ANALYSIS OF BATTERY STORAGE
FOR
COMMERCIAL BUILDINGS

PHASE 1 FINAL REPORT

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TRW.

ENERGY SYSTEMS GROUP

One Space Park
Redondo Beach, CA 90278

PREPARED FOR THE
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ABSTRACT

The application of battery storage to load leveling by the utility user represents a new concept in energy management. TRW Energy Management Systems Division has studied the possibility of combining an energy management computer/control system with a lead-acid/power processor system and explored the feasibility of demonstrating power management at a government facility. This report presents TRW's findings relating to the selection of a site, the system definition, specifications for the system components and the potential impact on oil consumption at the utility that can be achieved through user load leveling.

Candidate sites in the Washington, D.C. metropolitan area were evaluated by analyzing demand curves for electricity. Several facilities were found suitable, showing short term high peak loads that could readily be handled by energy stored during non-peak load hours. One site, the Department of the Treasury's Bureau of Printing and Engraving is recommended as the best of the sites evaluated.

Analysis using estimated production system costs of \$130/Kw for power processors and \$80/Kwh for lead acid batteries indicates a payback of nine years. However, if the Department of Energy's cost goals for batteries and converters are achieved, a payback in less than four years is possible. Furthermore, coupling battery energy storage with conventional computer based energy management is projected to offer substantial reductions in utility bills. Payback from a production system in less than two years is predicted.

System design is based on using present day technology where possible for the system components. Capacity for the system has been set at 1.1 megawatt-hour with a peak load capability of 600 kilowatts. Preliminary specifications are supplied.

Facility modification and system layout are presented, giving alternate placements for the batteries. Floor loading and system safety are two critical design parameters.

An analysis of the effect of daily load peaks on utility oil consumption completes the report. The use of relatively inefficient peaking generators to meet daytime peak loads uses a disproportionately large amount of oil. Load leveling through transfer of off-hour energy to peak periods offers real oil saving opportunities.

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FOREWORD

The Analysis of Battery Storage for Commercial Buildings Project was conducted under the direction of Mr. William Webster, Program Manager, Division of Energy Storage Systems, United States Department of Energy. At TRW, the Project Director was Mr. Edward Siegel. Other key contributors were Dr. Edgar Jacobi, Dr. Stanley Cohen, Mr. George Kunz, Dr. George Gelb, and Mr. Baruch Berman.

SUMMARY AND CONCLUSIONS

The benefits of a Power Management Battery Storage System (PMBSS) to utilities, ratepayers and the nation include:

- Reduction in required new power generation capacity (utility benefit).
- Curtailment of inefficient peaking usage (utility benefit).
- Decreases in peak demand and energy charges (ratepayers benefit).
- Conservation of oil (national benefit). The magnitude of oil conservation is indicated by the following:
 - Oil consumption by peak-power turbine plants is projected to run from 45-70 million barrels per year in the period of 1980-2000.
 - Oil consumption by all peak-power plants is projected to run from 500-600 million barrels per year in the period of 1980-2000.

In this report, a proof-of-value PMBSS demonstration is defined for the Bureau of Engraving and Printing facility in Washington, D. C. Some reasons for this selection follow:

- The facility has consistent daytime power demand peaks on the order of 1000 KW or greater.
- Monthly peak demand charges to the Bureau are about double what they were two years ago and now make up almost 40 percent of the total bill.
- Engineering data needed for the project is readily available.

Use of deep-discharge traction type lead-acid batteries is recommended because:

- Lead-acid batteries are immediately available.
- Deep-discharge capability is desirable because of the irregular discharge/charge pattern to be experienced and because no economic penalty is associated with the manner of energy extraction. (It is proven that battery capital cost per unit of throughput energy is independent of discharge mode.)

Other conclusions of the report follow:

- Charge control is vital for meeting battery life goals. Further, such control (and other tasks) can best be accomplished by a computer. Accordingly, incorporation of a load management computer into the PMBSS demonstration is recommended.
- Incorporation of uninterruptable power supply (UPS) is also recommended because:
 - Integration of UPS and PMBSS will result in combined capabilities for instantaneous backup power in case of utility failure and for peak demand reduction.
 - Numerous facilities in the U.S. have UPS equipment mainly to provide backup power for computers. The equipment includes storage batteries. Therefore, in many cases, UPS could be economically up-graded to a PMBSS in a program which might follow a successful PMBSS demonstration at the Bureau of Engraving and Printing.
 - The incremental cost of obtaining data on UPS while conducting the PMBSS demonstration is negligible.
- The PMBSS demonstration should not significantly affect the Bureau of Engraving and Printing production schedule.

The demonstration system is specified in some detail. Some of the more important system features are:

- Battery system elements are standard 2-volt cells.
- The system is specified to satisfy:
 - A peak demand of 600 KW for 15 minutes.
 - An energy demand of 1.1 MWhr over six hours of discharge.
- The voltage specification is 227/480VAC $\pm$ 10%, 3 Phase.

Three demonstration system layouts were identified at a specific location within the chosen facility. TRW will select one of these layouts during the next phase.

1.0 INTRODUCTION

1.1 ELECTRIC POWER DEMAND CONTROL AND ENERGY CONSERVATION

Developments in the national energy picture have stressed the need for energy conservation. Rising fuel costs and scarcity of investment capital have placed a burden on utilities which, in turn, is passed on to the user in the form of fuel adjustments and demand charges. In the face of these developments, new systems for energy management are rapidly developing. The Power Management Battery Storage System (PMBSS) program initiated and directed by the Energy Storage Systems Division of the Department of Energy (DOE) is aimed at effective energy management at the user or power consumer level within the user's own facility.

The expected benefits of this program are to:

- Provide a significant reduction in the rate of increase in electrical generation capacity and "spinning reserves."
- Curtail use of inefficient peaking generators. Excess nighttime generating capacity can be used for better utilization of utility capital equipment.
- Reduce consumer's utility charges through reduction in peak demand charges and substitution of less expensive nighttime energy use for daytime consumption.
- Reduce consumption of oil used for peak power generation.

As indicated in the expected benefits outlined above, the combined impact of these energy conserving and demand limiting practices will be felt at the utility level. For example, a concentrated effort at power demand control at the user level can reduce the peak-to-valley swings back at the generation site, particularly if the user leveling is coordinated through time of day pricing. Reducing the peak means less use of peaking equipment: generally that portion of the generating mix having the lowest efficiency and relying on the costliest petroleum distillate fuels, and thus the least attractive generation capacity from the utility's standpoint.

In order to demonstrate the practicality of utilizing battery energy storage for energy management at the consumer level, the DOE Energy Storage Systems Division is sponsoring a two phase demonstration project including installation and testing of a full scale PMBSS at a commercial type building. The purpose of this project is to establish the credibility of power management battery storage as a load leveling, energy conservation method for commercial buildings. Phase I of the project is the analysis phase and is the topic of this report. Phase II is the installation/demonstration phase expected to begin in the fall of 1978.

1.2 THE ROLE OF BATTERY ENERGY STORAGE

We have, for the purpose of this program, taken one means of energy control, that of demand control or demand limiting. Demand control is that control methodology which seeks to constrain the energy consumed in a given period, i.e., the average consumer load power level.

Electric utilities are forced to supply power to their loads at all times. In order to supply that service they must install generating, transmission and distribution equipment capable of handling the power. In order to recover their capital outlays and variable fuel costs necessary to service these power demands, utilities are allowed to impose a demand charge, that is, a charge which is directly related to the maximum user load which occurs during any fixed period - the demand period of a prescribed billing period. Demand charges vary from state to state; sometimes they are regressive - the higher the power demand, the lower the cost per KW consumed. Sometimes the rates reflect the time of day with lower power rates given for nighttime or other off-peak periods. For example, Table 1 (page 22) shows a rate schedule for time-of-day power rates which is being proposed by the Potomac Electric Power Company (PEPCO) for large commercial users in the Washington, D. C. area. In some areas of the country, the highest demand in a preset number of billing periods sets the rate for the next group of periods, the so-called ratchet clause.

There have been and are numerous approaches to controlling demand. Some employ simple time clock systems which turn equipment loads off and on according to duty cycles dependent on time of day or day of week. Others, utilizing analog or simplified digital systems, monitor the

consumption rate during the demand periods and turn equipment on and off based upon limits allowed for the demand periods. Still other load management systems may employ digital computers or microprocessors which monitor demand, predict consumption and take action based upon load priorities and the instantaneous status of individual load conditions through load sensing feedback signals.

In each of these cases, loads are removed (shed) or re-established with the assumption (and indeed in many cases an assumption which must be fine-tuned by actual experience) that productivity and safety are not jeopardized. Therefore, demand control has for the most part been relegated to systems whose interruption normally goes unnoticed by virtue of inherent storage of the controlled system such as the thermal storage of chilled water and distribution ducts of an air conditioning system. In those situations where all sheddable loads are used up and yet the power demand still exceeds a preset value, or if a lower value is to be reached, then other means of supporting the electrical load must be sought. In this case, the use of battery energy storage yields an additional degree of control flexibility in a load management system.

Other benefits of battery storage are evident - protection of critical processes in the event of outages, dual safety system, etc. Also, under certain power conditioning schemes, the use of battery storage can aid power factor correction.

1.3 PURPOSE

The purpose of this report is to present the results of Phase I of the DOE Energy Storage demonstration project which consisted of an analysis of battery storage for commercial buildings. In Phase I we have identified an appropriate site for a PMBSS demonstration. A number of other studies have investigated battery energy storage applications; most of these studies have concentrated on load leveling applications at central generating stations or at substation locations. By contrast, the PMBSS program will demonstrate battery energy storage at the utility customer's facility where lower voltage and power levels are normally experienced. The proposed electrical power level of the PMBSS demonstration can be as high as 600 kilowatts with about one megawatt-hour of

energy capacity. Besides choosing a site, we have identified the appropriate load center within the site which the PMBSS will serve in a demand control mode. Preliminary studies have identified other potential loads (of which air conditioning is a primary candidate) for additional demand control through shedding.

In Phase I we have also prepared a plan for the installation of the PMBSS at the site chosen for the demonstration and have assessed the impact of the adoption of PMBSS systems upon the national patterns of fuel consumption.

1.4 REPORT STRUCTURE

This report is structured in six major sections. The next section summarizes the results of the site selection task of this project*. The third defines the PMBSS system to be installed at the selected site. The fourth section discusses the site facility, design considerations and the resulting requirements of the PMBSS. The fifth discusses facility interfaces, plant changes, and the equipment specifications. The sixth and final section assesses the impact of the adoption of PMBSS systems upon the patterns of fuel consumption.

*Detailed report of Task I is given in "Analysis of Battery Storage for Commercial Buildings, Project Review," (Site Selection), by TRW Systems Group, February 9, 1978.

