Study of the Auxiliaries for Lead-Acid Battery Systems for Peaking Power

**Final Report for the
Period Ending Oct. 1976**

***Westinghouse Electric Corporation
Pittsburgh, Pennsylvania***

Date Published - Dec. 1976

**Prepared for the
Energy Research and Development Administration
Office of the Assistant Administrator for Conservation
Division of Electric Energy Systems
Work Performed Under Contract No. E (49-18)-2114**

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1.0 EXECUTIVE SUMMARY

The results of the study indicate that the most economic choice for a 10 MW, 40 MWH peaking power battery system using 5 KWH cells consists of a 1620 VDC, 10 string design. The projected cost of installing a total system is \$3,071,000 ($\$63.03/\text{KWH} + \$55.00/\text{KW}$) of which \$1,045,100 ($\$26.13/\text{KWH}$) is auxiliaries cost. This assumes there would be a modest development effort for fusing and monitoring systems, and the sharing of battery/power converter equipment. By comparison, a reference low voltage (770 VDC) design with present technology monitoring and fusing, and with no integration with power converter equipment, would have a total system cost of \$3,511,500 ($\$68.29/\text{KWH} + \$78.00/\text{KW}$) of which \$1,255,500 ($\$31.39/\text{KWH}$) is for auxiliaries. In both cases the costs assume a mature product line, with no allowance for one-time development costs.

The use of large capacity cells (49 KWH capacity) in a single string 1632 VDC battery design at the same 10 MW, 40 MWH rating using advanced technology fusing and monitoring systems, with shared equipment between the battery and power conversion gear, could lead to a total system cost of \$2,835,000 ($\$55.38/\text{KWH} + \$62.00/\text{KW}$), \$950,200 ($\$23.76/\text{KWH}$ in auxiliaries. Using conventional monitoring and protection devices in an 816 VDC (nominal), 2 string battery design, yields a total cost of \$3,309,500 ($\$63.24/\text{KWH} + \$78.00/\text{KW}$), \$1,264,700 ($\$31.62/\text{KWH}$ in auxiliaries cost.

The total cost per KW of the facility has been found to be a steadily decreasing function of system rating; in the range of from 1 MW to 10 MW, the total cost per KW decreases from \$462/KW @ 1 MW rating to \$325/KW @ 10 MW rating.

The above costs include the delivered costs of the battery and the installed costs of the auxiliaries and power conversion gear. The costs do not include the labor to put the cells in place (estimated at ~\$6,000 for the 10 MW, 40 MWH design using KW160-45 cells); the land costs for the facility, or any contingency margin.

Water cooling of the battery has been shown to be the most economic choice for virtually every climate in the continental United States, primarily because of its beneficial effect on battery life.

A predictive monitoring scheme has been shown to have the dominant effect in reducing cell replacement maintenance costs, whereas the choice of system voltage is less significant.

2.0 INTRODUCTION

In addition to the study of the manufactured cost of batteries for peaking power generation, a specific effort was directed toward studying the way in which the batteries should be used. Fundamental parameters, such as operating voltage, monitoring level, cell layout, interface with the power converter, etc., must be chosen before a total peaking power battery system can be fully evaluated.

This volume deals with the elements of the peaking power battery system which are neither the cells nor the power converter hardware per se, but which are nonetheless required to make the system work. These elements are termed the peaking power battery auxiliaries.

The study has been broken down into two major tasks. The first task, covered in Section 3, is concerned with the definition of the requirements for the auxiliaries, creation of a conceptual design which meets the requirements, and the performance of a cost estimate of that design. Since only one conceptual design is considered, little information is available regarding the effects of permutations around that design.

The second major task, covered in Section 4, delineates the effects of changes in auxiliaries design, using the Section 3 conceptual design as a benchmark. Section 4-1 addresses possible areas of hardware sharing with the power converter gear, including the effects of system dc voltage level. Section 4-2 addresses the system reliability by performing a Failure Modes and Effects Analysis (FEMA) on the battery system, as well

as investigating the interplay of system dc voltage, level of monitoring and cell failure rate on the system cost and performance. Section 4-3 evaluates the impact of cooling and ventilation systems design with particular emphasis on effects of varying climatic conditions. Section 4-4 evaluates the effects of system rating on auxiliaries costs, and Section 4-5 considers the effects of advances of technology in monitoring and protection devices with the use of large capacity cells.

By considering the individual permutations around the original conceptual design, a more optimum battery system can then be chosen. Such optimization is well worthwhile, because the selection of auxiliaries has a significant impact on the total system initial costs, repair and replacement costs, and system availability.

3.0 PEAKING POWER BATTERY PLANT DESCRIPTION

A. Function

The function of the plant is to supply power to the utility grid to satisfy daily peak demands. It will depend upon base load generation for the energy to be stored during low demand periods and subsequently delivered during peak demand. It is considered to be an unmanned plant.

B. Rating

The plant rating chosen for study is a 40 MWH, 10 MW system. The daily charge/discharge cycle will be a 4-hour constant rate discharge, 10-hour charge, 5 days per week. There will be a weekend equalizing charge of approximately 10-hour duration.

C. Plant Site

The site for the battery plant is chosen to be a rural or suburban area located virtually anywhere within the continental United States. The climatic conditions shown in Section 3.2 would be appropriate for many areas; Section 4.3 considers the effects of extremes in climatic conditions.

D. Functional Diagram

The plant is comprised of two major sections, the power conversion equipment and storage battery. The power conversion equipment interfaces the 60 HZ a.c. grid requirements with the d.c. battery as shown in the following diagram. The target of this study is the battery and its auxiliaries. Section 4.1 deals with possible integration of some of the battery and power conditioner auxiliaries.

E. Auxiliaries Description

The battery consists of a collection of lead-acid cells, connected in a parallel combination of strings, each of which is a series combination of cells of sufficient number to make up the d.c. system voltage. The battery auxiliaries consist of all hardware and systems required for operational control of the batteries as well as for the safety and protection of the installation and personnel. The auxiliaries under consideration are listed in Table 3-1.

TABLE 3-1

PEAKING BATTERY AUXILIARY SYSTEMS

OPERATIONAL

- VENTILATION
- TEMPERATURE CONTROL
- WATER ADDITION
- MONITORING
- CHARGE/DISCHARGE CONTROL
- BUS WORK
- MAINTENANCE REQUIREMENTS
- LAYOUT

SAFETY & PROTECTION

- ELECTRICAL PROTECTION
 - FUSING
 - ISOLATION
 - LOOP CURRENT INTERRUPTION
 - GROUND LEAKAGE PATH DETECTION
- ACID CONTAINMENT
- FIRE EQUIPMENT
- H₂ DETECTION
- STIBINE, ARSINE DETECTION

3.1 BATTERY AUXILIARY SYSTEM REQUIREMENTS

The auxiliary system requirements are divided into two functional groups, those pertaining to the operational aspects of the battery and those which are specific for safety and protection functions.

A. Operational

1. Ventilation:

During overcharge conditions, lead-acid batteries evolve hydrogen gas due to the electrolysis of water. The chief requirement of the ventilation scheme is to assure that the evolved hydrogen will be diluted with air to levels below the lower explosive limit (LEL) of 4%.

Design Condition

@ max. overcharge rate of 10%/hr (258 Amps/Cell)

H_2 evolution = .01474 ft³/AH

∴ H_2 evolution = 30,800 ft³/hr = 513 ft³/min

@ 1% concentration, flow rate ≈ 50,000 CFM

Although the room concentration of hydrogen may be kept well below the LEL, the "air" volume within the cells will necessarily contain highly explosive concentrations of hydrogen (and oxygen). A possible source of sparks which would ignite the gas is static discharge, due to low relative humidity and movement of dielectrics (people walking, flow of air in non-conducting ductwork, etc.). The ventilation scheme should be such that the possibility of static discharge is greatly reduced.

Design Condition

Maintain Relative Humidity > 60%

Prevent Static Charge Buildup on Surfaces

An additional requirement of the ventilation scheme is the control of acid mist. This mist is a result of the gassing of the cell, since the electrolyte forms a membrane over gas bubbles as they break the surface within the cell. If the mist is not adequately contained within the cell, corrosion of components outside the cell, electrical connection corrosion, and a gradual loss of sulphuric acid concentration will result.

The toxic gases arsine and stibine can be evolved during gassing periods of the cells as a product of hydrogen and the lead alloy materials. The amount of such evolution is difficult to quantify, being dependent on specifics of cell design and charge control, and provisions may have to be made for adequate disposal of these gases. In addition, the building concentration of these gases must be kept well below NIOSH standards of .2 to .5 mg/M³.

2. Temperature Control:

The temperature of the electrolyte affects the performance of the battery in two important ways: at high operating temperatures the cycle life of the cells is significantly reduced; at low operating temperatures the available cell capacity is reduced. It is, therefore, desired to limit the temperature range of the electrolyte for acceptable cycle life and capacity.

Design Conditions

Heat Rejection of the Battery = 9.5×10^6 WH/cycle weekdays
= 5.8×10^6 WH/equalizing charge

1% Summer Design Temperature Range:

Dry Bulb: 85°F (Seattle) to 115°F (Las Vegas)

Wet Bulb: 64°F (Denver) to 80°F (New Orleans)

99% Winter Design Temperature Range:

Dry Bulb: -35°F (Minnesota) to 33°F (Phoenix)

Optimum Electrolyte Temperature: $77^{\circ}\text{F} \pm 9^{\circ}\text{F}$ ($25^{\circ}\text{C} \pm 5^{\circ}\text{C}$)

3. Charge/Discharge Control:

The control of the charge/discharge process is important to the operation of the battery in several ways. At high rates of charge, the exothermic chemical reaction and I^2R losses can result in higher than desired operating temperatures. Also, overcharging is very inefficient, resulting in dissociation of water and the resultant hydrogen evolution as well as greater thermal losses. Finally, deep discharging beyond the rated capacity is deleterious to cycle life.

Design Conditions

Daily Charging: (5/week)	7 hours at constant current to 90% of previous discharge 3 hours at $\sim 4\%/hr$ to $\sim 102\%$ of previous discharge
Equalizing Charge: (1/week)	10 hours at $2-3\%/hr$
Discharge: (5/week)	4 hours at constant power up to 100% rated capacity

4. Water Addition:

The amount of water dissociated during the above overcharge condition must be replaced to maintain electrolyte level and specific gravity.

Design Conditions

Quantity:	@ 35% overcharge/week water usage = 650 gallons/week
Quality:	The limits of water impurities are listed in Table 3-2 from Vinal's reference text on storage batteries:

TABLE 3-2

RECOMMENDED MAXIMUM ALLOWABLE IMPURITIES IN WATER
FOR STORAGE-BATTERY USE

Impurity	Calculated as	Parts per Million Clear and "white"
Color		Trace
Suspended matter		100
Total solids		40
Calcium and magnesium oxides	CaO and MgO	5.0
Iron	Fe	8.0
Ammonia	NH ₄	50
Organic and volatile matter		10
Nitrates	NO ₃	5.0
Nitrites	NO ₂	5.0
Chloride	Cl	

Frequency of Addition: Determined by acceptable range of electrolyte level for cell operation.

5. Monitoring & Control:

The charge/discharge operation of the battery, as earlier outlined, will be under the control of the power converter equipment. However, to assure that each of the parallel strings is being properly charged and discharged, it will be necessary to monitor individual string currents continuously and integrate the current to accurately tell the usage of each string. The analogous control function is to be accomplished by individual string contactors which will be able to isolate each string as its limits of charge/discharge are reached. Of course, coordination with the power conversion equipment will be necessary, as rates and capacities are affected.

Design Condition

Monitor String Currents: $\pm .2\%$ accuracy

Integration: .2% accuracy

Other operational functions to be monitored are: cell temperature, for evaluation of cooling means; room relative humidity, for static

discharge control (this should include outdoor ambients as well as room ambients for control purposes); H₂, stibine and arsine concentrations; for evaluation of ventilation.

Design Condition

Cell Temperature	}	$\pm .5^{\circ}\text{C}$ Accuracy
Room Temperature		
Outdoor Temperature		
Room R.H.	}	$\pm 5\%$ R.H. Accuracy
Outdoor R.H.		
H ₂ Concentration	{	$\pm .2\%$ Concentration Accuracy ($\pm 5\%$ LEL)
Stibine		$\pm .005$ PPM
Arsine		$\pm .003$ PPM

The present NIOSH standards for threshold levels for the toxic gases arsine and stibine are 0.05 ppm ($\sim 0.2 \text{ mg/M}^3$) arsine, and 0.1 ppm ($\sim 0.5 \text{ mg/m}^3$) stibine. The threshold for arsine is expected to be lowered to 0.002 mg/m^3 in the near future. The methods used to detect these gases at these very low concentrations are usually time integrated methods, such as bubbling the gas through a liquid and determining the amount absorbed via colorimetry. Since this type of monitoring is not amenable to an automated method, no arsine and stibine detectors have been included in the conceptual design.

Additional work should be done to determine the feasibility of instantaneous concentration detectors for these toxic gases.

Another important monitoring and control function is the detection of types of failures, with proper compensation for the failure. Failures can be categorized into two groups: incipient failure, which is characterized by a relatively slow degradation of performance to the point where system malfunction can occur; and direct failure, characterized by an abrupt change in system performance and operation. It is likely that detection of incipient failure (viz., weak cells) and timely corrective maintenance will significantly reduce the probabilities of direct failures.¹ Therefore, emphasis is put on detection of early signs of malfunction so that appropriate action can be taken and later, more costly failures can be avoided.

To this end, the following additional monitoring should be performed:

- cell voltage: to determine the condition of individual cells or groups of cells and interconnects (knowing the state of charge, load and operating temperature as well from other detectors).

Design Condition $\pm .05$ volt/cell accuracy

- system leakage path to ground: this would detect a single path to ground (two are necessary for a fault in an isolated system), which might be caused by an acid leak or a grounding device left on after maintenance.

Design Condition: Δ isolation resistance of 20 db

¹See Section 4.2(b) (pp. 4-44 to 4-56) for other benefits of predictive monitoring.

The monitoring and control system should also perform status checks on the other auxiliaries (e.g., ventilation, cooling). It should communicate with the power conversion gear for electrical coordination, and it should communicate with the utility central station for status, early warning annunciation and failure diagnostics.

6. Bus Work:

The individual cells will be connected via intercell bus work into a series string of appropriate voltage to satisfy the d.c. voltage requirements of the power conversion gear. There will be a multiplicity of such strings connected in parallel by the interstring and/or main bus work to provide the required storage capacity of the plant.

The operational design requirements for the bus work are:

- limit surface temperature $< 140^{\circ}\text{F}$
- limit total I^2R loss $< 1\%$ of system storage capacity
- allow for individual cell replacement
- be compatible with layout requirements

In addition, the bus work must be designed to avoid the possibilities of battery room bus faults. It must:

- allow for severe mechanical abuse (viz., collision by a forklift truck)
- provide substantial barriers or large distances between main buses

7. Maintenance:

There is a large number of cells in a plant of this type, each of which must undergo routine preventative maintenance to achieve high performance and reliability. Water addition, which has been treated separately, is the most important maintenance item. Other periodic routine maintenance would include on a quarterly basis:

- a general visual inspection for signs of acid leakage, corrosion, case condition, etc.
- check of electrolyte for level, specific gravity, turbidity on selected cells
- general washdown and housecleaning of cells and facility

Provisions must also be made for corrective maintenance, should faulty components be discovered. These are:

- The faulty component must be identified. This is a particular requirement of the monitoring scheme, to aid in identifying which out of the large number of components is faulty.
- Assurance of electrical isolation. Once the component (within a string, for instance) has been identified as needing replacement or repair, that component must be electrically isolated from the rest of the system. This allows for continued operation of the plant (albeit at a reduced rating) while replacement occurs, and also assures

the maintenance personnel that, while working on the faulty component, they will not be subject to the high system voltages and currents. Such isolation should include the bus work and all possible auxiliary circuits that may pose a shock hazard.

- Acid-handling equipment. Aprons, footgear, face masks, gloves, and water showers must be provided in accord with safety standards for work around acids.
- Non-sparking tools. Because of the possibility of explosion due to hydrogen concentrations within the cell, hand tools to be used around the cells should have insulated handles and non-sparking working surfaces.
- Cell handling equipment. The size and weight of a single cell is far beyond the values that can be handled without mechanical aid. The combination of weight, acid, possibility of high voltage and current require the use of specialized equipment for the handling of the cells.
- A work station within or adjacent to the battery room, where repair of faulty components and recharge of repaired cells can be made. Provisions should be made for storage of a spare cell and other components to be used for immediate replacement during the repair period.

8. Layout:

The layout of the cells is not strictly an auxiliary, but it is an important design aspect which impacts many auxiliaries. In particular, the layout of the cells and the related equipment should achieve the following compromises:

- Limit total facility area. A natural objective of layout is to be efficient in use of floor area. In some circumstances, the total cost of a facility can be significantly affected by land and/or building costs.
- Limit bus work length. Bus work length is a strong factor in total bus losses and cost, both of which are items to be minimized.
- Maintenance Provisions. The layout must allow access for maintenance procedures and cell handling equipment. Specifically, access aisles should be provided on at least one side of each string for personnel and handling equipment; if aisles do not separate strings, barriers must be used between strings so that a safe working distance is maintained between personnel working on one string and adjacent energized strings.
- Limit fault capabilities. Bus faults can occur in several ways--a conductor can be (accidentally) placed across the main bus work, acid tracking paths can develop, reversing switchgear (normally a part of the power converter gear) can short, to name a few. The layout of the cells should be made either to put substantial distances between components at extremes of system voltage or to put substantial barriers between such components.

9. Enclosure:

The battery enclosure is the structure around the cells which provides protection of the components from the elements. In addition to being

compatible with all auxiliary systems, particularly ventilation and thermal requirements, it must also:

- (a) Protect water systems from freezing.
- (b) Prevent U.V. damage to components.
- (c) Protect components from ice, snow conditions.
- (d) Provide environment compatible with maintenance procedures, including a work station where cell repair can be effected.
- (e) Satisfy local building codes and restrictions.

B. Safety & Protection

Although some of the topics covered so far deal with safety and protection (particularly in the monitoring and maintenance requirements), the prime aspect has been operational. There are, however, requirements for auxiliaries that deal nearly exclusively with nonoperational modes. These are included in this section.

1. Electrical Protection:

(a) Fusing. Because a battery has considerable stored energy, it is difficult to "turn it off" as one might do with a passive device. Although bus faults are unlikely, it is possible that one would exist with as few as one and as many as all the strings driving the fault. It is a requirement, therefore, that each string have fusing capable of clearing a bolted fault.

(b) Isolation Provisions. The electrical isolation of the battery is divided into two categories: isolation of a string with respect to ground, and isolation of a string with respect to the rest of the battery.

- Isolation to Ground. The battery will be a floating, ungrounded design to eliminate the possibility of a power (current-carrying) fault due to a single ground path.

Design Condition

Nominal Resistance to Ground: 5-10 MEGΩ

Nominal D.C. Breakdown:* 200% system voltage

Impulse Breakdown: 1000% system voltage

- Isolation to Balance of System. As indicated earlier, string contactors/disconnects are required for charge/discharge and maintenance provisions.

(c) Loop Current Interruption. Should the voltage of an individual string be suppressed for any reason, loop currents from the rest of the strings could occur. Since it is impossible for the power converter to interrupt such currents, each string must have a provision to eliminate such loop currents.

2. Acid Containment:

Under normal conditions, of course, all of the acid electrolyte is contained in the cell jars or cases. The acid can escape, however, in the form of acid mist (covered earlier) and in the form of leakage from the cell jars. This latter form of leakage poses two distinct problems:

- Chemical Hazard. The acid must be collected and prevented from running off into the surrounding environment. Since any spilled liquid in the battery must be assumed to contain acid, the collection and containment scheme must be capable of handling rinse water and fire sprinkler water (if used) as well as acid from leaking cells.

*Over acid-contaminated surfaces.

- Electrical Hazard. The acid is a good conductor, so any acid path from the cells can present a grounding problem as well as a shock hazard. The cell supports and layout of the acid containment must define the paths of maximum leakage current to prevent carbon tracking, power follow and/or resultant fire. In addition, the acid containment scheme should collect separately the spills from each string to avoid the possibility of an unexpected shock hazard from one string to the next. Provisions should be made that all aisles are kept dry in the event of an acid leak, to reduce the shock hazard to maintenance personnel.

Design Condition

Tracking Path Over Acid Contaminated Surface: Voltage stress < 250 volts/inch at 2000 VDC design level.

3. Fire Equipment:

Fire equipment may be dictated by local building codes. In the absence of such, however, the following provisions should be made:

- Early Warning Devices. Smoke and heat detectors should be used in the battery facility to detect the first signs of fire. It is possible that other monitoring (cell condition, ground leakage path) would detect faults of the magnitude to start such a fire and, therefore, would be able to avert the fire by proper corrective action.
- Extinguishing System. Means should be considered to automatically extinguish a fire, such as a sprinkler system. The closed cell design should allow considerable water flow over the cells without

contamination of the electrolyte or damage to auxiliaries.

Acid containment should provide for this type of water flow.

3.2 CONCEPTUAL DESIGN

A. BATTERY DESCRIPTION

The overall peaking power battery system is shown in Fig. 3-1.

The battery auxiliaries include everything up to and including the D.C. main bus work, but do not include any power converter gear.

1. Cell Design

The cell design selected for the battery is the Westinghouse KW 160-45 cell, which was the subject of the Part I manufacturing cost study of this report. Seven series cells have been designed into a module, which is assembled at the factory and shipped to the site for installation and formation. The cell design specification and module specification are in the manufacturing cost study section; salient facts are summarized in Figure 3-2.

2. Battery Design

The seven cell modules are arranged into a battery as shown in Figure 3-3.

The battery specification is as follows:

Battery Specification

Energy Storage Capacity	39.9 MWH
Nominal Volatage	770 VDC
Number of (W) KW160-45 Cells	8085
Number of Parallel Strings	21
Number of Units per String	11
Number of Modules per Unit	5
Number of Cells per Module	7

The battery design provides for a fused disconnect at the 35 cell (70 volt) unit level. This provides assurance to maintenance personnel that any given module is isolated from both main buses and that the maximum operating voltage is 70 VDC during maintenance operations. The

BATTERY SYSTEM ONE LINE DIAGRAM

FIGURE 3-1

7 CELL MODULE

FIGURE 3-2

Weight:

Ampere-Hour Capacity:

Watt-Hour Capacity:

Nominal Voltage:

Start of Discharge:

Nominal Discharge Current:

End of Discharge:

Start of Charge:

End of Charge:

Equalizing Charge:

Equalizing Charge Initial Current:

Equalizing Charge Final Current:

Maximum Short Circuit Current:

Minimum Internal Resistance:

Water Cooling Flow Rate:

@ Pressure Drop:

Heat Evolution:

2850 lb Shipping
3560 lb Operating

2578 Ah

34,560 Wh

14.0 VDC

13.86 VDC

650 amps

12.67 VDC

14.7 VDC

17.15 VDC

16.45 VDC

150 amps

100 amps

20,000 amps

.70 milli OHMS

1.1 GPM

6.5 psi

2625 BTU/hr Discharge

2380 BTU/hr 7 hour 85% Charge

490 BTU/hr 3 hour 15% Charge

2000 BTU/hr Equalizing Charge

BATTERY CONFIGURATION

FIGURE 3-3

battery is an ungrounded design to prevent a power fault from a single path to ground. Specific features of the battery design will be covered under the next section.

B. DESIGN ELEMENTS

1. Layout

The layout of the battery is shown in Figure 3-4. Each string is 6.33 ft wide by 92.67 ft long with 3.25 ft wide aisles separating strings. End of string aisles of 9.5 ft with 4.0 ft outside aisles dictate an overall building size of approximately 110 ft x 210 ft (23,100 ft²). An adjoining maintenance shed of 20 ft by 30 ft (600 ft²) is provided for spare cell storage and component repair.

Each string is comprised of 55 free standing modules which are grouped into 11 units of 5 modules each. The modules are closely placed together with a 1" separation between modules. The 5 modules in each unit are connected in series by two flexible insulated cables per module as shown in Figure 3-5. These cables all have a bolted connection to the terminals on the module which are easily accessible from the aisles on either side of the string.

A hook-stick operated fuse provides the connection from unit to unit. This fusing provides the necessary isolation at the 70 VDC level for maintenance as well as providing protection in the event that multiple paths to ground within a string develop. Multiple grounding paths can develop from two (or more) acid leaks, or perhaps more likely, from grounding devices being left on different sections of a string as a result of possible maintenance procedures.

BATTERY & AUX. LAYOUT

FIGURE 3-4

Each string is thus a linear arrangement of modules that extends from one side of the room to the other, connected in a series serpentine manner. The maximum voltage from one module to the next is 28 volts. Because each string is similarly layed out, the differential voltage across each isle is essentially zero, thus minimizing the effects of a possible string to string fault.

The floor of the battery room is poured reinforced concrete, which has several features as can be seen from Figure 3-5. Each string is defined by a shallow trough in which the modules are free standing. On one side of the trough is a raised section which defines the aisle between strings. On the other side of the trough is a trench, towards which the trough has a slight slope. This trench is sloped in one direction toward a storage reservoir to provide the individual string acid containment. The trench also provides a runway for cooling water manifolds and electrolyte water addition manifolds.

The water addition manifolds provide shut-off valves for the supply and return manifolds at each 5 module unit. The 5 module water addition manifolds are interconnected to a small unit reservoir which is located over the trench and close to the modules to minimize the intrusion into the aisle.

The cooling water manifolds provide shut-off valves at each module location for the supply and return lines. A short and long flexible hose are, respectively, used to connect to the module cooling coil at the near and far side of the module.

FIGURE 3-5

On the side of the string opposite the trench is a ventilation duct. This duct connects to the ventilation manifold of each module in the string and in turn connects to the main ventilation duct at one end of the battery room. The string duct is 4 inches wide to minimize the intrusion into the aisle and is 25 inches high for adequate flow area.

On top of the ventilation duct is a plastic wireway for all string monitoring wires.

At the end of the string, there are underground provisions for all cables, wires, ducts, and piping as shown in Figures 3-6 and 3-7. This is done to allow for the use of an overhead system for module handling as well as to provide maximum mechanical protection for bus work at the ends of the string. A substantial barrier of dielectric material (e.g., glass polyester) provides mechanical protection of the end module. The sub-floor ventilation duct is poured in place; connection to the main duct is made at the outside wall of the building. That duct connects to a fan room, located at the center of the wall to minimize duct work.

Mounted on the string end barrier is an enclosure for the string contactor, fuse and disconnect. That connects directly to the sub-floor main bus work, located adjacent to the string ends. The main bus is a tapered design, which runs along the entire length of the building, with connections for each string. The bus exits the building at a separation of 95 ft, for underground connection to converter. Since each string has disconnects and fusing, there are no provisions for these in the main bus proper.

PLAN

ELEVATION

FIGURE 3-6

FIGURE 3-7

RESERVOIR END

The acid drain trench for each string is covered by grating for the entire length of the trench. The trenches have a uniform slope toward one side of the building until the end of the string, where a larger drop is used to clear the transverse main bus. Each trench empties into a separate reservoir. The reservoirs have sufficient capacity to contain the fire sprinkler water needed to fight a major fire (2,000 ft³ per string).

The water cooling plumbing is connected to main headers on the reservoir side of the building. These headers run in a perimeter trench shown in Figure 3-7 to the cooling tower, which is located near the middle of the building to lessen pumping losses.

The automatic water plumbing is connected to headers which run via the same perimeter trenching to the water treatment room.

The entire floor is coated with acid-resistant epoxy paint to avoid possible acid damage.

Details of each design will be covered in later sections.

2. Ventilation

The requirements for ventilation ostensibly allow use of any of four generic methods: roof exhaust, hoods, manifolds, and individual cell gas treatment. The first two are methods of diluting the cell effluent gases to the non-harmful levels, whereas the latter two are more aimed at confining or local treatment of the gases. A qualitative comparison of the ventilation methods is summarized in Table 3-3.

Because the roof exhaust and hood schemes are essentially dilution techniques, it is appropriate to quantify the amount of design airflow

TABLE 3-3

	Roof Exhaust	Hoods	Manifolds	Individual Cell Gas Treatment
Cost	Lowest	High	High	Unknown
Assurance $H_2 < 1\%$	Poor	Good	Good	Best
Acid Mist Control	Poor	Poor	Good	Good
Compatibility With Cranes	Good	Poor	Good	Good
Arsine, Stibine Control	Poor	Doubtful	Good	Best

required. The hydrogen dilution requires approximately 50,000 CFM, based on a maximum overcharge rate of 10%/hour and an allowable room hydrogen concentration of 1%. The amount of ventilation required for control of arsine and stibine is, however, not presently known.

Lead-acid cells contain varying amounts of antimony and arsenic in the grid alloy. During operation of these cells, it is possible that these alloy constituents could be liberated as the toxic gases stibine and arsine. The amounts of these gases which are given off have not been quantified to date. The amounts given off, if any, should be determined experimentally, with particular attention being paid to the charge/discharge control employed in a peaking power cell management schedule. If found to be necessary, appropriate means for disposal of these toxic gases must be employed.

Consideration must also be given to the effect that the ventilation system has on the normal operation of the battery. If a roof exhaust ventilation scheme is used during the winter months in a cold climate, the required room air changes may drop the room temperature to unacceptably low levels. A manifolding technique, however, permits minimum room air ventilation, since the evolved gases are confined; what dilution air that is required for safe concentrations in the manifolds can be supplied directly from the outside, thus minimizing room make-up air flow.

The ventilation approach chosen for the conceptual design is a manifold design. Although this is not the minimum cost design, it allows for better cold weather operation as well as providing for the contingency of disposal of arsine and stibine gases (e.g. with a scrubber) should the need for toxic gas disposal be determined. Section 4-3 of this report deals with a minimum ventilation scheme employing recombination of the evolved gases.

The overall ventilation scheme is shown in Figure 3-8. Each cell in a module is connected through a fused alumina flashback arrester to a module vent manifold as shown in Figure 3-9. The arrester should provide a site for collection and return of any evolved acid mist back to the cell. The manifold is connected at one end to the string duct as described in the layout section. The opposite end of the module manifold is fitted with a closure cap. At the end of the string the duct is connected via a buried section to the main ductwork. This ductwork is located on the outside wall of the building to minimize the chances of damage due to collision with cell handling equipment. The other end of the duct is connected via a buried

FIGURE 3-8

FIGURE 3-9

section to an inlet filter for outside air, which maintains the hydrogen concentration in the duct at less than 2%. The main duct connects to the fan room, to two ventilation fans connected in parallel. The sizing of the fans is such that operation of the facility is permitted should one fan fail, albeit at a reduced margin of safety in terms of duct work hydrogen concentration.

The mixture of air and hydrogen is then blown out a stack, mixed with additional outside air to keep exit hydrogen concentrations less than 1%. All of the ventilation ductwork will be operating under a partial vacuum (1-2" H₂O) so that ductwork leakage will result in air leaking into the duct, not gases and possibly acid mist leaking out.

The string ductwork is constructed from good dielectric strength materials (e.g., polypropylene or fiber glass) to maintain the system isolation from ground. The main ductwork and buried sections will also be of acid resistant material (e.g., fiber glass).

The specifications are as follows:

Module Manifold:	1.5" x 1.25" rectangular duct, molded in cover
String Duct:	4" x 25" x .090 wall
Main Duct:	Tapered, up to 24" x 42" x .125 wall
String Flow Rate:	1200 CFM
System Flow Rate:	25,000 CFM
	50,000 CFM at stack
Suction Fans (2):	12,500 CFM, 3" H ₂ O design (15 HP)
Stack Fan (1):	25,000 CFM, 2" H ₂ O design (15 HP)
Power:	≈ 28,000 watts running

3. Electrolyte Temperature Control

The design chosen for electrolyte temperature control is a water cooling type, using a closed tube evaporative cooling tower and a coiled tube heat exchanger immersed in the electrolyte of each cell. This method is considered superior to an air cooled system for the following reasons:

1. It improves cell life.
2. It reduces total floor space required.
3. It provides a tighter control of electrolyte temperature.
4. It minimizes temperature distributions from cell to cell.
5. It is compatible with the manifold ventilation scheme.
6. It is largely independent of room conditions.
7. It is usable in more climatic regions.

