&D. There has been interest on the part of both PREPA and SNL in validating the predictions of the thermal model once the Puerto Rico battery facility is completely operational. An additional task that remains is to measure the short circuit current on one of the cells. Such a measurement is of interest to PREPA to verify that some of the components in its facility have been sized correctly.

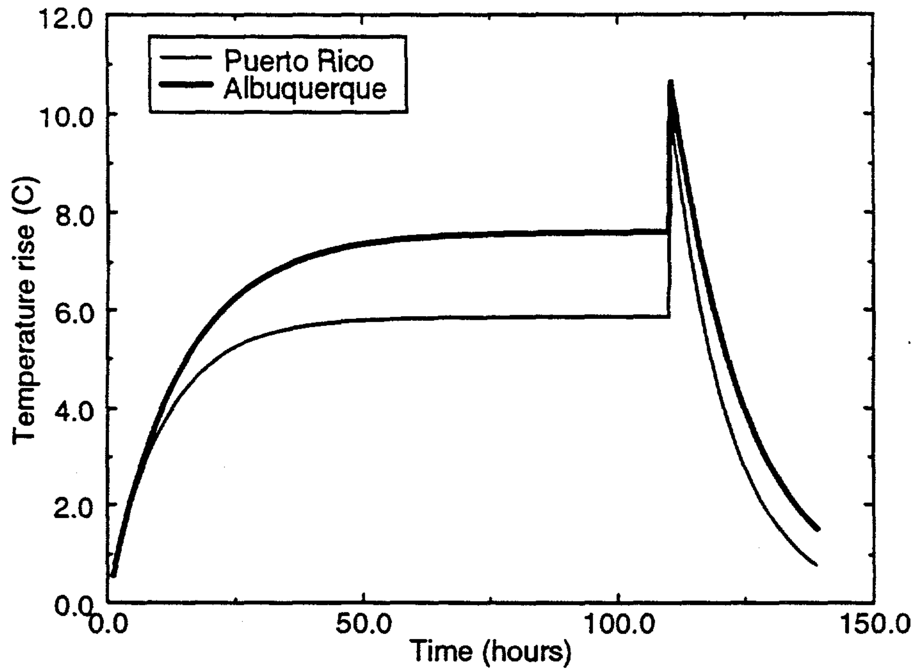


Figure 7-1. Predicted Battery Temperature Rise during a UES Cycle at the Puerto Rico BES Facility and at the SNL Testing Laboratory.

8. Industry Outreach

The Industry Outreach element consists of focused communication to promote interest in battery storage systems in the private sector and to provide forums in which ideas are shared, information is exchanged, and cooperative projects are initiated. These forums create opportunities to leverage limited government and private sector resources to projects that can expedite the early commercial introduction of battery storage systems. The private industry coordination includes utilities, customers, and suppliers.

Multiyear Program Plan

A multiyear program plan titled "Utility Battery Storage Systems Program Plan - FY 1994-1998" was completed and published in February 1994. The 46-page, fully illustrated document examines the past and future role of battery energy storage in the electric utility network, the critical issues in the acceptance of this technology by utilities, and an activity-by-activity description of the UBS program aimed at resolving each of these issues. Each of the five elements of the UBS program, 1) battery systems analysis, 2) subsystems engineering, 3) systems integration, 4) system field evaluation, and 5) industry outreach, are described in detail. The document was the result of an intensive effort by the UBS staff examining every aspect of the existing program against the stated goals and objectives. Consequently, the Plan represents a roadmap for the program activities leading to the realization of the program goals. Drafts of the plan were reviewed internally and by DOE/OEM prior to its final publication.

Since its publication, the Plan has been widely circulated, and several hundred copies have been distributed at conferences and utility expositions where the UBS program was represented.

IEEE T&D Exposition

Under the ongoing industry outreach activities, the UBS was showcased in an IEEE T&D Exposition held in Chicago April 11-14, 1994. This exposition typically focuses on T&D hardware and is used by utility vendors to display a wide range of the latest products. The exposition is held once every 2 yr and draws 10,000 to 12,000 participants, predominantly from the utility industry, during its 1-week duration.

In the past, OEM activities have been displayed at this exposition in a booth rented by the ORNL T&D program. This year, ORNL did not rent a booth; however, the AC Battery Corporation and Delco Remy jointly rented a large booth and offered to share it with the UBS. AC Battery Corporation displayed a complete container and a module, making this the first time that the AC Battery was publicly displayed to such a large audience. The hardware display was supplemented by brochures and background literature describing the system and its capabilities.