2.0 SITE SELECTION

The site originally proposed for the PMBSS demonstration was the Government Printing Office (GPO) in Washington, D.C. However, after considerable evaluation the GPO was rejected as a candidate site. A segment of the GPO operation could be adapted for the PMBSS demonstration, but the overall impact would be negative in terms of energy conservation and demand control. By study of the power demand load pattern data of the GPO it was found that large power demand peaks normally occur at night while daytime power demand is high but without significant peaks. The nighttime peaks normally do not affect the utility because overall demand is low. Furthermore, the GPO nighttime peaks rise from such a low base that they do not affect the peak demand charges. Recharging batteries in the daytime to shave the nighttime peaks would worsen the already high daytime demand.

Therefore, TRW contacted the Potomac Electric Power Company (PEPCO) to search the load pattern files of large users in the Washington area to identify more suitable candidates. Several with short term, relatively high demand daytime peaks were identified. TRW recommended selection of the Treasury Department's Bureau of Engraving and Printing located between 14th and 15th streets near D Street Southwest. The selection was made based on the following criteria:

- Large, consistent daytime power demand peaks on the order of 1000 KW or greater.
- No significant changes in the load pattern anticipated in the foreseeable future.
- Facility is convenient to the central D.C. area.
- Engineering data needed for the project is readily available.
- Qualified personnel at the Bureau are interested in supporting the project. Engraving and Printing facilities personnel have previously investigated installation of a computer based energy management system. Sheddable load inventory is available.

A photograph of the Bureau of Engraving and Printing Building is shown in Figure 1. Figure 2 shows a typical summer load pattern for the Bureau; Figure 3 shows a typical winter load pattern. Note the consistency of the daytime peak, nighttime "valley" pattern. Such a pattern is ideal for achieving the maximum benefit from battery storage systems where charging is done at night when electric power demand on the utility is low; discharging to shave the peak is done in the daytime, relieving the high power demand on the utility. Figure 4 shows the electrical power costs paid by the Bureau in recent years. Note the significant increases in the demand charge in the last two summers. The demand charge has more than doubled since FY 1976 while the energy charge has increased less than 30%.

Figure 1 . Bureau of Engraving and Printing

Figure 2. Bureau of Engraving and Printing Electrical Power Demand July 17-22, 1977

Figure 3. Bureau of Engraving and Printing Electrical Power Demand December 11-16, 1977

Figure 4. Bureau of Engraving and Printing
Electrical Power Costs

3.0 SYSTEM DEFINITION

The vast majority of electrical equipment used in the United States operates on 60 Hz alternating current (AC). Batteries, however, are direct current (DC) devices. Therefore, it is necessary to rectify the AC power used to charge the batteries and subsequently to invert the DC power supplied by the batteries to the load. Furthermore, it is necessary to control the amount of power supplied by the batteries and the timing of recharging based on the daily peaks and valleys of the plant load pattern.

Figure 5 shows a total battery/power conditioner/energy management computer schematic. Power flow from the plant power bus is switched by a tie breaker to insure a positive opening of the circuit under extended fault or servicing operations. The bus power flows through one or more coupling transformers to a power conditioner or processor acting as a rectifier during charge and an inverter during discharge. A battery disconnect isolates the DC source from the line. During discharge, the inverter produces a smoothed AC output compatible with the utility power.

The computer receives status information from a number of sources. For example, it monitors the power consumption of the incoming feeder lines to the plant and utilizes that information to institute control programs. Also, it receives status information on the controlled loads in the plant. The computer will issue numerous commands, such as the amount and time scheduling of power drawn from or sent to the battery and/or what and when loads are to be shed.

The power processor control center will be used as an interface between the energy management computer and the power processor. As it receives a command, for example, to send power to the line, it will translate this command into silicone controlled rectifier (SCR) firing signals. During battery charge, it will sense battery status and issue operating signals to the SCR's. The control center will also contain subsystem and logic programs for handling bus, battery and power processor faults as well as start up and shut down sequences.

Figure 5 . PMBS System Schematic

3.1 SYSTEM PAYBACK CALCULATIONS

TRW solicited the assistance of various manufacturers of components and systems that would have application in the proposed PMBSS design. Preliminary versions of system specification were submitted to the manufacturers with a request for quotes for hardware. Quotes were to include engineering, manufacturing and installation costs. Based on the figures received and TRW's estimates for the costs related to setting up and running a demonstration program, a payback analysis has been performed. Results of that analysis are presented in this section.

<u>HARDWARE COSTS</u>	<u>RANGE OF QUOTES</u>
Batteries:	\$100K - 300K
Processor:	\$150K - 400K
Computer:	\$ 20K - 80K
Control Center:	\$ 15K - 35K

The wide range in quotes is due in part to the uncertainty by the manufacturers in meeting specifications that represent new or advanced designs and the problem of mating with another supplier's hardware.

In order to simplify the costing exercise, TRW consulted one supplier who was interested in both the batteries and the processor for a "system" price. That bid came in at \$250K for a 600KW, 1.1 MW-Hr battery/processor combination.

Addition of the remaining components gives a total hardware cost (including engineering and installation) of \$450,000. Demonstration expenses for engineering, data gathering and reporting in a one year demonstration program are estimated to give a total system demonstration cost of \$791,000.

System Benefit

The PMBSS installation will provide dramatic reductions in utility bills through reduction of both demand and energy charges. To estimate the potential savings, we have used the time-of-day rate schedule shown in Table I, supplied by Potomac Electric as an example of the type of rate schedule that utility expects to implement in the near future.

TABLE I. PROPOSED PEPCO RATE SCHEDULE

DC - GT - MC

SCHEDULE OF MONTHLY CHARGES -

	<u>SUMMER MONTHS</u>	<u>WINTER MONTHS</u>
A. Customer Charge	\$120.00 per month	\$120.00 per month
B. Energy Charge		
On Peak Period	0.749¢ per kwhr	0.390¢ per kwhr
Intermediate Period	0.510¢ per kwhr	0.330¢ per kwhr
Off Peak Period	0.211¢ per kwhr	0.211¢ per kwhr
C. Demand Charge		
On Peak Period Billing	\$5.85 per kw	\$3.75 per kw
Demand		
Intermediate Period Billing	\$3.75 per kw	\$2.80 per kw
Demand		
Off Peak Period Billing	\$2.80 per kw	\$2.80 per hw
Demand		
D. Minimum Charge - The Customer Charge		

SEASON DESIGNATION -

SUMMER MONTHS, for purposes of application of this rate schedule, are the billing months of June through October, and WINTER MONTHS are billing months of January through May, plus November and December.

RATING PERIOD -

Weekdays - (Excluding Holidays)

On Peak Period	12:00 Noon	to	8:00 p.m.
Intermediate Period	8:00 a.m.	to	12:00 noon
	and	8:00 p.m.	to 12:00 midnight
Off Peak Period	12:00 midnight	to	8:00 a.m.

Saturdays, Sundays and Holidays

Off Peak Period All Hours

Holidays

New Year's Day, Washington's Birthday, Memorial Day, Independence Day, Labor Day, Columbus Day, Veterans Day, Thanksgiving Day, Christmas Day.

BILLING DEMANDS

The billing demands shall be the maximum 30 minute demands recorded during each rating period of the billing month.

The schedule is typical of the next generation of rate schedules that place a premium on energy use during those periods of the day when demand is highest. This type of schedule is already in effect in Southern California and will be initiated in other parts of the country in the near term.

Demand Savings

The elimination of 600 KW in peak demand through the use of stored battery power generates savings in peak demand charges. Using the appropriate summer and winter rates from Table 1-1:

Summer

$$600 \text{ KW} \times \$5.85/\text{KW} \times 5 \text{ months} = \$17,550$$

Winter

$$600 \text{ KW} \times \$3.75/\text{KW} \times 7 \text{ months} = \underline{\$15,750}$$

$$\text{Total} \quad \$33,300$$

The energy management computer is expected to achieve additional demand control savings through classical load shedding techniques. Based on the equipment complement at the proposed site, 10% of the present peak demand appears to be a reasonable estimate for this application. It is noted that TRW's own experience in industrial load shedding has yielded 10%-30% reduction in peak demand using load shedding techniques.

Summer

$$10\% \times 8600 \text{ KW} \times \$5.85/\text{KW} \times 5 \text{ months} = \$25,200$$

Winter

$$10\% \times 5600 \text{ KW} \times \$3.75/\text{KW} \times 7 \text{ months} = \underline{\$14,700}$$

$$\text{Total} \quad \$39,900$$

Combined savings, using stored power and load shedding:

$$\begin{array}{r} \$33,300 \\ \underline{39,900} \\ \$73,200 \text{ annually} \end{array}$$

Energy Savings

The computer control incorporated in the battery storage system is capable of controlling energy to improve plant efficiency and reduce overall energy use. Industry wide experience with computer based energy control indicates savings of 10% to 30% or more of facility energy is realizable. At the demonstration site, control of chillers, air handlers, lights, air compressors and other loads is estimated to readily save at least 10% of present energy use. Using the present figures for energy consumption, this translates to \$97,000 annually.

Energy Transfer Savings

The rate schedule shown in Table I offers an economic incentive for battery storage of inexpensive nighttime energy for use the following day. Transfer in the summer, according to the schedule would allow substitution of energy priced at 211 mills per kilowatt-hour for energy costing 749 mills per kilowatt-hour. Unfortunately, losses in the system cancel part of the savings. For example, assuming the full 1.1 megawatt-hour capacity of the system was used to offset an equal amount of daytime, on-peak energy.

Cost of energy at on-peak rate:

$$1100 \text{ KW-Hr} \times \$0.00749/\text{KWHr} = \$8.24$$

To supply this amount of energy, assuming a loss of 40% of the energy in the conversion from alternating to direct current for battery charging and subsequent inversion back to alternating current, the energy consumed during the off-peak hours for charging is

$$\frac{1100 \text{ KW-Hr}}{.6} = 1833 \text{ KW-Hr}$$

Cost of this energy at off-peak rate:

$$1833 \text{ KW-Hr} \times \$0.00211 = \$3.87$$

Overall savings for five summer months would be:

$$104 \text{ days} \times (\$8.24 - \$3.87) = \$454.48$$

A similar calculation for the winter months (with the smaller differential between on-peak and off-peak rates) yields the following:

Cost of on-peak energy:

$$1100 \text{ KW-Hr} \times \$0.00390/\text{KW-Hr} = \$4.29$$

Cost for off-peak charging energy:

$$1833 \text{ KW-Hr} \times \$0.00211/\text{KW-Hr} = \$3.87$$

Overall savings for winter months:

$$146 \text{ days} \times (\$4.29 - \$3.87) = \$61.32$$

Total annual savings through energy transfer: \$515.80.

Clearly, demand control savings far outweigh the energy transfer savings of the battery storage system.

Payback on Prototype System

We have reported the estimates in utility bill savings in four categories:

1. Demand savings through stored power substitution.
2. Energy transfer savings.
3. Demand savings through computer controlled load shedding.
4. Energy savings through computer load scheduling and efficiency improvement.

All four are realizable with the system described in the report, but only the first two can be attributed to the presence of an energy storage capability. Since investigation of stored energy for facility energy management is the purpose of the study, it is useful to consider payback from battery storage alone. In a later section, an analysis of the total system energy management payback is performed.