Section 4-3 will deal in detail with the effect of cooling system choice on battery life for various climatic regions.

The design chosen is shown in Figure 3-10. Each cell contains a coil of plastic tubing which acts as a liquid-liquid heat exchanger. The coils of the cells in a module are plumbed in series, formed from a single length of tubing to minimize chances for internal leaks. Each module line is connected in parallel to string distribution lines which, in turn, are connected to main headers. The collection header goes to a surge tank, then through the circulation pump, through the cooling tower, and back to the main distribution header. A 10% bypass filter maintains cooling water quality. Bypass plumbing can be provided to use the battery heat to heat the building during cold weather.

Water Cooling System
3-36

FIGURE 3-10

Included in the water cooling scheme is a deionized water loop for cooling of the main bus work and string static contactors. This is a self-contained unit of modest capacity (150,000 BTU/hr) compared to the cell cooling water system, employing a water/water heat exchanger, storage capacity, circulation pumps, and a bypass deionizer to maintain water resistivity in an acceptable range of .5 to 2 megohm-cm.

The water cooling specifications are as follows:

Module Heat Exchanger

Tubing Size: .625 OD x .500 ID Polyethylene Tubing
Required Flow Rate: 1.1 GPM
Pressure Drop: 6.5 PSI
Water ΔT : 5.0°F @ 2625 BTU/hr input

Circulation Pump

Flow: 1250 GPM
@ Pressure: 15 PSI
Required HP: 20 HP (16.5 KW)

Cooling Tower

Type: Wet Surface Air Cooler
Flow Rate: 1200 GPM
Inlet Temp: 85°F
Outlet Temp: 80°F
Design Wet Bulb: 70°F
Size: 28' x 14' x 9.3'
Fan HP: 40 HP
Spray Pump HP: 5 HP } 41.5 KW power

Deionized Water Cooling Loop

Rating: 150,000 BTU/hr
Flow Rate: 20 GPM
Inlet Temp: 100°F
Outlet Temp: 85°F
Circulation Pump: 20 GPM, 15 PSI (1/2 HP)

4. Water Addition

The water addition scheme is shown in Figure 3-11. Because the anticipated water usage would result in a relatively slow drop in electrolyte level, weekly water addition is acceptable. Water of sufficient purity¹ (from a demineralizer) is piped via plastic piping to distribution manifolds at each 5 module unit. The manifolds are overflow controlled to provide a fixed head to the gravity feed fill valve in each cell, as shown in Figure 3-12. The arrangement of the

¹See Table 3-2

CELL WATER ADDITION SYSTEM

AUTO FILL VALVE
MAINTAINS H₂, SUCH
THAT $H_2 \geq H_1$

VIEW A-A

FIGURE 3-12

distribution manifold is such that the manifold should not be emptied by normal water usage. Thus by detecting low manifold level, rapid indication of a leaking cell within the 5 module unit is made available. Sectionalization into the unit block is consistent with the philosophy of assurance of electrical isolation.

5. Electrical Protection

(a) Module Isolation. The module design provides for excellent isolation of the battery system from ground. The water cooling coils, immersed in the electrolyte, are of .0625 wall thickness polyethylene, which provides typical calculated isolation levels of $> 1,000 \text{ Meg } \Omega$ and 25,000 VDC breakdown (400 V/mil).

The base of the module provides a minimum standoff of the cells of 6" to ground. Assuming a worst case condition of one bus being grounded and a case rupture at the opposite end of the string, the surface voltage stress would be 160 volts/inch at end of charge conditions. This is considered an acceptable voltage stress for an acid contaminated surface, to prevent carbon tracking and power follow.

(b) Bus Design. There are three main bus lines at the positive and negative ends of the strings, as shown in Fig. 3-13. Each main bus line connects to seven contiguous strings; the buses are tied together at the end of each line, thus providing a three segment tapered design. This sectionalization into three lines is chosen to provide a nominal 5,000 amp bus line, to provide equal utilization among buses ($21 \div 3 = \text{integer}$), as well as allowing the option of sectionalizing the battery into 3

MAIN BUS LAYOUT

FIGURE 3-13

equally rated and independent elements. This latter point is dependent on power converter design philosophy, and is not considered in this conceptual design.

Each bus is a 3.0 square high conductivity copper tube with a 0.5" thick wall section (an industry standard), with deionized water circulating in the tube. The 5,000 amp rating is conservative for the amount of copper and for liquid cooling, but the choice was made to keep the bus losses to 18 KW @ 650 amps/string; water cooling is done to assure adequate operating temperature, which would not be assured with an air-cooled trench design. The joints will be brazed and the ends capped where the insulating cooling water supply lines are attached. The cooling water is supplied by the same deionized water loop for the static contactor cooling.

The string cables will be attached to a $3/8 \times 2 \frac{1}{2}$ " Cu bar welded to the bus at the centerline of each string.

The bus is hung from non-conductive supports spanning the main bus trench. The hanging support is non-conductive material supported by four bolts, each with a non-conductive spacer. The bus is able to move in the hanging supports for expansion and contraction.

The interconnecting cables between modules will be 300 MCM. There will be two in parallel, each being 2 feet in length. The total cable involved will be 5796 feet allowing 15 feet at each end for connection to disconnect boxes and buses. The total losses at 325A/cable will be 21.5 KW. The voltage drop per string will be 1.57V. The cables will be copper stranded, Type RHH, cross linked polyethylene.

(c) Fusing. Fusing will be divided into string protection (fast blowing type) and unit short circuit protection. As shown in Figure 3-2, each string will be fused at each end with a 900 amp, 1000 volt overcurrent fuse mounted in the enclosure that disconnects the string from the bus. It will be necessary to open the switch before access can be gained to the fuse. These enclosures will have an interlock switch tied into the fuse safety circuit as described below.

Every five modules (unit) will be fused with a hook switch fuse. This fuse will be rated higher than the string fuse and will protect against local short circuits. These fuses will be rated at 1200 amp at 1000 volts.

Each unit fuse switch will be mounted behind a cover equipped with an electrical interlock switch that will signal the computer to disconnect the entire string from the bus. This is to protect the operator from inadvertently opening a fuse switch under load without disconnecting the string from the bus through the main manual disconnects at each end.

The unit hook switch fuse-cover-interlock and the main string disconnect interlocks will all be wired in series. Once this circuit has been interrupted, the operator must manually reset the system through a push-button located on the string contactor disconnect box.

6. Maintenance Provisions

(a) Module Handling. The layout of the battery and auxiliaries has been designed to be compatible with an overhead method of module handling. This was done for several reasons:

- An overhead system allows access aisles to be narrower than the strings, since modules can be maneuvered over the strings. This allows a better floor space utilization.

- An overhead system allows more control of module placement, since there are three independent degrees of freedom in motion. This should minimize module and auxiliary damage due to improper placement or collision.
- An overhead system can be designed with non-conductive materials to avoid the possibility of grounding an operating string while working on an adjacent de-energized string. Thus personnel safety is enhanced.

The conceptual design for the module handling device is shown in Figure 3-14. It is a powered gantry that spans one string and that runs in the access aisles on either side of the string. The gantry is guided by differential speed control of the driven wheels. It has a walkway to facilitate movement from one side of the string to the other (as required for a single module hook-up). It has a translating crane with an integral spreader and strap configuration to provide stable 4 point suspension of a module. It is capable of lifting a module to clear the string for module replacement. It contains a tool box, emergency shower supply and storage for small parts. The main supports are non-conductive. The gantry is battery powered with integral charger.

(b) Isolation & Protection. Disconnect fuses have been provided at the 5 module (70 volt nominal) unit basis so that the maintenance personnel can be assured that any given module being worked on is disconnected at each end from the main bus work. Interlock sensors at each disconnect prevent the string contactor from closing until all disconnects are closed. This prevents load switching by the disconnect.

Disconnects for the monitoring circuitry are provided at the unit level to remove the shock hazard associated from the monitoring system.

BATTERY MAINTENANCE GANTRY

FIGURE 3-14

Grounding straps are provided to tie the water systems to ground at the manifold level, adjacent to the unit being worked on. These devices may be permanent.

Grounding straps may also be provided to securely ground the device being worked on, providing additional assurance that no high voltages will be present. It is likely that the battery power circuit would not intentionally be grounded, but rather that maintenance personnel would be well insulated to ground via rubber boots, insulated wrenches, insulating platforms, etc. This would lower the possibility of a high current fault from poorly managed maintenance procedures.

Indication of string status will be provided at the string contactor enclosure to indicate maintenance personnel that the string is not in operation and, therefore, safe to work on.

7. Facility

The layout section dealt with provisions in the facility for acid containment, ventilation ductwork, main buswork, string protection, water manifold systems, and major component placement. This section deals with the remaining aspects of the facility.

(a) Enclosure. The building enclosure which surrounds the battery is a minimum cost, pre-engineered structure. Because the battery cooling and ventilation requirements are independently met, the enclosure has broad ranges of acceptable temperature and ventilation rates. A specification for the enclosure follows:

Size: 210 ft x 110 ft x 15 ft ceiling
Span: 110 ft
Ventilation: 20,000 CFM circulation (during maintenance only)
Makeup: 2,000 CFM (winter), 20,000 CFM (summer)
Heating: 200,000 BTU/hr, 40°F thermostat

(b) Maintenance Room. A separately controlled maintenance room is provided for spare cell storage and on-site component repair. Specific provisions are:

- Size: 20 ft x 30 ft x 15 ft ceiling
- Overhead crane system for module handling and disassembly.
- Module diagnostic gear (high current load, voltmeter, etc.)
- Storage racks for spare components.
- Working surfaces for component repair and inspection.
- Acid handling equipment.
- Single cell and module charging gear (including spare cell trickle charger).
- Separate heating/ventilation from main room (50,000 BTU/hr heating, 1,250 CFM circulation, 10% makeup air).
- Lavatory

(c) Fire Protection. Fire protection of the facility is provided by an automatic sprinkler system.

- All sprinkler nozzles are open at all times.
- Water flow is controlled by a main valve.

- Early warning devices (smoke detectors and heat detectors) are employed.
- Flow Rate: 3,450 GPM total ($.15 \text{ GPM/ft}^2$)

The acid containment reservoirs have sufficient capacity to hold all of the fire sprinkler water for 90 minutes (~300,000 gallons).

8. Monitoring and Control System

Each element of the Battery Auxiliary System conceived will require control in order to provide the functions intended and described. These control elements should be coordinated and integrated on a systematic basis to simplify installation, operation and maintenance and to reduce costs.

Further the elements of the Battery Auxiliary system require monitoring to isolate incipient failure conditions providing operator warnings as well as to provide immediate alarm and related control functions.

The operating elements of the Battery system requiring control and/or monitoring are defined to include the following:

- A. Facility and utility functions
- B. Cell ventilation system
- C. Battery temperature regulating system
- D. Cell water addition system
- E. Battery charge/discharge control
- F. System maintenance function
- G. Monitoring and Control System Summary

A. Facility and Utility Functions

The monitoring and control functions required to integrate the facility and utilities into the Battery auxiliary system are tabulated in Table 3-5. Figure 3-15 indicates relative placement of the components within the Building.

Table 3-5 indicates several items relative to Building services which are monitored for Battery protection. No control functions are intended but because of danger to the battery system (i.e. freezing of coolant water) alarms are generated.

B. Cell Ventilation System

Because of the explosive and toxic gases generated during charging, the proper operation of the cell ventilation system is mandatory. The functions of this system are defined in Table 3-6. Control actions are also described in Table 3-6 where each functions relative importance can be visualized.

FACILITY AND UTILITY FUNCTIONS
TABLE 3-5

<u>Function</u>	<u>Control Units Required</u>	<u>Instrumentation</u>	<u>Control/ Monitoring Function</u>
Acid Containment	None Required Function by Drain & Reservoir	21 - Conductivity Sensors at Drains	Alarm Leaking Cell
Fire Warning as Smoke Detection	None Required	4 - Smoke Detectors	a) Terminate Charge/Discharge b) Alarm smoke detected c) Turn on fire extinguisher
Fire Extinguishing	1 - motor operated valve	2 - Valve position interlocks	Alarm valve position change
Building heating and/or cooling	Not part of Battery	4 - Temperature 4 - Wet Bulb	a) Report temperature and Humidity Daily b) Alarm low temperature
Building Venti- lation	Not part of Battery Auxiliary	4 - Fan Interlocks	Alarm fan off, Temperature High

FIGURE 3-15

CELL VENTILATION
TABLE 3-6

<u>Function</u>	<u>Control Units Required</u>	<u>Instrumentation</u>	<u>Control/ Monitoring Function</u>
Battery Manifold System	2 - Blowers	21 - Digital signals from flow switches	a) Control to energize during charge cycle. b) Alarm "no flow" and terminate charge cycle.
Stack	1 - Blower "on" for stack	1 - Blower "on" interlock 1 - Digital signal from vacuum switch	Alarm "stack" failure - terminate charge.

Figure 3-7 is a functional sketch of the cell ventilation system. This sketch establishes the approximate location of various sensors.

C. Battery Temperature Regulating System

Since Battery temperature variations do not normally cause catastrophic situations, the monitoring and control functions relating to the temperature regulating system have been minimized.

The functions intended are listed in Table 3-7 with the related physical relationship seen in Figure 3-10.

D. Cell Water Addition System

The cell water addition system provides the method of isolating electrolyte leaks. The monitoring occurs at the unit level (35 cell assembly) based on achieving a reasonable level of leak isolation. Control functions related to possible cell leakage will be originated elsewhere to de-energize a string. The leakage must be sufficient to cause an effect on cell voltage or to create a ground fault before the disconnect would occur.

Each unit has a water reservoir with sufficient capacity for several days of normal operation. The system will be energized to fill the reservoir while the reservoir is nearly full. If the reservoir falls below a half full limit, the level detector will function, indicating low level. Reasons for use of excess water include:

BATTERY TEMPERATURE REGULATING SYSTEM
TABLE 3-7

<u>Function</u>	<u>Control Units Required</u>	<u>Instrumentation</u>	<u>Control/ Monitoring Function</u>
Cell Heat Exchangers	Manual Gate Valves	None	None
Cooling Liquid Distribution	None	43 - Temperature Sensors 1 - Supply Line pressure switch	a) Alarm Temperature variation from norm. b) Calculate reduced storage capacity for Low temp. c) Alarm low pressure.
Coolant Storage Reservoir	None	1 - Level sensor	Alarm Low level
Cooling Tower	1 - Fan motor starter 2 - Pump motor starters 1 - Louver control system	1 - System on interlock	Alarm-cooling tower "off" or "on"
Coolant Pump	2 - Pump motor	2 - Motor starter interlock	Alarm cooling system failures
Demineralizer	None	1 - Conductivity analyzer	Alarm conductivity over range

- Leaking Battery Cell
- Malfunctioning water addition device
- Leak in the water manifold
- Malfunctioning cell causing excess gas formation or water evaporation

The monitoring system will give an alarm message indicating low level of reservoir identifying the unit and string of the faulty reservoir.

Table 3-8 tabulates the Control and Instrumentation functions with resultant monitor and control activities. Figure 3-11 attempts to relate these to the physical installation.

CELL WATER ADDITION SYSTEM
TABLE 3-8

<u>Function</u>	<u>Control Units Required</u>	<u>Instrumentation</u>	<u>Control/ Monitoring Function</u>
Unit reservoir & Manifold	None	231 - Liquid Level Detectors	Alarm "Low Level possible cell leak"
Water Distribution System	1 - Pump starter	1 - Starter Interlock	a) Control pump operation for periodic unit reservoir filling b) Alarm pump "not running"
Water Main Reservoir	None	1 - Level Detector 1 - Conductivity Analyzer	a) Alarm conductivity out of range b) Alarm water level low c) Start water addition from demineralizer
Demineralizer System	None	None	None

E. Charge/Discharge Control

Battery charge/discharge condition is monitored and controlled at the battery string level. Control is provided enabling the control system to separate a battery string from the battery system.

The control-system for charge/discharge control is defined in Table 3-9 and Figure 3-16. String current is monitored and integrated to compute ampere hours used. During discharge, the amount of ampere-hours withdrawn from each string will be computed; information regarding the amount of stored energy available will be communicated frequently to the dispatcher. It is expected that small variations in discharge capacity from string to string will be tolerated, so that the full 10 MW power level may be maintained throughout the 4 hour period.

During charge, the string current will also be monitored and integrated to compute the amount of charge returned to the string. A seven hour constant current or constant power profile to 90% of the amount previously withdrawn will be maintained, followed by a three hour constant potential profile until 102% to 104% of the amount previously withdrawn has been returned to the string. Each string will be separately disconnected from the bus by the static contactor as it reaches the final value of charge, thus achieving charge/discharge control.

In addition to the charge/discharge functions, the string disconnect function provided by the static contactor will be utilized to isolate a string for failures detected by the monitoring operation. Typical of failures which may initiate string disconnect are:

BATTERY CHARGE/DISCHARGE CONTROL
TABLE 3-9

<u>Function</u>	<u>Control Units Required</u>	<u>Instrumentation</u>	<u>Control Monitoring Function</u>
Main Bus String Manual Disconnect	None	21 - Switch Interlocks	a) Alarm switch "open-closed" b) If static contactor is energized, it will be de-energized
Main String Fuse	None	21 - Fuse blown interlocks	a) Alarm fuse blown
Static Contactor	Thyristor Firing Controls	42 - Thyristor Firing Controls	a) Initiate/terminate charge cycle b) Initiate/terminate discharge cycle c) Isolate string for detected failure conditions
String Current Shunt	None	21 - String currents	a) Input string current for calculation of level of charge b) Alarm "current out of range"
Main Bus Voltage	None	1 - Bus voltage	Required for various power and/or charge calculations

FIGURE 3-16

- 1) High cell resistance detected by
 - a) Lower string current and
 - b) High module voltage
- 2) Leaking electrolyte detected by
 - a) Watering system
 - b) High cell resistance
- 3) No string ventilation detected by
 - a) No vacuum on ventilation system
- 4) Individual cell short detected by
 - a) Lower string current and
 - b) Low module voltage
- 5) Low capacity cell detected by
 - a) Low module voltage.

Should a string be removed from service during discharge, signals would be sent to the power conversion gear to reduce the battery output level accordingly, and the dispatcher would be advised of the reduced system energy storage capacity.

The static contactor will consist of a pair of SCR devices back to back such that one device is for charging and the other is for discharge. These devices require adequate circuitry for gating them "on".

There will be no commutating circuitry. SCR "turn off" operation will be obtained by de-energizing the gate and, through communication with the power converter equipment, causing the DC Bus current to go to zero for an instant of time (approximately 1/2 cycle).

The SCR devices in the circuit provide isolation between strings such that a failure within a string will not be subject to circulating current from other strings. Neither can one string of battery cells be charged by adjacent strings. These conditions are true because only one SCR in the inverse parallel arrangement is energized during charging to allow energy to flow into the string. During discharge the other SCR is energized to allow energy to flow out of the string.

The amount of power lost in the static contactors at a nominal discharge of 650 amps per string is expected to be 16.4 KW total.

F. System Maintenance Function

The system maintenance function will be performed based on data available from the monitoring system. Many of the points monitored have been described previously. In addition to the previously described points, additional points are described in Table 3-10.

The method of obtaining intelligence to detect grounded conditions is shown in Figure 3-17. This method of detection will cause both voltages to shift in the event a ground is present.

SYSTEM MAINTENANCE FUNCTION
TABLE 3-10

<u>Function</u>	<u>Control Units Required</u>	<u>Instrumentation</u>	<u>Control Monitoring Function</u>
System Ground Detection	None	1 - Ground Detection network in- cluding 2- voltage monitors	Alarm system ground
Cell Failure Detection	None	1155 - Voltage monitors as module voltage	a) Alarm module voltage out of limit high/low as % of norm. established by 1155 modules b) Terminate charge/discharge for certain cell failures
Unit Isolation	1 - Fusible hook stick operated switch per unit or total of 231 switches	231 - Interlock on hook stick disconnect	a) Alarm switch open/close b) Terminate charge discharge function or inhibit its initiation

$V_1 = V_2 = \text{MONITOR}$

$R_1 = R_2 = R_3 = 1 \times 10^6 \text{ OHMS}$

GROUND DETECTION SCHEMATIC

FIGURE 3-17

The major element requiring monitoring in the battery system is the individual cells or increment of cells. Because of the large number of battery cells, these can be expected to have the highest incidence of failure in the system. Further the problem of locating a failed cell without some form of maintenance aid could become both time consuming and dangerous.

The method conceived for monitoring individual cell status is shown in Figure 3-18. Monitoring occurs at the module level. The monitoring/control system will develop daily, the average charge/discharge characteristic for battery modules. Each module will then be compared with the average and individual modules which are out of limits will be alarmed. The alarm will indicate module value out of limits and specify module location. If the out of limit condition is severe enough, the battery string involved will be separated from the system.

The status of all inputs will be summarized periodically in reports prepared by the monitoring system. These reports will be the guide for all battery and battery auxiliary maintenance activity.

1-1A - Monitor voltage across module plus Disconnect

2,3,4,5,2A etc. - Monitor voltage across Module only

MODULE MONITORING SCHEMATIC

3-67

FIGURE 3-18

G. Monitoring and Control System Summary

The preceeding sections have related the different battery auxiliary functions to their monitoring requirements. Table 3-11 summarizes this data for establishing hardware requirements of the monitoring and control system.

As listed in Table 3-11 the input output is composed of the following:

Analog Input Subsystem

1179 millivolt inputs from ground detection, cell voltage, and current shunts.

51 temperature measurements.

Contact Closure Input Subsystem

569 contact closure devices indicating system functions.

Contact Closure Output Subsystem

51 contact closure outputs controlling system functions.

A mini-computer has been selected as the basic logic unit for the monitor and control system.

SUMMARY OF INPUT/OUTPUT
TABLE 3-11

<u>System</u>	<u>Digital</u>	<u>Analog</u>	<u>Comments</u>
Facility	31		Alarm change of state.
	2 CCO	8	Calculate cooling - alarm temperature "out of limits".
Cell			
Ventilation	24		Alarm change of state - terminate Charge/Discharge
	3 CCO		
Battery	5		Alarm change of state.
Temperature	3 CCO	43	Recalculate storage capacity for low temperature
Regulation			alarm high temperature.
Water			
Addition	234		Alarm change of state.
	1 CCO		
Charge/	44		Alarm change of state - terminate Charge/Discharge
Discharge	42 CCO		Contact closure outputs to string static contactor.
		22	Integrate Amp hours storage for Charge/Discharge
			find average of string current - alarm out of limit
			terminate Charge/Discharge.
Maintenance		1,157	Alarm grounded condition
			generate average cell characteristic for Charge/Discharge -
			alarm out of limits.
	231		Alarm change of state for disconnect operation.
TOTALS	569 CCI		
	51 CCO		
	1,230 Analog		

The reasons for this selection include the following:

1. The complexity of the charge/discharge cycle requires integration of too many functions to be executed otherwise.
2. Daily computation of charge/discharge characteristics with related limits for failure isolation are necessary due to aging effects, temperature effects, level of charge effects, rate of charge/discharge effects, etc.
3. Its ability to communicate status and developing situations, allowing control decisions by others.
4. Its ability to relate inputs and make control decisions.
5. Its ability to communicate any status on demand for maintenance decisions.
6. Its ability to accumulate data for later statistical analysis.
7. Its ability to isolate exceptions and respond thereby preventing catastrophic situations from developing.

Figure 3-19 relates the input/output requirements in Block Diagram form to the proposed mini-computer system.

COMPUTER BLOCK DIAGRAM

FIGURE 3-19

An item requiring some explanation appears in Figure 3-19, namely, the isolation elements between the Analog Multiplexer and the Battery Modules.

Because the battery system is totally isolated from ground and is expected to regularly develop ground paths, the analog input subsystem must be designed to have a voltage to ground capability equivalent to the highest DC bus voltage. In this case the voltage is 1000 volts. At the time of this writing no standard equipment for analog multiplexing having this 1000 volt common mode capability can be found.

- a) Relay multiplexers have relays with 500 volt isolation capability.
- b) High speed multiplexers using semiconductor devices are lower rated than the relay multiplexers.

Consequently, the system has been conceived including voltage isolation for each voltage and current input.

Figure 3-20 demonstrates a method of wiring the battery module inputs. This circuit provides individual fuses which isolate a module in the event of an open circuit. The Zener diode and current limiting resistor causes the fuse to blow. Typically the isolation element will have a voltage divider on the input as shown and will require an external power supply. Connection to the analog multiplexer will be by individual twisted shielded pairs of wires. Multi-conductor cables are used to carry these signals to a central mini-computer system.

The typical method of installing this system is shown in Figure 3-21. String system inputs are accumulated in a single junction box. All signals are then connected to the central system through a single cable with 90 twisted, shielded pairs of conductors.

INDIVIDUAL BATTERY
MODULE VOLTAGE
MONITORING SCHEMATIC

FIGURE 3-20

MINI-COMPUTER INSTALLATION

FIGURE 3-21

9. Summary of Nominal Power Losses

The power losses of the cables, static contactors and main buswork are summarized below.

<u>Power Losses @ 650 amps/String</u>	
Inter-Module Cabling	21.5 KW
Static Contactors	16.4 KW
Main Buswork	<u>18.0 KW</u>
TOTAL	55.9 KW

This is 0.56% of the 10 MW discharge rating.

3.3 BATTERY AUXILIARIES COST ESTIMATES

The costs of the peaking battery auxiliaries have been estimated and a summary is shown in Table 3-12. Each major item is broken down to indicate the bases for cost estimates.

Should testing indicate that a method for arsine and stibine disposal be employed, the ventilation scheme could add a scrubber at the discharge end of the system at a cost penalty of approximately \$55,000 (\$1.38/KWH) at the size envisioned (25,000 CFM). The scrubber could probably be located in the fan room already provided. If a larger room would be required, there is adequate area adjacent to the fan room for expansion. Conversely, if the location of the plant and other considerations allowed the use of a simple roof exhaust, the elimination of the ventilation ductwork would save approximately \$25,000 (63¢/KWH).

These costs/KWH are based on the 4-hour rate. The conversion of these costs to a 10-hour rate is a factor of .81, since the 4-hour KWH rating is 81% of the 10-hour KWH rating.

It should be noted that these costs are based on a mature product line for each set of components specified. All one time developmental costs are assumed to have been written off.

TABLE 3-12
Battery Auxiliaries Costs

<u>Building & Slab</u>	<u>Total</u>	<u>\$/KWH</u>
23,100 ft ² @ 15.15 \$/ft ²	\$ 350,000	8.75
<u>Monitoring & Control</u>	442,000	11.05
Computer with input/output	175,000	
Computer startup and software	20,000	
Isolation	86,000	
Cabling	67,000	
Input Devices	16,000	
Static Contactors	78,000	
<u>Ventilation System</u>	48,000	1.20
Ductwork	24,500	
Fans and Stack	23,500	
<u>Acid Containment</u>	110,000	2.75
Concrete Work	100,000	
Excavation & Backfill	10,000	
<u>Buswork & Protection</u>	81,500	2.04
Intermodule Cabling	11,500	
Main Buswork	40,000	
Fuse Disconnects	23,000	
String Disconnects	7,000	
<u>Water Cooling</u>	117,000	2.93
Cooling Tower	54,500	
Piping	47,500	
Pumps, misc.	5,000	
Deionized Loop	10,000	

TABLE 3-12 (continued)

		<u>Total</u>	<u>\$/KWH</u>
<u>Maintenance*</u>		\$ 49,000	1.23
Room & Equipment	34,000		
Gantry	15,000		
<u>Fire System</u>		25,000	.63
23,100 ft ² @ ~\$1.08/ft ²			
<u>Water Addition</u>		33,000	.83
Demineralizer & Controls	5,000		
Piping	22,000		
Reservoirs & Hookups	6,000		
Auxiliaries Total		\$1,255,500	31.39
Battery Costs		\$1,476,000	36.90
Power Conversion (Estimated)		780,000	(\$78/KW)
System Total		\$3,511,500	\$68.29/KWH + \$78.00/KW (\$351.15/KW Total)

*Capital costs, not O&M

Conclusion

If the battery auxiliaries are ranked according to cost, the following listing is formed:

	<u>Auxiliary</u>	<u>Cost</u>	<u>Cost/KWH</u>
1.	Monitoring & Control	442,000	11.05
2.	Building & Slab	350,000	8.75
3.	Water Cooling	117,000	2.93
4.	Acid Containment	110,000	2.75
5.	Buswork & Protection	81,500	2.04
6.	Maintenance	49,000	1.23
7.	Ventilation	48,000	1.20
8.	Water Addition	33,000	.83
9.	Fire System	25,000	.63

The highest cost item, monitoring and control, is one which is presently undergoing rapid technological and cost improvements. During the course of the study, a new monitoring system has become available which will significantly alter the costs associated with monitoring a large number of voltage points. This new system is described and costed in Section 4.5 of this report.

The second-ranked item, building and slab, is considered to be at a minimal cost, commensurate with the requirements. The size of the building, however, can be affected by effective floor space utilization, which is in turn a function of battery module size, system voltage, system rating, and type of cooling used. These items are addressed in Sections 4.1, 4.3, and 4.4.

The third item, water cooling, is the subject of further study in Section 4.3 of this report; its costs are found to be more than justifiable.

The fourth item, acid containment, is one for which the requirements may be unnecessarily stringent. Local codes should be investigated and environmental experts should be consulted to more accurately assess whether such a voluminous containment scheme (essentially for contaminated fire water) is actually required.

The balance of items are considered appropriate in requirements and costs.

4.0 INTRODUCTION

As was previously mentioned, the study has been broken down into two major tasks. The first task, covered in Section 3, is concerned with the definition of the requirements for the auxiliaries, creation of a conceptual design which meets the requirements, and the performance of a cost estimate of that design. Since only one conceptual design is considered, little information is available regarding the effects of permutations around that design.

The second major task to be covered here in Section 4 delineates the effects of changes in auxiliaries design, using the Section 3 conceptual design as a benchmark. Section 4-1 addresses possible areas of hardware sharing with the power converter gear, including the effects of system dc voltage level. Section 4-2 addresses the system reliability by performing a Failure Modes and Effects Analysis (FEMA) on the battery system, as well as investigating the interplay of system dc voltage, level of monitoring and cell failure rate on the system cost and performance. Section 4-3 evaluates the impact of cooling and ventilation systems design with particular emphasis on effects of varying climatic conditions. Section 4-4 evaluates the effects of system rating on auxiliaries costs, and Section 4-5 considers the effects of advances of technology in monitoring and protection devices with the use of large capacity cells.

4.1. Battery/Power Converter Integration

This report has described and defined problems and prospective solutions for peaking battery auxiliary systems. We have thus far dealt only with the battery and its elements. We will consider in this section the effect of sharing the elements of the battery auxiliary system with the power converter equipment.

However, to consider sharing of elements, we must first define some of the elements of the power conversion equipment which will be required for the battery system conceived.

A. Conceptual 10 MW Power Converter

Let us first consider design parameters selected for the battery and the related effects on the power converter. The two most obvious are voltage and current.

1. Power converter voltage considerations.

Using 385 cells in series and an end of discharge voltage of 1.81 volts gives the minimum dc voltage of 697 volts.

Beginning discharge at 1.98 volts/cell = 762 volts

Top of charge at 2.6 volts/cell* = 1001 volts

Assuming the inverter is designed to operate at full current at beginning of discharge with 20% commutation voltage margin and 15° extinction angle, we have

*2.6 volts/cell top of charge is a "standard" value, which allows for cell designs other than the 160-45 (2.45 volts/cell top of charge).

$$762 = \frac{3}{\pi} \sqrt{2} E \times .8 \times \cos 15^\circ$$

where E is the nominal AC line voltage of the source.

$$\text{Thus } E = \frac{762 \pi}{2.4 \sqrt{2} \cos 15} = 730 \text{ volts}$$

The dc voltage available on charge at nominal line and 10° rectification end-stop is:

$$E_{dc} = \frac{3}{\pi} 730 \sqrt{2} \cos 10 = 971 \text{ volts.}$$

This falls short of our requirement of 1001 volts. Hence, we must increase the nominal AC line voltage to 753 volts.

