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CONCEPTUAL DESIGN OF A SODIUM SULFUR CELL FOR U.S. ELECTRIC VAN BATTERIES

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Abstract

A conceptual design of an advanced sodium/sulfur cell for U.S. electric-van applications has been completed. The important design factors included specific physical and electrical requirements, service life, manufacturability, thermal management, and safety. The capacity of this cell is approximately the same as that for the "PB" cell being developed by Silent Power Limited (10 Ah). The new cell offers a 50% improvement in energy capacity and nearly a 100% improvement in peak power over the existing PB cells. A battery constructed with such cells would significantly exceed the USABC's mid-term performance specifications. In addition, a similar cell and battery design effort was completed for an advanced passenger car application. A battery using the van cell would have nearly 3 times the energy compared to lead-acid batteries, yet weigh 40% less; a present-day battery using a cell specifically designed for this car would provide 50% more energy in a package 60% smaller and 50% lighter.

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EXECUTIVE SUMMARY

A cost-shared contract was awarded by Sandia National Laboratories to Beta Power, Inc. in July 1990 to design a common sodium/sulfur cell (and possibly module) for use in electric utility vans that are suitable for entry-level markets. The following four vehicles were considered as models for this study: G-Van, Tevan, ETX-II and the Ford MEV-2 (75-hp). The period of performance for this contract was 18 months. An integrated systems approach was used in that the performance and physical requirements of the entire battery system for these four vehicles established the primary cell design criteria. That is, specific cell requirements were determined based on battery requirements (e.g., sustained power, capacity, physical dimensions, weight). A constraint on this study was that the cell design must be capable of being built and qualified within a three-year period. During the first quarter of FY91, a task was added to consider the design of a high-performance cell for use in a passenger electric vehicle (EV) intended for commuter service.

The actual work consisted primarily of an analytical study which compared different candidate cell configurations, such as flat plate and tubular cells, and identified a relatively low risk conceptual-cell design for US van applications and also a medium risk, secondary, conceptual-cell design. The conceptual cell was used to prepare various conceptual battery designs for the four vans being considered.

The following cell configurations were evaluated:

Tubular Cells

- a) Central Sulfur b) Central Sodium

Flat Plate Cells

- c) Single Membrane d) Ribbed Electrolyte

Multi-Tube Cells

- e) Central Sulfur f) Central Sodium

Calculations of relative electrolyte stresses generated in flat plate cells and tubular cells highlighted the high risks associated with flat plate cell designs. A further analysis comparing general cell performance showed that, once realistic burdens had been assigned to the ribbed flat plate configuration, a central sodium cell configuration had the best overall performance for these EV applications. Multi-Tube

configurations were rejected for operational reasons concerning their inability to cope with electrolyte failures.

The conclusion was that the preferred configuration is central sodium tubular, with the medium risk option being central sulfur tubular. The only plausible benefit of the latter configuration concerned a potential for better calendar life, as demonstrated by a set of long-lived central sulfur cells at CSPL. The preferred overall dimensions¹ of the two conceptual cells are shown in schematic diagrams presented in Figures 1 and 2. Projected performance of these cells highlighted the significant improvements

Figure 1. Conceptual Design of Central Sodium Cell

Figure 2. Conceptual Design of Central Sulfur Cell

¹ All dimensions of drawings presented in this report are in millimeters.

that are possible over state of the art cells. The specifications for the preferred central sodium design are shown in Table 1 and, for reference, are compared with those of an advanced PB cell design.

Table 1. Advanced PB Cell Comparison

	Con- ceptual	Ad- vanced PB
Energy (kWh)	21.40	24.0
Weight (kg)	85.00	135.00
Resistance (mΩ)	17.50	32.00
Wh/kg	252	151
Wh/l	404	305
W/kg	616	212
W/l	987	428

Various conceptual battery design studies were completed using state of the art battery component designs:

a) An ETX-II battery using the Conceptual Cell.

- b) A G-Van battery using the Conceptual Cell.
- c) A TeVan battery using the Conceptual Cell.
- d) A Ford Escort (MEV2) battery using the Conceptual Cell.
- e) Ford Escort (MEV2) batteries using advanced PB cells.
- f) A passenger car battery, based on Impact requirements, using the Conceptual Cell.

These studies showed that significant improvements in battery performance are possible, and physical and performance comparisons between the different van batteries utilizing the Conceptual Cell are shown in Table 2. The study also highlighted battery packaging efficiency as a key factor requiring improvement over state of the art batteries. The question of the feasibility of battery modularity between the different vans was addressed. It was concluded that the MEV2 van, with a significantly different height constraint, was a special case. A high degree of modularity of battery internals could be achieved, provided a flexible scheme of electrical inter-connection was adopted. The higher energy density achieved with these batteries may also require active cooling when combined with high power, aggressive driving cycles.