The savings directly attributable to energy storage were calculated to be:

Demand Control	\$33,300
Energy Transfer	<u>500</u>
Total	\$33,800

Costs for the prototype system with a capacity of 1100 kilowatt-hours and 600 kilowatts peak power:

Batteries	\$100,000
Processor	150,000
Computer/control system	50,000
System Design	<u>50,000</u>
Total	\$350,000

If we use a discount rate of 10%, the cost of financing the prototype system (or alternatively, the return from a competing investment) is \$35000/year. Clearly, the \$34000 annual savings is insufficient to produce an economic return.

Payback for Production System

Next we extend the analysis to consider the return using estimated costs for an "off-the-shelf" system. If we eliminate the costs associated with system development and use hardware figures that potential suppliers indicate would be more representative of production systems, system costs are:

Batteries	\$88,000
Processor	78,000
Computer/control system	<u>30,000</u>
Total	\$196,000

Using a discount rate of 10% and the annual savings of \$34,000, system payback is calculated to be nine years. Still not very attractive in terms of the industrial marketplace where a payback of three years or less is usually demanded.

Payback for System Using Optimized Costs

As a final exercise in battery storage payback analysis, using the DOE target figures of \$30/kilowatt-hour for the batteries and \$65/kilowatt for the processor, system costs are:

Batteries: (1100 KW-Hr)(\$30/KW-Hr)	=	\$ 33,000
Processor (600 KW)(\$65/KW)	=	39,000
Computer/control center	=	<u>30,000</u>
Total		\$102,000

At that price and a 10% discount rate, payback is less than four years and moves into the range where industry would be interested in installing a system.

Total Energy Management System Payback

If in addition to the savings produced directly by the battery storage

capability, the energy and demand savings potential of the system is fully tapped, payback is more attractive. Utility bill savings are:

Demand control (batteries)	\$ 33,300
Demand control (computer)	39,900
Energy savings (computer)	97,000
Energy transfer savings (batteries)	<u>500</u>
Total	\$170,700

At that rate of savings and a 10% discount rate, the demonstration system yields a payback in $6\frac{1}{2}$ years while a production system is calculated to have a very attractive payback of $1\frac{1}{4}$ years.

3.2 MARKET POTENTIAL

The payback calculations suggest limited prospects for battery storage in energy management in and of itself. When coupled with a total energy management system, the prospects are much brighter.

In our discussion with battery/power processor suppliers, an untapped market for demand control using battery storage became evident. At the present time there are thousands of uninterruptible power systems (UPS) installed nationwide. These systems are used primarily to prevent catastrophic effects resulting from utility power failures. The cost of these systems is justified by the potential economic loss they prevent should there be a utility interruption.

UPS systems contain most of the hardware needed for the battery storage system described in this report. In fact, the designs submitted by potential suppliers were based on modifications to the UPS they are building now.

By increasing the capacity of present UPS systems and adding a computer control system, the owners of UPS systems can convert their systems from expensive "insurance policies" against power failures to demand control systems that will yield annual savings in utilities bills as well as protecting against the effects of power interruptions.

4.0 REQUIREMENTS

While there are a number of advanced battery systems under development which promise to better lead-acid batteries in terms of life cycle costs, uncertainty in their achieving commercialization and low cost in the near future forced us to concentrate solely on the well-developed lead-acid system*. This section, among other things, provides the technical basis for accounting for the economy of operation of lead-acid batteries within the context of a battery energy storage system.

A cursory evaluation of industrial power usage schedules shows that power demand up to 3 MW would satisfy a large number of industrial users. Load management, i.e., load shedding systems, generally reduces no more than 20% of the electrical demand and thus a storage system at least equivalent in power to the loads shed appears reasonable. A stored power level of 600 KW meets this criterion in a large number of cases.

In terms of load duration the selection is more site specific. Peak demand periods vary from location to location ranging from 15 minutes to 1 hour or more. An installation may have two or more peak power usage periods during the day, for example, mid-morning and mid-afternoon peaks.

Two worst case load duration profiles from the Bureau of Engraving and Printing are discussed below: (1) a maximum peak power occurrence, (2) a maximum total energy (KW hr) occurrence.

Figure 6 shows a load profile for a one-week period in November 1977. On the third day of the week, the maximum peak occurred. As shown in more detail in Figure 7, this peak increased by almost 800 KW above the 6170 KW cutoff line in the half-hour between 13:45 and 14:15. The PMBSS will be required to respond to peak power demands such as this.

*For a thorough review, see Storage Batteries by Vinal, G. W., John Wiley and Sons.

Figure 6 . Maximum Power Peak Profile

Figure : 7 . Detail of Maximum Power Peak Profile

The power management computer continuously monitors connected load in the facility and predicts what the average power demand will be in the next demand interval. When the prediction exceeds the cut off level selected by the operator, stored power will be used to limit the peak demand. If sufficient energy is available, the load curve will follow the cut off line, chopping off the peak load that the utility must supply.

Figure 8 shows a four-day load profile from August 1977. The maximum total energy supply profile occurred on the fourth day (August 10, 1977). The detail of the maximum energy profile is shown in Figure 9. In this instance the PMBSS must supply power at varying levels for about 2-1/2 hours in the morning and for another two hours in the afternoon. It is unlikely that the Bureau would recharge during the lunch hour because of the possibility of causing a demand peak. Therefore, the PMBSS would have to store sufficient energy for the entire day's peak shaving operation.

Figures 6 and 8 show a proposed charge cutoff power level which is about 1 MW below the discharge cutoff level. The proposed charge cutoff level was chosen to preclude a peak demand caused by the PMBSS. Therefore, charging could occur in the time periods shown in Figures 6 and 8, for example. During the intervals shown, a minimum of 3.2 MW-hours of charging energy is available.

4.1 FACILITY ELECTRICAL CHARACTERISTICS

Figure 10 shows the electrical power distribution schematic for the Bureau of Engraving and Printing building. Power is supplied by the Potomac Electric Power Company (PEPCO) at 13.2 KV, 3 Phase through four feeders numbered 15620, 15621, 15623, and 15624 in Figure 10. A single KW hour meter monitors all four feeders. All of the power apparatus shown in Figure 10 is owned by the Bureau with the exception of the current and potential transformers on each feeder for metering.

The load which will be shared by the PMBSS is the pump room equipment connection shown by the arrow at the bottom center in Figure 10. Actually, there are air compressors as well as pumps which make up this load. Hence, personnel at the Bureau refer to this room as the power plant rather than the pump room.

Figure 8 . Maximum Energy Supply Profile

Figure 9 . Detail of Maximum Energy Profile

The power plant load normally receives its power in parallel from feeders D3 and A6 connected to incoming feeders No. 15620 and No. 15624. This power is fed through two 1000 KVA transformers stepping the voltage down to 277/480V from 13.2 KV.

Figure 11 shows more detail of the transformer/circuit breaker system which feeds the power plant load. Figure 12 shows the 480 V metal clad switchgear distribution center which supplies power to the various pumps and compressors. Figure 13 is a wiring diagram for miscellaneous motors in the power plant.

As Figure 12 shows, the largest part of the load consists of a set of compressors;

- 450 hp centrifugal (Ingersoll-Rand)
- 250 hp reciprocating (Joy Mfg.)
- (2) 125 hp reciprocating (Joy Mfg.)

These compressors supply various air operated devices on the Bureau's printing presses. The 450 hp unit operates primarily during the day shift while the 250 hp unit is used during the night shift. The two 125 hp units' primary purpose is for standby in case of failure of the 450 and 250 hp units. It should be noted that the two 125 hp units are driven by synchronous motors. Although power factor control (correction) does not appear to be a problem with this load at the present time, these synchronous motors could be used for power factor correction by over-excitation of their field windings.

Other significant connected loads are the cooling tower pumps fed through a motor control panel (MCP) and house booster pumps fed through power panel PR-480-A. As indicated in Figure 12 much of the connected load is normally in the standby mode. However, the total potential connected load is just under 1500 KW. About two-thirds of the total potential connected load is made up by the four air compressors.

Figure 14 shows a recording chart of the line current of one of the phases of power flow into the power plant. The date of the recording is February 22, 1978. The recording was taken to learn about the magnitude and variation of the power demand of the power plant. Actually,

Figure 11. Step Down Transformers and Protection Gear

Figure 12 . Metal Clad Switchgear and Major Connected Loads

Figure 13 . Power Panels for Miscellaneous Motors

Figure 14 . Power Plant Current

several successive 24 hour periods of current data recording was done. The data shown in Figure 14 is that for the beginning of a 12 hour daytime period typical of period for which the PMBSS will be supplying power to this load.

In Figure 14 , note the inrush current which occurs at the time of startup of the 450 hp compressor at 6:40 AM. This inrush is approximately 2750 A at the peak. After the inrush the current settles to about 850 A, but then increases to 1000 A at 9 AM. As Figures 15 and 16 show, the line current holds at 1000 A until the end of the day shift at 4:15 PM, with a short dip to 850 A between 3:00 and 3:40 PM. After that the 450 hp compressor shuts down and the 250 hp compressor starts up with an inrush current of about 1500 A. The sawtooth shaped trace after 4:15 PM indicates the on-off operating mode of a reciprocating compressor.

The apparent power during the day shift with the 1000 A current draw is approximately 830 KVA. Assuming a power factor of 0.8, the real power is about 660 KW. Thus, on this particular day, the PMBSS could have shaved 660 KW from the overall facility power demand during peak periods assuming it supplies power only to the power plant load.

A significant factor affecting the design of the PMBSS is the large inrush current at the time of startup of the 450 hp compressor. Although this startup usually occurs before peak demand periods occur in the rest of the facility, it may be necessary for the PMBSS in parallel with the utility to accomodate this startup transient occasionally. Therefore, it was necessary to seek information on the voltage "droop" of the utility supplied power on the low voltage side of transformers in Figure 11.

A test was conducted at the 480 V switchgear to find the extent of the voltage droop. The test was conducted using a high speed Honeywell Visicorder, at various instrument recording speeds and gains to optimize the readability of the resultant data. Because the input terminals of the recorder are limited to 300 VAC, a small, control circuit-type transformer (.05 KVA, 480/120 V) was connected to the starter bus, and the recorder was connected to the control transformer secondary.

Nominal bus voltage as recorded at the control transformer secondary was 307 volts, peak-to-peak. Three starts of the compressor were

Figure 15 . Power Plant Current

Figure 16. Power Plant Current

accomplished with the Visicorder connected as previously described. The results of test No. 1 were unfortunately destroyed by a malfunction in the paper rewind mechanism. Test No. 2 showed a drop to 298 volts (2.9%) for 8.8 seconds during the autotransformer starting stage. When the motor starter circuit switched from autotransformer to across-the-line, voltage dropped to 278 volts (9.4%) with exponential recovery for 2.7 seconds. Final steady-state voltage was, however, only 302 volts as compared to the original 307 volts.

Test No. 3 results were similar. Voltage dropped to 297 volts with the autotransformer in for 7.9 seconds. When the motor switched to across-the-line, a drop to 281 volts (8.5%) was measured with an exponential recovery for 3.1 seconds to a final voltage of 302 volts.