This revises the commutation voltage margin to 22%.

With a nominal line voltage of 753 and 100% station arrester protection on the high side of the transformer, inverter valve transient voltage capability of approximately 3700 volts is required. Two 1800 volt (nominal rating) devices in series can be applied to satisfy this rating.

2. Power converter current considerations.

The dc current for 10 MW at 697 volts dc is 14,350 amps.

Since the maximum average current per thyristor is approximately 800 amps, a minimum of 18 parallel paths, or 6 bridges, can be used. This will require refrigerated coolant. If 8 bridges are employed, the average current drops to 598 amps and straightforward liquid cooling can be used.

The considerations of voltage and current therefore have lead us to a modularity of 8 thyristor bridges and we find our first opportunity for integration by using common liquid cooling means.

The voltage requirement of 2 devices in series leads to 12 devices per bridge. With 8 thyristor bridges the total count becomes 96 thyristors.

The device failure rate will be approximately .6% per 1000 hrs. Thus equipment failure due to thyristor failure can be expected, on the average, every 1736 hours. Assuming 14 hour/day, 5 days per week operation, this corresponds to a failure leading to a partial outage every 6 months, which may be tolerable. If not, device redundancy using 3 devices per string will give more than acceptable mean time to partial outage.

Since the battery strings are fully protected by appropriate fusing against external and internal faults, the power conversion equipment will also rely on this fusing for short circuit protection when fed by the battery.

The fuses in the battery circuit are needed only to clear D.C. fed faults (discharge mode), and there must be adequate A.C. (charge mode) protection in the power conversion gear. Thus, the voltage rating which the fuse must clear is 2.0 volts per cell equivalent to 770 volts. This would be equivalent to a full load current of approximately 700 amps per string with the state-of-the-art cell design. This fuse rating is attainable with minimal fuse development.

D.C. input to the converter equipment therefore does not require short circuit protection. The protective elements in the conversion equipment will be a high speed static dc interrupter for the repeated clearing of inverter commutation faults without fuse blowing, high speed DC breakers for isolation and clearing converter faults, and an ac tie breaker.

This common fusing protection therefore represents the second opportunity for Battery/Power Converter Integration.

As can be seen from Figure 3-1, the power conversion gear is visualized to consist of 4 D.C. modules connected to a single A.C. transformer. Each module consists of two thyristor bridges, a D.C. reactor, a high speed commutating circuit, a high speed D.C. breaker, and reversing switchgear.

The D.C. rating of each conversion module is:

- 2,500 kilowatt

- 762 volts beginning of discharge

- 3,280 amps beginning of discharge

- 697 volts end of discharge

- 3,590 amps end of discharge

- 1,001 volts end of charge

- 525 amps end of charge

The reversing switchgear provides another area for integration of the battery and power conversion gear. Since each string

already has inverse parallel thyristors as static contactors (see Figure 3-16), these could be arranged into a bridge circuit with additional devices as a solid state reversing switch for each string. This will be explored in detail in Section 4-1b(3).

The power conversion equipment will require the monitoring of a fair number of quantities for status annunciation. Many electrical quantities will need to be monitored by analog means for both normal operating and protective considerations. Others can be monitored on a binary ("go - no go") basis.

Since it is intended for the peaking station to be unattended, the monitoring system will require some minimum level of decision making prior to transmission of status. Further this status data must be reflected in normal operation of the Converter Equipment.

It is visualized that the volume and complexities of the decisions will require the Converter Monitoring System to be computer based. Further it is likely that the information processing and transmission capability required will far exceed that of a micro-processor, or even a modest collection of micro-processors. We envisage needing a minicomputer and using only a fraction of its capability.

The monitoring and control system provides another opportunity for integration of the Battery and Power Converter Systems.

Since the battery system will require far more computer capability than the converter, but also less than that available through the use of a "standard" minicomputer, it would be advantageous to combine the hardware requirements, and as much as possible the software, for both the battery system and the power conversion equipment.

There are many items grouped under the heading of Power Conversion Equipment. These items include:

- Main Power transformer
- Power factor correction capacitors
- Harmonic filters
- System Tie Breaker
- Thyristor firing control system

Since we do not visualize methods of integrating items other than those previously discussed, we have not attempted to conceive their form in a total system. We have therefore limited our interest to an awareness of their existence for the purpose of this study.

B. Shared Equipment and Cost Relationship

1. Shared Cooling.

Some form of cooling of the power semiconductors will be required in the power converter design. Two choices have been mentioned, refrigerated cooling and circulated water cooling.

Assuming a design without redundancy, conversion equipment cost would be some \$78/KW on a 10 MW (end of discharge capability) base. With device redundancy, the cost increases to about \$85/KW.

These costs predicate integrating the conversion equipment and battery cooling systems. Thus, they anticipate the "free" availability of 32 gallons per minute of circulating de-ionized water at an inlet temperature no higher than 85°F (effluent temperature then 107°F). Should the coolant not be available, then a 6 bridge conversion equipment with associated cooling, including refrigeration of the coolant, can be provided for the same specific cost - the extra cost of cooling equipment is offset by the saving in inverter costs.

The above cost, however, are assuming only that the power conversion equipment will "Borrow" cooling water from the battery system. The battery system requires de-ionized water for cooling the Main Bus. By getting de-ionized water from the converter cooling system rather than incorporating a second de-ionizer and taking advantage of economies of scale in this cooling system, a savings of approximately \$1/KW or \$10,000 will be realized on the total system. Further effect as higher reliability and increased availability should also be recognized.

2. Shared DC Fault Protection.

The total peaking system as described includes fusing in the battery strings and at the string connection to the main bus plus high speed dc breakers in the converting equipment. The dc breakers are specified due to concern of fuse ability to absorb the necessary energy to clear faults when the reactive elements of the converter are involved.

A complete system design including the reactive elements in the conversion equipment will allow a thorough short circuit analysis to be made. At that point the fuse characteristics can be manipulated with the objective of elimination of the high speed dc breakers. These are expensive devices requiring extensive maintenance if operated frequently. It will be highly desirable to eliminate them.

The cost related to the dc breakers is estimated to be \$120,000 or \$12 per kilowatt. Depending on fuse analysis, this cost can be reduced or eliminated.

The fuses in the battery string which make this savings possible will be the first fuse in the string located at the positive bus. This fuse will be rated for protecting the string and is expected to be the only fuse involved in short circuit protection. The protection provided is 21 fuses at approximately \$4,200 total included in the conceived system.

Therefore when the integration of the battery and converter equipment is considered, the string fuses which were provided for safety during maintenance allows a station cost reduction of \$120,000 or \$12/kilowatt.

3. Battery String Contactor and Reversing Switchgear.

Included in the converter equipment are motor operated switches for reversing the main bus connections to the power converter between charge and discharge cycles. Concurrently static contactors and disconnects have been specified as battery string contactors.

The battery string static contactors are inverse parallel connected thyristors. To build this static contactor into a full thyristor bridge and reconfigure the main bus would allow the motor operated bus reversing switches to be eliminated.

In the conceived battery system, the static contactors are included at \$78,000. The bus reversing switches are estimated to cost \$45,000 for a total system increment of \$123,000 or \$12.30/KW.

If a combination isolation reversing thyristor bridge is substituted the cost is estimated to be \$124,000 or \$12.40/KW.

It therefore appears that there are no equipment extra costs or penalties associated with either choice. However, due to additional losses from the increased number of thyristors, operating losses would increase by .2% in the discharge mode and about .1% in the charge mode. To offset these disadvantages, there is some gain in equipment footprint -- the dc reversing switchgear, being simply motor driven disconnects of conventional form, occupy a considerable pad area -- about 24 square feet, net, per conversion equipment module.

The enclosure for the static disconnect would become higher and possibly wider. However, the space it occupies at the end of the battery string is outlined by the width of the battery module and not its own width. It will therefore occupy no more space because of the addition of the thyristors.

Another penalty paid to use the concept of distributed reversing appears in the loss of safety when the two dc buses must be run on the same vicinity. Further these circuits must enter each string reversing/disconnecting unit. Since the battery represents an extremely low impedance source of energy which cannot be "turned off", any action which brings the two buses together is to be avoided or at least minimized. The results of bus proximity are expected to be catastrophic.

The recommendation would be against the string disconnecting/reversing static units.

Other methods of combining these two functions have been considered. For instance, we can use diodes in conjunction with motor driven disconnects as string isolating switches. Allow these to perform one-half the reversing function with the other half being accomplished at the converter by a motor driven switch as before.

Again the equipment costs are a stand-off. However, for this system a third dc bus is required which imposes a large cost penalty (approximately \$2.00/KW). A gain of efficiency of .07% in discharge on the plus side of the ledger. But, since we again have two buses brought together into each string contactor cabinet with possible catastrophic results, the recommendation is again against integration of this function.

4. Monitoring and Control

The power converter equipment has been described to include monitoring and control functions which can be integrated with that of the battery system.

We have not attempted to define the details of the power converter monitoring as has been done for the battery system. Only a nominal allowance for monitoring has been made for the converting equipment, approximately \$10,000. When this sum is related to the \$175,000 allotted for the battery system, it seems insignificant.

With a complete analysis of the converter equipment and monitoring requirements specified in detail, a better conclusion could be drawn. The \$10,000 allotment in the converter equipment will allow approximately 150 analog points to be monitored and added to the battery computer based monitoring system. Integration of all control and communication functions within a single unit will greatly simplify operating functions, improve reliability and standardize maintenance procedures. It is apparent that a different level of monitoring will be available from the \$10,000 allotment in the converter equipment than will be obtained for the battery system. In the following section on Reliability, the advantages of the level of monitoring specified for the battery will become obvious; without integration, an equal level of monitoring in the converter would require a substantial cost increase, in excess of \$80,000 for computer equipment and software alone.

The shared equipment with associated cost can be summarized as follows:

Item	Integration Cost Advantage
1. Shared Cooling	\$ 10,000
2. Shared D.C. Fault Protection	120,000
3. Combined Reversing/Disconnecting Battery String Contactors	Not Recommended
4. Monitoring and Control	* - 0 -

* \$80,000 penalty if not integrated.

These cost savings can reduce the auxiliaries and power conversion costs substantially, and are tabulated in the conclusions for section 4.1.

C. System voltage effects and Cost Relationship

The cost of the peaking battery system is dependent on the system voltage due to considerations of power converter component sizing, battery module withstand voltage capability, layout, bus design, and protection equipment rating. In order that these terms are compared without the introduction of other extraneous changes in design, it would be appropriate to determine the best choice for overall battery size which would minimize the extraneous factors.

Battery size

The use of 8100 (W) KW 160-45 cells per battery is a selection which yields many choices for system voltage while coming very close to the 40 MWH rating. Table 4-1 indicates three total cell selections and the number of strings available. Figure 4-1 shows the system voltage vs the number of parallel strings for the three cases.

Table 4-1

<u>Number of Cells</u>	<u>Total Capacity</u> MWH	<u>Available Nos. of Strings</u>
8100	39.99	1,2,3,4,5,6,9,10,12,15, 18,20,25,27,30
8085	39.92	1,3,5,7,11,15,21,33,35
8064	39.81	1,2,3,4,6,7,8,9,12,14,16, 18,21,24,28,32

Both the 8064 and 8100 cell cases have equal numbers of choices available in the range of interest for voltage, but the 8100 cell case is preferred since it has closer to 40 MWH of available energy.

40 MWH BATTERY

FIGURE 4-1

One other advantage of the 8100 cell desing is that a single module size of 9 cells in series and a single unit size of 5 modules (45 cells, 90V) can be used for all voltages. This is shown in Table 4-2.

Table 4-2

Voltage	# Strings	Cells/String	Cells/Module	Module/Unit	Unit/String
810	20	405	9	5	9
900	18	450	9	5	10
1080	15	540	9	5	12
1350	12	675	9	5	15
1620	10	810	9	5	18

This is convenient for comparison purposes, because the same basic floor utilization (per module) is used throughout, so any changes in building size (and cost) would be purely a matter of system voltage not complicated by changes in the basic module size. Thus the 8100 cell battery will now be used instead of the 8085 cell battery as a constant in future cell comparisons.

Effect of a 9 cell module (8100 cell battery)

A building size of 110 FT X 210 FT (23,100FT²) is required for a battery of 770 VDC nominal and 8085 cells (21 strings). Should this design be altered to one of 8100 cells at 810 volts (20 strings) a 9 cell module design, 5 modules/unit, 9 units/string is used. Each string is 75 FT long on a 11.17 FT pitch, so the building size is changed to 95 ft X 233 ft (22,135 FT²) for a slight (4%) improvement in floor area. This improvement (worth \$14,600) is due to the better floor utilization of a module with 9 cells versus a module with 7 cells. This basic change also has an impact on the monitoring costs, since 900 module voltages are now necessary, versus the original 1155. This alone would reduce the monitoring costs by \$51,000. Elimination of one of the static contactors is worth an additional

savings of \$3,700. A savings of about 20% in the ventilation ductwork (worth \$4,900) would be made because of the elimination of one string and a 12% shortening of the remaining string ducts. It is expected that an increase in the module base section will be necessary to handle the increased weight and length of the 9 cell module. This cost penalty (going from 6" to 8") is worth approximately \$6,000. A redesigned bus using two sections (instead of the former 3) would further reduce the cost to \$34,000 for the main bus alone. Reduction of the number of inter-connecting cables between modules reduces that cost to \$9,000. Reduction of the number of unit disconnect fuses lower that cost to \$18,000.

These costs are summarized in Table 4-3. The net effect is a cost savings of 4.9% to a total of \$1,172,500 (\$29.31/KWH) for the 8100 cell system. This is the low voltage benchmark for future comparisons.

The change in design also changes the nominal losses in the cabling, buswork and contactors, as are summarized below:

<u>Power Losses @ 650 amps/String</u>	
Inter-Module Cabling	17.5 KW
Static Contactors	15.6 KW
Main Buswork	<u>25.1 KW</u>
TOTAL	58.2 KW

This is 0.58% of the nominal 10 MW discharge rating.

Table 4-3
810V Battery Auxiliaries Costs

<u>Building & Slab</u>		<u>Total</u>	<u>\$/KWH</u>
22135 ft ² @ 15.15 \$/ft ²		\$335,400	8.39
<u>Monitoring & Control</u>		387,000	9.68
Computer with input/output	158,000		
Computer startup and software	20,000		
Isolation	67,000		
Cabling	52,000		
Input Devices	16,000		
Static Contactors	74,000		
<u>Ventilation System</u>		43,100	1.08
Ductwork	19,600		
Fans	23,500		
<u>Acid Containment</u>		110,000	2.75
Concrete Work	100,000		
Excavation & Backfill	10,000		
<u>Buswork & Protection</u>		68,000	1.70
Intermodule Cabling	9,000		
Main Buswork	34,000		
Fuse Disconnects	18,000		
String Disconnects	7,000		
<u>Water Cooling</u>		117,000	2.93
Cooling Tower	54,500		
Piping	47,500		
Pumps, misc.	5,000		
Deionized Loop	10,000		
<u>Maintenance</u>		49,000	1.23
Room & Equipment	34,000		
Gantry	15,000		

Table 4-3 (continued)

<u>Fire System</u>		
22,135 ft ² @ \$1.08/ft ²	24,000	.60
<u>Water Addition</u>		
	33,000	.83
Demineralizer & Controls	5,000	
Piping	22,000	
Reservoirs & Hookups	6,000	
Subtotal	\$1,166,500	29.16
8" Base Penalty	6,000	.15
TOTAL	\$1,172,500	\$29.31/KWH

Module Design Factors for Increased Voltage

It was indicated earlier that a 6 inch high base for the module would be expected to be adequate for stand-off over an acid-contaminated surface for a nominal voltage of 770 VDC. This is equivalent to a height/voltage ratio of 7.79 inches/KV.

To maintain the system standoff capability as the DC voltage is increased, it would be reasonable to maintain the same height/voltage ratio. The height of the base for the 1620 VDC (nom) situation would have to be 12.48" high. It is estimated that ~40% of the weight of the base is in the height-related items (risers and side walls). Applying an original cost of ~\$40 per module for the total base cost at 770 VDC, one can derive the effect of system voltage on battery base cost as shown in Figure 4-2.

Effect of Operating Voltage on Costs.

The 810 volt, 8100 cell design (20 strings) would employ a layout of strings as shown in Figure 4-3. The strings are 75 feet long, on a 11.17 foot pitch, with a total building size of 95 feet x 233 feet (22,135 ft²). If a 1620 volt (10 string) design is considered, the layout of the strings is considerably changed, as shown in Figure 4-4. The strings are now 150 feet long, on a 11.17 foot pitch, to yield a total building size of 170 feet x 120 feet (20,400 ft²). This change further reduces the building costs to \$309,000. Main bus costs are reduced to ~ \$20,000, whereas the penalty for the required higher module bases (~\$20,000 over the original 6" high base) must be factored. The monitoring and control system would not appreciably change from the 810 volt case, as the module isolators are still within their rating. The number of string contactors has been

FIGURE 4-2

BASE HEIGHT VS VOLTAGE

BASE COST VS VOLTAGE

FIGURE 4-3 810 VDC, 8100 CELL LAYOUT (20 STRINGS)

FIGURE 4-4 1620 VDC, 8100 CELL LAYOUT (10 STRINGS)

cut in half, but their voltage rating has doubled, so the contactor cost would only be marginally reduced. The price of the fused disconnect is expected to rise due to the higher voltage rating (to ~\$35,000). The auxiliaries costs for the 1620 volt design are summarized in Table 4-4.

The power losses for the 1620 VDC design are summarized below.

Note that the only effective change is in the main buswork area:

Power Losses @ 650 amps/String

Inter-Module Cabling	17.5 KW
Static Contactors	15.6 KW
Main Buswork	<u>6.0 KW</u>
TOTAL	39.1 KW

This is 0.39% of the nominal 10 MW discharge rating.

TABLE 4-4

1620V Battery Auxiliaries Costs

<u>Building & Slab</u>		<u>Total</u>	<u>\$/KWH</u>
20,400 ft ² @ 15.15 \$/ft ²		\$ 309,000	7.73
<u>Monitoring & Control</u>		380,000	9.50
Computer with input/output	158,000		
Computer startup and software	20,000		
Isolation	67,000		
Cabling	52,000		
Input Devices	16,000		
Static Contactors	67,000		
<u>Ventilation System</u>		43,100	1.80
Ductwork	19,600		
Fans	23,500		
<u>Acid Containment</u>		110,000	2.75
Concrete Work	100,000		
Excavation & Backfill	10,000		
<u>Buswork & Protection</u>		69,000	1.73
Intermodule Cabling	9,000		
Main Buswork	20,000		
Fuse Disconnects	35,000		
String Disconnects	5,000		
<u>Water Cooling</u>		117,000	2.93
Cooling Tower	54,500		
Piping	47,500		
Pumps, misc.	5,000		
Deionized Loop	10,000		

TABLE 4-4 (continued)

<u>Maintenance</u>		\$ 49,000	1.23
Room & Equipment	34,000		
Gantry	15,000		
<u>Fire System</u>			
20,400 ft ² @ ~\$1.08/ft ²		22,000	.55
<u>Water Addition</u>		33,000	.83
Demineralizer & Controls	5,000		
Piping	22,000		
Reservoirs & Hookups	6,000		
Subtotal		\$1,132,100	28.30
12" high base penalty		20,000	.50
Total		\$1,152,100	\$28.80/KV

Power Conversion Costs

As can be seen from the description of the power converter, there is a maximum end of charge capability of 1001 volts at a line voltage of 753 VAC. This is nearly a perfect match of the transient voltage rating of the devices (3800 volts) versus the max transient condition (3700 volts). If, however, the base case for comparison of voltage is changed to 810 volts (nominal), the power conversion gear would be capable of only 2.47 volts per cell (at 753 volts ac). If the transient margin were reduced to zero, the ac voltage would increase to 773 volts, and the end of charge voltage would rise to 1028V, equivalent to 2.54 volts per cell. This is considered to be adequate for the (W) KW160-45 cell design. If the full 2.6 volts per cell would be required, higher voltage class components would be required at a cost penalty of ~\$1/KW.

The base case for comparison of effect of dc voltage variation is thus 810 VDC (nominal) with a maximum end of charge capability of 2.54 VDC. The number of dc power conversion modules is 4, with a base power rating of 2.5 MW. As the voltage level of the battery is increased, the number of power conversion modules decreases and the power conversion cost per KW also decreases. Thus we can see in Table 4-5 the effects of possible quantum increases in dc voltage level on conversion equipment specific costs and on the battery string configuration.

Table 4-5
8100 CELL BATTERY CONFIGURATIONS

<u>DC Voltage Nominal</u>	<u>Conversion Equipment Module Power</u>	<u>Cost, No Redundancy</u>	<u>Cost, With Redundancy</u>	<u>No. of Strings</u>
810	2.5 mW	\$78/kW	\$85/kW	20
1080	3.33 mW	\$67/kW	\$72/kW	15
1620	5 MW	\$62/kW	\$66/kW	10

Against these gains must be weighed possible increases in cost and decreases in reliability for the battery installation, together with the increasing impact of power conversion equipment outages on system availability. Also, at the present time dc fusing for the 1620V/5 MW case is expected to be available with modest development, and thus would become an important item in any development plans.

Overall Effect of Voltage on System Cost

Table 4-6 summarizes the cost benefit to be gained from increased DC voltage. There is a net savings of 5.3%, or about \$180,000 to be gained in system capital costs by going to the higher voltage (1620 VDC) design. The section on reliability will assess the net costs of partial outages in each voltage design. When these costs are combined with the capital costs of table 4-6, the net impact of DC voltage on system costs can be more thoroughly evaluated.

Table 4-6

Voltage Effect on Total Battery System Cost

	810 VDC		1620 VDC	
	Total	\$/KWH	Total	\$/KWH
Battery (8100cells)	1,476,000	36.90	1,476,000	36.90
9 Cell module base Penalty	6,000	.15	20,000	.50
Auxiliaries	1,166,500	29.16	1,132,100	28.30
Power Converter (w/o redundancy)	780,000	\$78/KW	620,000	\$62/KW
<hr/>				
TOTAL	\$3,428,500	\$66.21/KWH + \$78/KW	\$3,248,100	\$65.70/KWH + \$62/KW
		(\$342.85/KW Total)		(\$324.81/KW Total)

4.1 CONCLUSION

A cost improvement in the battery and power conversion gear of \$130,000 could be made by integrating cooling systems and dc fault protection gear at 810 VDC. Integration of monitoring and control gear does not show a significant cost improvement, due to differences in the type of monitoring and control between the two systems. A 1620 VDC battery system, compatible with the highest nominal dc fuse rating presently available, shows an initial cost savings of \$180,400 compared to a 810 VDC system without integration.

If the cooling systems and D.C. fault protection were integrated at the higher voltage, the net cost effect would not be the sum of the two effects taken independently, since there would be only two high speed D.C. breakers to be eliminated in the 1620 VDC case, instead of four in the 810 VDC case.

The costs effects are summarized below:

Nominal Voltage	<u>Total Facility Costs*</u>			
	w/o Integration		Integrated	
	\$ Total	\$/KW @ 4 hr	\$ Total	\$/KW @ 4 hr
810 VDC	\$3,428,500	\$342.85	\$3,298,500	\$329.85
1620 VDC	\$3,248,100	\$324.81	\$3,168,100	\$316.81

*Includes battery, auxiliaries and power converter.

4.2 RELIABILITY

This section deals with the reliability of the battery and auxiliaries. Because there is such a large number of components and the interaction among them is not obvious, it was deemed appropriate to conduct a Failure Modes and Effects Analysis (FMEA) on the conceptual design of section 3.

4.2(a) FMEA Analysis

"Conduct an FMEA on a nominal design to identify the criticality of certain types of failure and the required corrective action."

This task has been performed using (W) Corporate procedure by raising the following questions for each component in the assembly:

1. In what manner (mode) can the item fail under normal use or reasonably foreseeable misuse.
2. For each mode of failure, what are the root causes of this failure mode.
3. For each mode of failure, what are the effects at the system level.
4. What is the level of importance of each effect: Importance is the combined weight of probability (likelihood of occurrence) and criticality (impact on the system if it happens). The following weights have been used in this analysis:

<u>PROBABILITY</u>		<u>CRITICALITY</u>	
WEIGHT	LEVEL	WEIGHT	LEVEL
4	very likely	4	hazard (personnel related)
3	fairly probable	3	loss of operating revenue
2	not too likely	2	effect on environment
1	unlikely	1	harm to equipment

IMPORTANCE (WEIGHT) = PROBABILITY (WEIGHT) + CRITICALITY (WEIGHT)

5. Starting with the most important items first, what corrective action is needed to prevent or counteract each significant potential effect.

An FMEA has been completed for each of the following subsystems of the conceptual design of Section 3.2 (refer to Section 4.2(c)):

1. Ventilation
2. Acid Containment
3. Maintenance Gear
4. Module Assembly
5. Monitoring and Control
6. Electrical Protection
7. Electrolyte Water Addition
8. Temperature Control
9. Facilities

The FMEA in its detailed entirety is shown in Section 4.2(c). It has provided inputs to each reliability subtasks. Key items which have surfaced relating to 4.2a are tabulated in Table 1.

The purpose of this analysis is to surface and document as many potential problem areas as could occur under normal use or reasonably foreseeable misuse of the system elements. Many of these considerations have been made as part of the normal design process. The FMEA, however, provides documentation and structure to this process. Of special relevance is the importance rating of each potential effect, which determines the extent of further consideration that is warranted. This has resulted in a more detailed analysis of potential problem areas and in some cases has required alternative design approaches and trade-off studies. It recommends areas for further study where detailed solutions appear to be out of the scope of the subject conceptual study.

The top items discussed in Table 1 have importance weights of 7, 6 or 5. These include all personnel hazard items which range from unlikely to very likely. It also includes all loss of revenue items which range from not too likely to very likely. Items of lesser importance can be gleaned from the detailed FMEA.

Unless noted by an asterisk (*), the corrective action items listed in Table 1 are already incorporated in the conceptual design.

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
1-a-3	7	<p><u>Purpose</u> - To prevent hydrogen build-up because of a closed inlet or a blocked or clogged filter.</p> <p><u>Action</u> - Provide detection of a closed-off filter by flow measurement through the duct-work. Requires periodic inspection and maintenance.</p>
1-d-1	7	<p><u>Purpose</u> - To prevent H₂ explosion and noxious gas buildup due to blocked ducts, open ducts or connections.</p> <p><u>Action</u> - Provide flow detection through duct-work for module and strings and detection for loss of vacuum with a pressure/vacuum switch. Conduct periodic visual inspection and maintenance.</p>
3-VI-3	7	<p><u>Purpose</u> - To prevent battery wash-down from causing a shock hazard when wetting batteries. Condition exists until they are dry.</p> <p><u>Action</u> - To be evaluated, i.e. distributed grounding system, high pressure wash-away of surface acid with deionized water, minimize moisture traps, etc.</p>
1-a-5	6	<p><u>Purpose</u> - To prevent dust and acid mist build-up in duct-work which could lead to tracking paths.</p> <p><u>Action</u> - Provide periodic inspection and cleaning.</p>

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
1-b-2	6	<p><u>Purpose</u> - To prevent the consequence of a false indication that the ventilation air flow is normal (when the flow really is zero).</p> <p><u>Action</u> - Calibrate normal setting when system is ON and LO setting when fans are off (through the NO/NC contacts of the low set point). Requires further evaluation.</p>
1-c-1	6	<p><u>Purpose</u> - To prevent noxious gases and explosive H₂ mixture from leaking into the building through a leaky or clogged flashback arrester.</p> <p><u>Action</u> - Assure documented precautionary procedures during fabrication, installation and service of flashback arresters. Provide building monitor for H₂ detection. Noxious gas detection to be further evaluated.</p>
1-e-1	6	<p><u>Purpose</u> - To prevent loss of vacuum on batteries and buildup of explosive and noxious gases.</p> <p><u>Action</u> - Provide computer alarm through flow detector. Investigate fail safe mechanisms.</p>
2-c-3	6	<p><u>Purpose</u> - To prevent excessive acid fumes and combinational fumes from acid attack on other materials that might be in the trenches.</p> <p><u>Action</u> - Provide periodic trench inspection and maintenance. Consider existing acid detection signals as alarms to this condition.</p>

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
3-III-a-1	6	<p><u>Purpose</u> - To prevent motorized gantry crane from causing a hazard due to battery dropping on personnel and/or acid spill during hoist operations.</p> <p><u>Action</u> - Provide operator control (guidance), tip proof hoisting procedure, drop proof design of hoist and backup safety cable. Assure appropriate structural provisions on batteries for safe hoisting (additional eye-let for safety cable).</p>
3-III-c-1	6	<p><u>Purpose</u> - To prevent burns or eye problems and to maximize control effectiveness if they occur during battery maintenance, change over, etc., when using motorized gantry.</p> <p><u>Action</u> - Water in gantry reservoir must be assured via interlock to drive train. Assure fail safe water discharge system (gravity feed vs. pump dependency). In addition, provide portable container of neutralizing solution. (Assure adequate eye wash stations along gantry route which will be connected to building water supply).</p>
3-V-a-1	6	<p><u>Purpose</u> - To prevent motorized hoist from causing hazard due to battery dropping on personnel and/or acid spill.</p> <p><u>Action</u> - (Refer to 3-III-a. Provisions should be the same as 3-III-a regarding control of the hoist.</p>
3-V-b-1/2	6	<p><u>Purpose</u> - To prevent H₂ explosion and provide gas control (stibine, arsine).</p> <p><u>Action</u> - Precautions and controls in storage-room should be equal to those in the battery room. Provide H₂ gas detection and adequate ventilation (and control per 1-d-1). Provide arsine, stibine detection.*</p>

*Indicates not provided in conceptual design.