In preparation for this exposition, four new brochures were prepared:

1. "Let Batteries Charge Up Your T&D Application," describing three T&D applications of battery energy storage at PG&E, Oglethorpe Power Corporation, and Southern California Edison.
2. "New & Improved Battery Systems for Utility Applications," describing the existing and advanced battery technologies being developed through the UBS.
3. "Utility Battery Storage Systems – Program Overview," a synopsis of the UBS Multi-Year Program Plan.
4. "AC Battery – From Factory to Full Field Operations," illustrating the transportation and installation of the prototype AC Battery container from the factory to the PG&E test site in San Ramon, Califormia.

In addition to these, a UBG brochure was produced highlighting the existence of the group and providing background information on battery systems, their applications, and the utilities making up of its governing Steering Committee. A complete set of the brochures is included in the inside back cover pocket of this report.

These brochures supplemented a full line of posters that were displayed on the booth walls. One poster traced the significant events in the emergence of BES in utility applications, another described the full range of BES applications, and a third described the UBS and its activities. Reply cards were also included to allow the recipient to contact the UBS for additional information about the UBS program and BES technology.

The booth was set up and manned by UBS and Energetics staff through the duration of the exposition. A photo of the booth showing the wall posters is shown in Figure 8-1. Figure 8-2 is a photo of the AC Battery container and the module as it appeared from an adjacent booth. Four hundred brochure packets were handed out, and several response cards were received.

The posters and other material prepared for this exposition were designed for reuse at future conferences and exhibitions as the opportunity arises.

Metlakatla Village Battery Project

Metlakatla Village, situated in southern Alaska, operates a large lumber mill that causes an intermittent spike load on the electric system of the village. The village is supplied primarily by several small hydro units. Since the hydro units cannot respond to the rapid fluctuations caused by the mill operation, the village installed a 3.3-MW diesel unit, which is operated in a lightly loaded condition so that it can pick up the sudden demand from the mill. In this mode, the diesel is loaded to only about 750 kW. The part load diesel operation consumes about 400,000 gallons of fuel annually, at a cost of $360,000. A BES system could readily off-load the diesel and provide not only the ride-through capability but also backup power to the island system.

The UBS identified this project, and detailed presentations on battery technology and applications were made by a joint SNL, GNB, and General Electric (GE) team to the Board of Directors of Metlakatla Power & Light. By installing a battery storage system, the village will benefit from direct fuel cost savings as well as savings related to the maintenance expenses normally incurred in operating large diesel units. The Board requested that GNB prepare a formal proposal for the project. Subsequently, GNB teamed with GE to prepare the proposal for a 1-MW/1.27-MWh BES system that can carry the mill load and allow the village to shut down the diesel. In mid-May, the Metlakatla Village Council voted unanimously to purchase the battery system. However, since the Rural Electrification Association (REA) underwrites the Metlakatla system, the village needs this agency's approval to proceed with the project. The REA has expressed reservations in granting this approval, and DOE and SNL staff met with REA staff to resolve the issues raised by the REA. This meeting was successful in resolving REA concerns

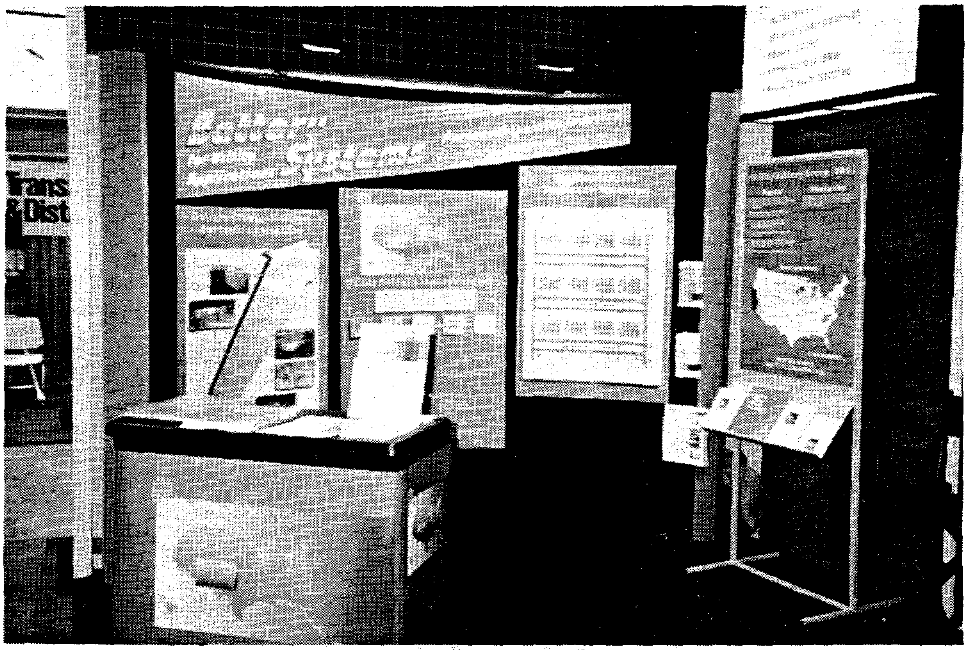


Figure 8-1. Posters at the IEEE T&D Exposition in Chicago Depict History, Program Elements, and Applications of the UBS Program, as well as Information on the Utility Battery Group

Figure 8-2. AC Battery on Display at IEEE T&D Show

about the readiness of the technology and its application. The REA wants DOE/SNL to remain involved in an advisory/support role to Metlakatla Village during the course of the project. At present, Metlakatla Village and the GNB/GE team are negotiating acceptable terms for a contract to purchase the system.