The changes in readings between the tests can be attributed to the progressive heating of the motor windings, increasing the impedance of the motor and thus limiting inrush. Test No. 1 could have shown the greatest voltage drop (probably 11%) since the windings would have been cold at that time.

Figure 17 shows a schematic diagram of the grounding for the power distribution system at the Bureau. As shown at the lower left in Figure 17, there is a 5 OHM ground well beneath the incoming main switchgear room. All of the 13.2 KV switchgear line-ups are tied to this ground. All secondary substation grounds throughout the Bureau are tied to the 13.2 KV line-up ground. That includes the 480 volt substation on the second floor that feeds the metal-clad switchgear in the power plant. The ground wires are carried internally in the 13.2 KV armor-clad which feeds the high voltage side of the secondary substations. The size of this ground wire is generally about #1/0. The aforementioned ground well is also connected to the main incoming water line and several building columns by cadwelded bare copper conductors of sizes ranging from 500 MCM to #4/0.

The linear distance from the ground well to the power plant metal-clad gear along the ground wire path is approximately 600 ft. The power plant metal-clad gear is, however, only 50 ft. from the water main which is also tied to the ground well but by a considerably shorter conductor length. The power plant gear appears to be sufficiently grounded for our

Figure 17. Facility Power Grounding

purposes, however, a good insurance measure would be to run a length of bare copper #1/0 from the water main to the power plant gear to complete the network. This proposed ground connection is shown dotted in Figure 17.

4.2 FACILITY MECHANICAL CHARACTERISTICS

Following the selection and approval of the Bureau of Engraving and Printing as the best of the sites evaluated for the installation of a PMBSS, TRW personnel inspected the site. Figure 18 shows a drawing of the selected area, located in the basement of the Bureau's main building. A discussion was held with the responsible managers and engineers concerning the installation aspects of the PMBSS demonstration project. The selected area, situated along the west side of the main building, has the following approximate dimensions: length 65 feet; width 45 feet; height 15 feet, but restricted in certain places due to overhead ducting. At present, this area is partially occupied by the "Bindery Section."

The entrance (two doors) is on the east side, from a hallway with access to elevators. The north end leads to a large vault and must be kept open. The west side has several large windows towards 15th Street interrupted by triangular shaped columns. Alongside the columns and windows runs a 2.5-foot wide covered channel, for piping and cabling, and must be left accessible. On the south side, a wall separates the area from the power plant. Within the "Bindery" area, there are eight square supporting columns approximately 18x18 inches. The floor is of concrete construction, six inches thick and allows a load of maximum 250 lbs/ft².

Figures 19 through 22 are photographs of some of the equipment which make up the power plant load. Figure 19 is a photograph of the 450 hp centrifugal compressor and its associated control panel in the power plant. Figure 20 shows the 250 hp reciprocating compressor and associated controls. Figure 21 shows the incoming main water lines at the right with the house water pressure booster pumps. Figure 22 shows the 480 V switchgear distribution center for the power plant. The physical connection of the PMBSS to the load will be made at a bus within this center.

4.3 BATTERY CHARACTERISTICS

Lead-acid batteries can be broadly classified according to one of three categories: automotive or SLI (starting, lighting and ignition);

BUREAU OF ENGRAVING AND PRINTING -
Main Building Basement, Northend and Southend Main Section

Figure 18. Plan View of Area for Installation of PBMS

Figure 19. 450 hp Centrifugal Compressor

Figure 20. 250 hp Reciprocating Compressor

Figure 21. House Water Booster Pumps

Figure 22. 480V Metal Clad Distribution Center

industrial (fork lift trucks, etc.); and stationary (communication service such as telephone). Stationary batteries are designed for very long service – up to 20 years on continuous, constant float charge. They are meant to discharge only a few times during that period in the event of power failure. Thus they are designed to have very limited deep discharge cycle performance. Stationary lead-acid cells are built with relatively soft lead-alloy grids which minimize corrosion, but do not allow for severe environmental service such as vibration or a wide range of ambient temperatures.

A comparison of SLI and industrial batteries can be found in Table II . SLI batteries are designed to provide short bursts of discharge power while the engine is cranking followed by moderately long recharge periods as the vehicle proceeds. Their depth of discharge between recharge events is usually very shallow – less than 10% of the rated capacity (ampere-hours) of the battery. Since these batteries are for mobile use, they must be light, compact, vibration resistant and able to withstand underhood temperatures from well below 0°F to over 150°F.

The pasted plate SLI battery has evolved to a point where lifetimes of 150-200 cycles at 100% rated capacity discharge are possible. Service lives above five years in automotive applications are attainable given reasonable maintenance and proper voltage regulator operation. Since nearly 50 million SLI batteries are produced in the U.S. every year, their production is highly evolved and they have the lowest cost per KWH of any lead-acid type.

Industrial or motive (traction) type lead-acid batteries are normally used in fork lifts, mine cars, submarines and other traction applications where the discharge energy must be maximized to give good range. In many cases, the batteries are used as counterweights or ballast and, therefore, packaging volume is more important than weight.

Traction battery cells are designed for a large number of deep discharges by resorting to more costly methods of separator design, deep sediment walls, heavy grids and heavy steel cases. Presently available industrial batteries are capable of discharging 90% of their rated

TABLE II. LEAD-ACID BATTERIES CHARACTERISTICS

	<u>AUTOMOTIVE</u> ¹	<u>INDUSTRIAL</u> ²
Nom. Operating Voltage, V	1.98	1.94
Capacity Available, A h	33 - 340	180 - 2175
Nom. End of Charge Voltage, V	2.53	2.55 - 2.65
Recom. Charge Rate	>C/20	22.5A/100 A h cap.
Recom. Overcharge (%)	5 - 40	5 - 15
Watt hr/lb	12.7 - 21.8	8.56 - 11.0
Watt hr/cu in.	0.79 - 1.6	1.08 - 1.37
Impedance (ohms)	0.0010 - 0.0024	-
Cycle Life (100% d.o.d.)	150 - 250	1000 - 2000

¹Automotive rated at 20 hr rate

²Rated at 6 hr rate

capacity as much as 2,000 times. For a normal eight hour work shift, service lives of 7-10 years are common. The traction type lead-acid battery is readily adaptable to the type of service required in a peak shaving application and is, therefore, recommended for the PMBSS demonstration.

The capital cost of a lead-acid battery is directly related to the amount of lead used in the battery as the latter determines the theoretical energy capacity. On the other hand, the service life of the battery in terms of the number of cycles to failure is roughly inversely proportional to the depth of discharge as shown in Figure 23 . However, shallow discharge means poor utilization of the lead, i.e., the capital costs are not being fully utilized during each discharge.

A battery which has a large excess capacity or is used only in shallow discharge service will have a larger number of cycles to failure than a battery with limited excess capacity or operated on deep discharge. Further, if the discharge period is held constant for each of these batteries, the battery with the excess capacity will have a higher average voltage during discharge. The ability of a battery to provide good voltage regulation is important in consideration of interfacing power processing equipment.

The major portion of the lead inventory in a battery is contained as active electrochemical materials on the plates. The plate grids, which act as current collectors and a substrate for retaining the active materials, may account for almost 50% of the total lead weight; the weight ratio between active materials and grid depends on a number of parameters such as design depth of discharge, operating temperature and discharge rate. As the ratios change, lead utilization and plate cycle life also change.

Utilization — the amount of charge or ampere hours removed to the theoretical availability of electrochemical charge — is a function of current density or rate of discharge, and temperature. The discharge capacity, C , that is, the number of ampere-hours which can be withdrawn to some prescribed voltage is given by:

$$C = f(Ti^m)$$

Figure 23. Cycle Life for Typical Industrial Motive Power Battery

where T is the temperature and i is the current density. For example, in typical SLI plates, 35% of the theoretical capacity at 25°C (77°F) can be withdrawn at 50 mA/cm^2 (322.6 mA/in^2) but only 25% can be obtained if the current is raised to 240 mA/cm^2 (1548.4 mA/in^2). If the temperature increases from 25°C (77°F) to 50°C (122°F), the capacity at constant current drain increases by about 7%.

Cycle life is also affected by temperature, current density, overcharging, as well as, depth of discharge. Temperature has the strongest effect next to depth of discharge and must be controlled to insure good service life. Ignoring the temperature effect, the relationship between cycle life and depth of discharge has been found to be logarithmic. For example, Figure 23 shows the relationship for a traction-battery which might be considered for this application.

Cell voltage during discharge can be described by the empirical relationship as suggested by Shephard.

$$E = E_0 - K\left(\frac{Q}{Q-it}\right)i - Ri$$

where:

E_0 = the open cell voltage (charged)

Q = the rated capacity of the cell

i = the current density

t = the total time of discharge

R = the resistance

K = a constant of proportionality.

The rate of discharge or current density and the time of discharge to a specific voltage is usually expressed by the Peukert equation:

$$i^m t = \text{const.}$$

Figure 24 shows the terminal voltage versus time of discharge for several discharge rates. The shape of the constant current discharge trajectories would be given by Shephard's equation, while the relationship between the time to cut-off voltage and current follows according to the Peukert equation.

Figure 24. Discharge Characteristics and Energy Output of Typical Lead-Acid Battery

If we combine the ideas introduced above, we can establish a relationship between the throughput of energy, i.e., the total energy delivered by the battery in the course of its discharging over the number of cycles corresponding to end of cycle life, and the initial cost of the battery. This exercise produces the interesting result that the capital cost per unit of throughput energy is independent of the manner in which energy is extracted. The logic behind this conclusion is given in the appendix. This further supports our recommendation that a deep discharge traction battery can be easily adapted to the peak shaving application.

4.4 OTHER CONSIDERATIONS FOR LEAD-ACID BATTERY ENERGY STORAGE SYSTEMS

4.4.1 Charge Control

The life of a lead-acid battery is highly dependent on the method of charging. Although lead-acid batteries may be charged at very high rates, i.e., 10 to 20 times their ampere-hour capacity, no manufacturer would normally recommend this type of charging except in emergency circumstances. High charge rates, in this case greater than the ampere-hour rating, result in low charging efficiency because much of the current goes into parasitic losses such as grid corrosion and gas production, and much of the energy delivered to the battery terminals is dissipated as heat in various forms of polarization. Poor charging procedures also result in active material shedding because high charge rates give rise to poor adhesion of the active material to the plates. Maintenance, in terms of watering, is also increased.

The battery industry generally recommends charging at moderate rates up to the gassing voltage. The charge rate is then reduced to the so-called finishing rate where approximately 5-15% over charge (excess ampere-hours) are delivered at constant voltage. Most industrial chargers accomplish this by a combination of constant current charge up to gassing and then a switch to constant voltage for a specific time period. A typical charge control characteristic for an industrial traction battery is given in Figure 25.

It should be recognized that industrial load management such as at the Bureau usually does not allow for either well-defined discharge powers or periods, nor are the recharge periods as regular as one might wish.