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
3-V-c-2	6	<p><u>Purpose</u> - To prevent H₂ explosion and provide noxious gas control(stibine/arsine).</p> <p><u>Action</u> - All maintenance charging should be done in storage room(if normally partitioned).</p>
5-d-3	6	<p><u>Purpose</u> - To prevent charge buildup in ductwork and subsequent sparking, leading to explosion.</p> <p><u>Action</u> - Provide humidity control to automatically actuate a humidifier until safe humidity level is reached.</p>
5-d-4	6	<p><u>Purpose</u> - To prevent problems due to condensation.</p> <p><u>Action</u> - Refer to 3-VI-c (page 4-71).</p>
6-b-3	6	<p><u>Purpose</u> - To prevent unit cables from arcing or burning which could effect personnel.</p> <p><u>Action</u> - Assure design maximizes battery to ground isolation in the battery string configurations. Backup design with a ground fault detector which is part of a trip circuit.</p>
6-e-1	6	<p><u>Purpose</u> - To prevent shock hazard to personnel servicing modules.</p> <p><u>Action</u> - (Same as 6-b-3)</p>
1-e-1,2	6	<p><u>Purpose</u> - To prevent an explosive hazard due to loss of air/gas balance in the string duct work.</p> <p><u>Action</u> - Provide the modulating dampers with limited control about the nominal such that they can never be set in either extreme of full open or full closed.</p>

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
1-c-2	5	<p><u>Purpose</u> - To prevent explosion in building or battery due to leaking H₂ gas.</p> <p><u>Action</u> - Assure documented precautionary test procedures during fabrication, installation and service of flashback arrestors, to prevent fractures, junction leaks or clogging.</p>
1-d-2	5	<p><u>Purpose</u> - To prevent explosion in duct work due to static charge buildup.</p> <p><u>Action</u> - Provide investigation for minimizing static charge buildup i.e.: controlled humidity, conductive coating strip in duct work, etc.</p>
1-d-3	5	<p><u>Purpose</u> - To prevent isolated cell explosion due to static charge buildup in duct work.</p> <p><u>Action</u> - Investigate an acceptance test for each flash back arrestor in its installed state.</p>
1-d-4	5	<p><u>Purpose</u> - To prevent poor connections in the duct work system which could lead to a leaky ventilation system or could impair the effectiveness of the flash back arrestors.</p> <p><u>Action</u> - Provide for mechanically sound maintainable and replaceable leak joints such as screw connections, compression type fittings, O-ring flange fittings, etc. Develop initial and periodic leak tests.</p>
1-f-1 1-f-2	5	<p><u>Purpose</u> - To prevent loss of adequate battery ventilation.</p> <p><u>Action</u> - Provide a flow switch in each string duct work to shut down the system if there is loss of flow in <u>any one</u> duct.</p>

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
2-a-5	5	<p><u>Purpose</u> - To prevent shock hazard due to battery case leakage of electrolyte.</p> <p><u>Action</u> - Provide for ground fault detection system. Provide periodic visual inspection for leakage.</p>
2-a-6	5	<p><u>Purpose</u> - To prevent cell acid release due to external short circuits.</p> <p><u>Action</u> - Provide for the controlled fusing (or melting) of terminal or connection to open under short circuit conditions.</p>
2-c-1	5	<p><u>Purpose</u> - To prevent a personnel hazard due to an overflow in an acid spill trench.</p> <p><u>Action</u> - Design trenches for worst case capacity condition. Provide for periodic inspections of the trenches. Clean out when necessary. Provide initial and periodic calibration of detectors.</p>
3-I-c	5	<p><u>Purpose</u> - To prevent shock to personnel due to conductivity in cell make-up water or cooling water.</p> <p><u>Action</u> - Provide grounding of the water thru a metallic fitting or grounding strap at each module.</p>
3-I-d	5	<p><u>Purpose</u> - To prevent shock to personnel when servicing equipment.</p> <p><u>Action</u> - Strap is grounded at the time of servicing equipment. Advantages and disadvantages of this technique need to be carefully investigated.</p>
3-II-1	5	<p><u>Purpose</u> - To avoid computer missed detection of malfunctioning modules and to avoid false alarm of functioning modules by the computer.</p> <p><u>Action</u> - Calibrate computer module detection initially and periodically.</p>

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
3-III-b-2	5	<p><u>Purpose</u> - To prevent an acid spill due to a collision or lurch of the gantry crane.</p> <p><u>Action</u> - Assure appropriate guidance of the crane along the battery. i.e.: use of a fixed guide rail*, positive steering system, acceleration/velocity governor, operator skill, etc.</p>
3-III-d-2	5	<p><u>Purpose</u> - To prevent an operator from standing on the gantry walkway while it is in motion.</p> <p><u>Action</u> - Assure an "operator present" interlock (mechanical or electrical) is tied into the traversing system.</p>
3-III-g-1	5	<p><u>Purpose</u> - To prevent a catastrophe to personnel due to a collapse of the gantry crane from overstress or acid corrosion of the electrically non-conductive supporting members.</p> <p><u>Action</u> - Assure that the material chosen is structurally secure, is electrically non-conductive and is chemically insensitive to acid attack.</p>
3-IV-a-1	5	<p><u>Purpose</u> - To prevent acid burns to personnel due to misuse or nonuse of safety gear.</p> <p><u>Action</u> - Provide education on required safety habits and provide instructions on use of the equipment provided for their safety.</p>
3-V-b-3	5	<p><u>Purpose</u> - To prevent H₂ explosion and control noxious gas (arsine, stibine).</p> <p><u>Action</u> - Same as 3-V-b-1/2.</p>

*Indicates not included in conceptual design.

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
3-VII-d	5	<p><u>Purpose</u> - To prevent H₂ explosion due to sparking or short circuit by tools.</p> <p><u>Action</u> - Provide highly insulated tools. Use non-metallic tools where possible or practical.</p>
4-a-1	5	<p><u>Purpose</u> - To prevent dumping of acid due to failure of a cell base on hoisting.</p> <p><u>Action</u> - Provide initial structural qualifications testing on battery base. Have lifting lugs and supports on integral part of the battery base structure, etc.</p>
5-a-1/2	5	<p><u>Purpose</u> - To prevent overcharging/undercharging of batteries due to an error in the module voltage transducer.</p> <p><u>Action</u> - Qualify transducer to be compatible with the environment (temperature, humidity, resistance, etc.). Set up test procedure, calibration procedure and periodically implement. Provide computer program to have a running comparison of all 21 string voltages. Set up limits based on the moving voltage averages over the charge-discharge cycle.</p>

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
5-b-2	5	<p><u>Purpose</u> - To prevent overcharge/under-charge due to inability to shut-off string via computer controlled static switch.</p> <p><u>Action</u> - Current monitoring will indicate malfunction of static switch. Set up warning system to operator for predetermined time, then program to shut down system.</p>
6-a-2	5	<p><u>Purpose</u> - To prevent ground fault shock hazards.</p> <p><u>Action</u> - Provide periodical cleaning of bus trench of any accumulative acid or debris and provide a ground fault detector (see 6-b-3).</p>
6-e-2	5	<p><u>Purpose</u> - To prevent inadvertent shutdowns due to the high sensitivity of the ground fault detection device.</p> <p><u>Action</u> - Assure a shutdown occurs when 2 (or more) ground faults are detected and design 1 detected alarm as a warning to the control room only. Provide a sufficient number of detectors at designated key locations which are sufficiently sensitive to detect a fault at their particular building locations*.</p>

*Indicates not included in conceptual design.

TABLE 1

<u>FMEA Item No.</u>	<u>Importance Weight</u>	<u>Description of Corrective Action</u>
7-a-2	5	<p><u>Purpose</u> - To minimize the risk of a system shutdown due to loss of pump pressure in electrolyte water addition assembly.</p> <p><u>Action</u> - Assure adequate water supply for electrolyte addition assembly with sufficient pressure, flow, level monitoring and redundancy in the pumping system.</p>
8-b-1	5	<p><u>Purpose</u> - To prevent high temperature in cells (hot spots).</p> <p><u>Action</u> - Assure cell voltage monitoring has enough sensitivity to detect cell temperature change via Δ Cell Voltage vs. Δ Cell Temperature characteristic and/or provide adequate cooling water flow detectors and temperature monitors.*</p>
9-a-3	5	<p><u>Purpose</u> - To prevent fire due to overheating of the building heating and ventilation system.</p> <p><u>Action</u> - Provide for a early warning temperature rise, with remote operation of the heating shutdown controls. Turn on sprinkler system at a predetermined critical temperature.</p>
9-a-9 9-a-10	5	<p><u>Purpose</u> - To prevent explosions from accumulated H₂ and to prevent toxic gas buildup because of building ventilation problems.</p> <p><u>Action</u> - Assure the detection of fan failure and provide for H₂ detection in strategic places.</p>

*Not included in conceptual design.

4.2(a) CONCLUSION

The number of corrective actions of importance weight 5 or higher which are not included in the conceptual design are few and are summarized below:

1. Provide arsine and stibine detection. Because these toxic gases, if generated, are effectively removed via the ventilation ductwork, and because the operation of the battery is not permitted if the ventilation system is inoperative, it is felt that detection of arsine and stibine is not routinely required. Hand-held instruments may be necessary to assure that an "inoperative" building does not have unsafe levels of arsine and stibine.

2. Provide maintenance gantry guide rail. It is felt that an effective guide rail system to avoid collisions of the gantry and string components would create more problems (tripping hazard, site for water puddling, etc.) than would be solved. The gantry would have good human factors engineering applied to the design to make guidance and operation straightforward.

3. Provide multiple ground fault detectors. The use of redundant detectors is to be adopted in future designs.

4. Provide electrolyte temperature monitors. It is expected that module temperature information would provide the assurance that the cooling system avoids hot spots. Future systems should employ such safeguards, or depend upon routine inspection and documentation of individual module operating temperatures.

4.2(b) Parametric Analysis: Costs vs Cell Failure Rate

The maintenance costs of the battery system are expected to be related to the rate of cell failures, ease of locating and repairing the failure, and the fraction of the total system debilitated by the failure. The first item, cell failure rate, is taken to be an independent parameter in the analysis. The second item, ease of locating and repairing the failure, is dependent on the type of monitoring system. A predictive system, such as in the conceptual design, is able to detect incipient cell failures before the string in which the cell is located must be shut down. Maintenance crews can be scheduled in advance, thus providing improved efficiencies in cell/module replacement. This reduces both labor costs and downtime. A non-predictive system would be a simpler type, which would provide no warning of shutdown, but would isolate a string when one of its cells goes out of normal operating bounds.

The last item, fraction of system lost for one failure, is related to the system operating voltage. This is so because for a given total number of cells, a higher operating voltage results in a fewer number of parallel strings; since a single cell failure will necessarily remove an entire string from service until repair/replacement is effected, the fraction of the total system lost for a single failure is also a function of voltage.

The combined effects of the above on annual maintenance costs are summarized below. The derivations and conclusions follow.

Figure 4-5 shows the calculated annual combined cost of maintenance labor and energy loss as a function of early warning capability, bus voltage (number of parallel strings), and cell failure-rate. Because of linearity and a common zero origin of the curves, the following failure cost factors are easily obtained.

Failure Cost Factors Annual \$ per 1%/Year Failure Rate				
<u>Monitoring System</u>			(Effect of Monitoring)	
	Predictive	Non-Predictive		
Voltage	810V	26,020	40,700	$\Delta_M = (14,680)$
	1620V	26,930	49,820	$\Delta_M = (22,890)$
(Effect of Voltage)		$\Delta_r = (910)$	$\Delta_r = (9,120)$	

Cell failure-rate was judged to lie in the range .01% cell/failure/year to 10% cell/failures/year with almost absolute certainty. As the cells age over the useful life of the system, they are expected to increase somewhat in failure-rate. The average system cell failure-rate will, therefore, increase with system age although a slight offset to this effect will be due to cell attrition requiring replacement with newer cells. The Table 2 sensitivity factors can be used to estimate the resulting cost increase with any estimated increase in failure-rate.

FIG. 4-5

It is noteworthy that these sensitivity figures are annual rates. Any consideration for preventive investment, i.e., the initial and operating costs of predictive monitoring, needs to be weighed against the sum of each estimated yearly saving over the useful life of the system.

Cost Analysis

There are two major cost components which are due to the unreliable performance of cells and when combined comprise the total cost of cell unreliability. (This model does not include the cost due to failures of system components other than cells.) The first cost component is the cost of maintenance labor, and the second represents the cost of power loss due to each cell failure which results in a temporary string outage.

Maintenance Labor Cost

The maintenance manpower cost associated with the cell failure repair can be rationalized as follows:

TABLE 2
Labor Costs of Cell Failures

<u>Operation</u>	<u>Non-Predicting Monitor</u>	<u>Predicting Monitor</u>
Notification	1.0 hrs lost time	Can be scheduled in advance
Travel	1.5 hrs	
Trouble Shooting	1.5 hrs	1.0
Replace	3.0 hrs	3.0
Number of Repairs	1 repair	Schedule 2 repairs
Average Repair Time	6 hrs/cells	4 hrs/cell failure
Man Hrs/Repair @		
2 Men/Repair	12 hrs/cell failure	8 hrs/cell failure
Costing at \$20/hr	\$240/cell failure	\$160/cell failure

Figure 4-6 graphically displays the estimated maintenance cost associated with two distinct options in monitoring system problems, predictive and non-predictive. The cost of labor is observed to be independent of string voltage.

Cell Failure Cost

The cost of a cell failure not only includes the replacement cost of the failed cell at \$150/cell* but the impact of losing the series string to which the cell belongs until the failed cell replacement is made. This loss is assumed to be equivalent to the string power rating for the downtime during the discharge mode.

For a monitoring system which is non-predictive, i.e., does not provide early warning that shutdown may occur, the average number of lost discharge hours per failure is taken to be 4.5 hours/ failure. This is calculated assuming a random distribution of failures only during the charge or discharge cycles (not during idle periods), with an assumed total repair cycle time of approximately 10 hours per failure. This accounts for the lost discharge time while waiting for the string to be inserted back into the battery in the proper charge/discharge phase.

For a monitoring system which is predictive, i.e., could recognize incipient failures before they dictated string shutdown, and would provide early warning of this event for timely preventative maintenance scheduling, the average number of lost discharge hours per failure is taken to be .45 hours/failure. This allows for the condition that demand maintenance can be effectively performed during idle periods 90% of the time.

*Approximately \$30/KWH assuming a recycled cell.

FIGURE 4-6

The energy loss mathematical model is:

$$\text{Lost Energy} = \left(\frac{\text{Total String Cells}}{n \text{ strings}} \right) \left(\frac{\text{Power Loss}}{\text{String Cell}} \right) \left(\frac{\text{String Hours Downtime}}{\text{Cell Failure}} \right) \left(\frac{\text{Cell Failure}}{\text{Year}} \right)$$

where:

1. The total usable energy per year is based on a system with a capacity of 10 MWH @ 4 hours/day, 5 days per week, 50 weeks per year or 10,000 MWH/year.
2. The total # of cells chosen for the evaluation was 8,100, since this gives a versatile string combination selection and is the closest to providing 40 MWHR capacity, as was earlier discussed.
3. Calculations were made for $n = 1, 5, 10, 15, 20$, and 25 strings.
4. Cell failures per year ranged from .1% to 10% per year of the 8,100 cells.
5. As stated before, $\frac{\text{string hours downtime}}{\text{failure}}$ is 4.5 hours for unpredictable monitoring and .45 hours for predictive monitoring.
6. Power lost per string cell is calculated from $\frac{10,000 \text{ MWH/year}}{8100 \text{ cells}} \times \frac{\text{yr}}{50 \text{ weeks}} \times \frac{\text{week}}{5 \text{ days}} \times \frac{\text{days}}{4 \text{ hrs}} = 1.2345 \text{ KW/cell}$
7. Voltages are calculated at 2V cell.
8. It is assumed 1 cell will fail at a time.
9. A cell failure results in shutdown of its string via the monitoring system control of the string contactor.

10. The impact of a string shutdown is the loss of that string for a period of time to allow for repair/replacement. This loss is assumed to be equivalent to the string power rating for the downtime during the discharge mode.

Figure 4-7 shows the energy loss vs cell failure rate for six string voltage combinations for each case of:

- (a) predictive monitoring
- (b) non-predictive monitoring

Note that for a given failure rate, the greater number of parallel strings provides for a substantially smaller energy loss. Also note that for a given failure rate, the energy loss with a non-predictive monitoring system is estimated to be ten times that with predictive monitoring. Figure 4-8 shows a one string power loss as a function of system voltage.

Figure 4-9 shows the lost power and the available power at three voltage levels for the predictive monitoring and the non-predictive monitoring. Note that a 1% energy loss (100 MWHRS/yr) results from a cell failure rate in the range of 1% using a non-predictive monitoring system, while the predictive system can tolerate a cell failure rate of 10%, given the same loss allowance.

Using a nominal cost of 5¢/KWH for loss of power and \$150 for the replacement cost of an individual cell Figure 4-5 depicts the overall costs (labor + replacement + string downtime) for various string configurations, failure-rates and predictive/non-predictive options. The value of 5¢/KWH

was chosen for the cost penalty for loss of power and storage capacity on the rationale that any deficit in plant rating would have to be made up by buying the "lost" energy from a neighboring utility. It was estimated that such peak power would cost approximately this value.

It should be noted that cell unreliability is the only basis for the subject calculations. For a more complete system cost model, the FMEA in Section 4.2(c) can be used to construct a fault tree (FTA). The effects on system maintenance cost of other primary system failures, i.e., ventilation failure, acid spill, flooding, etc., or of monitor malfunctions, i.e., voltage false alarm trip, H₂ gas false alarm, etc., would provide a more comprehensive evaluation of the effects of unavailability and unreliability. Such a study was, however, out of the scope of this work.

A secondary effect which might be worth investigating is the impact of two or more simultaneously disabled strings, based on the likelihood and consequences of these occurrences.

FIGURE 4-7

FIGURE 4-8

PREDICTIVE MONITORING: 0.45 Hrs STRING DOWNTIME PER CELL LOSS

NON-PREDICTIVE MONITORING: 4.5 Hrs STRING DOWNTIME PER CELL LOSS

4.2(b) CONCLUSION

The annual maintenance costs associated with cell failures are proportional to cell failure rate, strongly dependent on the type of monitoring system used, and weakly dependent on the system voltage. The predictive monitoring system reduces system downtime by providing early warning of cell failure, soon enough to schedule repairs before partial shutdown is required. Should a partial shutdown occur, the impact of such a loss is directly proportional to system voltage.

Because the impact of system voltage on maintenance costs is small for the predictive monitoring case (~\$911 annually for a 1%/year failure rate), the best choice for a system design is the 1620 VDC design with the predictive monitoring scheme.

4.2.C Effects of an Unprotected Failure

The FMEA has helped to illuminate where detection and protection equipment are needed to avoid or minimize personnel hazard, loss of operating revenue, or costly damage to equipment. The FMEA enumerates and judges the criticality of the effects (in the EFFECTS and CRITICALITY columns) for each assembly's primary equipment failure modes under the assumption that there is no protection. It also denotes possible ways to detect and protect against these effects (in the CORRECTIVE ACTION column).

The detailed FMEA listing, therefore, provides a comprehensive review of the effects of unprotected failures.

The use of the FMEA to evaluate the impact of unprotected failures is outlined by the following example:

Assume the failure mode - water addition fill valve sticks open during a fill period.

1. Locate the appropriate assembly listed on page 4-29 (electrolyte water addition).
2. Find the component in the FMEA detail sheet (7d)
3. Observe the failure effect - cell overflows →
- acid leakage → ground fault
4. Observe the corrective action - level detector (reservoir) detects loss of H₂O.
5. Also note the related corrective action, in this case to ground fault detection.

The failure effect, an overflowing cell, necessarily leads to a ground fault. If left undetected, the ground fault can lead to high I₂R losses at the cell base (covered under FMEA section 4a) which would

necessarily lead to fire. By detecting the ground fault and providing for prompt corrective action (disconnecting the string and performing replacement maintenance), the ultimate unprotected failure effect--fire--is avoided.

The detailed FMEA listing is tabulated below.

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MB-3350

PART, ASSEMBLY OR PROCESS				P N		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
1) Ventilation - Gas Removal										
a)		Inlet Filter (21)	Remove Particulates	a) No Air Passage Through Filter	<ul style="list-style-type: none"> Clogged With Particulates Inlet Surface Covered Full of H₂O 	2	1	<ul style="list-style-type: none"> Loss of Air Flow ⇒ Hi Concentration of Acid Mist in Duct Work Loss of Air Flow ⇒ Hi Negative Pressure on Battery ⇒ Excessive Stress on Covers or Case ⇒ Acid Spill 	<ul style="list-style-type: none"> Use Flow Detectors With Hi & Lo Set Points - Lo to Detect Closed Off Filter Hi to Detect No Filter or High Leakage Duct Work Maintenance Procedure 	
				b) Loss of Filtering Action	<ul style="list-style-type: none"> Missing Large Tear to Filter 	3	4	<ul style="list-style-type: none"> Hydrogen Buildup Dust Gets in Fan & Duct Work — With Fans Off - Wind Pressure & Negative Bldg Pressure could put Dust in Electrolyte 	<ul style="list-style-type: none"> Flash Back Arrestor could be Designed as a Check Valve Inspection of Duct Work at Periodic Intervals & Clean when Necessary 	
b)		Flow Detector (21)	Detect Loss of Flow	False Alarm <ul style="list-style-type: none"> Stuck at Hi Setting Stuck at Lo Setting Out of Tolerance 	Welded Contacts Not Calibrated	2	1	Will Indicate No Filter or Torn Filter or Clogged Filter	Hydrogen Detectors in Building	
				Missed Detection <ul style="list-style-type: none"> Out of Calibration Stuck Between Hi & Lo 	Not Setup Properly Over Stressed	2	4	Never Indicates Filter Malfunction	Check Lo Setting when System Shut Down & Normal Setting when System on (thru NC & No Contacts of "Lo" Set Point)	

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

PROBABILITY

ALPHA: H - HIGH
M - MODERATE
L - LOW
U - UNLIKELY

NUMERIC: SCALE 1 TO 10
1 - HIGHLY PROBABLE
TO
10 - IMPROBABLE

CRITICALITY

ALPHA: C - CRITICAL
MA - MAJOR
MN - MINOR
I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
10 - CATASTROPHIC/
SAFETY HAZARD
TO
1 - INSIGNIFICANT

PAGE 1 OF 1

WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MB-3350

PART, ASSEMBLY OR PROCESS				P N				PREPARED BY		DATE	
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE	
1)	Ventilation - Gas Removal										
c)		Flash Back Arrestor (8085)	Cools Gases Below their Ignition Temp & Traps Acid Mist	Leaky-Fractured	In-Service Damage	2	4	Gas Contaminates get into Building ⇒ Toxic and/or Explosive H ₂ Mixture	<ul style="list-style-type: none"> Hydrogen Gas Monitor Gas Detection System Pressure Relief - Blowout Disc. in Module Cover. 		
			Poor Connections	Workmanship Problem in Fabrication or Installation							
			Clogged up	Acid Mist Attack							
			Allows Hot Gases to Reach Battery (Flashback)	Not 100% Effective Against all Mixtures of Air/Gas & Protection "Cannot be Assured"				Gas Buildup in Battery ⇒ Pressure Forces Gas Outside thru Cover or Ruptures Case Walls			
				Cracked, Fractured		1	4	Explosion in Battery ⇒ Acid Spillage Flying Debris Flying Acid			

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PAGE 2 OF 2

WESTINGHOUSE FORM 4384H

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA FTA, MB-3354

1)

PART, ASSEMBLY OR PROCESS				P. N.		PREPARED BY		DATE		
Ventilation - Gas Removal										
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
d)		Duct Work, Fiberglass, Plastic (Polyethylene)	Transport Gasses	Loses Vacuum/Flow	<ul style="list-style-type: none">• Duct Work Damaged to Atmosphere• Failure to Connect a module• Broken/Ruptured Module Connector	3	4	Loss of Vacuum on Batteries ⇒ Gas Build-up ⇒ Explosive Mixture ⇒ Explosion.	<ul style="list-style-type: none">• Flow Detection - Total String• Vacuum Detection• Flow Detection on each Module• Visual Inspection	
				Explosion in Ductwork	Static Charge Buildup	1	4	Electric Arc⇒ Ignites Explosive Mixture ⇒ Explosion in Duct ⇒ Back to Battery ⇒ Plant Shutdown	<ul style="list-style-type: none">• Coat Duct Work with Conductive Coating (stripe)• Control Humidity on Inlet (spray inlet filter with H₂O)	
						2	3	Isolated Cell Explosion	<ul style="list-style-type: none">• Use Flashback Arrestors on Battery Exhaust Port• Use Semiconducting Median	
				Glued Junctions Fracture (Arrestor to Pipe) (Arrestor to Cover)	<u>Vibration Temp Change</u> <u>Accidental Jarring</u> <u>Poor Choice of Cement</u> <u>Poor Clamp</u>	1	4	H ₂ Arsine, Stibine to Room Air	<ul style="list-style-type: none">• Screwed Connection• Force Fit With Twist to Lock	
Clamped Junction Leak (Pipe to Duct-Work)	<u>Workmanship Problem</u> <u>Tubing Changes Characteristic (Brittles, Softens, etc)</u>									

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 TO
 1 - IMPROBABLE

CRITICALITY

ALPHA: C - CRITICAL
 MA - MAJOR
 MN - MINOR
 I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
 10 - CATASTROPHIC/
 SAFETY HAZARD
 TO
 1 - INSIGNIFICANT

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MB-3350

PART, ASSEMBLY OR PROCESS				P.N.		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
1) Ventilation - Gas Removal										
e)		Modulating Damper (21 Req'd)	Balance Air/Gas Flow	Closed Off	<ul style="list-style-type: none"> Operator Error Mechanism Error 	2	4	Loss of Vacuum on Batteries ⇒ Gas Buildup ⇒ Explosive Mixture ⇒ Explosion	<ul style="list-style-type: none"> Flowmeter/ Indicator Use Failsafe Protection 	
				Open Wide	<ul style="list-style-type: none"> Operator Error Mechanism Error 	1	4	Too High Vacuum ⇒ Loss of Flow in other Strings ⇒ H ₂ Buildup in these strings ⇒ Explosive Condition		

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

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NUMERIC: SCALE 1 TO 10
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TO
1 - IMPOSSIBLE

CRITICALITY

ALPHA: C - CRITICAL
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MN - MINOR
I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
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SAFETY HAZARD
TO
1 - INSIGNIFICANT

PAGE 1 OF 1

WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR T-E FMEA/FTA, MB-3350

1)

Ventilation - Gas Removal											
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE	
f)		String Fans (2 Req'd)	Move Gasses From Battery	Loss of Flow/Vacuum	Motor Burnout Belt, Shaft Pin, Coupling Loss or Breakage Fan Vanes Fly Apart Power Loss Manual Shutdown of Motors Over Temp Shutdown	1	4	Loss of Air Flow/Vacuum H ₂ Buildup ⇒ Explosive Condition	Flow Switch to Shut-off System		
				Loss of 1 Fan (2 Pumps in Parallel)	(Same as Above)	1	4	Partial Loss of Air Flow ⇒ H ₂ into Battery Room ⇒ Possible Explosion or Health Hazard	<ul style="list-style-type: none">Backflow Damper in Both PumpsDesign for 3% H₂ Concentration Worse Case		

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

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PAGE 5 OF 5

WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, A18-J35J

PART, ASSEMBLY OR PROCESS				P/N		PREPARED BY		DATE		
1) Ventilation - Gas Removal										
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
b)		Stack Fan (Req'd)	Dilute Stack Gases to Safe Level	Loss of Air Flow	Motor Burnout Belt Shaft Coupling Loss or Breakage Fan Vanes Fly Apart Loss of Input Power to Fan Motor Manual Shut Down of Motor (error) Over Temp Shutdown	2	2	Stack Exhausts Not Reduced to Desired 1% Level	Flow Switch	

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TO
1 - IMPROBABLE

CRITICALITY

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MN - MINOR
I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
10 - CATASTROPHIC,
SAFETY HAZARD
TO
1 - INSIGNIFICANT

PAGE 6 OF

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA, FTA, MIB, ETC.

PART, ASSEMBLY OR PROCESS				P/N				PREPARED BY		DATE			
2 Acid Containment													
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE			
a)		Battery Case Polypropylene (8085 Total)	Contain Electrolyte	Rupture of Case	Hi Temp	1	3	Personnel Hazard	<ul style="list-style-type: none"> Visual Leak Check Acid Sensor to Cut-off String Ground Fault Protection 				
					Mechanical Abuse	1	3	Loss of String					
					Fire	1	2	Loss of Acid					
					Material Quality Change With Use	1	1	Maintenance Clean-up					
					Earthquake	1	3	Short Ckt Problem ⇒ Avalanche to Other Cells					
					On Removal/Placement	1	4	Short to Ground					
					Explosion			Personnel Hazard					
				External Short Ckt	Accidental	2	3	Heat up Electrolyte ⇒ Meltdown Walls ⇒ Acid Release	<ul style="list-style-type: none"> Design Terminals to Melt Open Fuse Each Cell/Module Monitor Cooling H₂O for increase in Temp. Monitor Voltage 				
				Internal Short Ckt	Insulating Breakdown Between Plates	1	3						
b)		Acid Spill Holding Tank (21 Req'd)	Contains Run-off Electrolyte Mixture	Overflow	No Maintenance Major Catastrophe	2	2	If there is no place for overflow ⇒ will contaminate local surroundings or go down drain without treatment	<ul style="list-style-type: none"> Sensor to Detect Spillage for String Isolation Level Sensor to Detect Height of Liquid in Tank to Indicate when to Neutralize & Dump Guards Barriers from Acid Problem 				
				Electrical Tie between Strings on Overflow									
				Leak to Soil									
				Personnel Hazard						1	2	Burns etc - Personnel Hazard	

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

PROBABILITY

ALPHA: H - HIGH
M - MODERATE
L - LOW
U - UNLIKELY

NUMERIC: SCALE 1 TO 10
10 - HIGHLY PROBABLE
TO
1 - IMPROBABLE

CRITICALITY

ALPHA: C - CRITICAL
MA - MAJOR
MN - MINOR
I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
10 - CATASTROPHIC;
SAFETY HAZARD
TO
1 - INSIGNIFICANT

PAGE 7 OF 7

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA, FTA, M'B, J350

PART, ASSEMBLY OR PROCESS				P. N.		PREPARED BY		DATE		
2 Acid Containment										
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
c)		Acid Spill Trench (21 Req'd)	Contain. Electrolyte During Spill & any other Plumbing Leak Segregate String spills	Overflow	Not Enough Slope	1	4	Personnel Hazard	Visually Inspected Detector	
				Fail to Drain	Trash in Trench	1	3	Burns		
				Leak to Soil	Cracked Concrete	3	3	Fumes		
						1	3	String to String Fault		
						1	3	Main Bus Fault		

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

PROBABILITY

ALPHA: H - HIGH
 M - MODERATE
 L - LOW
 U - UNLIKELY

NUMERIC: SCALE 1 TO 10
 10 - HIGHLY PROBABLE
 TO
 1 - IMPOSSIBLE

CRITICALITY

ALPHA: C - CRITICAL
 MA - MAJOR
 MN - MINOR
 I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
 10 - CATASTROPHIC/
 SAFETY HAZARD
 TO
 1 - INSIGNIFICANT

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, M8-3350

PART, ASSEMBLY OR PROCESS				PREPARED BY				DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART ASSEMBLY OR PROCESS NAME	PART ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
3) Maintenance Gear										
I ISOLATION EQUIPMENT										
a)		Disconnect Fuses (1176)	Overcurrent Protection & Isolation Switch to Service Units	Fuse will not Blow Fuse Blows Inadvertantly Switch will not Open Switch will not Close Switch Opened Under Load Switch Closed Under Load Switch Opens Inadvertantly	Wrong Fuse Size Welded Contacts Bent Bracket Pilot Switch Malfunction	1 2	1 2	Conductors Will Melt - Batteries Destroyed Opening Switch Under Load ⇒ Arcing ⇒ Operator Hazard ⇒ Destruction to Switch	<ul style="list-style-type: none"> Preventive Maintenance Long Stick for Disconnect Motor Operated Switch Switch in Cover of "Fuse Switch" shuts down String thru Computer Monitor Other Fuses will Blow 	
b)		Monitoring Signal Disconnects (1155/8085)	Connector to Feed Data Acquisition Unit	Not Connected Mechanical Support Material Corroded Contacts Corroded	Operator Error Acid Spill Acid Mist	2 2	2 1	Loss of Unit Status Data ⇒ Safety Hazard Circulating Currents, Leakage Voltage Inter & Intra Units ⇒ Safety Hazard	<ul style="list-style-type: none"> Unit Disconnect with Female Connections on Power Side. 1000 Volt Isolation Needed for Voltage Monitor Computer to Recognize Pulled Disconnect Eliminate Disconnect Fail Safe Wiring 	

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

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CRITICALITY

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA FTA, MB-3250

3)

PART, ASSEMBLY OR PROCESS Maintenance Gear				P. N.		PREPARED BY		DATE		
ITEM NO	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
I ISOLATION EQUIPMENT										
c)		Water System Grounding (Cell Makeup & Cooling H ₂ O)	Safety-Grounds Water Advarious Places in Plumbing System	Becomes Ungrounded Leaking Joints	Ground Strap Breaks Corrodes, Loosens Mechanical Abuse	1	4	Leakage Currents ⇒ Voltage ⇒ Personnal Hazard ⇒ Mild Shock	• Routine Maintenance Check and when servicing a Local Cell ⇒ Check on Local Groundings • Use Fitting with MTG Flange at Unit Ground • Use Expansion Joints in Feed Lines	
d)		Unit Ground Straps	Connect Equip. to Gnd. when Servicing	Equipment Not Grounded	Broken Ground Strap	1	4	• Hazard - Cannot Detect Dangerous Voltage	• Grounding Stick Equip- ed with Ground Test	