Utility Battery Group

The UBG held its regular biannual meetings in November 1993 in San Ramon, California, and in May 1994 in Dallas, Texas. UBS staff attended the Steering Committee meeting as well as the general meetings.

The San Ramon meeting showcased the newly installed AC Battery prototype at PG&E's MGTF in San Ramon. The prototype unit had recently been delivered to PG&E for testing, and, at the time of the UBG meeting, testing was still in the startup stage.

The Dallas meeting marked an evolutionary milestone for the UBG. At this meeting, the voting members of the Steering Committee passed a resolution allowing nonutility participation in the Steering Committee through an Advisory Group. Until that time, the Steering Committee meetings were open only to the original eight founding utilities of the UBG.

Other Industry Outreach Activities

UBS staff attended and made presentations at the Northeast Electric Utility Battery Conference in Albany, New York. Two presentations were made to the over 125 attendees at this annual meeting, one being an overview of the UBS Program, and another on a recently completed applications analysis done by UBS. Both talks generated many questions, and over 20 requests for more information were received. Of the attendees, more than 24 eastern utilities were represented, with many manufacturers and consultants also present. A key issue raised at the meeting involved the perceived poor reliability of VRLA batteries for utility applications. Since this technology is being developed by UBS for these applications, the perception of poor performance by the industry is significant to future market penetration. Data presented at the meeting will be reviewed and discussed with the UBS lead-acid battery developer to investigate the reliability issue.

DOE/OEM and UBS staff visited PREPA to present the results of the thermal tests performed on the PREPA batteries at SNL and tour the recently completed 20-MW spinning-reserve/frequency-regulation battery system. Other issues discussed during the meeting included the 5th International Battery Conference that will be held in Puerto Rico and hosted by PREPA in July 1995.

At the time of the visit, the battery system was in the startup testing phase. Problems that are normally expected during the startup of a complex facility such as the PREPA battery system were being resolved by both PREPA staff and the subsystem vendors. This battery system was procured on a piecemeal basis and the major components were assembled on-site by the different vendors. Consequently, the predominant problems encountered were in the controls and integration area. PREPA was aggressively pursuing understanding their root causes, and it was evident that, with this experience, future battery systems installed by PREPA will be acquired on a turnkey basis.

Appendix: Presentations and Publications

Presentations

Akhil, A., "Battery Storage Opportunities Analysis Preliminary Report," Seventh Utility Battery Group Meeting, Dallas, Texas, May 1994.

Akhil, A., "Opportunity Analysis for Batteries in Utility Applications," Sixth Utility Battery Group Meeting, Pleasanton, California, November 1993.

Corey, G., "Results of the Power Processing Workshop," Seventh Utility Battery Group Meeting, Dallas, Texas, May 1994.

Corey, G., "Overview of DOE/SNL AC Battery Project," Sixth Utility Battery Group Meeting, Pleasanton, California, November 1993.

Eidler, P., "The Zinc/Bromine Battery for Storage Applications Update," ibid.

Flemming, R., and H. Meyer, "AC Battery Project Status and Plans," ibid.

Jungst, R., "Dynamic Thermal Testing of Lead-Acid Batteries for the PREPA System," ibid.

Norris, B., "AC Battery Test Results," Seventh Utility Battery Group Meeting, Dallas, Texas, May 1994.

Norris, B., "Benefits Analysis of Transportable Battery Systems," Sixth Utility Battery Group Meeting, Pleasanton, California, November 1993.

Publications

Akhil, A., et al., *Battery Energy Storage: A Preliminary Assessment of National Benefits (The Gateway Benefits Study).* Sandia National Laboratories, SAND93-3900, December 1993.

Braithwaite, J.W., and W.L. Auxer, "Sodium Beta Batteries," *Handbook of Batteries*, Chapter 12, McGraw Hill, January 1995.

Butler, P.C., *Utility Battery Storage Systems Program Report for FY93.* Sandia National Laboratories, SAND93-3899, February 1994.

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

McNamee, M., et al., *Sodium Sulfur Battery Development: Core Technology Test and Evaluation Program.* Sandia National Laboratories, SAND94-1029, May 1994.

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