The following table shows the typical charge control characteristics for a traction battery. The table is divided into two main sections: "Normal Charge" and "Fast Charge". Each section contains a list of parameters and their typical values.

Parameter	Normal Charge	Fast Charge
Charge Rate (Amps)	0.1 C	0.5 C
Charge Voltage (V)	2.30 - 2.40	2.40 - 2.50
Charge Time (Hours)	10 - 12	2 - 3
Temperature (°C)	20 - 30	20 - 30
State of Charge (%)	80 - 90	50 - 60

Figure 25. Typical Charge Control Characteristics for Traction Battery

Therefore, it is important to utilize the program control, logic, and memory capabilities of the load management computer to track the status of the battery and to perform recharge when and if possible, taking into account the local past history of the battery.

4.4.2 Temperature and Gassing Control

Previous sections have indicated the effect of temperature on cell performance and life. Gassing, the result of overcharge potentials and corrosion, leads to loss in water and the buildup of explosive gases (hydrogen). There is ample evidence that industrial traction batteries in load management service can adequately cope with either problem.

Studies have been performed on the temperature rise and heat transfer from large industrial batteries to be used in substation load leveling situations. In no case was the need for external forced convection cooling indicated as long as space was left between battery containers to allow for natural convection cooling.

The liberation of explosive gases can be minimized by proper charge control. For the small hydrogen production which will always occur, catalytic vent caps are available to prevent the external release of gas.

4.4.3 Electrolyte Management

Localized electrolyte depletion or concentration may develop in large lead-acid batteries, particularly in those where dense separators and fiber mats are used to retain active materials. Concentration and thermal gradients can, under favorable circumstances, be used to aid in electrolyte homogenization; however, to insure good mixing, modern long-life installations may employ other means. The most favored appears to be an airlift type of system where air bubbles are released at the bottom of the cells and their stirring motion as they rise to the top of the cell distributes the bulk electrolyte. The stirring action also aids in transfer of heat from plates to electrolyte. Airlift systems are common and were recommended for EPRI's BEST Facility.

Hydrogen evolution means loss of electrolyte water and the need for electrolyte level checks. In large installations as envisioned here, the number of cells in series-parallel connection may be several hundred. Automatic watering systems which maintain a constant liquid height may be

necessary. Other maintenance procedures will involve periodic cleaning of battery terminals to rid accumulation of moisture and acid bearing dust and dirt, checking for leaks, checking for proper grounds, and signs of external corrosion on the batteries or support structures.

4.5 POWER PROCESSOR

Figure 26 shows a simplified single line diagram of the necessary components of the power processor and the proposed connection relative to the PEPCO supply and the Bureau's power plant load. When the batteries are being charged during off peak hours, power flows from PEPCO through the rectifier to the batteries. At the times when peaks are to be shaved, power will flow from the batteries through the inverter to the load in parallel with the PEPCO supply. The amount of power supplied by the battery/inverter combination will be determined by the load management computer which will cause the inverter to lead the voltage phase of PEPCO sufficiently to supply the desired amount of current from the inverter.

Other equipment needed for smooth, stable operation of the power processor includes transformers, interphase reactors, and filters. This is shown in the block diagram of Figure 27. The size and cost of harmonic filtering equipment can be minimized by using a high order (e.g., 12) step wave inverter with first harmonic the 11th. The envelope dimensions for the power processor module containing the rectifier, inverter, and the auxiliary equipment is shown in Figure 28. Two modules with these approximate dimensions will be needed for the PMBSS demonstration. The most critical component in the power processor is the inverter because it must supply AC power to the load in a manner not to upset either the operation of the parallel utility power supply or the operation of the equipment making up the load.

4.5.1 Inverter

The inverter is made up of thyristors (SCR's) operated to form two conventional 12 step waves with first harmonic the 11th. The two 12 step waves are operated at variable phase displacement from one another, and the resulting waves are combined to produce a three phase output wave whose amplitude is controlled by the value of the relative phase displacement.

Figure 26 . Simplified Single Line Diagram for Power Processor

Figure 27 . Power Processor Auxiliaries

Figure 28 Power Processor

The SCR's are controlled by a digital logic control. This digital control precisely determines the firing of each SCR based on a digital voltage command. Current control logic is also a part of this digital control.

The connection of the power components is as shown in Figure 29. The schematic shown in Figure 29 illustrates the power stage configuration of a typical 12 stepped wave inverter. The SCR's are arranged in four three phase bridge inverters. Within each three phase bridge the thyristors are fired at precisely 120° intervals. The two bridges associated with an output transformer are operated at variable phase with respect to one another, so that the voltage appearing on each transformer primary is a quasi-square wave of variable pulse width. The SCR's associated with transformer T2 are each fired at exactly 30° after the corresponding SCR in the set of SCR's connected to transformer T1. The secondaries of the two transformers are combined in a zig-zag connection to construct a line-to-line voltage waveform of the desired step heights and times.

The power filter consists of a series inductance and parallel capacitance to attenuate the 11th, 13th, and higher harmonics. The series inductance is composed of the leakage reactance of the transformer and a small lumped reactance in each phase.

The normal output waveform of this inverter is shown in Figure 30 which illustrates normal line-to-line output.

Consideration was given to the use of uninterruptible power supplies (UPS) for this type of service. In an UPS, the batteries are charged and maintained on float until there is an interruption of power from the utility link. At that time, the UPS transfers the power flow to discharge the battery by inversion of DC power to AC line frequency. In most UPS applications, this power transfer and frequency synchronization must be accomplished within a few cycles of the line failure. Since the AC service is lost, the UPS must also be capable of self-commutating, that is, it must provide its own means to turning off the inverter SCR's. During charging of the battery, typical UPS systems have separate rectifier sections and provide recharge and float charge control similar to other industrial chargers.

Figure 29. 12 Step Wave Inverter Schematic

Figure 30. Inverter Output Waveform

For energy management control, the line will always be present and during discharge the inverter can rely upon the line for synchronization. Further analysis and examination of self-commutation schemes showed that there would be major benefits by self-commutation; not only would the energy storage power processor be able to provide emergency stand-alone power but the processor could provide some power factor control by controlling the firing of the inverter elements relative to the line. Based on these considerations, it is recommended that maximum use be made of the UPS technology and hardware in the PMBSS demonstration.

4.6 BATTERY REQUIREMENTS

The following requirements are to be met with a lead-acid battery subsystem capable of being developed and/or modified for installation at the Bureau of Engraving and Printing. The battery subsystem will be installed in a power management system which, under computer control, is capable of either discharging through a controllable inverter to a 480 VAC distribution system, or delivering charging power at controlled rates from the same 480 VAC distribution system.

4.6.1 Discharge Power and Energy Requirements

Two conditions of discharge have been established to which the battery subsystem must be capable of responding.

4.6.1.1 Power Requirements

The maximum design power profile delivered at the distribution interface is shown in Figure 31. A peak power of 600 KW is required for 15 minutes. For computation purposes, the interconnected power processor may be considered to have the efficiency characteristics shown in Figure 32.

4.6.1.2 Energy Requirements

The maximum design energy profile delivered at the distribution interface is shown in Figure 33. A total of 1.1 MW-hrs is required over a six-hour discharge period. The interconnected power processor may be considered to have the efficiency characteristics shown in Figure 32.

4.6.2 Charge Power and Energy Considerations

During weekday operation, the available distribution system charging power and charging time is shown in Figure 34. It must be assumed that

Figure 31. Distribution Line Load Demand - Maximum Power Profile

Figure 32. Power Processor Efficiency*

*
$$\frac{\text{Output Power of Processor, Either Direction}}{\text{Input Power to Processor}}$$

Figure 33. Distribution Line Load Demand - Maximum Energy Profile

Figure 34. Charging Power Available from Distribution Line

the charging period can begin immediately after the termination of the maximum energy discharge period. Efficiency of the interconnected charging power processor is as shown in Figure 32.

During weekend periods, charging power is available for 56 continuous hours. The available charging power from the distribution system is the same as the maximum level shown in Figure 34. Interconnected power processor efficiency values shown in Figure 32 are to be used.

4.6.3 Discharge Duty Cycles

The battery shall be capable of discharging once per day for five workdays according to:

1. Discharges of the type in Section 4.6.1, or:
2. Discharges of the type in Section 4.6.2, or:
3. Alternating discharges of the types in Sections 4.6.1 and 4.6.2, consisting of three types 4.6.2 and two of the type 4.6.1.

4.6.4 Battery Voltage

The minimum allowable battery voltage on discharge is to be 360 volts. The maximum allowable battery voltage on charge is limited to 600 volts.

4.6.5 Site Considerations

4.6.5.1. Physical Constraints

The battery will be situated on the floor plan area(s) defined in Section 5.0. Crane or forklift equipment will be provided.

4.6.5.2 Safety Considerations

All cells should be equipped with flame arrestors and electrolyte mist suppressors. Estimations of hydrogen evolution rates and total hydrogen evolved per charge cycle should be made.

4.6.5.3 Ambient Atmosphere

The battery will be housed in a dry, ventilated, quasi-constant temperature area. Ambient temperatures from 55°F to 85°F are expected.

4.6.6 Battery Life

A battery life in excess of five years, with the weekday cycle defined in Section 4.6.3 is required. A work year consists of 52 weeks.

4.7 POWER PROCESSOR REQUIREMENTS

The following requirements are to be met by a bilateral power processor capable of being developed and/or modified for installation at the Bureau of Engraving and Printing.

The power processor is an integral portion of the energy management system. It includes those components and subsystems needed to interconnect the power distribution line and the battery subsystem. The processor receives commands from an on-site computer as to the sense and magnitude of desired power flow through the processor.

4.7.1 General Considerations

The processor shall be designed to meet the following requirements and goals:

4.7.1.1 Location and Operating Environment

Equipment will be housed inside protected building. The installation site will be dry; ambient air temperature will range from 55°F to 85°F. The design enclosure should be of an indoor, metal-clad type (NEMA 12).

4.7.1.2 Maintenance

The converter design must be easily maintained (i.e., its components and subsystems must be accessible), and required maintenance must be held to a minimum. Maintenance requirements should be appropriately balanced with equipment costs and reliability.

4.7.1.3 Acoustic Noise

In operation, the equipment must meet all applicable NEMA, ANSI, OSHA, IEEE, etc., standards for acceptable noise levels.

4.7.1.4 Safety

Same as Acoustic Noise above.

4.7.1.5 Modularity

Modularity is encouraged to enhance economy and reduce repair time.

4.7.1.6 Life

The expected life of the electrical power processor equipment must be 20 years or more.

4.7.1.7 Power Rating Base

The power base used for rating the equipment should be: (1) the peak discharge power at minimum battery voltage and, (2) the peak charging power at maximum battery voltage.

4.7.1.8 Design Load Profiles

4.7.1.8.1 Discharge

Figures 31 and 33 represent design discharge power profiles for the installation. In Figure 30, the maximum power delivered to the distribution system is 600 KW for 15 minutes.

4.7.1.8.2 Charge

Figure 34 represents the profile of available distribution line power which might be used to charge the battery subsystem.