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WESTINGHOUSE FCPM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA FTA, NB-3000

3) **Maintenance Gear**

PART, ASSEMBLY OR PROCESS				P.N.		PREPARED BY		DATE		
ITEM NO	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
II MODULE IDENTIFICATION										
		Module Identification - Inherent in Computer	Identify Failed Part	Wrong Identification No Identification	Installation Wiring Error Noisy-Weak Signals Computer Malfunction	2	3	Personnel Hazard Loss of Equipment Use	Part of Checkout Procedure	
III MOTORIZED GANTRY										
a)		Crane	Service Modules: a) Cross-over b) Lift c) Transporter d) Eye-wash & Shower Rinse e) Tool Box f) Storage Bin	Flat Tire Collapse of Structure Motor Outage Battery Failure Pendent Bad Pendent Cord Bad Contactor Out Fuses Out "Battery" Stuck in up Position Brake lets go with Battery Hoisted Battery Lowering Speed for high-set down too hard Floor Cracks	Sharp Object Acid Spill Open Winding Not Charged Equipment Aging Short Circuit Pendent/Wire Broken • Worn Brake Shoe • Sheared Pin Jog Circuit not in Cable Breaks Hook Breaks Load + String Weight	2 2 1	4 1 2	Spilled Battery ⇒ Acid ⇒ Personnel Hazard Not Able to Repair Batteries Damage to Primary & Adjacent Equipment	<ul style="list-style-type: none"> • Hard Rubber Tires • Steel Rails/Wheels • Dual Tires • Battery Charge Indicator • Protective Cable (Pendant) • Spare Parts Availability • Safety On Brake System (Rotary Damper with Shock Absorbers) • Hoist Speed - Slow only within 2 ft of Ground thru Jog Action Switch • Manual Hoist Operation • Manual "Up" Hoist Lock-Interlocked to Drive Train - • Check Floor Loading 	

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SAFETY HAZARD
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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA FTA, MB-JJ50

3)

PART, ASSEMBLY OR PROCESS				P. N.		PREPARED BY		DATE		
ITEM NO	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE S	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
III MOTORIZED GANTRY										
b)		Drive Train	Propel Gantry	Drive Mechanism gets out of sync	Sensing Equipment Unbalanced Drive Motors Operator Control Dependency	2	2	Gantry Turns ⇒ Crashes into String; if carrying Battery ⇒ Broken Case	• Steel Rails - Wheels • Guide Channel - Rubber Tires	
				Won't Drive	Uncharged Drive Batteries Open Winding Elect Controls Out	1 2	4 1	Acid Spill Maintenance Nullified on Batteries	• Warning on Lo Battery Voltage • Spare Motor Available • Manual Operation	

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WESTINGHOUSE FORM 43849

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 2. Identify all the possible failure modes which the part or assembly might incur.
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 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MB-33041

3)

PART, ASSEMBLY OR PROCESS				P/N		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
III MOTORIZED GANTRY										
c)		Water Shower Emergency	Safety Washoff Shower	No Water Insufficient H ₂ O	Ruptured Tank Evaporation of H ₂ O Poor Maintenance - Never Filled	2	4	Burns, Eye Hazard to Operator	<ul style="list-style-type: none"> • Personnel Eye Washer Container • Lo H₂O Interlocked to Drive Train • Closed System - Pressurized with CO₂ Air Pressure • Nozzles Located Strategically • Preventive Maintenance Schedule 	
				Too Inaccessible in Emergency Situation	Design					
				Valve Not Opening	Corroded Shut					
d)		Walkway Over String	Operator Mobility Aid	Collapse Slippery Operator Falls off Not Enough Clearance	Design - Operator Habits	1 3	3 2	Operator Hazard Equipment Collision	<ul style="list-style-type: none"> • Non Slip Surfaces • Safety Rails • Personnel Detector Tied into Drive/Hoist Mechanism 	
e)		Spare Parts Bins (Not Applicable)								
f)		Tool Box (Not Applicable)							Non Sparking Tools	
g)		Non Conductive Main Support	Support Equipment	Crack Under Load	Corrosion Due to Environment	1	4	Battery Falls ⇒ Acid Splash	Use Materials With Good Mechanical Elec'l Chemical Properties	

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
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 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA VB-3350

3)

PART, ASSEMBLY OR PROCESS				P N		PREPARED BY		DATE		
Maintenance Gear										
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
IV ACID HANDLING EQUIPMENT (Maintenance Room and Battery Room)										
a)		•Face Mask •Gloves •Aprons •Portable Acid Detector •Portable Fan •Neutralizing Squeeze Bottle	Protect Personnel	• Failure to Wear it – • Torn, Broken	Misuse Deterioration { Air Damage Hot/Humid Ambient Dirty	2	3	Hazard to Personnel	Instructions to Personnel on <u>Not</u> Wearing Safety Item Maintain Inventory on Safety Items	
b)		Hydrometer	Measure Specific Gravity of Acid	• False Alarm • Missed Detection	Mechanical Abuse Damaged	2	1	Bad Cell Undetected	Periodic Calibration	
c)		Acid Bottles	Contain Acid Kept in Maintenance Room	Breakage Infiltration of Dust Moisture Used as H ₂ O	Mechanical Abuse Leaving Top off Bottles No Warning Labels	1 1	3 1	Hazard to Personnel Reduced Quality of Acid in Cell	• Special Storage Area for Acid Bottles • Clearly Marked • Area Monitors for Acid Contamination	
V MAINTENANCE ROOM										
a)		Overhead Crane	Gen'l Heavy Moving	Ramming Batteries With Lift General Breakdown Cable Breaking With Load	Inexperienced Operator or Crane too fast for Control Runaway Crane Motors, Switches, Elec. Controls, Broken Cable, Binding Age Shorting Out Batteries & Burning thru	2 1	4 1	Fire Dumping Load Holdup Operation Damage Load	"Low Load" Switch Interlocked with Drive Mechs. Good Preventive Maintenance Program Manual Backup on Hoisting & Traversing Good Training Program	

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

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WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, WE-3350

3)

PART, ASSEMBLY OR PROCESS				P/N	PREPARED BY			DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
Maintenance Gear										
V MAINTENANCE ROOM										
b)		Storage Room For Spare Module	Keep Replacement Module	Fumes/H ₂ /Stibine/Arsine Buildup	Poor Ventilation Overcharging Cracked Case Acid Spill	2	4	H ₂ Explosion	<ul style="list-style-type: none"> • H₂ Detectors with Alarm • Auto Water Flush System • Electric Door Guard (Indicates Occupied Room) • Ventilation Monitor • Acid Detection • Shower Wash Station • Tie H₂ Detection Alarm into Charger Shutdown • Appropriate Grounding Facilities 	
						2	4	Personnel Overdose Stibine Arsine		
						2	3	Fumes, Possible Burns		
c)		Charger	Keep Module Charged	Undercharging Not Charging Overcharging	Charger Malfunctioning Grounding	1	1	Spare Module not usable when needed	<ul style="list-style-type: none"> • Ground Fault Detector • H₂ Monitor • Monitor Charging I/E • Limit Alarms Hi/Lo • Periodic Maintenance 	
						2	4	H ₂ /Toxic Gases Given off (see 5B)		
d)		Work Surfaces		Acid Etch Acid Corrosion Acid Disintegration Toxic Fumes	Spilled Acid	2	2	Personnel Hazard Maintenance Problem	<ul style="list-style-type: none"> • Choose Suitable • Material-Nonconductive • Acid Resistance (See Vb also) • Floor to be epoxy coated • Neutralize for Periodic Cleaning 	
				Burning (Electrical) Arcing Shock	Accidental Tie to Battery Terminals Causing Shorting	1	3	Short Circuit Battery Damage Personnel Damage		

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, WS-3350

3)

PART, ASSEMBLY OR PROCESS Maintenance Gear				P/N	PREPARED BY			DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
VI		Washdown Equipment (Hose-Water Washdown)	Clean Acid Prone Surfaces	Hose too Cumbersome Hose Ruptures Creates Ground Path	<ul style="list-style-type: none"> Hose too Long - Operator Difficulty Too Much Pressure Acid Attack Age Water Splashing 	1	2	<ul style="list-style-type: none"> Wash Not Performed Properly 	<ul style="list-style-type: none"> Water Outlet Every 50 Ft With Quick Disconnect Adequate Drainage Spec Hose for this Environment & Usage Std. Maintenance Procedure Eliminate Moisture Traps Nozzle Designed for Gentle Spray Pressure Regulator 	
						1	2	<ul style="list-style-type: none"> Acid Sprayed around Fumes/ Splash on Personnel 		
						3	4	<ul style="list-style-type: none"> System Wet-Shock Hazard 		
VII	INSTRUMENTS	Voltmeter	Measure Voltage Safely	False Reading Missed Detection Operator Shock	Overvoltage Open Test Lead/Meter Test Leads Improperly Insulated Probes not Protected	1	1	Improper Test Results⇒ Wrong Conclusions⇒ Wrong/Dangerous Actions	<ul style="list-style-type: none"> Self Testing Meters Calibration Procedures in Maint. Schedule Design Probes & Battery Terminal Compatability 	
		Clamp on Current Meter	Measure Current	False Reading Missed Detection Operator Shock	Improper Scale Insulation Damage Short Circuit Current While Taking Reading	1	2	Open Power Circuit on Load		

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
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 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, WS-3350

3) **Maintenance Gear**

PART, ASSEMBLY OR PROCESS				P. N.		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
VII INSTRUMENTS										
		Tools/Instrumentation		Loss of Instruments & Tools	Theft Arcing - Sparking	2 1	2 4	Loss of Time H ₂ Explosion-Short Circuit	• Security Control Non Sparking Tool	
		Hydrogen Analyzer								
		Acid Pumps	To Remove Battery Acid For Repair	Fail to Pump	Pump Corroded Motor Burnout	1	1	• Delay in Repair Work		

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

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WESTINGHOUSE FORM 43849

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MB-3350

- STEPS: 1. List each part or assembly in the design.
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5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

PART, ASSEMBLY OR PROCESS				P.N.	PREPARED BY			DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE S	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
4)	Modules - Structure - Insulation									
a)		Base - Polyethylene (1155)	Support for 7 Cells Electrical Insulation	Cracked Base Holds Leaking Acid Flash over to Ground	Lifting Manufacturing Defect Cell Leak Dripping Acid-Surface	1 1 1 1	4 2 2 1	Dump Acid on Hoisting Cracked Cases on Lifting Hi-Heat (I ² R) on Base ⇒ Fire	<ul style="list-style-type: none"> Design & Test Earthquake Proof Design Aisle Such that Support can be put under Module for Lifting or Make Aisle Wide Enough to Move Module at Floor Level Assures Direct Drainage of Acid & Rinse to Acid Trench 	
b)		Cell Case (8085)	Acid/Lead Plates Containment	Rupture Bow-warp Weak Walls	Internal Pressures External Damage Overheating/Softening of Case Manufacture Process	1 1 1 1	3 1 1 1	Dump Acid ⇒ Grd. Path Personnel Hazard ⇒ Shock Will not Fit into Base	<ul style="list-style-type: none"> (See 8a) - Mold Cavity in Bottom & Sides of Case - Use reinforcing Ribs as Water Channels Choice of Material Assure Direct Drainage of Acid & Rinse to Acid Trench 	

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

PROBABILITY

ALPHA: H - HIGH
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U - UNLIKELY

NUMERIC: SCALE 1 TO 10
10 - HIGHLY PROBABLE
TO
1 - IMPROBABLE

CRITICALITY

ALPHA: C - CRITICAL
MA - MAJOR
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NUMERIC: SCALE 1 TO 10
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WESTINGHOUSE FORM 42849

- STEPS: 1. List each part or assembly in the design.
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 3. Determine the effect of each failure on the product performance.
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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, V8-3350

4) **Modules - Structure - Insulation**

PART, ASSEMBLY OR PROCESS				P/N				PREPARED BY		DATE	
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE S	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE	
c)		Cover (1155)	Protect Internals of Battery, Acting as Seal	Cover Comes Loose, Cover Not Put on Properly, Cover Put on End Around "+" Mark on "-" Terminal.	Not Sealing to Case Ceramic Arrestor Attachment Not Sealing ⇒ Material/ Glue Not Compatible With Arrestor	1	2	Cell Contamination	<ul style="list-style-type: none"> Design & Test Key Cover to Case Positive Method for Checking if cover is Seated throughout its Length 		
					Loses Cooling Capability	Cover Squeezes Tubing Carrying Cooling H ₂ O - Loss of Flow	2	1			Atmosphere Contaminates Cell
											Overheating of Module

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PAGE 1 OF 1

WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, WB-3350

5)

PART, ASSEMBLY OR PROCESS				P/N		PREPARED BY		DATE		
Monitoring & Control										
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
a)		Charge/Dis-charge Control (21)	Transductor Computer	Change Calibration Burn Open Program Blown Hardware Breakdown ⇒ Dead Computer Switch	Temp Change Short Circuit Current Hi-Volt Spikes Operator Error	1	4	• Incorrect Charge/Discharge Information ⇒ Overcharge/Under-charge	• Check Calibration Automatically • Supply Voltage Protection for Load on Shunt • Comparison Monitor of String Currents, Cell Voltages Program Computer Alarm • Provide Manual Override for Charging Batteries	
						1	4	Open Circuit Voltages		
						1	3	Charge/Discharge Control off		
b)		String Isolation Static Switch (21)	Disconnect/Connect String To System	Fail Open - One Polarity	• Trial • Controls (Turn On)	2	2	Cannot Put String on Line - No Chg/Disch.	• Monitor Voltage Across Thyristors • Access Disconnect Switch	
				Shorts Out of Willmot Turn off	Short Circuit Current	1	4	Cannot Shut off String Via Computer Control ⇒ Overcharge/Under-charge	Monitor Voltage Across Thyristers - Shutdown Converter if malfunctions	
c)		Module Voltage Sensor (1155)	Measures Module Voltage	Open Circuit Short Circuit		1	3	Incorrect Computer Info. - String Disconnect	Isolation System	

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WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MB-3350

5) **Monitoring & Control**

P.N. ASSEMBLY OR PROCESS				P.N.				PREPARED BY		DATE	
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE	
d)	Critical Parameters - Monitors	Room Temp	Measure Room Temp for Control	False Reading Missed Detection	• Out of Calibration • Welded Contacts	1 1	1 2	False Alarm Cooling Systems Water Addition Freeze	• Hi & Lo Limiting with Alarm • Redundant Temp Monitor		
		Smoke Detectors - Refer to Section 9-d									
		Humidity Monitor	Maintain Humidity	False Reading Missed Detection	Vibration Mechanical Abuse Ruptured Sensor	2 2	4 4	Lo Humidity - Static Charge Buildup Sparks Fire Hi-Humidity - Condensation on Equipment (Water Pipes, Air Ducts)	Regular Maintenance Fail Safe Controller		
e)	Current Regulation Element		(See 5a & 5b)								

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, VS-3350

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6)

PART, ASSEMBLY OR PROCESS				P N		PREPARED BY		DATE		
Electrical Protection										
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
a)		Bus Isolation	Isolate Bus From Ground & Opposite Polarity Buss	Short to Ground Leakage Resistance Path to Gnd	Foreign Object Dropped across Bus Acid Path Across Insulators Water in Bus Trench	1 1	3 4	• Loss of Power Due to Blown Fuse, Breaker Trip, Parasitic Losses • Ground Fault ⇒ Shock ⇒ Personnel Hazard	• Ground Fault Detectors • Convenient Means to Clean Bus Work.	
b)		String Isolation: Between Strings and in Strings	Isolate Strings From Ground & Each Other Isolate Inter-String Elements	Short to Ground Resistance to Ground Circulating Currents Between Strings	• Acid Leak on Battery Case • Loose Cables • Cables Which Touch	1 1 2 1	3 1 4 3	• Battery Heating • Battery Discharge • Arcing/Burning Personnel Hazard • Loss of String	Configuration of String Ground Fault Detectors Torque Requirements or Cable Terminals Insulate Cables & Connections	
c)		Fusing	(See 1a)							
d)		Surge Protection (Not Applicable)								
e)		Ground Path Detection by DC Current Monitor	Detect Bus Isolation From Ground	• Missed Detection • Distributive Resist. to Ground • Detector Degrades to a Low Resistance to Gnd Condition • False Alarm - Too Sensitive	• Insufficient Resistance to Ground • Insensitivity • Instrument Calibration	2 2	4 3	• Hazardous - To Personnel Shock Hazard • Loss of System	• Use Hi Freq Ground Fault Detector • Individual String Detection or Multiple Ground Fault Detection • Shutdown Requires 2 Detectors Alarm only on 1 Detector to Reduce False Alarm Probability	

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WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA VS-3350

7) **Electrolyte Water Addition**

PART, ASSEMBLY OR PROCESS				P.N.	PREPARED BY		DATE			
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
a)		Pump	Move Water to Fill Reservoirs	<ul style="list-style-type: none"> • Impellor Out • Motor Fails • Insufficient Capacity • Contaminates Water Purity • Bearings Bind 	<ul style="list-style-type: none"> • Poor Design • Normal Wear • Contaminations 	1	3	<ul style="list-style-type: none"> • Batteries Run Dry ⇒ Low Battery Life 	<ul style="list-style-type: none"> • Water Detection in Reservoirs • Duty Cycle Limit Control • Water Flow Detection • Redundant Pump • Pump Pressure Detection • Non Contaminating Parts used for Water Contact 	
						2	3	<ul style="list-style-type: none"> • System Shut Down 		
b)		Pump Motor Starter	Supplies Power & Protects Motor	Coil Burn Out Heaters (overcurrent) under/over Sensitive	Bad Components	1	3	<ul style="list-style-type: none"> • Batteries Run Dry 	<ul style="list-style-type: none"> • Aux Contact Wired to Safety System 	
c)		Manifold Reservoirs & (1155)	Contain H ₂ O	Leaks Contaminates H ₂ O Purity	<ul style="list-style-type: none"> • Temp Change (Expansion/Contract) • Connections Leak/Tears • Choice of Materials 	1	1	<ul style="list-style-type: none"> • Shorten Battery Life 		
d)		Fill Valve	Maintain Elect. Level	Fails Open (Overflows) Fails Shut	Device Could Leak Plugged By Debris	2	2	<ul style="list-style-type: none"> • Cell Overflows Acid Leakage Gnd Fault 		<ul style="list-style-type: none"> • Purge Manifold Systems before Tying into Battery
e)		Level Detector	Sense Usage of H ₂ O	Contaminates H ₂ O Missed Detection False Indication	Poor Choice of Mat'l Float Sticks	1	3	<ul style="list-style-type: none"> • Cell Runs Dry 	<ul style="list-style-type: none"> • Level Detector Feeds Data Signal Continuously to Detect Loss of H₂O • Detect Gassing by Monitoring Cell Voltage Changes 	
						1	1	<ul style="list-style-type: none"> • Shorten Battery Life 		
						1	2	<ul style="list-style-type: none"> • H₂O Usage in Error Does not Detect an Abnormally Gassing Cell 		
						1	2	<ul style="list-style-type: none"> • Temporary String Shut-down 		

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WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA FTA, MB-3350

PART, ASSEMBLY OR PROCESS				P. N.		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
7)	Electrolyte Water Addition									
f)		Demineralizer Assembly	Purify H ₂ O	Water Contamination	<ul style="list-style-type: none"> • Filter Clogged • Plumbing Leaks • Too Long Time Between Replacement of Filter Media 	1	3	• Shorten Battery Life	<ul style="list-style-type: none"> • Monitor Water for Purity • Provide Periodic Maintenance • Differential Pressure Monitor Across Filter for Clogged -up Detector 	

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WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, MS-3350

PART, ASSEMBLY OR PROCESS				P.N.		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
8)	Temperature Control of Battery Electrolyte									
a)		Heat Exchanger Plastic Tubing 1.01 GPM @6.5 Psi (8085)	Carry Cooling H ₂ O Using Polyethylene Tubing	<ul style="list-style-type: none"> Hose Ruptures in Electrolyte Breaks Loose From Restraints 	<ul style="list-style-type: none"> Hi Temp Deterioration of Plastic Density of Material 	1	1	<ul style="list-style-type: none"> Dilutes Cell Acid Low Cell Voltage 	<ul style="list-style-type: none"> Increase Wall Thickness Change Material of Tubing Use Flow Detectors at Outlet of each Module Mold Cavity in Bottom & Sides of Case as Guideway for Hose Provide for Overflow Tube for all Batteries 	
					1	2	<ul style="list-style-type: none"> Overflow of Acid 			
					1	1	<ul style="list-style-type: none"> Overheating of other Cells Loss of String 			
					1	1	<ul style="list-style-type: none"> Poor Cooling Increased Heating of Cell 			
					1	2	<ul style="list-style-type: none"> Contaminate Electrolyte 			
					1	1	<ul style="list-style-type: none"> Shutdown System if Large enough Leaks 			
b)	(Con't - Refer to Next Page)	Water Flow Distribution (1155)	Equalizing Flow in each Module (1155 Points)	<ul style="list-style-type: none"> Unequal Flow Leakage at Pipe Joints Water Temp too Hot Water Temp too Cold 	<ul style="list-style-type: none"> Configuration Restriction in Piping Loose Fittings 	2	3	<ul style="list-style-type: none"> Hot Spots ⇒ Reduced Life of Some Cells 	<ul style="list-style-type: none"> Flow Monitors in each String, Unit or Module Regulation on each String, Unit or Module Monitor outlet Water Temp (No Waterflow - No Hi Temp) Orientation of Equipment Assure Cell Voltage Monitor is Sensitive Enough to Detect Water-flow problems before Damage is done. 	

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WESTINGHOUSE FORM 43849

- STEPS: 1. List each part or assembly in the design.
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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA VE-3350

PART, ASSEMBLY OR PROCESS											PREPARED BY		DATE	
8) Temperature Control of Battery Electrolyte														
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE				
b)	(Cont.)	Water Flow Distribution (con't)		Condensation H ₂ O Line Freezeup Electrolyte Overheat (Cooling H ₂ O In-efficient)	• Cooling Tower Break-down	1	3	Batteries Overheat	• Monitor Cell Temp & Cooling H ₂ O					
						1	1	Battery Voltage Change: at 90% Charge - ~25% Voltage Change from 30°F/40°F⇒ Effect Charge/Discharge ⇒ Loss of Power						
					Water Temp Low	2	1	• Wet Flow ⇒ False Indication of Battery Leakage in Trenches	• Design Cooling Tower Capacity to be Compatible with Local Temp/Humidity Index					
					Water Temp High	1	3	• Cooling H ₂ O Freezeup						
									• Insulate Plumbing	• Assure Adequate Building Heat				
									• Aux Water Heater					
				• Hi Electrical Conductivity of Water	Fe ions in H ₂ O	1	2	Short to Ground only with Cooling Coil Rupture	• Continuous Conductivity Analysis					
									• Continuous Filtration					
									• Use only Plastic Copper or Bronze Material in Plumbing					

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WESTINGHOUSE FORM 43849

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Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA F-1, US-2350

9) **Facilities**

PART, ASSEMBLY OR PROCESS				PREPARED BY							DATE	
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE		
a)		Building Heating & Ventilation	Maintain Bldg. Temp.	Overheating	<ul style="list-style-type: none"> • Loss of Control • Extreme High Ambient Temp & Humidity 	1	2	<ul style="list-style-type: none"> • Fire Alarm 	<ul style="list-style-type: none"> • Provide Early Warning 			
						1	3	<ul style="list-style-type: none"> • Fire Extinguisher (including Sprinkler System) on 	<ul style="list-style-type: none"> • Provide for Manual 			
						1	4	<ul style="list-style-type: none"> • Fire 	<ul style="list-style-type: none"> • Override on Temp Control System 			
						1	1	<ul style="list-style-type: none"> • Cell Volt Decreases Loss of String(s) 	<ul style="list-style-type: none"> • Provide for Battery Cooling H₂O Heat Building 			
						1	1	<ul style="list-style-type: none"> • Personnel Discomfort 	<ul style="list-style-type: none"> when needed 			
									<ul style="list-style-type: none"> • Provide Sprinkler System Activators 			
				Insufficient Heating	<ul style="list-style-type: none"> • Loss of Control 	1	1	<ul style="list-style-type: none"> • Discomfort 	<ul style="list-style-type: none"> • Lo Temp Warning System 			
					<ul style="list-style-type: none"> • System Undersized 	1	3	<ul style="list-style-type: none"> • Thermal Cycling of Component Leading to Cracking/Fracture 	<ul style="list-style-type: none"> With Redundancy in Strategic Locations 			
					<ul style="list-style-type: none"> • Extreme Low Amb. Temp and Wind 	1	3	<ul style="list-style-type: none"> • H₂O Lines in Bldg. frozen ⇒ Loss of Sprinkler, & Other System 				
				• Inoperative Ventilation	<ul style="list-style-type: none"> • Loss of Fanbelt 	1	4	<ul style="list-style-type: none"> • H₂ Buildup in Pockets ⇒ Possible Explosion 	<ul style="list-style-type: none"> • Detect Loss of Fan Starter Alarm 			
				• Poor Distribution of Airflow (Refer to Sectional)	<ul style="list-style-type: none"> • Bldg Hi Temp Shuts-down Starters 	1	4	<ul style="list-style-type: none"> • Arsine-Stibine Buildup ⇒ Health Hazard 	<ul style="list-style-type: none"> • H₂ Detection System - 			
					<ul style="list-style-type: none"> • Doors Left Open 	1	1	<ul style="list-style-type: none"> • Heat Not Adequately Circulated 	<ul style="list-style-type: none"> Locate Detectors in Strategic Locations 			
b)	Deleted - Duplicated Elsewhere											

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 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA/FTA, M6-3350

9) **Facilities**

PART, ASSEMBLY OR PROCESS				P N		PREPARED BY		DATE		
ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
c)		Building	<ul style="list-style-type: none"> Shelter Climate Control Enclosure Protection to Environment from Acid Contamination 	<ul style="list-style-type: none"> Collapse - Structural Failure Containment Loss of Internal Climate Crack in Acid Containment 	Earthquake Wind Accumulation Snow Fire Rain, Snow, Ice Buildup Fault Movement	1	4	• Personnel Death/Injury	<ul style="list-style-type: none"> Design to Relieve Ice & Wind Loading of Stresses Fireproof Automatic Fire Equipment/Monitor Safety Exits Fire Walls - Divide Bldg. into Rooms Safety Alarms made Fail Safe Use non-flammable mat'l in Designs (battery cases) All Automatic Problem Controls Provided with Manual Override Safety Shelters At Strategic Locations - Respirators - Water Deluge Systems, Fire Extinguishers Locate on High Ground Good Drainage Systems Provide for Sump Pump System Hi Drain Water Warning Systems 	
						1	3	• Equipment Damage		
						1	3	• Exposure to External Environment (Wind, Snow, Rain)		
						3	2	• Seepage of Battery Acid to Coil		
					Wash Down System "Runaway"	1	1	• Fill up Acid Drainage Systems → Acid Spillage into Local System		
						1	3	• Battery Damage		
						1	2	• Controls Damaged		

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

PROBABILITY

ALPHA: H - HIGH
M - MODERATE
L - LOW
U - UNLIKELY

NUMERIC: SCALE 1 TO 10
10 - HIGHLY PROBABLE
TO
1 - IMPROBABLE

CRITICALITY

ALPHA: C - CRITICAL
MA - MAJOR
MIN - MINOR
I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
10 - CATASTROPHIC:
SAFETY HAZARD
TO
1 - INSIGNIFICANT

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- STEPS: 1. List each part or assembly in the design.
 2. Identify all the possible failure modes which the part or assembly might incur.
 3. Determine the effect of each failure on the product performance.
 4. Estimate or calculate the probability of occurrence and the degree of criticality of each failure (see Suggested Keys).
 5. Identify and carry out corrective or preventative actions to prevent or minimize the potential failure.

Failure Mode and Effects Analysis Criticality Analysis

SEE A GUIDELINE FOR THE FMEA F-1A VB-3350

9) PART, ASSEMBLY OR PROCESS P.N. PREPARED BY DATE

ITEM NO.	PART, ASSEMBLY OR PROCESS NUMBER	PART, ASSEMBLY OR PROCESS NAME	PART, ASSEMBLY OR PROCESS FUNCTION	FAILURE MODE(S)	FAILURE CAUSE(S)	PROBABILITY	CRITICALITY	FAILURE EFFECT(S)	CORRECTIVE ACTION OR PREVENTATIVE ACTION	RESPONSIBILITY DUE DATE
d)		Fire/ Smoke Detection	Detect Possible Fires	Missed Detection	<ul style="list-style-type: none"> • Insensitive or out of Calibration • Ventilation System Reducing Smoke Concentration 	1	4	<ul style="list-style-type: none"> • Undetected Smoke ⇒ Fire • Loss of System 	<ul style="list-style-type: none"> • Locate Detectors Strategically for Redundancy • Specify Fail Safe Detection System • Locate Detectors in Ventilation System 	
				False Detection	• Detector Malfunction	2	1	<ul style="list-style-type: none"> • Fire Fighting Equip Put on Alert • Sprinkler System Activated 	<ul style="list-style-type: none"> • Require 2 Alarms to Activate Sprinkler/Fire-Fighting Equip. 	
e)		Sprinkler System	Extinguishes Fires Cleans Battery Surfaces	<ul style="list-style-type: none"> • Fail to put out Fire • Flooding of Building Drainage System 	<ul style="list-style-type: none"> • Corroded Parts • Loss of Water Supply • Wrong Type or Not Enough of Deterrant (Water or Chemical) • Loss of Ability to Control i. e. - won't Turn Off 	1	3	<ul style="list-style-type: none"> • Fails to operate ⇒ Fire Spreads • Acid Water Gets to Soil 	<ul style="list-style-type: none"> • Routine Maintenance on Equipment • Locate Sprinklers Strategically • Control of Sprinkler Supply • Investigate Effect of Sprinkler Liquid on Acids, Wires, Electricity and Materials it will come in Contact with 	
						1	2	• Shock Hazard ⇒ String Shutdown		

SUGGESTED KEYS: CHOOSE ALPHA OR NUMERIC

PROBABILITY

ALPHA: H - HIGH
 M - MODERATE
 L - LOW
 U - UNLIKELY

NUMERIC: SCALE 1 TO 10
 10 - HIGHLY PROBABLE
 TO
 1 - IMPROBABLE

CRITICALITY

ALPHA: C - CRITICAL
 MA - MAJOR
 MN - MINOR
 I - INSIGNIFICANT

NUMERIC: SCALE 1 TO 10
 10 - CATASTROPHIC/
 SAFETY HAZARD
 TO
 1 - INSIGNIFICANT

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4.3 Evaluation of Ventilation/Thermal Balance Alternatives

It was indicated in Section 3.2 that the selection of cooling system would have an effect on the cycle life of the cells, depending on the type of climate encountered. This section deals with calculations of cooling system performance and operating energy usage of alternate designs for several geographic locations. Also included in this section is an evaluation of the feasibility and probable economics of a ventilation scheme employing recombination of the evolved gases.

A. DESCRIPTION OF THE DESIGNS

1. Water-Cooled Design

The water-cooled design to be studied is identical to the conceptual design of Section 3.2.

2. Forced-Air Design

A conceptual design for a forced air cooling system has been made which requires few changes to other aspects of the battery design. The same seven cell module is used and in the same electrical arrangement. The physical arrangement, however, is modified to accommodate the forced air requirements.

As can be seen from Figure 4-10, the battery strings are laid out very similarly to the original conceptual design. What has changed is the spacing of the cells at the inter-unit level. There is now a space of approximately 20 inches between modules of adjacent unit blocks (of five modules each). Alternate spaces (with top and side baffles) serve as distribution plena for the cooling air, which is supplied via sub-floor ductwork. The other inter-unit spaces provide the exhaust location for the cooling air. Each module, with its solid cover, sides and base and with the air gap between individual cells of the module, provides the ducting for the cooling air through the five-module unit. The cooling air, which was drawn from the outside of the building at the exterior walls and blown through the sub-floor ductwork and through the modules, is finally exhausted via roof ventilators.

This design does not alter most of the other auxiliaries (e.g., it is still compatible with the overhead handling approach). Because of the added inter-unit spaces, however, this design does increase the building size (from 110 ft x 210 ft - 23,100 ft², to 130 ft x 210 ft - 27,300 ft²).

Required Building Size	27,300 ft ²
Flow Rate	160,000 SCFM
@ Operating Pressure	3" H ₂ O
Fans (4)	40,000 SCFM
Motors (4)	35 HP
Total Power Consumed	94.1 KW

PLAN VIEW

ELEVATION VIEW

FIGURE 4-10 FORCED AIR DUCT
& REGISTER LAYOUT

3. Evaporative Design

The previous two conceptual designs for electrolyte cooling are relatively straightforward applications of conventional cooling methods. It is expected that the water-cooled design will offer superior performance at the expense of higher capital costs. It would appear advantageous to combine the two systems to obtain a design with superior performance as well as lower capital cost. The evaporative design is aimed at providing such an alternative.

This concept uses the same layout as the forced air design, complete with fans, sub-floor ducting, etc. To improve the heat transfer at the cell walls (over the forced air values), a method has been devised to keep the cell surfaces wet. This changes the mechanism for heat transfer to an evaporative (wet surface) mode. It is analogous to transforming the entire battery into a large wet surface air cooler.

Because the amount of evaporative water needed to remove the battery heat is theoretically very small (~6 GPM at 100% usage for the entire battery), the associated distribution piping can be much smaller than that required for conventional water cooling (1200 GPM).

The conceptual design would, of course, provide considerably more water than the theoretical value. The excess water will be routinely collected by the acid containment trenchwork and reservoirs. This excess water will be automatically tested for pH (to assure that cumulative acid contamination does not occur) and recirculated in the water cooling system.

As is seen in Figure 4-11, each module is fitted with a series of inter-cell water tubes that supply the cooling water to the surfaces of the individual cell walls. To aid in providing a uniform wetting of the cell wall, a thin layer of open cell foam is applied to the cell walls. To assure that the nozzles of the supply tubing are not clogged by contaminants in the cooling water supply, the supply and recirculating water will be filtered and demineralized.

The evaporative cooling specifications are:

Required Floor Space: 130 ft x 210 ft(27,300 ft²)

Air Flow Rate: 160,000 CFM

Water Flow Rate: 50 GPM

Recirculation Rate: ~40 GPM

Total Power Consumed: 94.1 KW

4. Natural Convection

The last cooling system to be considered is a low flow rate forced air design. It is termed natural convection because the flows are as low as what would be expected for a single cell under natural convection cooling alone.

The module of Figure 3-1 is still used as the basic building block of the design, for it provides considerable advantages in terms of handling ease, hook-up ease, and efficient floor space utilization. The modules do not lend themselves very well to an unassisted air cooling mode, however, due to the tight spacing, solid top cover, and horizontal cell ribs.

To provide circulation of the room air to the interior cells of the module, a layout similar to the forced air design is used. However,

EVAPORATIVE COOLING CELL DETAIL

FIGURE 4-11

FIGURE 4-12

CIRCULATION FLOW
("NATURAL CONVECTION") LAYOUT

instead of sub-floor supply ducts for each inter-unit register, there is a small fan (460 CFM for two units) at each register plenum to draw room air into the unit. The exhaust from each unit is routed out the other inter-unit spaces on either side, as shown in Figure 4-12. Roof mounted ventilators assure a total room air exchange of ~50,000 CFM (~8 room changes per hour).

The natural convection specifications are:

- Floor Space Required: 130 ft x 210 ft (27,300 ft²)
- Flow Rate (Circulation): 50,000 CFM (~215 CFM/unit)
- Flow Rate (Room Exhaust): 50,000 CFM
- Total Power Consumed: 9.8 KW

B. PERFORMANCE EVALUATION FOR FIVE U.S. CITIES

A computer program has been developed which simulates the performance of each of the cooling systems in five U.S. cities. The simulation is based on hourly weather tape data (dry bulb and wet bulb temperatures) which cover an entire year for each of the following cities:

- Atlanta, Georgia
- Santa Maria, California
- Wilmington, Delaware
- Madison, Wisconsin
- Mobile, Alabama

The mathematical model used for the cooling systems is a first order differential equation based on a heat balance:

$$\dot{Q} = (K1) * \dot{T} + K2 * (T - T2)$$

where:

- $\dot{Q}$ = heat generated in the cell (watts)
- $K1$ = thermal mass of the cell (watt-hours/°F)
- T = electrolyte temperature (°F)
- $K2$ = heat transfer coefficient (watts/°F)
- $T2$ = heat transfer fluid temperature (°F)

The thermal mass of the cell ($K1$) is taken to be 33 WH/°F regardless of the type of cooling system employed. The heat generated in the cell ($\dot{Q}$) is assumed to follow the following profile:

- 88 watts - 4 hour discharge (12 noon - 4 pm daily)
- 100 watts - 7 hour 85% charge (10 pm - 5 am daily)
- 44 watts - 3 hour 15% charge (5 am - 8 am daily)
- 100 watts - 6 hour equalizing charge (10 pm - 4 am Saturday night)

The heat transfer coefficient ($K2$) and heat transfer fluid temperature ($T2$) are functions of the specific cooling system. Table 4-7 summarizes these values as well as the power consumption for each cooling system under consideration. In the table TW stands for wet-bulb temperature, TD refers to dry-bulb temperature, both from the weather tapes.

The "system on" characteristics for the forced air and natural convection systems account for the heat transfer from the cells to the

TABLE 4-7

System	System On Characteristics			System Off Characteristics		
	$K2$ (watts/°F)	$T2$ (°F)	P (KW)	$K2$ (watts/°F)	$T2$ (°F)	P (KW)
Water Cooled	20	$TW+10$	58	.115	TD	5.0
Forced Air	2.42	TD	94.1	.115	TD	0
Evaporative	18	$TW+10$	94.1	.115	TD	0
Natural Convection	1.32	TD	9.8	.115	TD	0

surrounding air as well as the average temperature rise of the cooling air from the outside condition. The "system on" characteristics for the water cooled and evaporative designs are based on a ten degree average approach to ambient wet bulb temperature. The "system off" characteristics are based on having the cells in a reasonably well insulated building ($U = .10 \text{ BTU/ft}^2 - ^\circ\text{F} - \text{hr}$). The power term in the water cooled design allows for circulation of the coolant to building heaters during cold weather operation.

The computer program determines the state of the cooling system by the electrolyte temperature. If the temperature is greater than 80°F , the system characteristics are for the "on" condition. If the electrolyte temperature is less than 70°F , the system characteristics are switched to the "off" values. No modulation of any of the systems was attempted; it was felt that the relative merits of the various cooling systems would be adequately demonstrated by this simple on/off characteristics with the 10°F hysteresis for the control loop. It should be noted that a particular advantage of the evaporative design was, therefore, not modeled. This is, of course, that the water for the evaporative system can be turned off to yield a more gradual loss of heat transfer coefficient (approaching that of the forced air design) and, therefore, a somewhat better modulation capability during cool weather would be achieved.

The computer program solves the basic differential equation for each one hour interval, using the weather tape data and appropriate system parameters. The program uses the electrolyte temperature from the previous interval as the initial condition, determines whether the system should be on or off, and computes the electrolyte temperature for the end of the

one-hour interval. However, because the water cooled and evaporative systems have such high capability for fast rates of change in temperature (should the system be turned on when the outside temperature is below freezing), the program does not permit the electrolyte temperature to fall below 60°F if the system is turned on. Without this provision such conditions could yield very low (and unrealistic) electrolyte temperature at the end of the one-hour interval.

Once the program determines the electrolyte temperature, a correlation for effective cycle life is made. This correlation is based on information from N. J. Maskalick of the Westinghouse Electric Corporation Research Labs¹. Mr. Maskalick projects a logarithmic relationship between cell cycle life and operating temperature; if this is converted into a cell life derating factor, the form becomes:

$$M = \text{EXP}\{6600(T - 77)/[(536.76)(459.76 + T)]\}$$

The cell life derating factor is defined as the number of cycles expected for life at 77°F divided by the number of cycles expected for life at the operating temperature. This definition is the reciprocal of what one would normally expect (numbers greater than unity mean shorter life), but it is numerically much handier in that a summation of the derating factors for each cycle directly yields the effective number of cycles on the cell. When this summation totals the design value for cycle life at 77°F, the cell can be expected to be at the end of its useful life.

Some care must be used in interpreting the value of design cycles at 77°F, since testing is rarely done at such a low temperature. Life tests on cells often approach average electrolyte temperatures of 90°F to 100°F. If the number of life cycles is predicted from these tests without

¹Accelerated Life Testing of Lead-Acid Industrial Motive Power Cells,

Maskalick, N.J., Journal of Electrochemical Society, Vol. 122, No. 1, Jan. 1975

compensation for temperature effects, a substantial increase in expected life can be achieved by operating at the 77°F optimum value. (The derating factor at 95°F = 1.49, the derating factor at 77°F = 1.0, thus a 49% increase in expected cycle life might be achieved. This would be equivalent to ~10.5 years of service if originally specified for 7.)

The program also totals the amount of power used by each of the cooling systems throughout the year. This was done with the same on/off logic for the electrolyte temperature control; the program merely summed up the "on" or "off" power value as appropriate for each hour interval throughout the year.

A sample of the hourly printout for Madison, Wisconsin, is shown in Table 4-8 for reference. Tables 4-9 through 4-13 detail the overall performance of all the cooling systems for each city. Table 4-14 summarizes the cell life derating factor for each combination of cooling system and city. Table 4-15 summarizes the annual operating energy required for each situation. Table 4-16 summarizes the effective battery life, assuming that a nominal 95°F life test temperature yields 1750 cycles, or 84 months of life.

TABLE 4-8

MADISON

			WATER SYSTEM			AIR SYSTEM			EVAP. SYSTEM			NAT. CONV. SYSTEM		
TA	TWET	Q	T	M	POWER	T	M	POWER	T	M	POWER	T	M	POWER
9.0	3.0	.0	64.8	.75	5.0	64.8	.75	.0	64.8	.75	.0	64.8	.75	.0
11.0	10.0	.0	64.6	.75	5.0	64.6	.75	.0	64.6	.75	.0	64.6	.75	.0
12.0	12.0	.0	64.4	.74	5.0	64.4	.74	.0	64.4	.74	.0	64.4	.74	.0
11.0	11.0	.0	64.2	.74	5.0	64.2	.74	.0	64.2	.74	.0	64.2	.74	.0
16.0	15.0	.0	64.1	.74	5.0	64.1	.74	.0	64.1	.74	.0	64.1	.74	.0
14.0	13.0	.0	63.9	.73	5.0	63.9	.73	.0	63.9	.73	.0	63.9	.73	.0
15.0	14.0	.0	63.7	.73	5.0	63.7	.73	.0	63.7	.73	.0	63.7	.73	.0
13.0	12.0	.0	63.5	.73	5.0	63.5	.73	.0	63.5	.73	.0	63.5	.73	.0
20.0	18.0	.0	63.4	.72	5.0	63.4	.72	.0	63.4	.72	.0	63.4	.72	.0
24.0	21.0	.0	63.2	.72	5.0	63.2	.72	.0	63.2	.72	.0	63.2	.72	.0
29.0	26.0	.0	63.1	.72	5.0	63.1	.72	.0	63.1	.72	.0	63.1	.72	.0
32.0	28.0	88.0	65.7	.77	5.0	65.7	.77	.0	65.7	.77	.0	65.7	.77	.0
34.0	29.0	88.0	68.2	.81	5.0	68.2	.81	.0	68.2	.81	.0	68.2	.81	.0
37.0	32.0	88.0	70.8	.86	5.0	70.8	.86	.0	70.8	.86	.0	70.8	.86	.0
38.0	32.0	88.0	73.3	.92	5.0	73.3	.92	.0	73.3	.92	.0	73.3	.92	.0
37.0	33.0	.0	73.2	.92	5.0	73.2	.92	.0	73.2	.92	.0	73.2	.92	.0
36.0	33.0	.0	73.1	.91	5.0	73.1	.91	.0	73.1	.91	.0	73.1	.91	.0
35.0	32.0	.0	72.9	.91	5.0	72.9	.91	.0	72.9	.91	.0	72.9	.91	.0
33.0	31.0	.0	72.8	.91	5.0	72.8	.91	.0	72.8	.91	.0	72.8	.91	.0
33.0	31.0	.0	72.7	.90	5.0	72.7	.90	.0	72.7	.90	.0	72.7	.90	.0
33.0	32.0	.0	72.5	.90	5.0	72.5	.90	.0	72.5	.90	.0	72.5	.90	.0
33.0	32.0	100.0	75.4	.96	5.0	75.4	.96	.0	75.4	.96	.0	75.4	.96	.0
33.0	32.0	100.0	78.3	1.03	5.0	78.3	1.03	.0	78.3	1.03	.0	78.3	1.03	.0
33.0	33.0	100.0	81.2	1.10	5.0	81.2	1.10	.0	81.2	1.10	.0	81.2	1.10	.0
34.0	33.0	100.0	68.1	.77	58.0	80.7	1.09	94.1	67.5	.80	94.1	82.3	1.13	9.8
34.0	33.0	100.0	69.0	.83	5.0	80.4	1.08	94.1	70.4	.86	.0	83.4	1.16	9.8
34.0	33.0	100.0	71.9	.89	5.0	80.0	1.07	94.1	73.3	.92	.0	84.4	1.18	9.8
34.0	33.0	100.0	74.8	.95	5.0	79.7	1.06	94.1	76.1	.98	.0	85.4	1.21	9.8
34.0	33.0	44.0	76.0	.98	5.0	77.7	1.02	94.1	77.3	1.01	.0	84.7	1.19	9.8
34.0	33.0	44.0	77.2	1.00	5.0	75.9	.98	94.1	78.5	1.04	.0	84.0	1.17	9.8
34.0	33.0	44.0	78.4	1.03	5.0	74.3	.94	94.1	79.7	1.06	.0	83.3	1.16	9.8
34.0	33.0	.0	76.2	1.03	5.0	71.4	.88	94.1	79.5	1.06	.0	81.4	1.11	9.8
34.0	34.0	.0	76.0	1.02	5.0	68.8	.82	94.1	79.4	1.06	.0	79.5	1.06	9.8
35.0	34.0	.0	77.9	1.02	5.0	68.6	.82	.0	79.2	1.05	.0	77.8	1.02	9.8
36.0	35.0	.0	77.7	1.02	5.0	68.5	.82	.0	79.1	1.05	.0	76.1	.98	9.8
37.0	36.0	88.0	80.3	1.08	5.0	71.1	.87	.0	81.6	1.11	.0	77.2	1.01	9.8
37.0	37.0	88.0	67.1	.79	58.0	73.6	.92	.0	69.1	.83	94.1	78.3	1.03	9.8
37.0	36.0	88.0	69.7	.84	5.0	76.2	.98	.0	71.6	.88	.0	79.3	1.05	9.8
37.0	36.0	88.0	72.3	.90	5.0	78.7	1.04	.0	74.2	.94	.0	80.2	1.08	9.8
36.0	35.0	.0	72.1	.89	5.0	78.5	1.04	.0	74.1	.93	.0	78.5	1.04	9.8
35.0	35.0	.0	72.0	.89	5.0	78.4	1.03	.0	73.9	.93	.0	76.8	1.00	9.8
34.0	34.0	.0	71.9	.89	5.0	78.2	1.03	.0	73.8	.93	.0	75.1	.96	9.8
34.0	34.0	.0	71.7	.88	5.0	78.1	1.03	.0	73.6	.92	.0	73.5	.92	9.8
35.0	34.0	.0	71.6	.88	5.0	77.9	1.02	.0	73.5	.92	.0	72.0	.89	9.8
34.0	34.0	.0	71.5	.88	5.0	77.8	1.02	.0	73.4	.92	.0	70.5	.86	9.8
34.0	33.0	100.0	74.4	.94	5.0	80.6	1.09	.0	76.3	.96	.0	72.1	.89	9.8
33.0	33.0	100.0	77.3	1.01	5.0	80.3	1.08	94.1	79.1	1.05	.0	73.5	.92	9.8
33.0	32.0	100.0	80.1	1.07	5.0	79.9	1.07	94.1	82.0	1.12	.0	74.9	.95	9.8
33.0	32.0	100.0	65.1	.75	58.0	79.5	1.06	94.1	67.5	.80	94.1	76.2	.98	9.8
36.0	29.0	100.0	68.0	.81	5.0	78.9	1.04	94.1	70.4	.86	.0	77.4	1.01	9.8
30.0	29.0	100.0	70.9	.87	5.0	78.4	1.03	94.1	73.3	.92	.0	78.5	1.04	9.8
29.0	28.0	100.0	73.7	.93	5.0	77.8	1.02	94.1	76.2	.98	.0	79.5	1.06	9.8
27.0	25.0	44.0	74.9	.95	5.0	75.5	.97	94.1	77.3	1.01	.0	78.8	1.04	9.8
26.0	24.0	44.0	74.1	.94	5.0	74.1	.96	94.1	78.5	1.03	.0	78.0	1.02	9.8

TABLE 4-9

ATLANTA

60.5 = AVERAGE DRY BULB TEMPERATURE (F)
 54.1 = AVERAGE WET BULB TEMPERATURE (F)

WATER SYSTEM

.978 = MEAN BATTERY LIFE DERATING FACTOR
 90.5 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 57.5 = LOWEST ELECTROLYTE TEMPERATURE (F)
 75.0 = MEAN ELECTROLYTE TEMPERATURE (F)
 282155.0 = POWER USAGE (KWHR)

FORCED AIR SYSTEM

1.172 = MEAN BATTERY LIFE DERATING FACTOR
 108.0 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 62.7 = LOWEST ELECTROLYTE TEMPERATURE (F)
 82.9 = MEAN ELECTROLYTE TEMPERATURE (F)
 618861.9 = POWER USAGE (KWHR)

EVAPORATIVE SYSTEM

.984 = MEAN BATTERY LIFE DERATING FACTOR
 90.8 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 56.1 = LOWEST ELECTROLYTE TEMPERATURE (F)
 75.9 = MEAN ELECTROLYTE TEMPERATURE (F)
 426832.5 = POWER USAGE (KWHR)

NATURAL CONVECTION SYSTEM

1.479 = MEAN BATTERY LIFE DERATING FACTOR
 123.7 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 63.9 = LOWEST ELECTROLYTE TEMPERATURE (F)
 92.5 = MEAN ELECTROLYTE TEMPERATURE (F)
 77604.9 = POWER USAGE (KWHR)

TABLE 4-10

MADISON

47.0 = AVERAGE DRY BULB TEMPERATURE(F)
 41.8 = AVERAGE WET BULB TEMPERATURE(F)

WATER SYSTEM

.923 = MEAN BATTERY LIFE DERATING FACTOR
 93.1 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 55.8 = LOWEST ELECTROLYTE TEMPERATURE(F)
 73.1 = MEAN ELECTROLYTE TEMPERATURE(F)
 177162.0 = POWER USAGE(KWHR)

FORCED AIR SYSTEM

1.071 = MEAN BATTERY LIFE DERATING FACTOR
 110.4 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 59.2 = LOWEST ELECTROLYTE TEMPERATURE(F)
 79.0 = MEAN ELECTROLYTE TEMPERATURE(F)
 470023.3 = POWER USAGE(KWHR)

EVAPORATIVE SYSTEM

.929 = MEAN BATTERY LIFE DERATING FACTOR
 93.4 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 55.5 = LOWEST ELECTROLYTE TEMPERATURE(F)
 73.4 = MEAN ELECTROLYTE TEMPERATURE(F)
 242871.2 = POWER USAGE(KWHR)

NATURAL CONVECTION SYSTEM

1.280 = MEAN BATTERY LIFE DERATING FACTOR
 124.2 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 60.4 = LOWEST ELECTROLYTE TEMPERATURE(F)
 85.9 = MEAN ELECTROLYTE TEMPERATURE(F)
 65796.1 = POWER USAGE(KWHR)

TABLE 4-11

MOBILE

66.4 = AVERAGE DRY BULB TEMPERATURE (F)
 50.5 = AVERAGE WET BULB TEMPERATURE (F)

WATER SYSTEM

1.050 = MEAN BATTERY LIFE DERATING FACTOR
 93.9 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 57.5 = LOWEST ELECTROLYTE TEMPERATURE (F)
 78.6 = MEAN ELECTROLYTE TEMPERATURE (F)
 331060.0 = POWER USAGE (KWHR)

FORCED AIR SYSTEM

1.252 = MEAN BATTERY LIFE DERATING FACTOR
 111.4 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 64.0 = LOWEST ELECTROLYTE TEMPERATURE (F)
 85.8 = MEAN ELECTROLYTE TEMPERATURE (F)
 639802.5 = POWER USAGE (KWHR)

EVAPORATIVE SYSTEM

1.050 = MEAN BATTERY LIFE DERATING FACTOR
 94.1 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 59.6 = LOWEST ELECTROLYTE TEMPERATURE (F)
 78.6 = MEAN ELECTROLYTE TEMPERATURE (F)
 515378.4 = POWER USAGE (KWHR)

NATURAL CONVECTION SYSTEM

1.626 = MEAN BATTERY LIFE DERATING FACTOR
 126.4 = HIGHEST ELECTROLYTE TEMPERATURE (F)
 64.0 = LOWEST ELECTROLYTE TEMPERATURE (F)
 97.2 = MEAN ELECTROLYTE TEMPERATURE (F)
 80740.8 = POWER USAGE (KWHR)

TABLE 4-12

SANTA MARIA

55.7 = AVERAGE DRY BULB TEMPERATURE(F)
 50.6 = AVERAGE WET BULB TEMPERATURE(F)

WATER SYSTEM

.904 = MEAN BATTERY LIFE DERATING FACTOR
 82.9 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 60.7 = LOWEST ELECTROLYTE TEMPERATURE(F)
 72.5 = MEAN ELECTROLYTE TEMPERATURE(F)
 121074.0 = POWER USAGE(KWHR)

FORCED AIR SYSTEM

.993 = MEAN BATTERY LIFE DERATING FACTOR
 93.1 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 64.3 = LOWEST ELECTROLYTE TEMPERATURE(F)
 76.4 = MEAN ELECTROLYTE TEMPERATURE(F)
 591030.2 = POWER USAGE(KWHR)

EVAPORATIVE SYSTEM

.905 = MEAN BATTERY LIFE DERATING FACTOR
 82.9 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 60.6 = LOWEST ELECTROLYTE TEMPERATURE(F)
 72.5 = MEAN ELECTROLYTE TEMPERATURE(F)
 150089.0 = POWER USAGE(KWHR)

NATURAL CONVECTION SYSTEM

1.269 = MEAN BATTERY LIFE DERATING FACTOR
 107.9 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 64.3 = LOWEST ELECTROLYTE TEMPERATURE(F)
 86.9 = MEAN ELECTROLYTE TEMPERATURE(F)
 76419.1 = POWER USAGE(KWHR)

TABLE 4-13

WILMINGTON

53.5 = AVERAGE DRY BULB TEMPERATURE(F)
 48.5 = AVERAGE WET BULB TEMPERATURE(F)

WATER SYSTEM

.947 = MEAN BATTERY LIFE DERATING FACTOR
 91.7 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 57.7 = LOWEST ELECTROLYTE TEMPERATURE(F)
 74.2 = MEAN ELECTROLYTE TEMPERATURE(F)
 216580.0 = POWER USAGE(KWHR)

FORCED AIR SYSTEM

1.099 = MEAN BATTERY LIFE DERATING FACTOR
 110.0 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 63.6 = LOWEST ELECTROLYTE TEMPERATURE(F)
 79.9 = MEAN ELECTROLYTE TEMPERATURE(F)
 532444.8 = POWER USAGE(KWHR)

EVAPORATIVE SYSTEM

.947 = MEAN BATTERY LIFE DERATING FACTOR
 91.9 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 56.4 = LOWEST ELECTROLYTE TEMPERATURE(F)
 74.2 = MEAN ELECTROLYTE TEMPERATURE(F)
 314103.5 = POWER USAGE(KWHR)

NATURAL CONVECTION SYSTEM

1.335 = MEAN BATTERY LIFE DERATING FACTOR
 125.0 = HIGHEST ELECTROLYTE TEMPERATURE(F)
 63.6 = LOWEST ELECTROLYTE TEMPERATURE(F)
 38.0 = MEAN ELECTROLYTE TEMPERATURE(F)
 71725.0 = POWER USAGE(KWHR)

TABLE 4-14
Cell Life Derating Factor

	<u>Water</u>	<u>Forced Air</u>	<u>Evaporative</u>	<u>Natural Convection</u>
Atlanta	.978	1.172	.984	1.479
Madison	.923	1.071	.929	1.280
Mobile	1.050	1.252	1.050	1.626
Santa Maria	.904	.993	.905	1.269
Wilmington	.947	1.089	.947	1.335

TABLE 4-15
Annual Operating Energy (MWH)

	<u>Water</u>	<u>Forced Air</u>	<u>Evaporative</u>	<u>Natural Convection</u>
Atlanta	282	619	427	78
Madison	177	470	243	66
Mobile	331	700	515	81
Santa Maria	121	591	150	76
Wilmington	217	533	314	72

TABLE 4-16

Cycle Life (Months)
(Based on 95°F = 84 months)

	<u>Water Cooled</u>	<u>Forced Air</u>	<u>Evaporative</u>	<u>Natural Convection</u>
Atlanta	128	107	127	85
Madison	135	117	135	98
Mobile	119	100	119	77
Santa Maria	138	126	138	99
Wilmington	132	115	132	94

C. COST ESTIMATES

1. Water Cooled Design

The costs for this design are detailed in Table 3-12. The building and slab and cooling costs total \$467,000.

2. Forced Air Design

The costs for the forced air design are summarized below:

<u>Building & Slab 27,300 ft² @ 15.15/ft²</u>	\$414,000
<u>Air Cooling System</u>	69,000
Sub-floor Ductwork	\$27,000
Plena, Registers	\$7,000
Fans	\$35,000
<u>Deionized Water Loop With Air Cooler</u>	12,000
<u>Credit for Elimination of Module Cooling Coils</u>	- 7,000
-Total	\$488,000

3. Evaporative Design

The costs for the evaporative design are the same as for the forced air design, except that water distribution piping must be added to wet the sides of the cells. This added cost is estimated below:

Module Manifolds	\$ 6,000
String Piping & Hook-up Valves	12,000
Pumps, Recirculation Plumbing, etc.	5,000
	<u>\$ 23,000</u>
Forced Air Sub-Total	<u>488,000</u>
Total	\$511,000

4. Natural Convection

The costs of the items pertaining to the natural convection design are summarized below:

<u>Building & Slab</u>	\$414,000
<u>Air Cooling System</u>	27,200
Plena	\$4,700
Circulation Fans	\$11,500
Roof Exhaust Fans	\$11,000
<u>Deionized Water Loop With Air Cooler</u>	12,000
<u>Credit for Elimination of Module Cooling Coils</u>	- 7,000
	\$446,200

The cooling system related costs are summarized in Table 4-17.

TABLE 4-17

<u>System</u>	<u>Cooling System Capital Costs Total (including building & slab)</u>	<u>Net Total (less \$350,000 for original building & slab)</u>
Water Cooled	\$467,000	\$117,000
Forced Air	488,000	138,000
Evaporative	511,000	161,000
Natural Convection	446,200	96,200

D. DESIGN TRADE-OFF EVALUATION

From the preceding sections, it is seen that the four methods of electrolyte cooling can be compared on the bases of capital cost, battery life, and operating energy consumption. It is appropriate to derive weighting factors which would be used with the above cost/performance indices to arrive at an overall ranking of the cooling systems for each location.

The method chosen to facilitate this comparison is based on total cooling-related monthly costs to the utility. These costs are obtained in the following manner:

1. Present Value Capital Costs

The present value capital costs are comprised of two terms: the cooling system related capital costs (including the costs of a larger building, etc.) as shown in Table 4-17, and the total battery present value costs. This last item is derived by assuming that the battery will last as long as shown in Table 4-16 for the various combinations of cooling system and location. The initial cost of the battery is taken to be \$36.90/KWH or \$1,476,000 total. However, when the battery is to be replaced at the end of the first life cycle, the replacement cost is taken to be \$29.87/KWH or \$1,194,800 total. This cost is discounted back to present value by applying the correction $(1 + i)^{-N}$, where i is the monthly discount rate and N is the time being considered, in months. Should another full replacement cycle be required, the additional cost of \$1,194,800 is discounted from two-cycle times in the future and added to the present value total.

This process continues until the design lifetime for the facility is reached (this is taken to be 20 years, for the purposes of this analysis). If there is only a fractional component of battery cycle life required to fill out the balance of 20 years, only that fraction of the \$1,194,800 is considered.

Once all of the total capital costs are added together (direct capital plus present value of replacement batteries), a total monthly capital cost is calculated which would cover the principal and interest on a constant payment payback schedule over the full 20 years. This calculation is of the form:

$$P = \frac{C * i * (1 + i)^{240}}{(1 + i)^{240} - 1}$$

where C is the total capital, P the monthly cost, and i the cost of money. For this analysis, the discount rate for present value calculations and the cost of money rate are taken to be the same value.

2. Cost of Operating Energy

A monthly cost attributable to the various combinations of cooling system and location has been assigned by taking the annual power consumption from Table 4-15, dividing by 12 to obtain an average monthly figure, and applying a typical cost of electricity of 5¢/KWH. This is summarized in Table 4-18.

3. Total Cost

A computer program was developed to perform the total monthly capital cost calculations, to factor in the monthly energy costs, and to give as output the total cooling system related monthly costs for each combination of cooling system and location. A copy of the computer program is listed in Table 4-19.

Two cases were run, one with an 8% per year cost of money and one with a 12% per year cost of money. The total costs are summarized in Table 4-20 and Table 4-21.

TABLE 4-18
Monthly Energy Cost @ 5¢/KWHR
(DOLLARS)

	<u>Water</u>	<u>Forced Air</u>	<u>Evaporative</u>	<u>Natural Convection</u>
Atlanta	1175	2579	1779	325
Madison	738	1958	1013	275
Mobile	1379	2917	2146	338
Santa Maria	504	2463	625	317
Wilmington	904	2221	1308	300

TABLE 4-19
Computer Program

```
5 PRINT "INTEREST RATE (PERCENT)=": DEMAND I
6 PRINT "OPERATING ENERGY COST $/KWH=": DEMAND D
7 PRINT "RELATIVE CAP. COST=": DEMAND C1
9 PRINT "ANNUAL OPERATING ENERGY MWH=": DEMAND E
10 PRINT "CYCLE LIFE (MONTHS)=": DEMAND N
11 P=240/N
12 P1=1
13 P2=P-1
14 P2=1 IF P>2
15 P3=P-2
16 P3=0 IF P2<1
17 P3=1 IF P>3
18 P4=P-3
19 P4=0 IF P3<1
22 I1=I/1200
23 I2=1/(1+I1)N
24 I1=I/1200
25 U=P1*I2+P2*I22+P3*I23+P4*I24
26 C=1476000+U*1194800+C1
27 I3=1/(1+I1)240
28 M=C*I1/(1-I3)
30 PRINT "CAPITAL=": PRINT IN FORM "102", C, PRINT
31 PRINT "MONTHLY CAPITAL COST=": PRINT IN FORM "72", M, PRINT
32 PRINT "MONTHLY ENERGY COST=": PRINT IN FORM "82", E*D*1000/12, PRINT
33 PRINT "TOTAL MONTHLY COST =" : PRINT IN FORM "82", M+E*D*1000/12, PRINT

34 PRINT
40 GOTO 9
```

In all cases the water cooling system has the lowest total cost, indicating that the water cooled design is the best choice for every climate being considered. The air cooled designs (natural convection and forced air) are almost identical in overall cost, but both are ~13% more costly than the water cooled design. The evaporative design did not yield the capital cost savings that had been hoped for, but it was the closest to the water cooled design with only a ~4% cost penalty.