4.7.2 Electrical Considerations

4.7.2.1 DC Voltage Range

The ratio of minimum to maximum battery voltage during operation will be 0.6, corresponding to maximum discharge and maximum charge conditions. The maximum battery voltage will be limited at 600 VDC; the minimum voltage will be 360 VDC.

4.7.2.2 AC Voltage

The processor will operate into a 3 $\emptyset$, 480 V 60 Hz distribution system. Voltage excursions from +10% to -10% of the nominal voltage are to be expected in normal, steady state operation.

4.7.2.3 AC Voltage Transient

Operation without interruption is required under +20% distribution line voltage transients of five cycles duration.

4.7.2.4 AC Voltage Unbalance

Phase-to-phase voltage unbalances on the AC system not exceeding 3% are to be expected. The processor must operate into such an unbalanced system.

4.7.3 Power Processor Performance

4.7.3.1 Power Rating

The processor must be capable of covering a range of output power levels from zero to 800 KW at power factors of ± 0.90 , at the maximum and minimum battery voltages discussed above. Charge and discharge power ratings should be equal.

4.7.3.2 Processor Frequency

Synchronized with the utility.

4.7.3.3 Power Factor Correction (PFC)

Dynamic PFC should be supplied so as to control the power factor of the power processor at the AC side of the transformer to a level no worse than 0.95 lagging. Leading power factor operating capability is desirable; near-unity power factor operating is preferred, unless such a feature interferes with attainment of other goals (e.g., cost).

4.7.3.4 Efficiency

Ninety-five percent conversion efficiency (one way) is required at full load operation. At 25% load, the efficiency should not fall below 90%.

4.7.3.5 Harmonics

Harmonic voltages or currents introduced into the distribution network should not exceed, in total, 5% of the fundamental. Single harmonic distortion should not exceed 3% of the fundamental. Filters should be provided and identified.

4.7.3.6 Electromagnetic Interference (EMI)

Appropriate standards should be adhered to to insure that there is no interference with local utility communications, local TV, radio, and hi-fi reception and other operations in the vicinity such as telephone, telegraph, railroad, etc. equipment.

4.7.3.7 Phase Displacement

Locked to the utility per PFC and frequency requirements.

4.7.4 Other Considerations

4.7.4.1 Cooling

Appropriate choice of cooling techniques should be employed to allow

suitable performance of the equipment. System should be designed to reject heat to ambient air.

4.7.4.2 Protective Coordination

All necessary equipment to protect the power processing equipment and its DC supply from damage due to transient overvoltages initiated in the AC system must be provided. Internal protection of power processing equipment against overheating, overvoltage, etc., must be provided. If thyristors or other power handling component strings are in series and/or parallel, protective means must be provided to properly grade voltages across thyristors or strings and to provide for proper current distribution through the paralleled devices. In addition, coordination between the distribution and battery subsystem protective devices should be provided to insure proper and automatic sequencing of corrective actions.

4.7.4.2.1 Restoration of Operation

Automatic restoration of processor operation is expected within ten cycles after the utility recovers into $\pm 10\%$ band.

4.7.4.3 Fault Current Supply

The processor design should be such as to limit the battery short-circuit contributions to faults on the AC system. Means of isolating the batteries from a faulted DC bus (before the processor) should be supplied, as well as the means of limiting AC contributions to a DC system fault.

4.7.4.4 Isolated Operation Considerations

Operation disconnected from the AC system or during AC system outages affects a number of the specifications. To the extent possible, without sacrificing the ability to meet other goals, these considerations should be factored into the processor design as follows:

4.7.4.4.1 Rating Base

The converters will have to supply transient loads for motor starting, feeder pick-up, etc.

4.7.4.4.2 DC Voltage Range

The DC voltage range in operation with batteries is unchanged.

4.7.4.4.3 AC Voltage Range

The AC system voltage and frequency will be determined by the converter and source. The nominal voltage should be supplied within the +10 to -10% limits already discussed. Unbalance may reach a maximum of 25% of rating at any rating.

4.7.4.4.4 AC Voltage Regulation

Shall be $\pm 5\%$.

4.7.4.4.5 Harmonics

Harmonic requirements of the AC system and its loads will be similar to those of the distribution system.

4.7.4.4.6 Frequency

60 Hz ± 0.1 Hz.

4.7.4.4.7 Power Factor

$\pm .95$.

4.7.4.4.8 Fault Current

Sufficient fault current will be available from the batteries to allow proper operation of utility system protective equipment. The available fault current must be coordinated with all such devices (fuses, reclosures, breakers, etc.) on the distribution system.

4.7.4.4.9 Phase Displacement

$120^\circ \pm 1^\circ$.

4.7.4.4.10 Over Load

150% for 30 seconds and 125% for 10 minutes.

4.7.4.4.11 Ground

Four wire distribution system, fully grounded.

4.8 ENERGY MANAGEMENT COMPUTER

Control of electrical peak demand through automatic load shedding is a task that is increasingly being assigned to a computer. For the battery storage demonstration program, an energy management computer will be adapted to perform special tasks related to energy storage and

utilization in addition to the normal functions of energy management. The computer hardware and operating software must be capable of performing all of the following:

4.8.1 Load Monitoring

Use of stored energy for load leveling is to be accomplished in direct response to facility connected load. The computer will monitor connected load by sensing utility meter generated pulses and calculating the number of watts represented by their rate of appearance. When connected load is sensed to exceed a preset limit, the computer will signal the power processor to begin drawing on stored energy.

When monitored facility demand falls, the processor will be instructed to reverse the power flow to recharge the batteries. Both the charge and discharge cycles will be optimized by the computer to achieve maximum load leveling by the system.

4.8.2 Battery Monitoring

Battery life will be maximized by monitoring key parameters of performance (temperature, voltage, current, etc.) by the computer. Data will be logged to be displayed when requested by the system operator or will be available for continuous monitoring.

Alarm conditions will be constantly searched for and displayed immediately upon detection on the computer display, at the system operator's control center or at any remote location desired.

4.8.3 Battery Charge Control

The key to long battery life is precise control of charging rates. The computer will be programmed to provide the power processor with optimum charge rate data. This will extend battery life while maximizing the availability of stored energy on a daily operating schedule.

4.8.4 Load Control

All the normal capabilities of the energy management computer will be retained. The computer, in addition to calling for stored energy during peak power periods, will have the ability to automatically cycle sheddable loads for load leveling. Also, automatic start-up and shut-down of facility electrical loads according to a time-of-day, day-of-week schedule will be available.

5.0 SPECIFICATIONS

5.1 FACILITY LAYOUT

In analyzing different battery/cell, power processor and control arrangements within the given area of the Bureau's Bindery Section we arrived at three possibilities from which we will select one after more detailed evaluation and analysis in the next phase of this project. The three layouts are shown in Figures 35, 36 and 37 and labeled Layout A, B, and C, respectively.

Layout A, Figure 35, is a wall-enclosed area of 38 by 43 feet between the windows on 15th Street and the main hallway. Within this area is the room (14.5 x 23 ft) for the power processor and controls. The entrance to the PMBSS installation is from the hallway to the control room, and from the control room to the battery room. Unless the local building code and safety regulations require otherwise, one access door to the PMBSS is considered adequate. The control room is also directly adjacent to the power plant. This provides for the shortest electrical connections between the two installations. The walls are approximately 15 ft high. One wall would be parallel to the 15th Street window. This wall also parallels the 2.5 ft covered channel for conduits and piping. The 43 ft wall would connect to the hallway wall and enclose the area. As already mentioned, the entrance from the hallway is through the control room. This hallway door is already in existence. Another door leading into the battery room must be installed in addition to the two walls for the control room. The ventilation and air conditioning system for the area of the power processor and controls is already in existence and is assumed to be adequate. The battery room, however, requires a special ventilation system which will exhaust the low level but potentially hazardous hydrogen gas generated during the charging cycles of the batteries to the atmosphere. There will also be the necessity of installing a run-off and flushing system in the concrete floor for acid spills that might occur.

Figure 35. 350 Cell One-Tier Arrangement

Figure 36. 350 Cell Two-Tier Arrangement

Layout C

Figure 37. 38 Twelve-Cell Batteries

The dimensions of an individual cell corresponding to Layout A are shown in Figure 38 . The weight per cell plus pad is approximately 600 lbs. Thus, the total weight of the 350 cells required including pads is approximately 210,000 lbs.

The area of the L-shaped battery room in Figure 35 is about 1200 ft². When all cells are installed the floor loading is about 175 lbs/ft² which is considerably below the limit of 250 lbs/ft² for this floor.

As shown in Figure 35 the cells are arranged in a way that permits easy access and servicing from the isles. Transport of the cells will be by means of a small lift truck or portable crane.

Layout B, Figure 36 is similar to Layout A. The control room is the same. The battery room, however, has only 870 ft² of usable area vs. 1200 ft² in Layout A. It represents a more compact installation made possible by using a 2-tier stacking method (Figure 39) for the cells in the first row against the wall and the two center rows in the north-south direction. The total number of cells is again 350. Total weight of cells and racks is about 210,000 lbs resulting in a floor loading of approximately 240 lbs/ft² which is still below the allowable limit of 250 lbs/ft². The transport and servicing of the cells is the same as in Layout A case and is done from the isles where a small lift truck can circulate.

Layout C, Figure 37 , depicts a still more compact installation than the two previous ones, namely 38 modules with 12 cells each. The module dimensions are shown in Figure 40 . Such an arrangement would require less space than Layouts A and B. However, due to the considerable weight of the modules (3500 lbs) an overhead crane would have to be installed. Ventilation and floor drainage requirements are similar to Layouts A and B. The required area in this case is approximately 600 ft². Total weight of batteries plus racks is about 135,000 lbs resulting in a floor loading of 225 lbs/ft².

The entrance from the hallway is directly to the battery room, and as before a door is provided between battery room and control room. The control room dimensions are the same as for Layouts A and B.

Figure 38. Dimensions of a Single 2 Volt Cell

Figure 39 2-Tier Cell Arrangement

Figure 40. 12 Cell Module

5.2 IMPACT OF THE PMBSS INSTALLATION ON THE PRODUCTION SCHEDULE

The installation of the PMBSS at the Bureau of Engraving and Printing should not affect the Bureau's production schedule significantly. The primary upset caused by the installation will be the removal of two trimming cutter machines from the Bindery Section. There are several of these trimming cutters at other locations in the Bureau's building complex which could handle the additional trimming load while these two are being relocated. These machines will be relocated to the north end of the Bindery room or to a location of secondary choice in the Bureau's building complex. It is estimated that the removal and replacement of these machines will require one week with full production beginning a day or two after replacement at the new location.

The second significant change will be the re-routing of several low hanging air conditioning ducts in the area of the proposed PMBSS Layouts A, B, or C. These ducts supply air to office zones adjacent to the Bindery Section. It may be necessary to temporarily relocate office personnel while these ducts are being re-routed. The changes to the ducting system should have no impact on the production schedule of the Bureau.

Other changes to the facility necessary for the PMBSS installation are 1) floor drains and water supply for washing down acid spills, 2) installation of walls, 3) installation of battery gas ventilation system, 4) water supply for batteries, 5) wall drilling and installation of electrical conduits and cabling, 6) possible installation of overhead crane for handling of 12 cell battery modules. None of these changes should affect the Bureau's production schedule.

Final connection of the PMBSS power cables to the 480V distribution center bus for the power plant will be done on a weekend when printing machines are not scheduled for operation. The power plant electricity would be off for 8 to 16 hours while these connections are being made. The power off periods would be during a period when few personnel are in the building, because air conditioning cooling tower pumps and house water pumps would be inoperable.

The impact of the continued operation of the PMBSS on the Bureau's production schedule will be insignificant. Because of the basic concept of parallel operation with the utility supply and the protective gear built into the PMBSS, breakdowns or faults in the PMBSS will not affect the operation of the Bureau's power plant.

5.3 EQUIPMENT SPECIFICATION

5.3.1 Environment

Ambient Temperature:	0°C (32°F) to 40°C (104°F)
Relative Humidity:	0 to 95 percent
Heat Rejection:	220,000 Btu/hr at rated load

5.3.2 System Efficiency

92% @ full load
92% @ 75% load
91% @ half load

$\left(\frac{\text{Output Power of Processor}}{\text{Input Power to Processor}} \right)$, either direction

5.3.3 Electrical

Input

Voltage:	277/480 VAC, <u>+10%</u> , 3Ø
Frequency:	60 Hz <u>+5%</u>
Power Factor:	0.9 lag (nominal)
Voltage Transient:	<u>+20%</u> for 5 cycles
Voltage Unbalance:	≤ 3% Ø - Ø

Output

Power Rating:	0 to 800 KW
Power Control:	Infinite over rated range
Power Factor:	<u>+0.90</u> controllable
Energy Rating:	≥ 1.1 MW-hr
Voltage:	227/480 VAC, 3Ø
Regulation:	<u>+5%</u> , 0 to 100% load, min. to max. battery voltage
Transient Response:	<u>+8%</u> , 50% step load change
Harmonics:	5% in total of fundamental 3% of fundamental for single harmonic

Frequency: Synchronized with utility
(60 Hz)

Current:

Overload: 125% for 10 minutes

Current Limit: 150% for 30 seconds

Fault Clearing: 300% for 10 cycles

Duty Cycle:

Daily cycle of rated energy, 5 days per week, 52 weeks per year.

5.3.4 System Life

Battery: ≥ 5 years

Balance of System: ≥ 20 years

5.3.5 Mechanical

Floor Loading $\leq 250 \text{ lb/ft}^2$

Cooling: Forced Air

Cable Entry: Top or bottom

Hydrogen Build-up: $\leq 0.5\%$ by volume

Equipment Enclosures: Indoor, metal-clad

5.3.6 Operator Interface

Display: Alpha-numeric CRT

Data Entry: Teletype keyboard

Control Panel: Status lights; manual override switches

5.3.7 Printer Utility Interface

Relay contact closures at utility power meter; closure frequency proportional to power demand.

5.4 MANPOWER

The only manpower required for the continued operation of the PMBSS will be between 0.1 to 0.2 man-years per year, because of the highly automated nature of the system. Most of that time will be used to servicing and replacing batteries. It will be necessary to monitor electrolyte specific gravity and water level in the batteries periodically. The power processor, load and computer status will be displayed upon

demand by the operator, but other manual operations will not normally be required. All control functions will be under computer control with optional manual override.

6.0 OIL SAVING POTENTIAL

6.1 OBJECTIVE

The purpose of this section of the report is to indicate the oil savings potential if peak power demands were satisfied by stored power generated by base-load plants during periods of low demand. It should be emphasized that the savings are purely potential and no attempt was made to estimate market penetration by either lead-acid batteries or other more advanced power storage devices.

6.2 INTRODUCTION/BACKGROUND

In most parts of the nation power must be instantaneously generated to satisfy demand. Further, demand fluctuates widely throughout the day, week and year. Accordingly, during short periods of high demand, power companies find it economical to satisfy demand by utilization of special facilities or peaking plants.

The amount of energy (KWhr) generated by peaking facilities is small relative to the total amount of electric energy demanded. Hence, in principal, it should be possible to satisfy peak demand from non-peaking (base-load) plants if power demand and supply could be decoupled in time through use of storage devices.

The above situation is illustrated in Figure 41. In this figure, the power capacity required is plotted against the number of hours during the year (1971) for which the capacity is required. The curve is based on statistics from the Western Systems Coordinating Council (WSCC), but the curve is typical of those experienced by other National Electric Reliability Councils (NERC).

Figure 41 is reproduced from Reference 1. In that report, peak load was defined as arising from power demanded for 2000 hours or less per year. Intermediate demand was associated with 2000 to 5000 hours demand and base-load with power demand for 5000 hours or more per year. It is further seen that the area corresponding to peak energy demand is less than unused base-load energy capacity. Hence, as stated above, it is theoretically possible to transfer peak demand to base-load demand.

Figure 41 . WSCC Load Duration Curve for 1971

Peak power demands are often satisfied by either combustion turbines or older less efficient steam plants which were formerly on base-load duty. In 1976, about 85 percent of combustion turbines were fueled by oil according to Reference 2. Further data on turbine oil consumption are available from the same reference. So it seems natural to consider transfer of load from turbines as a source of oil savings.

Federal law now forbids construction of new power plants fueled by oil or gas (except for combined-cycle plants and for plants in areas with severe air pollution problems). Hence, there is a tendency for older plants assigned to peak duty to be fueled by oil while the newer plants assigned to base-load duty will be mainly fueled by coal or enriched uranium. The shift in fuel sources is indicated by the following projections taken from Reference 2 (NERC Report).

Electric Generation by Principal Energy Sources

ENERGY SOURCE	TRILLIONS OF KWH		PERCENT	
	1977	1986	1977	1986
Nuclear	0.281	0.990	13.1	27.7
Coal	1.010	1.698	46.9	47.5
Oil	0.369	0.520	17.1	14.6
Gas	0.252	0.100	11.7	2.8
Hydro	0.233	0.238	10.8	6.7
Other	<u>0.008</u>	<u>0.025</u>	<u>0.4</u>	<u>0.7</u>
TOTAL	2.153	3.571	100.0	100.0

Based on the above arguments and data, it was decided to check the validity of the following assumptions used by EPRI (Ref. 3) and others to analyze storage-device oil savings:

- All peak-loads are generated by oil.
- Increments in base-loads due to peak shifting can be generated by non-oil sources (principally coal and nuclear)

Investigation of the above assumptions and derivation of potential oil savings will now be described.

6.3 ANALYTICAL APPROACH

Projections on oil burned turbines to the end of 1986 are available in Reference 2. The projections are mainly based on data associated with existing plants and planned deletions and retirements. Hence, the NERC projections should be quite accurate. Turbine oil consumption between 1987 and 2000 was estimated by assuming that the 1986 consumption would grow at the compound rate of 3.6 percent per year. This rate was chosen since:

- The rate was used in the "medium" demand case in the Marker Oriented Program Planning Study (MOPPS) as reported on pp. 6-29.
- The rate also corresponded to the predicted compound growth rate of turbine oil consumption in the period 1976-1986.

Estimation of total oil consumption due to all peak plant demands however is complicated by the uncertainty in answers to the following demands:

- How much peak power is projected to be generated in the time period of interest?
- Is it safe to base oil-savings calculations on national averages or should regional differences be considered?
- Is there enough non-oil base-load capacity to handle shifted peak demand at the national level? At the regional level?
- It is the assumption that oil is mainly used to generate peak loads correct at the national level? At the regional level?

These questions will now be considered.

Peak power demand was estimated by the formula:

$$\text{Peak Load Energy} = \frac{\text{LF(p)} [\text{Annual Energy from System}]}{\text{LF(s)}}$$

$$\text{where LF} = \text{Load Factor} = \frac{\text{Annual Energy Supplied to Load}}{\text{Peak Demand (MW)} \times 8760 \text{ hours}}$$

and p and s refer to peak and system.

The peak load factor is taken as 0.08 based on a 1976 PEA estimate quoted in Reference 5. This value is consistent with the 0.05 to 0.15 range quoted by Southern California Edison personnel. The peak load factor was checked by estimating annual peak energy generated in 1971 in the various reliability council areas. These energy values corresponds to the area bounded by the ordinate, the load curve, and the second dotted line from the top in Figure 41. Similar curves for 1971 were obtained for the other councils (with one omission). Rough estimates of the 1971 peak load factors are listed below.

ESTIMATION OF 1971 PEAK LOAD FACTORS

RELIABILITY COUNCIL	ESTIMATED PEAK LOAD FACTOR
East Central Area Reliability Coordination Agreement (ECAR)	0.064
Electric Reliability Council of Texas (ERCOT)	No Data
Mid-Atlantic Area Council (MAAC)	0.050
Mid-America Interpool Network (MAIN)	0.052
Mid-Continent Area Reliability Coordination Agreement (MARCA)	0.056
Northeast Power Coordinating Council (NPCC)	0.064
Southeastern Electric Reliability Council (SERC)	0.073
Southwest Power Pool (SPP)	0.073
Western Systems Coordinating Council (WSCC)	0.078

Although the weighted average of the peak factors are a little lower than 0.08, the latter national value was considered to be reasonable and was used.

The national system load factors LF(s) was 0.62 in 1976 with a goal of 0.69 in 1985 according to Reference 1. In the calculations, the following national system load factors were used:

<u>1982</u>	<u>1983</u>	<u>1984</u>	<u>1985</u>	<u>1986</u>
.66	.67	.68	.69	.69

Note that the initial year for potential savings calculations was taken as 1982 on the basis that large scale use of lead-acid batteries for power storage is not feasible until then (See Reference 1).

Given a peak and system load factor, peak energy generated then can be calculated from the data on energy generation presented in Reference 2. The data (historical and projected) in Reference 2 are presented both on a national (NERC) and regional-council basis. After examining the data and consulting with Southern California Edison personnel, it was decided to continue the analysis on regional basis for the following reasons:

- Currently, it is almost impossible to shift demand from one council region to another. As a matter-of-fact, there are difficulties even in inter-utility transfers.
- If the oil equivalent of estimated peak energy generated is calculated at the regional level, the following is noted:
 - In some regions (e.g., MARCA), the peak equivalent oil demand is much larger than the total amount of oil consumed by the entire council. Therefore, it is clear that a substantial portion of peak power is being generated from non-oil energy sources.

- In other regions (e.g., NPCC and WSCC), the peak equivalent oil demand is much smaller than the total amount of oil consumed by the council. Therefore, substantial amounts of oil must be consumed by base and intermediate-load plants.
- It is not clear by a cursory inspection of the NERC data whether or not nuclear and coal base-load plants within a region could handle peak load transfers. (Later analysis however did indicate that such shifts were feasible at the regional level.)