TABLE 4-20

Total Cooling Related Monthly Costs (\$)*

Cooling-Related Capital (Principal + Interest @ 8%)
+ Operating Power Usage (@ 5¢/KWH)

	<u>Water Cooled</u>	<u>Forced Air</u>	<u>Evaporative</u>	<u>Natural Convection</u>
Atlanta	20,365	23,687 +16%	21,414 +5%	23,899 +17%
Madison	19,430	22,212 +14%	20,073 +3%	21,990 +13%
Mobile	21,307	24,750 +16%	22,442 +5%	25,376 +19%
Santa Maria	19,004	21,984 +16%	19,493 +3%	21,914 +15%
Wilmington	19,801	22,631 +14%	20,573 +4%	22,517 +14%

*Refer to pages 4-110 and 4-111.

TABLE 4-21

Total Cooling Related Monthly Costs*

Cooling-Related Capital (Principal + Interest @ 12%)
and Power Consumption @ 5¢/KWH

	<u>Water Cooled</u>	<u>Forced Air</u>	<u>Evaporative</u>	<u>Natural Convection</u>
Atlanta	23,298	26,583 +14%	24,457 +5%	26,563 +14%
Madison	22,408	25,139 +12%	23,168 +3%	24,736 +10%
Mobile	24,184	27,616 +14%	25,435 +5%	27,998 +16%
Santa Maria	22,001	24,959 +13%	22,606 +3%	24,665 +12%
Wilmington	22,760	25,553 +12%	23,649 +4%	25,241 +11%

*Refer to Pages 4-110 and 4-111.

E. Evaluation of the recombination of evolved gases

The original ventilation scheme involved ducting of outside air through the string ducts to maintain the hydrogen concentration within the ducts to less than 2%. Outside air was used to avoid the temperature control problem of introducing large amounts of potentially freezing outside air into the building per se. Rather, the cold air would be confined within the ductwork. In this way the room air temperature and humidity control could be made independent of the cell ventilation scheme.

This system does have some drawbacks, though:

- ° The hydrogen concentration in the small module manifold itself would necessarily be quite high, since no dilution air is introduced into the manifold.
- ° The effectiveness of the system in limiting room air changes is predicated on fairly good sealing of all joints, cell jars, and end closure caps. If much leakage occurs, then forced room air exchange will naturally occur.
- ° The expected operating vacuum in the duct will necessarily complicate the water addition scheme, which uses a pressure balance technique to regulate the water addition flow.
- ° The problems of duct sweating and thermal stresses associated with the conveyance of freezing air through the ductwork may pose serious operational difficulties.

For these reasons alternates to the original ventilation scheme which avoid the above problems should be considered. A recombination scheme which fulfills the requirements is considered below.

Catalyst Manifold design

This design resembles very closely the original ventilation scheme in that the module manifolds are connected to string ducts which in turn are collected via main ductwork to a pair of ventilation fans. There are, however, some major changes as can be seen from Figure 4-13: The mixture of gases is passed through a honeycomb catalytic converter to oxidize the 2% hydrogen, through a heat exchanger to condense the steam and lower the output temperature to 150° F, and finally exhausted either into the building or outside, depending on the ambient conditions. In addition, the intake air for the system is directed through each module manifold.

This system is expected to avoid the potential problems of the original design in the following ways:

- ° Because the air intake of the system maintains air flow through each module manifold (at ~22 CFM/module), the hydrogen concentration is kept below 2% in all of the ductwork, including the module manifold.
- ° Because the system can be operated in essentially a 100% recirculating mode, any leakage of the ductwork, joints, etc., merely provides additional room air circulation, not additional makeup air flow.
- ° Because the air intake is now distributed, the expected operating vacuum is expected to be insignificant in terms of affecting the water addition scheme.

FIGURE 4-13
CATALYST VENTILATION SCHEME

- ° Because the air flow through the ductwork is at room ambient, these would be no problems associated with duct sweating and thermal stresses.

In addition, the proposed system has the advantage that room relative humidity during the winter will be well controlled by the circulation of high water content air from the cell ventilation system. During the summer months, the ventilation scheme will exhaust the air to the outside, thus avoiding the problems of added heat load and humidity increase during warm weather periods.

Also of benefit is the fact that the string ductwork can now be a tapered design, in line with the distributed inlet scheme. This amounts to a savings of \$4,000 in the ductwork costs.

The overall costs of this scheme is shown in Table 4-22

Table 4-22
Ventilation Costs (21 string, 8085 cell design)

	<u>Catalytic</u>		<u>Original</u>
String Ducts	\$8,500		12,500
Filters	1,000		4,000
Dampers	4,000		4,000
Collection Ducts	4,000		4,000
Fans (2)	12,000	(3) + Stack	23,500
Honeycomb Catalyst	16,000		---
Heat Exchanger & Diverter	10,000		---
	<hr/>		<hr/>
	\$55,500		\$48,000

As can be seen from Table 4-22, the added cost of the catalyst and heat exchanger is nearly balanced by elimination of one fan and reduction in ductwork and filter costs.

It is possible that the catalytic operation and subsequent condensation of the steam would also remove any arsine and stibine from the ventilation air, to be collected in the liquid condensate. If this is the case, the use of the catalyst would amount to a net savings approaching \$45,000 over the original scheme with a scrubber added in. It should be pointed out, however, that the arsine and stibine act as poisons to the catalyst, and the effects of these substances and possible self-cleansing schemes should be investigated.

The possibility of acid mist in the air does not pose a problem to the catalyst, however, and any acid would be collected in the condensing heat exchanger, where it could be neutralized or disposed.

4.3 CONCLUSION

The best choice for battery cooling in all climatic regions studied is a water cooling design employing a large wet surface air cooler (~200-ton capacity) and plastic cooling coils immersed in the electrolyte of each cell. In comparison with a natural convection design, the cost penalties of the water cooled design (associated with the water systems increased capital costs and operating energy costs) are more than offset by the cost advantage of prolonged battery life with water cooling.

A catalytic conversion scheme for recombination of evolved hydrogen would involve a cost penalty of approximately \$7,500 (20¢/KWH), but would provide a possible solution to several operational problems, particularly associated with cold weather operation. In addition, should a positive means of arsine and stibine gas removal become desirable, the catalytic conversion scheme may be integrated into the removal hardware so that the total cost would be \$45,000 less than the original ventilation scheme with a scrubber added on.

4.4 EFFECTS OF SYSTEM RATING

It is expected that the specific costs (\$/KWH) of the battery system is going to be related to the nominal rating of the system. This section deals with the effects of system rating (MW) on the cost of each of the auxiliaries and power converter gear.

Effect of Reducing Ratings on Power Conversion Equipment Cost

The effect of any reduction in system rating is to increase the specific cost of the power conversion equipment. The major factors for the increase are the components at the ac intertie, i.e., the transformer, harmonic filters, power factor correction and associated switchgear and the ac tie breaker. The specific cost on a \$/KW basis of all of these items escalates with decreasing power rating, and escalates more rapidly the more the power is decreased.

In addition, power reduction to the point that inverter module power rating must be decreased causes further escalation in specific costs. This is due largely to the dc inductor, dc switchgear, dc interrupter and ac inductor specific cost increases which occur. To a large extent, specific cost increases in the active portions of the power conversion equipment can be avoided if the dc voltage level can be adjusted to maintain good device utilization as module power is decreased. This amounts to maintaining 5 strings per power conductor module (3400 - 3600 amps maximum per module) and adjusting the system voltage according.

Thus, for a 5 MW installation at either 810 VDC or 1620 VDC nominal voltage, only ac tie components would influence cost. The increases resulting are shown in Table 4-23.

Table 4-23

<u>DC Voltage</u>	<u>10 MW System</u>	<u>5 MW System</u>
810V	4 Modules - \$78/kW	2 Modules - \$82/kW
1620V	2 Modules - \$62/kW	1 Module - \$66/kW
*1080V	3 Modules - \$67/kW	2 Modules - \$74/kW

When the power level is further reduced, to between 1 and 2 MW, further escalation occurs as shown in Table 4-24, retaining the use of liquid cooling and adjusting the dc voltage as shown to maintain good utilization of semiconductors.

Table 4-24

<u>DC Voltage</u>	<u>2 MW System</u>	<u>1 MW System</u>
648V	1 Module - \$94/kW	--
324V	--	1 Module - \$113/kW

Description of Designs

1. 5MW, 20MWH Design

The design chosen for the 5MW rating is a 10 string, 810 volt (4050 cell) design, employing the 9 cell module, 45 cell unit, 405 cell string arrangement as shown in section 4-1. This design was selected in preference to a 1620 volt, 5 string design, because of the reduced power loss per failure of a 10 string design versus a 5 string design (10% vs 20%).

*Force Reduction of Semiconductor Utilization

The layout of the battery is shown in Figure 4-14. Each string is 75 feet long, on a 11.17 foot pitch, with one side isle of 10 feet and end isles of 10 feet, yielding a building of 95 feet x 120 feet (11,400 ft.²). The ventilation system would consist of essentially half of the 10 MW system ductwork, with one manifold fan and a smaller (12,500 CFM) mixing fan and stack.

The acid contaminant scheme would consist of exactly half of the 10 MW system, i.e. 150,000 gallons in 10 reservoirs. to provide a 90 minute, .15 GPM/Ft.² capability. The main bus design is reduced to a single water cooled square tube, and since the width of the building is reduced, the length of the main bus is significantly lowered. The other bus and protection elements are as in the 10 MW case, but fewer due to the reduction in modules, units and strings.

The cooling system employs a cooling tower, rated at 1.5×10^6 BTU/HR at the design conditions of before; the coolant water flow rate is 600 GPM. The distribution piping is as in the 10 MW case, but for the smaller 10 string layout. No change in the maintenance area is expected for the 5 MW case, so the specific cost would effectively be doubled. The fire sprinkler system would remain proportional to total building area. The water addition scheme would not be greatly different in the demineralizer and controls, but the piping and reservoir components are almost exactly proportional to system size.

4-126

FIGURE 4-14 5 MW/20 MWH BATTERY LAYOUT

Because the 9 cell module is retained, a \$3,000 penalty for the 8 inch base must be assessed. The predictive monitoring and control system is considered to be critical to performance. Therefore, the same level of monitoring and control as in the 10 MW case is used. Costs have been adjusted to represent the revised equipment and manpower levels.

The cost summary is detailed in Table 4-25.

The power losses in the cabling, contactors, and main buswork are summarized below.

Power Losses @ 650 amps/String

Inter-Module Cabling	8.8 KW
Static Contactors	7.8 KW
Main Buswork	<u>6.0 KW</u>
TOTAL	22.6 KW

This is 0.45% of the nominal 5 MW discharge rating.

TABLE 4-25

5MW, 810V Battery Auxiliaries Costs

		TOTAL	\$/KWH
Building and Slab		\$173,000	8.65
Monitoring and Control		\$230,000	11.50
Computer with Input/Output	\$105,000		
Computer Startup and Software	16,000		
Isolation	34,000		
Cabling	32,000		
Input Devices	6,000		
Static Contactors	37,000		
Ventilation System		\$ 25,300	1.27
Ductwork	12,300		
Fans and Stack	13,000		
Acid Containment		55,000	2.75
Buswork and Protection		28,000	1.40
Intermodule Cabling	4,500		
Main Buswork	11,000		
Fuse Disconnects	9,000		
String Disconnects	3,500		
Water Cooling		65,000	3.25
Cooling Tower	33,000		
Piping	20,500		
Pumps, Misc.	3,500		
Deionized Waterloop	8,000		
Maintenance		49,000	2.45
Room and Equipment	34,000		
Gantry	15,000		
Fire System		12,500	.63
11,400 Ft. ² @ \$1.08/Ft. ²			

Table 4-25 (continued)

Water Addition		\$ 18,000	.90
Demineralizer and Controls	\$ 4,000		
Piping	11,000		
Reservoir and Hookups	3,000		
Sub Total		\$655,800	\$32.79/KWH
Base Penalty		<u>3,000</u>	.15/KWH
Aux. Total		\$658,800	\$32.94/KWH

2. 1MW, 4MWH Design

The design chosen for the 1MW, 4MWH rating is based on the power conversion utilization requirement of a 5 string minimum battery layout. It consists of 810 cells, 5 strings, 162 cells per string, for a nominal voltage of 324 volts. The 9 cell module is retained; however, a 54 cell unit is now required (3 units per string) for isolation. Thus, the layout of the battery is as in Figure 4-15; each string is 30 feet long x 11.17 feet pitch, yielding a building of 45 x 60 feet (2700 ft.²). The acid containment reservoir has 40,000 gallon capacity, consistent with a 90 minute, .15 GPM/Ft.² (405 GPM) fire sprinkler system.

The ventilation scheme would be a manifold scheme, but would operate at 5,000 CFM throughout the system, without a separate mixing fan. The buswork and protection elements are analogous to the original 10 MW case, except that the reduced voltage rating and higher cell unit level have reduced the fused disconnect costs. The main buswork is a single water cooled 3" square section with 1/4" wall, otherwise the same as the 10 MW case. Since the main buswork is current and length dependent, and to a large degree independent of the system voltage, the main bus costs are at a somewhat higher specific cost at the lower voltage of the 1MW system. The water cooling system is based on the same design conditions as the original, but at the lower rating (300,000 BTU/HR) its

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FIGURE 4-15 1MW, 4MWH BATTERY LAYOUT

specific costs are somewhat higher. Because of the reduced number of cells in the facility, the need for a separate maintenance room is reduced, so the maintenance provisions will be limited to a gantry. Any spare cells, etc. will have to be transported to the site during maintenance. The water addition scheme is reduced from the 10MW case, but again at somewhat higher specific costs for the demineralizer and controls; the reservoirs and piping benefit somewhat from the change in unit level.

The power losses for the inter-module cabling, static contactors, and main buswork are summarized below:

Power Losses @ 650 amps/String

Inter-Module Cabling	1.75 KW
Static Contactors	3.9 KW
Main Buswork	<u>1.75 KW</u>
TOTAL	7.4 KW

This is 0.74% of the nominal 1 MW discharge rating.

It is visualized that 1MW systems will find application as Load Leveling Systems being applied by Industrial and commercial activities rather than Utilities. As such any loss of service can cost the business unit involved a severe penalty because of a single high demand. This cost can

be reflected over an entire billing period. This cost makes reliability extremely critical perhaps even more so than for the utility. The predictive Monitoring system is the single most important item to improve reliability. It has been included in cost estimates at the same monitoring level as in the 10MW system with equipment and manpower levels revised to reflect actual costs.

The cost summary is detailed in table 4-26.

Table 4-26

1MW, 324V Battery Auxiliaries Costs

		Totals	\$/KWH
Building and Slab	2700 FT ² @ \$15.15/FT ²	\$41,000	10.25
Monitoring & Control		\$84,500	21.13
Computer with Input/Output	63,000		
Computer startup and software	4,000		
Isolation	not required		
Cabling	6,000		
Input Devices	1,500		
Static Contactors	10,000		
Ventilation System		\$ 9,500	2.38
Ductwork	4,500		
Fan & Stack	5,000		
Acid Containment		\$14,000	3.50
Buswork & Protection		\$ 9,500	2.38
Intermodule Cabling	1,000		
Main Buswork	4,000		
Fuse Disconnects	1,000		
String Disconnects	1,500		
Water Cooling		\$19,000	4.75
Cooling Tower	8,000		
Piping	4,000		
Pumps, Misc.	2,000		
Deionized Loop	5,000		
Maintenance			
Gantry		\$15,000	3.75
Fire System		\$ 4,000	1.00
Water Addition		\$ 4,400	1.10
Demineralizer & Controls	1,700		
Piping	2,200		
Reservoirs & Hookups	500		
Sub Total		\$200,900	50.23/KWH
Base Penalty		\$ 600	\$.15/KWH
Total	4-134	\$201,500	\$50.38/KWH

Total System Costs

The total system costs of the 10 MW, 5 MW, and 1 MW ratings are summarized below:

	10 MW (1620 V)		5 MW (810 V)		1 MW (324 V)	
	Total	Specific Costs \$	Total	Specific Costs \$	Total	Specific Costs \$
Battery	1,476,000	36.90	738,000	36.90	147,600	36.90
Base Penalty	20,000	.50	3,000	.15	600	.15
Auxiliaries	1,132,100	28.30	655,800	32.79	200,900	50.23
Energy-Related Total		<u>65.70/KWH</u>		<u>69.84/KWH</u>		<u>87.28/KWH</u>
Power Converter	620,000 + (\$62/KW)		410,000 (\$82/KW)		113,000 (\$113/KW)	
Totals	3,248,100 (324.81/KW)		1,806,800 (361.36/KW)		462,100 (462.10/KW)	

When the total costs/KW are plotted on log/log paper against station power rating (in MW), the data almost perfectly fits the curve of:

$$\text{\$ Cost/KW @ 4-hr Rate} = \$462.10 (\text{MW Rating})^{-.1531}$$

4.4 CONCLUSION

The cost/KW of the 4-hour peaking power battery systems is steadily a decreasing function of the system rating. The costs can be approximated by the relation (for systems from 1 MW to 10 MW):

$$\text{Total Cost/KW (@ 4-Hr Rate)} = \$462.10 (\text{MW rating})^{-.1531}$$

4.5(a) ADVANCED TECHNOLOGY

In the world of today, technology and the "state-of-the-art" are extremely dynamic in seeking and finding new levels of stability. Since peaking or load leveling systems incorporating batteries as a source of energy have not been implemented, there has been no attention paid to problems which may be unique to this application. More specifically, systems for battery auxiliaries have not been visualized as large battery banks have not existed.

Perhaps the concepts of battery auxiliary systems expressed in Sections 3.2 and 3.3 of this report can begin to draw attention to those items needing the attention of technology resources to advance their "state-of-the-art." Typical of such items are:

- (a) Battery cooling systems
- (b) Battery ventilation needs and methods
- (c) Battery watering systems
- (d) DC bus construction
- (e) DC high voltage fault interruption
- (f) DC high current protection
- (g) Monitoring of battery cells
- (h) Monitoring of battery systems

Let us consider the effects of possible advances of technology on the monitoring and control system.

A. "State-of-the-Art" Battery

The monitoring and control system conceived and described in Section 3.2 consists of a system made of "off-the-shelf" devices. These devices are then applied in a conventional manner in system development with a mini-computer to achieve the results described. The level of monitoring for the battery (at the 7-cell module) was chosen as an economic compromise to achieve a reasonable cost. However, the most desirable level would be at the individual battery cell or 8085 system inputs.

It is expected that advanced technology will permit the monitoring of each individual cell without increasing cost. In looking at advanced technology and monitoring opportunities, we should first consider our objectives.

The basic objective of the monitoring system is to keep the battery system in efficient operation at the highest possible power level. The method of accomplishing this is to constantly monitor the "health" of each battery element.

In addition to the battery elements, a large number of battery auxiliary systems are monitored. However, the monitoring of the battery elements represents 2/3 of the monitoring system input-output and, when grouped with the required isolating units, also represents 2/3 of the monitoring and control cost. For this reason, our major concern is with the available technology and its advance to affect the monitoring of individual battery cells.

There are a number of conditions which might be monitored to determine battery cell "health." These conditions include:

- Cell voltage
- Cell current
- Cell stored energy
- Gas evolution
- Electrolyte temperature
- Electrolyte specific gravity
- Electrolyte conductivity
- Electrolyte level

For the conceived system, cell voltage and cell current were selected for monitoring with storage capacity being calculated. This selection was based on using conventional apparatus without expensive instrumentation. The most effective indicators of cell "health" are thought to be these items plus electrolyte temperature and specific gravity.

Cell temperature would be a good indicator of the cell's losses, but since the cells are water cooled, excess heat would probably be absorbed before a significant temperature differential is observed. Inexpensive instrumentation for measuring specific gravity does not exist today. Advanced technology may well develop this instrumentation if needed, but efforts are not expected to be made in the near future.

We will now consider directions for advanced technology to take in the battery monitoring system. Figure 4.5-1 illustrates the elements of the conceived system of Section 3.2 for a single battery module voltage measurement. As previously stated this represents "off-the-shelf" components using conventional techniques and system philosophy.

PRESENT MONITORING SCHEME

FIGURE 4.5-1

As a step in advanced technology, we should first consider the impact of remote multiplexing which is currently being introduced by several manufacturers. Problems of isolation would be overcome by using the measured quantity (module voltage) for the instrumentation power supply. System isolation is gained through the communication link.

A typical system for monitoring module voltage might be as shown in Figure 4.5-2. The isolation modules shown in Section 3, Figure 3-20, have been eliminated and the multiplexing originally in the central mini-computer is eliminated.

The communication system is transformer coupled, providing the isolation from system and earth ground. All electronic components would be mounted in non-metallic (plastic) housings and no earth grounds would be introduced in the local multiplexing system. The input/output requirements for a 1620 volt system as described in Section 4.1 are tabulated in Table 4.5-1. The interconnections for this input/output are shown in Figure 4.5-3.

While costs for this system will provide an appreciable saving (see Table 4.5-2) monitoring is still being performed at the module level. It is extremely likely that advanced technology will provide means of monitoring individual cells at a reasonable cost. Also, there is at least one other consideration still desirable, when adequate development incentives are available.

The battery system represents a low impedance energy source normally ungrounded and possibly subject to frequent grounds. A monitoring and

FIGURE 4.5-2 TYPICAL REMOTE I/O CONNECTIONS

TABLE 4.5-1
1620 Volt 10 String 8100 Cell
Summary of Input/Output

<u>System</u>	<u>Digital</u>	<u>Analog</u>	<u>Comments</u>
Facility	31 2 CCO	8	Alarm change of state. Calculate cooling - alarm temperature "out of limits."
Cell Ventilation	13 3 CCO		Alarm change of state - terminate charge/discharge.
Battery Temperature Regulation	5 3 CCO	22	Alarm change of state. Recalculate storage capacity for low temperature alarm high temperature.
Water Addition	*180 1 CCO		Alarm change of state.
Charge/ Discharge	22 20 CCO	11	Alarm change of state - terminate charge/discharge. Contact closure outputs to string static contactor. Integrate AMP hours storage for charge/discharge find average of string current - alarm out of limit terminate charge/discharge
Maintenance		2 *900	Alarm grounded condition generate average cell characteristic for charge/discharge - alarm out of limits.
	<u>*180</u>		Alarm change of state for disconnect operation.
TOTALS	71 CCI 29 CCO 33 Analog	*360 CCI *900 Analog	

*Remote input-output multiplexing.

MINI-COMPUTER INSTALLATION

Figure 4.5-3

control system using metallic conductors for interconnection and signal distribution places circuit connections at every battery module which could have full dc voltage available when specific ground conditions occur. The only method of removing the unsafe voltage is to clear the ground fault. It would therefore be highly desirable to eliminate the network of metallic conductors that interconnect the monitoring system.

It is visualized that the technology associated with fiber optics will yield developments allowing a non-conducting interconnection system. Figure 4.5-4 illustrates a concept using fiber optics to develop a cell voltage sensor. The connection of the computer to the fiber optic communication system is shown in Figure 4.5-5.

Note that this concept considers monitoring of each cell voltage. It also incorporates the philosophies expressed earlier of distributed multiplexing and use of the measured quantity for power supply to the module. Taking advantage of today's technology for large scale integration and hybrid component construction, we would expect some dynamic improvement in system cost even with the increased number of monitored points as seen in Table 4.5-2.

In addition to this advance of technology, we expect to see continued reductions in the cost of computer hardware. These reductions are most likely to occur in the cost of computer memory and memory devices. The costs included in the conceived system cost reflect some of the benefits already obtained in the basic computer from micro-computer introduction. We would expect the cost shown in Table 4.5-2 to become available through the introduction of advanced technology.

TYPICAL MODULE VOLTAGE SENSOR

A.T. MONITORING SCHEME

Figure 4.5-4

A.T. COMPUTER HOOKUP

FIGURE 4.5-5

TABLE 4.5-2
Monitoring and Control Costs

	<u>Section 3 Base</u>	<u>1620 Volt Remote I/O</u>	<u>Advanced Technology</u>
Computer with Input/Output	175,000	85,000	83,000
Computer Startup & Software	20,000	20,000	20,000
Isolation or Remote I/O	86,000	96,000	93,500
Cabling	67,000	32,500	10,000
Input Devices	16,000	9,500	9,500
Static Contactors	<u>78,000</u>	<u>67,000</u>	<u>67,000</u>
TOTAL	442,000	310,000	283,000

4.5(a) CONCLUSION

The use of advanced technology monitoring systems, which are expected to be attainable within a short period of time, will have the advantages of:

- reducing monitoring costs by \$159,000 from that in section 3.3
- allowing individual cell monitoring versus module monitoring, and thus improve the ability to detect individual cell abnormalities
- eliminating the intrinsic safety hazard of monitor wiring throughout the battery

Choice of Optimum Design

The optimum design for the peaking power battery system is one which has the best combined effects from the considerations of power conversion integration, system voltage, reliability, cooling means, and reasonable advances in technology. The design will be based on the 10 MW, 40 MWH rating, utilizing the (W) 160-45 cell.

The battery will be a 1620 VDC, 10 string design with 8100 cells (900 modules). The life of the battery is expected to be 10-11 years in most areas of the country, since water cooling is employed. Monitoring of individual cells via optical channels will assure excellent predictive capability without compromising safety or isolation requirements. The high speed dc fuses in the string make unnecessary the high-speed dc breakers in the power converter gear, and the battery and power conversion gear share monitoring and cooling systems. Costs for the design are listed below:

1620V DC, 10-String Battery Costs

	<u>Total</u>	<u>\$/KWH</u>
Battery	\$1,476,000	\$36.90
1620 VDC Base Penalty	20,000	.50
Auxiliaries*	1,025,100	25.63
Energy Total		63.03/KWH
Power Converter**	550,000	<u>55/KW</u>
System Totals	\$3,071,100	\$307.11/KW

*Includes optical monitoring system, shared deionized water loop.

**w/o high speed dc breaker, with shared monitoring system.

4.5(b) DESIGN USING LARGE CAPACITY CELLS

The size of the cell used in the peaking power battery design has a significant effect on the auxiliaries. Major items affected are the number of parallel strings, layout, bus design, monitoring requirements, and D.C. fault protection capability. This section deals with the auxiliaries required for use with large capacity cells.

CONCEPTUAL DESIGN USING LARGE CAPACITY CELLS

Design Description

Cell Design:

The cell employed in this design is the WE67, which has the following characteristics:

Length:	53"
Width:	27"
Height:	72"
Weight:	approximately 5000 lbs
Ampere-Hour Capacity:	25,000
Watt-Hour Capacity:	49,000
Average Voltage:	1.96V
Watt-Hour Energy Efficiency:	78%

Battery Design:

The use of the large capacity cell effectively reduces the number of cells required for a 10 MW, 40 MWH battery by an order of magnitude. An energy storage capability of 39.98 MWH is provided by 816 cells, compared to the 8100 cell arrangements of prior sections.

The battery characteristics are as follows:

Energy Storage Capacity:	39.98 MWH
Nominal Voltage:	816V
Nominal Current:	12,255 amps
Number of Strings:	2
Number of Cells:	816

Layout:

The cells are arranged in two electrical strings of 408 cells each, yielding a nominal D.C. voltage of 816 volts. The strings are arranged into four rows each, for a total of 8 rows, as shown in Figure 4-20. Each row is comprised of 102 cells and is 255 ft long by 4.92 ft wide with a 3.50 ft aisle between rows. At the end of the rows there are 10-foot

FIGURE 4-20

LAYOUT OF LARGE CAPACITY CELL DESIGN

access aisles with 8-foot side aisles yielding an overall building size of 275 ft x 80 ft (22,000 ft²).

A word of explanation is in order at this point. If one compares the total floor area of this design (22,000 ft²) with that of the 810 VDC design employing KW160-45 cells in 9-cell modules, - reference Figure 4-3 -(22,135 ft²), the fact that the total floor area is nearly the same may seem illogical. One would have thought, perhaps, that the large capacity cell would have a significantly smaller footprint per KWH, primarily due to its increased height.

There are three reasons why this expectation is not fully realized:

- (1) Because of the size of the large capacity cell, the sidewalls must be fairly thick (4" each) to resist bowing and warping. This increases the footprint of the cell.
- (2) The construction of the KW160-45, 9-cell module allows for tight packing of the cells into a unit of similar capacity to the large cell. This tight packing effectively reduces the footprint of the KW160-45 cells.
- (3) The aisle between rows in each design is approximately 3.5 ft (4 ft nominal less room for the ventilation ducts, etc.). However, the row width in the large cell design is only 4.92 ft, compared to the KW160-45 9-cell module row width of 7.67 ft. Because the aisle is a larger fraction of the row width for the large capacity cell design, its impact on total floor area is greater there than with the 9-cell module design.

INTERCELL
BUSWORK

VENT
DUCT

INTERCELL BUSWORK

INST.
WIREWAY

VENT
DUCT

CELL

AISLE

AISLE

TROUGH

TRENCH

WATER
ADDITION
PIPING

WATER
COOLING
PIPING

FIGURE 4-21

The rows of cells are arranged with an acid containment trough/trench system similar to the original scheme, as shown in Figure 4-21. Since the requirements for water addition and water cooling are similar to before, the trench provides a convenient location to run the water systems manifolding. The ventilation scheme is also very similar, with a 6" wide x 42" high duct running along each row. The instrumentation wireway is again on top of the ventilation duct.

At the end of the rows, there are underground provisions for all connections, as in the original design. Again, this is to allow use of an overhead method of cell removal and transport. At the end of each row is a disconnect/protection device which can isolate the row for maintenance purposes as well as interrupt faults. The bus work leading from one row to the next (in the string) is run in a trench at the end of the rows. Because of the layout of the cells, there is no main bus proper, just intercell bus work and inter-row tie bus work.

The acid trenches are covered for their entire length by grating, and they drain into a common reservoir at one end of the building. The reservoir is a 300,000 gallon capacity, sufficient to contain the water from the .15 GPM/ft², 90-minute sprinkler system.

A water cooling tower virtually identical to the one originally specified is used to control electrolyte temperature, and it is located adjacent to the acid containment reservoir. As before, the water system is connected to row piping via transverse trench work at the reservoir end of the building. The auto water plumbing is similarly located.

Ventilation:

The ventilation system is directly comparable to that of the original design. Instead of 21 strings, there are now 8 rows, but the effective system is virtually identical. The duct work hydrogen concentrations are kept below 2% (25,000 CFM total) with mixing to 1% for disposal.

Water Cooling:

The specifications for the water cooler are identical to that of the original design; the 2% increase in energy efficiency (76% - 78%) is not sufficient to cause a reduction in cooling system capacity. The plastic tube heat exchanger for each cell is now individually connected to the water system manifolding via flexible hose and shutoff valves. Because there are no requirements for a deionized water loop, however, none need be supplied (for battery purposes only).

Water Addition:

The water addition scheme is the same as the original design, with the following exceptions: the number of individual fill valves is significantly lower (816 vs 8085), and the "unit" reservoir has been replaced by a 6-cell reservoir, yielding another reduction in quantity (136 vs 231). All other aspects of the water addition scheme are identical to the original design.

Electrical Protection:

Isolation

The WE67 cell has a base design integral with the cell that provides the 6" minimum tracking distance required. The cooling coil in the cell electrolyte is of the same electrical quality as in the original design.

Bus Design

The intercell bus work consists of two pairs of 1/4" x 6" copper bars clamped to the cell posts. The bars are designed for approximately 45°F rise over ambient (in air) and are expected to dissipate approximately 1/2% of the discharge power capability (approximately 50,000 watts). The bus work will be lead coated to prevent corrosion.

Where the bus work goes into the trench work, the copper is increased 50% and is insulated and metal sheathed for mechanical protection and for limits on thermal losses to allow the universal use of an air cooled design. Because of the layout of the rows and strings, there is no main bus work per se; only intercell and short inter-string (and string to power converter) subfloor sections.