The capacity of nuclear/coal base-load plants to handle peak load shifts in the 1982-1986 period was checked as follows:

- The peak load energy for each region (calculated as described above) was compared to the sum of "feasible" increments from nuclear and steam-coal power.
- In calculating feasible increments, it was assumed that, currently, base-load nuclear and coal plants have about a 0.7 load factor and that it would be possible to increase this factor to around 0.9. (Note the corresponding capacity factors are lower than the load factors).

The analysis indicated that the nuclear/coal base-load could handle peak shifting with the possible exception of the NPCC region in the early eighties. Since a further shift to nuclear/coal base-load is anticipated after 1986, the EPRI assumption about the feasibility of base-load plants being able to absorb peak shifting appears to be correct.

Potential oil savings were then estimated by the following procedures:

1. The estimates of peak-load energy generated in each region for the years 1982-1986 were converted into estimates of equivalent oil burned per year using the following factors from Reference 1.
 - 11,000 Btu per KWhr
 - 5.83 million Btu per barrel of oil.

2. The total amount of oil consumed annually by region for 1972-1986 was then obtained from Reference 2. The smaller of the values for peak equivalent oil and total oil consumed was then taken as the total savings potential for the appropriate region and year.
3. Results beyond 1986 were extrapolated as follows:
 - Peak equivalent consumption of oil for 1986 for each region grew at the compound rate of 3.6 percent per the MOPPS report (Ref. 4).
 - The quantities of oil projected for use in each region in 1986 by NERC (Ref. 2) were then decreased by approximately 4 percent per year until the year 2000.
4. The smaller of the values for peak equivalent oil and total oil consumed for each region and each year in the period 1987-2000 was taken as the total savings potential (including turbine consumption) for the appropriate region and year.
5. The regional minimums of peak and total consumption by year were then aggregated to obtain a national projection.

The negative growth factor for oil consumed by the power sector was estimated as follows:

1. It was assumed that power production would grow at the 3.6 percent rate used above.
2. But it was also assumed that the percentage of energy derived from oil to make electricity would drop from the 14.6 percent in 1986 projected by NERC to about 5 percent. The 5 percent figure was arrived at by comparing the following projections:
 - 5.5 percent oil share in 2000. EPRI Reference 3.
 - 2.1 percent oil share in 2000. MOPPS Reference 4.
 - 1.5 to 2.6 percent oil share in 2000. SRI Reference 6.

Since EPRI's estimate was given the most weight (for reasons explained below), their projection was only rounded down slightly.

3. Based on an electric growth rate of 3.6 percent and an oil-share reduction of from 14.6 to 5 percent of power energy sources, the negative growth rate was estimated to be:

$$1 - [(1.036)^{14}(5/14.6)]^{1/14} \doteq .04$$

It should be noted that had a lower power growth rate and oil share percentage in 2000 been used, the oil saving potential after 2000 would be quite small. However, it is possible that the low oil shares projected by MOPPS and SRI are based partly on energy storage and load management. On the other hand, the EPRI methodology involved an estimation of oil requirements without regard to energy storage and load management. Then the potential for new energy storage and load management was compared with the requirement to displace petroleum-derived electric energy (assumed to be dedicated to peak generation after 1985).

The numerical results of the procedures described are exhibited in Table III, while the potential oil savings from turbines and total peak facilities are plotted in Figure 42.

6.4 COMPARISON OF STUDY AND EPRI RESULTS

It is interesting to compare these results with that projected by EPRI (Ref. 3) for the year 2000. It will be recalled that the EPRI analysis was done on a national basis on the assumption that from 1985 on, oil will essentially be used for peaking while coal and uranium will be largely used for base-load plants.

The pertinent comparisons are displayed below.

EPRI 2000 Results			This Study 2000 Results		
Equipment for Saving Oil	Billions kWh Per Year	Equivalent Oil MMB/Year	Equipment for Consuming Oil	Billions kWh Per/Year	Equivalent Oil MMB/Year
Batteries	90	168	Oil Turbines	44	81
Load Mgt.	140	262			
Pumped Hydro	55	102			
Thermal-Mech.	<u>95</u>	<u>178</u>	Other	<u>219</u>	<u>411</u>
TOTAL	380	710		263	492

TABLE III. ESTIMATED PEAK OIL EQUIVALENT AND TOTAL OIL CONSUMPTION
(MILLIONS OF BARRELS OF OIL PER YEAR)

YEAR	NERC PROJECTIONS					EXTRAPOLATED VALUES														
REGION	82	83	84	85	86	87	88	89	90	91	92	92	93	94	95	96	97	98	99	00
ECAR																				
Equivalent	110.5	115.0	118.2	126.1	134.0															
Total	49.0	49.0	48.3	48.2	48.3	46.2	44.5	42.8	41.2	39.4	38.0	36.6	35.0	33.7	32.4	31.2	30.4	28.8	27.7	
ERCOT																				
Equivalent	42.0	43.0	45.5	47.0	50.3	52.0	54.0	55.8	57.9	60.2										
Total	42.0	44.4	49.6	68.8	70.5	67.9	65.1	67.0	60.1	57.9	55.2	53.2	51.0	49.4	47.5	45.5	43.6	41.9	40.6	
MAAC																				
Equivalent	45.9	46.9	49.0	50.5	53.5	55.1	57.2	59.2	61.5											
Total	78.5	76.4	74.2	70.6	67.3	65.0	67.2	59.9	57.8	55.1	53.0	50.9	48.8	46.8	45.1	43.4	41.5	39.9	38.5	
MAIN																				
Equivalent	49.5	51.5	53.5	56.5	59.8															
Total	16.1	15.2	17.1	12.3	20.2	19.4	18.6	17.8	17.2	16.7	15.8	15.2	14.6	14.1	13.6	13.0	17.5	12.0	11.6	
MARCA																				
Equivalent	27.3	30.5	31.7	33.5	35.1															
Total	4.0	4.4	4.4	4.5	4.7	4.5	4.3	4.2	4.0	3.8	3.7	3.6	3.5	3.3	3.2	3.0	2.9	2.8	2.7	
NPCC																				
Equivalent	53.2	55.0	56.5	59.0	62.0	64.0	66.3	68.8	71.1	73.9	76.2	79.8	81.5	85.0	81.1	91.1	95.0	98.4	102	
Total	214.8	219.2	200.0	264.0	198.2														114	
SERC																				
Equivalent	139.5	146.0	154.0	162.0	171.0															
Total	138.5	132.5	137.6	145.3	146.5	151	136	130	125	120	115	110.5	108	102	97.5	94.2	90.7	87.0	84.0	
SPP																				
Equivalent	57.0	58.0	62.2	65.2	70.0	72.0	74.8													
Total	77.0	66.0	65.6	75.9	79.4	76.1	73.3	70.2	67.8	65.0	62.3	60.0	57.5	55.5	53.3	51.2	49.0	47.3	45.5	
WSCC																				
Equivalent	118.5	120.3	125.9	133.9	140.0	145	150	155	161	167	173	180								
Total	230.5	231.5	233.1	241.3	243.2	234	225	216	207	199	191	184	176	170	163	156	150	144	139	
NERC	524.2	524.3	546.5	573.3	595.5	599.2	604.0	6038	603.0	598.8	592.2	589.8	575.9	559.2	543.7	528.6	515.6	502.1	491.0

Figure 42. Potential Oil Savings by Shift of Peak to Base Power Load

APPENDIX

The energy delivered by the battery during a discharge is simply:

$$W = \int_0^t E i dt$$

and the energy, W_R , delivered when the battery is operated at its rated current, i_R , to a specified cut off voltage is:

$$W_R = \int_0^{T_R} E i_R dt$$

The capital cost of the battery per rated energy throughput is:

$$\left(\frac{\$}{\text{KWH-cycle}} \right)_{\text{Rated}} = \left(\frac{\text{Capital Cost}}{W_R} \right) \left(\frac{1}{N_o} \right)$$

where N_o is the number of cycles to end of life at rated current.

At a different current density, i , a discharge for the rated time will give a non-rated depth of discharge since:

$$\text{depth of discharge} = \frac{\int_0^{T_R} i dt}{\int_0^{T_R} i_R dt}$$

Corresponding to the different depth of discharge, the capital cost per throughput energy is:

$$\left(\frac{\$}{\text{KWH-cycle}} \right) = \left(\frac{\$}{W_R} \right) \left(\frac{1}{N_o} \right) \left(\frac{W_R}{W} \right) \left(\frac{N_o}{N} \right)$$

where W is the discharge energy at the new conditions and N is the cycle to failure for the new depth of discharge.

Using Shephard's equation it is possible to integrate the energy output for different current levels to rated discharge time. The energy ratio,

W_R/W can be then formed as a function of $\frac{\Delta E}{E_o}$, where $\frac{\Delta E}{E_o} = \frac{E_o - E}{E_o}$

and E is the cell voltage after time T_R , that is, E_1, E_2 , etc. of Figure 43 . Figure 44 shows the results of that computation for a typical industrial traction battery rated for a 2 hour discharge. Figure 45 shows the original data from which Figure 44 was constructed.

In a similar manner, one can relate $\frac{\Delta E}{E_0}$ to depth of discharge by $\int_0^{T_R} i_R dt$, and expressing $\frac{\Delta E}{E_0}$ in terms of

$$\frac{\int_0^{T_R} i_R dt}{\int_0^{T_{R1}} i_R dt} .$$

Using the logarithmic relationship between depth of discharge and cycle life, gives cycle life in terms of $\frac{\Delta E}{E_0}$. Figure 46 shows the results of this process for the same industrial battery as in Figure 44 .

If one overlays Figures 44 and 46 , it is apparent that the relationships between cycle life and energy extraction are quite similar and as an approximation it is fair to use

$$\frac{W_R}{W} \approx \frac{N}{N_0} .$$

Substituting this into the relationship for capital costs per throughput energy gives

$$\left(\frac{\$}{\text{KWH-cycle}} \right) = \left(\frac{\$}{W_R} \right) \left(\frac{1}{N_0} \right) \left[f \left(\frac{\Delta E}{E_0} \right) \right] \left[\frac{1}{f \left(\frac{\Delta E}{E_0} \right)} \right] = \left(\frac{\$}{W_R} \right) \left(\frac{1}{N_0} \right) = \text{constant}$$

Using the above reasoning, it appears that for lead-acid batteries, the capital cost per throughput energy is independent of the manner in which energy is extracted.

Cost projections for lead-acid batteries in utility load leveling service were presented at the 1975 Workshop on Lead-Acid Batteries*. Major battery manufacturers stated at that time their belief that load-leveling lead-acid batteries could be built and delivered for costs ranging from \$5-/KW/hr to \$80/KW/hr.

* Workshop on Lead-Acid Batteries, co-sponsored by ERDA, EPRI, and ILZRO, at EPRI Headquarters, Palo Alto, California, November 18, 1975.

Figure 43 . Discharge Characteristics and Energy Output of Typical Lead-Acid Battery.

Figure 44 . Energy Output as Function of Terminal Voltage Regulation for Typical Industrial Motive Lead-Acid Battery.

Figure 45. Plate Discharge Characteristics of Industrial Traction Type Lead-Acid Battery

Figure 46 . Cycle Life as Function of Terminal Voltage Regulation.

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