Since there are not any static contactors (see below) nor any main buswork per se, the total power loss at the nominal discharge rating of 6,130 amps/string is 50 KW, or 0.50% of the nominal 10 MW discharge rating.

Disconnect/Protection Devices

The configuration of Figure 4-22 shows a total of 10 contactors for the system. It is envisioned that one of the devices per string (marked A) would be at the approximately 1000 VDC, approximately 7,000 amps full load rating. However, because the other devices would only interrupt a maximum row/row fault of approximately 400 VDC, the voltage ratings for the other devices (marked B) can be similarly reduced. The negative bus devices (marked C) can be simple disconnects,

FIGURE 4-22

as they are out of any row/row fault circuits. It is noteworthy that this level of protection/disconnect is roughly 3 times as coarse as the original system (102 cells vs 35 cells), with the attendant problems of personnel safety and increased probability of uninterruptable faults due to multiple ground paths not embracing a protection device.

A further problem with this approach exists with D.C. circuit breakers that are currently available. These breakers cannot accommodate the rate of rise of current that would occur on a direct bus fault. Protection from catastrophic effects of a bus fault in the form of current limiting fuses or current limiting reactors will be required.

Maintenance Provisions:

An overhead gantry will be used for cell handling (removal, transport and installation).

Isolation provisions are somewhat compromised by the increase in fully connected cells (102 vs 35 cells), but the other provisions of monitoring disconnects and water system ground hold.

Facility:

The provisions for the building and maintenance room have not changed from the original design.

Monitoring and Control System:

The monitoring and control system is identical to that described in Section 3.2-B-8 with the following exceptions:

- The number of voltage points are reduced from 1155 to 816.
- The thyristor contactors are replaced by electromechanical devices.
- The isolation fuse status devices are replaced by status and control of additional electromechanical devices.
- Two of the contactors (marked A) replace the power converter high speed dc interrupters.

Cost Estimate

The costs of a peaking battery design employing large capacity cells have been estimated and are summarized in Table 4-30.

Table 4-30

		<u>Total</u>	<u>\$/KWH</u>
<u>Building & Slab</u>		\$ 333,000	\$ 8.33
22,000 ft ² @ \$15.15/ft ²			
<u>Monitoring & Control</u>		293,500	7.34
Computer with Input/Output	152,500		
Computer Startup and Software	20,000		
Isolation	61,000		
Cabling	50,000		
Input Devices	10,000		
Main Contactors (2)*	(120,000)		
<u>Ventilation System</u>		49,500	1.24
Duct Work	26,000		
Fans & Stack	23,500		
<u>Acid Containment</u>		110,000	2.75

*These replace the power converter contactors, therefore, the cost is not added to auxiliary total.

		<u>Total</u>	<u>\$/KWH</u>
<u>Bus Work and Protection</u>		\$ 270,000	\$ 6.75
InterCell Bus	53,000		
Tie Bus	17,000		
Row Contactors (6)	180,000		
String Disconnects (2)	20,000		
<u>Water Cooling</u>		106,500	2.66
Cooling Tower	54,500		
Piping	47,000		
Pumps, Misc.	5,000		
<u>Maintenance</u>		49,000	1.23
Room & Equipment	34,000		
Gantry	15,000		
<u>Fire System</u>		23,700	.59
22,000 @ approximately \$1.08/ft ²			
<u>Water Addition</u>		29,500	.74
Demineralizer & Controls	5,000		
Piping	20,000		
Reservoirs and Hookups	4,500		
TOTAL		\$1,264,700	\$31.62/KWH

EFFECTS OF ADVANCED TECHNOLOGY DEVICES

The impact of advanced technology for the large capacity cell auxiliaries is expected to lie in two major areas: monitoring systems, and fuse systems.

The use of an optically-coupled system as described in section 4.5(a) would result in the following estimated costs:

Monitoring and Control

Computer with Input/Output:	75,000
Computer Startup and Software:	10,000
Isolation	: 10,000
Cabling	: 8,000
Input Devices	: 6,000
Main Contactors	: - 0 -
	<u>\$109,000</u>

This is a savings of \$184,500 from the state-of-the-art case.

The use of fuses and manual disconnects to replace row contactors as shown in Figure 4-22 will provide appreciable savings. However, these devices do not currently exist in the necessary ratings. When available, it would be expected that the cost of these devices would allow the return of the philosophy of providing unit isolation for maintenance at lower voltage levels. Figure 4-23 represents a battery system incorporating high speed dc breakers, identified as (A), to perform a first line of defense. Isolation for maintenance and protection from row-to-row faults plus an additional line of defense is performed by the fused disconnect switches, typified by B in Figure 4-23.

FIGURE 4-23

The cost comparison of the breaker arrangement of Figure 4-22 and the fused disconnect of 4-23 is as follows:

	<u>Buswork and Protection</u>	
	<u>Breaker</u>	<u>Fused Disconnect</u>
Intercell Bus	\$ 53,000	\$ 53,000
Tie Bus	17,000	17,000
Row Contactors	180,000	30,000
String Disconnects	<u>20,000</u>	<u>20,000</u>
	\$270,000	\$120,000

As expected the cost savings is appreciable. The resultant systems savings for advanced technology cells with advanced technology monitoring and fusing is as follows:

	<u>Total</u>	<u>\$/KWH</u>
Battery	\$1,264,800	\$31.62
Auxiliaries	930,200	23.26
Power Converter	<u>780,000</u>	<u>\$54.88/KWH + \$78/KW</u>
	\$2,975,000	\$297.50/KW @ 4-hr rate

The final comparison necessary to complete the picture with the advanced technology cell is that of the high voltage connection for 1632 volts. This arrangement is shown in Figure 4-24.

The obvious disadvantage that can be seen from this figure is the one of system availability. Because a single battery string is incorporated, any failure causes complete system loss. It would be necessary to carefully evaluate this effect to use this connection.

The effect of the 1632 volt selection on cost is as follows:

Battery	\$1,264,800	\$31.62
High Base Penalty	20,000	.50
Auxiliaries	930,200	23.26
Power Converter	<u>620,000</u>	<u>\$55.38/KWH + \$62/KW</u>
	\$2,835,000	\$283.50/KW @ 4-hr rate

FIGURE 4-24

ADVANCED TECHNOLOGY
BATTERY SYSTEM
ONE LINE DIAGRAM

4.5(b) CONCLUSION

A design using large capacity cells and state-of-the-art auxiliaries would cost:

	<u>816V DC, Large Cell Design</u>	
	<u>Total</u>	<u>\$/KWH</u>
Battery	\$1,264,800	\$31.62
Auxiliaries	1,264,700	31.62
Power Converter	<u>780,000</u>	<u>\$63.24/KWH + \$78/KW</u>
	\$3,309,500	\$330.95/KW @ 4-hr rate

Effects of Advanced Technology Devices would yield the following costs:

	<u>816V DC, Large Cell Design</u>		<u>1632V DC, Large Cell Design</u>	
	<u>Total</u>	<u>\$/KWH</u>	<u>Total</u>	<u>\$/KWH</u>
Battery	\$1,264,800	\$31.62	\$1,264,800	\$31.62
Auxiliaries	930,200	23.23	950,200	23.76
Power Converter	<u>780,000</u>	<u>\$54.85/KWH + \$78/KW</u>	<u>620,000</u>	<u>\$55.38/KWH + \$62/KW</u>
	\$2,975,000	\$297.50/KW @ 4-hr Rate	\$2,835,000	\$283.50/KW @ 4-hr Rate

5.0 SUMMARY AND CONCLUSIONS

The costs of various 10 MW, 40 MWH, peaking battery system designs have been estimated. Each design shares the features of:

- Multi-cell module design. The use of a seven or nine cell module provides ease of handling, superior floor space utilization, significant reduction in the number of field hook-ups and superior mechanical protection for the cells.
- Predictive Monitoring. By detecting incipient failures of individual cells before immediate action is required, corrective action can be scheduled so that system downtime and labor costs are minimized.
- Water Cooling. The use of a water cooling design to control electrolyte temperature has been shown to be cost effective in all regions of the continental United States, due to beneficial effects on cell life and floor space utilization.
- Manifold Ventilation. The use of manifolds in an induced-draft design provides positive control of the evolved gases, relieves some operational difficulties associated with cold weather operation, and is compatible with methods of handling arsine and stibine gases, should the need arise.

The costs are summarized in Table 5-1. The minimum cost design using the KW160-45 cell has the benefits of:

- Increased Voltage. Within the limits imposed by fuse design, increased voltage substantially improves power converter costs.
- Improved Monitoring Technology. Use of recent technological improvements in monitoring and control show a significant cost benefit.
- Shared Equipment. Sharing of a deionized water loop, monitoring, and protection equipment between the battery and power conversion gear show some cost benefits.

The effects of system rating on the battery design and costs have been evaluated. The 1 MW (4 MWH) and 5 MW (20 MWH) designs share the same features as the 10 MW (40 MWH) design, but at somewhat elevated costs. Table 5-2 summarizes the effects of system rating on total costs; note that within the range of ratings studied, the total cost per KW obeys a simple mathematic relation.

If a large capacity cell design (49 KWH) is used, large changes are seen in layout, buswork and protection requirements. Table 5-3 summarizes the costs for a 10 MW, 40 MWH battery with present technology and advanced technology devices. Also included is a cost estimate of a higher voltage design.

TABLE 5-1

10 MW, 40 MWH BATTERY COST SUMMARY

	<u>770 VDC</u>		<u>810 VDC</u>		<u>1620 VDC</u>		<u>1620 VDC*</u>	
	<u>Cost</u>	<u>\$/KWH</u>	<u>Cost</u>	<u>\$/KWH</u>	<u>Cost</u>	<u>\$/KWH</u>	<u>Cost</u>	<u>\$/KWH</u>
Building & Slab	350,000	8.75	335,400	8.39	309,000	7.73	309,000	7.73
Monitoring & Control	442,000	11.05	387,000	9.68	380,000	9.50	283,000	7.08
Ventilation	48,000	1.20	43,100	1.08	43,100	1.80	43,100	1.80
Acid Containment	110,000	2.75	110,000	2.75	110,000	2.75	110,000	2.75
Buswork & Protection	81,500	2.04	68,000	1.70	69,000	1.73	69,000	1.73
Water Cooling	117,000	2.93	117,000	2.93	117,000	2.93	107,000	2.68
Maintenance	49,000	1.23	49,000	1.23	49,000	1.23	49,000	1.23
Fire System	25,000	.63	24,000	.60	22,000	.55	22,000	.55
Water Addition	33,000	.83	33,000	.83	33,000	.83	33,000	.83
High Base Cost	-		6,000	.15	20,000	.50	20,000	.50
Auxiliaries Total	1,255,500	31.39	1,172,500	29.31	1,152,100	28.80	1,045,100	26.13
Battery	1,476,000	36.90	1,476,000	36.90	1,476,000	36.90	1,476,000	36.90
Energy Total	2,731,500	68.29/KWH	2,648,500	66.21/KWH	2,628,100	65.70/KWH	2,521,100	63.03/KWH
Power Converter	780,000	78/KW	780,000	78/KW	620,000	62/KW	550,000†	55/KW
TOTAL	3,511,500	351.15/KW	3,428,500	342.85/KW	3,248,100	324.81/KW	3,071,100	307.11/KW

*With optical monitoring system, shared deionized water loop.

†w/o high speed breaker, with shared monitoring system.

TABLE 5-2

COST SUMMARY

1 MW to 10 MW @ 4-hr Rate

	<u>10 MW(1620 V)</u>		<u>5 MW(810 V)</u>		<u>1 MW(324 V)</u>	
	Total	\$/KWH	Total	\$/KWH	Total	\$/KWH
Auxiliaries	1,132,100	28.30	655,800	32.79	200,900	50.23
High Base Cost	20,000	.50	3,000	.15	600	.15
Battery	1,476,000	36.90	738,000	36.90	147,600	36.90
Energy Total	2,628,100	65.70/KWH	1,396,800	69.84/KWH	349,100	87.28/KWH
Power Converter	620,000	62/KW	410,000	82/KW	113,000	113/KW
TOTAL	3,248,100	324.81/KW	1,806,800	361.36/KW	462,100	462.10/KW

The total cost/KW of the peaking battery system, when plotted against system rating, obeys the relation:

$$\text{Total } \$/\text{KW @ 4-hr Rate} = \$462.10(\text{MW Rating})^{-.1531}$$

TABLE 5-3

COST SUMMARY

10 MW, 40 MWH Battery Using Large Capacity Cells

	<u>816V</u>		<u>816 V*</u>		<u>1632 V*</u>	
	<u>Total</u>	<u>\$/KWH</u>	<u>Total</u>	<u>\$/KWH</u>	<u>Total</u>	<u>\$/KWH</u>
Auxiliaries	1,264,700	31.62	930,200	23.23	950,200	23.76
Battery	1,264,800	31.62	1,264,800	31.62	1,264,800	31.62
Energy Total	2,529,500	63.24/KWH	2,195,000	54.88/KWH	2,215,000	55.38/KWH
Power Converter	780,000	78/KW	780,000	78/KW	620,000	62/KW
TOTAL	3,309,500	330.95/KW	2,975,000	297.50/KW	2,835,000	283.50/KW

*Using Advanced Technology Monitoring and Protection Devices

5.1 RECOMMENDATIONS FOR FUTURE WORK

During the course of this study there were several times when the course of action was dictated by the limitations of some of the components or by the lack of information in a specific area. These have been pointed out elsewhere in this report, but it is appropriate to summarize here the areas where future work could be directed.

- **Arsine and Stibine Generation.** It is not known what actual quantities of arsine and stibine would be generated in an operating lead-acid peaking power battery. It is recommended that tests be run to quantify the generation rates of these gases as functions of life, depth of discharge, amount and rate of overcharge, temperature, etc.; the range of the independent variables to be according to expected peaking power operation.

- **Fuse Application.** The maximum voltage used in this study was consistent with the ratings of presently available fuses. It is recommended that:

- a) A system analysis be undertaken to define the effect of interaction of several parallel strings of fused batteries. Such an analysis should define the appropriate fuse characteristics to adequately protect a D.C. fed main bus fault at various locations. In particular, it may be possible to eliminate the high-speed electro-mechanical breaker in the main buswork and replace it with a less costly disconnect.

- b) The feasibility of fuse system applications at voltages higher than 1600 VDC should be explored with fuse manufacturers.

- **Cost Effectiveness of Water Cooling.** The work done in this study to indicate that the use of water cooling was economic was based on a present value analysis. An additional analysis should be done using utility values for cost of money and operating power penalties.

- Monitoring and Control. This study has shown that a monitoring system which can detect incipient failures in cells is well worthwhile. Although the advances in monitoring technology in general are expected to be almost directly applicable, some specific developments would be appropriate:

- a) Development of a fast response Arsine and Stibine detector for low concentrations.

- b) Development of low cost specific gravity transducers.

- c) Development of low cost distributed logic voltage sensors (as outlined in Section 4.5(a) of this report.)

- Effect of an Acid Spill. The need for a large reservoir system is based on the requirement to collect all fire sprinkler water for a 90 minute duration. The actual environmental impact of a diluted acid spill is not known. It is recommended that such an impact be evaluated, with the goal of reducing the size and cost of the acid reservoir.

- Recombination Ventilation Schemes. Section 4.3(E) of this report shows a manifold ventilation scheme employing a catalytic converter for recombination of the evolved gases. Because such a system has distinct operational advantages in both cold and hot ambient weather, it is recommended that follow-on work be done to demonstrate the feasibility of this and related ventilation schemes in a test program.

- FMEA Analysis. The Failure Modes and Effects Analysis performed in Section 4.2 of this report proved to be a valuable exercise in systematically delineating the causes, effects and corrective actions for specific component and subsystem failures. It is recommended that such an analysis be undertaken in any future Peaking Power system studies.

APPENDIX

"A GUIDELINE FOR THE FMEA/FTA"

● Why Conduct An FMEA/FTA?

In 1960 there were fewer than 50,000 *product liability suits* recorded in the U. S. per year. In 1970 the number of suits recorded reached 500,000 and by 1975 it is estimated this figure will climb to well over one million product liability suits annually. Not only have the number of suits increased but so has the size of the average recovery. Individual judgments are being awarded for sums of \$500,000 and even \$1,000,000 and above. *Product warranty costs* continue to increase leading to higher product costs and reduced profits. Poor product reliability also effects the company's reputation and results in "lost sales". With this *growing claims consciousness* on the part of the consumer and *rising warranty costs*, it is essential that our products be *reliable and safe* for their *intended use and reasonably foreseeable misuse*.

Ⓜ Management Guide MG-P62 states that it is the *Engineering Manager's responsibility* to develop and implement programs to ensure that the design engineer fully carries out his responsibility for *all elements* in the design of a product, including *safety and reliability*. How can the Engineering Manager ensure that his design is safe and reliable? What are the tools or techniques that he can use? Two tools are the *Failure Mode & Effects Analysis* (FMEA) and the *Fault Tree Analysis* (FTA).

The *FMEA* is a technique for systematically identifying, analyzing and documenting the possible failure modes within a design and the effects of such failures on system performance and personnel safety. The *FMEA* is a *bottom-to-top analysis* which begins at the bottom, the component level and works upward to the end product or system level where the effect of the failure on system performance or personnel safety is determined.

The *FTA* is similar to the *FMEA* in that it too is a technique for systematically identifying, analyzing and documenting potential safety and reliability problems. The *FTA* differs from the *FMEA* in its method of documentation and in the fact that it is a *top-to-bottom analysis*. It begins with an assumed undesirable event at the top or system level and identifies the events at subsequent lower levels in the system that can cause the undesirable top event.

The purpose of both the *FMEA* and *FTA* is to identify areas in the design or hardware where improvements are required to ensure the system will be reliable and safe for its intended use and reasonably foreseeable misuse. The *FMEA/FTA* can serve to increase the efficiency and productivity of design reviews, by focusing design review emphasis on weak areas in the design; it can also serve as a source of material for use in preparing reliability and quality assurance test programs, and in preparing care and use books or repair and maintenance manuals.

Appendix A provides an example of the *FMEA* and *Appendix B* provides an example of the *FTA*.

● Who Conducts the FMEA/FTA?

Generally, the *FMEA* or *FTA* can be performed more quickly by the responsible design engineer because he is most familiar with his design. Having a reliability engineer perform the analysis allows a fresh objective analysis of the design. If the analysis is conducted by the design engineer, it should be checked by the reliability engineer, and vice versa. Together they go over the possible failure modes, possible causes, how failures would be evidenced or detected, the consequences of failures both on the performance and safety of the product.

● When To Use FMEA/FTA?

The *FMEA/FTA* should become an integral part of the normal product design process.

The primary purpose of the *FMEA/FTA* is, as stated earlier, to identify areas in the design or hardware where improvements should be made to ensure the system will be reliable and safe for its intended use and reasonably foreseeable misuse. Positive action must be taken to correct the deficiencies highlighted by the *FMEA* or *FTA* before the job can be considered completed. Design changes can be made most effectively during the design stage. Making the necessary changes after the product is in production is more costly. *No new product design or major redesign should be released for production without an FMEA or FTA having been conducted and the follow up actions accomplished.*

Use the *FMEA* when primary emphasis is to be placed on assuring that *each component in the design will be examined* for possible failure modes and the effect on the overall design.

Use the *FTA* when primary emphasis is to be placed on analyzing specific undesirable top events for identifying causes and their probabilities of occurrence.

FMEA

● FMEA Procedure

The *FMEA* procedure described in this guideline is a basic procedure which should have application in most Ⓜ divisions. Some divisions, because of specific customer requirements, may need to use a more detailed procedure. A list of References is included for those who wish to further pursue the technique of *FMEA*.

There is no *one* right way to perform an *FMEA* or *one* right format to use. The important thing is that a form such as the one shown in Figure 1 be used to guide the analysis through a systematic process and document the results.

The *FMEA*, as described herein, is sometimes called a Failure Mode Effects and Criticality Analysis (*FME & CA*) because the criticality of each failure mode is analyzed in this procedure.

STEP 1 - Collect the Data to be Used in the Analysis

First, collect the information for conducting the *FMEA* including drawings, schematics, layouts, parts lists,

bill of materials, information on the operating environment, and any other descriptive information on system operation which may be available. Other useful documents might be the product design specification and other specifications, industry or association standards, and perhaps particulars from the contractual requirements. If the system is in the early stages of its design and development, the information available for FMEA may be limited, and the depth of analysis will be limited. However, if the design is completed or a prototype hardware model exists, the analysis will result in a thorough examination of the system.

STEP 2 - *Prepare a Form for the Analysis*

Figure 1 describes a sample form which can be used for the FMEA. There is no *one* correct form to use. Prepare a form which best suits the person conducting the analysis and the design or hardware being analyzed.

STEP 3 - *Sequentially list each part to be analyzed by part number and by name.*

STEP 4 - *Briefly describe the function(s) of each part in the system.*

STEP 5 - *List the possible failure modes in which each part can fail.*

Frequently there are two or more failure modes for a part, each of which could cause different effects on the system performance or personnel safety.

STEP 6 - *List the effect each failure mode would have on system performance.*

For each failure mode identified for a particular part, list the effect which that failure could have on the system performance. It is quite useful to describe the effect on system performance as it would be seen through the eyes of the user. For example, if an "O" ring would be missing or broken in a hydraulic system it would be better to explain the effect as "loss of system braking capability" rather than "loss of hydraulic pressure". Or if a resistor would fail open in a temperature sensing circuit it would be better to explain the effect as "system surface temperature goes to maximum of 900°F" rather than "loss of temperature sensor".

STEP 7 - *List the criticality of each failure mode and the ensuing result on system performance or personnel safety.*

The Criticality Analysis is done by establishing a ranking of the seriousness and implications of the failure. For example, a failure might be Critical, Major, Minor or Insignificant. The *Critical* failure is one which causes or can cause harm to personnel. It is a *safety hazard*. The *Major* fault is one which causes serious effect on operation and

requires immediate attention. A *Minor* fault is one which does not cause immediate concern but will require attention in the near future. A failure which is *Insignificant* is one which can be tolerated because it has little or no effect on operation. One popular method of using this measure is as follows:

C - Critical: There is a safety hazard.

MA - Major: System performance is out of control; system is in need of immediate repair; service is required immediately.

MN - Minor: System performance is degraded but operation can continue; repair or correction is needed at earliest opportunity.

I - Insignificant: Failure has no immediate effect on system performance.

STEP 8 - *List the measure of probability of the failure mode occurring.*

Enter the measure of probability of the failure mode occurring. This entry may be very subjective and relate closely to the experience of the analyst, or it may be quantitatively calculated from actual test data or field use or from reference to an established part failure rate handbook. Another useful technique is to rank the *relative probability* of a part failure to the other possible failure modes in that system. For example, one method of establishing relative probability of failures is:

	H - High
Relative degrees of probability	M - Moderate
of failure occurring.	L - Low
	U - Unlikely

STEP 9 - *Review the analysis, determine where corrective action is dictated and follow up to see that appropriate action is taken.*

This is the most important step in the FMEA. The FMEA points the way to product improvement. The completed FMEA should be reviewed by the analyst to determine what follow up actions are required. Unless positive actions are taken to correct the deficiencies identified by the analysis, the task is only partially completed. The action items which are generated by the FMEA should be documented as shown by the Action/Responsibility column in Figure 1. Another very effective way to implement the follow up action is to use a separate "Action Items" sheet. The "Action Items" sheet should list each required action item as identified by the FMEA, the person responsible for the action, and a date for completing the action item. The *Engineering Manager* should review the findings and recommendations of the FMEA and the Action Items list with the design engineer or reliability engineer making the analysis and ensure that corrective action is taken.

FAILURE MODE AND EFFECTS ANALYSIS

Identify the product, part sub-system, or equipment which is to be analyzed by the FMEA.

Identify the product by drawing number and revision number/letter.

Identify who completed the FMEA.

Identify who checked the completed FMEA. It is recommended that one person, for example, a design engineer, do the actual analysis, and another person perhaps a reliability engineer associated with the design, check the FMEA.

FAILURE MODE & EFFECTS ANALYSIS									
PRODUCT _____				DONE BY _____					
DRAWING # _____ REV. _____				CKD BY _____					
CODE:				C - Safety Hazard MA - Major Fault - Requires Prompt Service MN - Minor Fault - May Require Future Service I - Insignificant			RELATIVE PROBABILITY OF OCCURRENCE: (PROB)		H - High M - Moderate L - Low U - Unlikely
*This item suggested for further investigation or action.									
ITEM #	LINE/ PART NO.	DESCRIPTION	FUNCTION OF PART	MODE OF FAILURE	EFFECT ON SYSTEM	CRIT	PROB	REMARKS	ACTION/ RESPONSIBILITY
	STEP 3		STEP 4	STEP 5	STEP 6	STEP 7	STEP 8	STEP 9	

Enter the date when the FMEA was performed and the date when it was checked. The dates along with the revision number/letter provide good traceability, if needed, to the specific revision and when it was done.

As items are entered on the form, number them sequentially. This permits easy reference.

Enter the part number as it appears on the drawing, part list, etc.

Enter a brief description of the part as it appears on the drawing or part list used as reference.

Enter a brief description of the function(s) of the part being examined for possible failure modes.

Enter the failure mode which the part could possibly incur. Frequently there are 2 or more failure modes for a part, each of which could cause different effects on a system.

For each failure mode identified, enter the effect which that failure could have on the system performance.

Under criticality, enter the degree of criticality which can be associated to the part failure and the ensuing result.

Enter the measure of the probability of occurrence of the failure mode.

Required follow up action.

This column is provided for clarifying or supplemental remarks as may be required.

Figure 1

FTA

● FTA Procedure

There are two significant differences between the FTA and the FMEA. The first is the method of documentation. The FTA uses a set of standard logic symbols to represent events and relationships in the hardware. The FMEA as we have seen uses a part by part tabular form to identify failure modes. The second difference is the starting point of the analysis. The FTA begins at the top of the system with a statement of an undesired event in the system. The FMEA begins at the bottom, the component level and works upward to the system level where the effect on the system performance is described.

The FTA begins with a statement of an undesired event. This establishes the top of the tree. Next, the events which can lead to the top event are identified. The events which can cause the next level are identified. A tree of events is thus established until the undesired events and failures are traced to the lowest identifiable level which most often leads to the component level.

A set of logic symbols, Figure 2, are used to develop the fault tree. They are standard symbols which should be used when performing fault tree analysis.

STEP 1 - *Collect the data to be used in the analysis.*

Same as in Step 1 in FMEA procedure.

STEP 2 - *Identify the Top Event (A Fault, Failure or Personnel Hazard).*

The top event is the starting point for the analysis and should therefore be well defined. It is an event, a malfunction, or failure which affects system performance or personnel safety. The top event should be definable and measurable.

In some cases there may be more than one top event in which case each fault tree can be developed individually. For example consider a steam iron. The functions of a steam iron are:

- (1) to provide heat for ironing,
- (2) to provide steam when required,
- (3) and a necessary and inherent requirement to be reasonably safe for use.

Of course the "system" is going to be hot beyond human tolerance when it is being used and that is an acceptable feature but the possibility of electrical shock hazard must be considered. So, in defining the top events there are three possible events which could be defined as top events:

- (1) temperature, absence of or too high
- (2) steam, none or present when not required
- (3) Injury hazard, electrical shock.

Note that these three top events can be readily defined and measured.

STEP 3 - *Develop the Fault Tree*

The development of a fault tree begins by stating the top undesired event such as a safety hazard, a system failure or some definable fault. (Use an *event* rectangle as indicated

in Figure 2.) The starting point for the FTA is thereby established. The analysis continues by identifying the events on the next level down which could cause the top event. The analyst must study the events to determine if they will occur as an AND function or an OR function to cause the top event. (See Figure 3 examples.) The fault tree development continues in this manner downward from the top event and accounts for all of the contributing events which can lead to the top event. The development of the tree is concluded when the lowest possible level is reached to which a basic failure event can be assigned. The basic failure events are represented by a circle on the fault tree. The basic events are generally hardware failures, errors of commission, or errors of omission.

STEP 4 - *Assign Quantified Values of Probability to Each Event on the Fault Tree*

The quantification of the basic fault events can come from several sources among which are: established source of component failure rates; failure rates from actual field use; estimates of rates of occurrences. For example, consider a gasoline driven motor-generator set. There are established failure rates for the electrical components which make up the voltage regulator "subsystem". These failure rates come from established sources of component failure rates. As for the motor, years of experience in using that type of motor may provide reliable failure rates. These failure rates come from actual field use. And an estimate may have to be made that one time in every x uses the operator will forget to check the gasoline tank and it will be empty. This is an estimated rate of occurrence based on the best information available. These are the kinds of data which are used to determine the probability of the top undesired event occurring.

STEP 5 - *Review the analysis, determine where corrective action is dictated and follow-up to see that appropriate action is taken.*

As in the FMEA, this is the most important step in the FTA. The completed FTA should be reviewed by the analyst to determine what follow-up actions are required. Unless positive actions are taken to correct the deficiencies identified by the analysis, the task is only partially completed. The action items which are generated by the FTA should be documented on an "Action Items" sheet. The "Action Items" sheet is a very effective way to implement the follow-up action. It should list each required action as identified by the FTA, the person responsible for the action, and a date for completing the action. The *Engineering Manager* should review the findings and recommendations of the FTA and the Action Items list with the design engineer or reliability engineer making the analysis and ensure that corrective action is taken.

● Revisions

As design changes occur during the production life of the product, the FMEA and/or FTA should be revised to be kept current with the latest configuration.

FAULT TREE ANALYSIS LOGIC SYMBOLS
The RECTANGLE identifies an event, usually a malfunction, that results from the combination of fault events through the logic gates.
The AND GATE describes the logical operation whereby the coexistence of all input events is required to produce the output event.
The OR GATE defines the situation whereby the output event will exist if any or all of the input events are present.
The CIRCLE describes a basic fault event that requires no further development. This category includes component failures whose frequency and/or mode of failure are derived or known.
The DIAMOND describes a fault event that is considered basic in a given fault tree, however, the causes of the event have not been developed, either because the event is of insufficient consequence or the necessary information is unavailable.
The INHIBIT GATE describes a causal relationship between one fault and another. The input event directly produces the output event if the indicated condition is satisfied.
The HOUSE indicates an event that is normally expected to occur.
The TRIANGLE indicates a transfer symbol. A line from the apex of the triangle denotes a transfer in and a line from the side denotes a transfer out.

Figure 2

Figure 3

APPENDIX B

An Example of FTA

The steam iron example in the FMEA is used again here, this time applying the techniques of the FTA.

The steam iron performs two major functions: (1) provides heat, (2) provides steam. Suppose the undesired event was stated as "No Steam from Iron". This undesired event implies that there is no heat to make steam or no water to make steam.

The Fault Tree for "No Steam from Iron" would look like the tree shown in Figure 6.

Suppose a Fault Tree which looked just like the "No Steam from Iron" example was of a system for which event probabilities were available. The analysis could then be quantified as shown in Figure 7.

The event probabilities are:

C1	.005	C5	.001
C2	.0005	C6	.001
C3	.0005	C7	.80
C4	.002	E1	.06

This type of analysis permits a quantification of the top event or any of the lower contributing events. In the example of Figure 7 it can be seen that the top undesired event, R1, has a probability of occurrence of .058, or about 1 out of every 17 times. Further inspection shows that event R2 will occur 1 out of every 125 times and R3 will occur 1 out of every 20 times (occurrence probabilities of .008 vs. .050). It can be seen that events comprising R3 influence the undesired top event R1 more than R2 does. Further investigation shows that event R5 influences R3 more than does R4, and so on.

An analysis of this type is of value in identifying the areas where more effort such as design, test, or inspection would be of greatest value.

Figure 6

Figure 7

● Headquarters Assistance

For additional information and assistance, contact the Product Integrity Laboratory Manager, Headquarters Engineering & Development, R&D Center, Pittsburgh, Pa. 15235, or call on WIN 236-7280.

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