Table 2. Comparison of Projected Battery Parameters Against Targets

BATTERY DETAILS	VEHICLE			
	ETX-II	MEV2	G-Van	TeVn
Projected Weight(kg)	400	310	496	400
Target Weight(kg)	500	400	500	500
Projected Energy(kWh)	54	43	69	54
Target Energy(kWh)	45	40	60	50
Projected Peak Power(kW)	111	89	145	76
Target Peak Power(kW)	65	65	48	60
Projected Nominal Voltage	348	348	224	174
Target Nominal Voltage	342	342	216	180
Minimum Load Voltage	250	250	160	145
Specific Energy(Wh/kg)				
Projected	135	139	139	135
Target	90	100	120	100

Costs were estimated using a costing methodology developed for EPRI, but adjusted for inflation. The methodology used standard assumptions to generate battery selling price.

Relative levels of battery cost of energy and power are shown in Figure 3, which also compares the Conceptual Cell with an advanced PB cell.

Figure 3. Relative Battery Price

Summary

The program has concluded that central sodium tubular cells are the preferred configuration and has specified overall cell dimensions suitable for both van and passenger car applications in the 21st century. Furthermore, batteries employing the conceptual cell can approach the long term goals of the United States Advanced Battery Consortium (USABC) even when state of the art battery packaging is adopted. For example, the projected performance of the conceptual-cell MEV2 battery with the relevant USABC long-term goals are shown in Table 3. Several conceptual battery designs have been completed for the U.S. van applications and for a conceptual advanced passenger car.

Table 3. Projected Performance of MEV2 Battery

	MEV-2	USABC Long Term Goal
Specific Energy (Wh/kg)	139	200
Energy Density (Wh/l)	190	300
Specific Power (W/kg)	290	400
Power Density (W/l)	400	600

1.0 INTRODUCTION

Over the past several years, development of sodium/sulfur batteries has successfully progressed towards commercial development. These batteries offer significant improvements in performance over currently available batteries and promise acceptable cost and life.

Developers of the sodium/sulfur technology have concentrated on their own specific cell designs for electric vehicle batteries. These cells show continuing improvements in performance as the technology matures, but their basic designs were defined for perceived applications which existed a number of years ago. Current advanced electric vehicle applications in the U.S. now demand higher performance from the batteries, thus the existing cell designs of developers may not be at an optimum for these applications.

Over the past decade, Sandia National Laboratories (SNL) have managed the U.S. Department of Energy (DOE) sponsored programs for the development of sodium/sulfur technology. Recognizing that the optimum cell for U.S. electric vehicle batteries may not be offered by state-of-the-art cells, a Request for Quotation (RFQ) was issued in December 1989 to address this issue.

The RFQ, SNL RFQ 54-5324, defined a statement of work which would be directed towards four specific objectives: (a) examining alternative cell configurations; (b) defining a conceptual sodium/sulfur cell design for four U.S. van applications; (c) establishing the feasibility of battery modularity between the U.S. vans; and (d) defining conceptual battery designs.

Beta Power, Inc. (BPI) was awarded the 12 month contract, with a main subcontractor being Chloride Silent Power (CSPL), a worldwide leader in the development of sodium/sulfur technology. The four U.S. vans chosen as models for the study were the Ford/DOE ETX-II van, the G-Van, the Chrysler TeVan, and the DOE IDSEP van. Work commenced in July 1990; in the course of the contract, the study was modified to (1) examine the Ford/DOE MEV-2 van rather than the IDSEP van and to (2) include the study of an advanced electric passenger car battery.

The technical effort on this contract was structured into the following six tasks:

1. Identification of Battery Requirements: Determine the battery requirements with input from vehicle manufacturers.
2. Analysis of Battery Requirements: Analyze the battery specifications of the four vehicles to identify requirements for a common cell.
3. Cell Design: Use the quantitative requirements obtained in Task 2 to design a conceptual sodium/sulfur cell for electric van applications.
4. Battery Design: Determine the feasibility of a common module design and complete a conceptual design of a battery system for the MEV-2 vehicle using the results from Task 3.
5. Program management.
6. Advanced Passenger EV Battery.

The remainder of this report contains a detailed description of the results obtained from the performance of the five technical tasks. The report is roughly structured to be consistent with the program's task and subtask organization. Also of note, a comprehensive conceptual design of the MEV-2 van battery was completed using an advanced PB cell. This activity was included in the program to provide a baseline battery design to both this effort and to the DOE/Ford Motor Modular Electric Vehicle Development (MEVP) Program. Because the principal objective of this program involves the conceptual cell, the majority of the PB-based battery design is contained in Appendix A.

2.0 BATTERY REQUIREMENTS DEFINITION

2.1 ELECTRIC VAN MANUFACTURERS INTERFACE

Technical interfaces were established with all the manufacturers or developers of the four electric vans which were specified at a first contract review meeting held shortly after the start of the contract. At this time, the IDSEP vehicle specified in the RFQ was considered to be inappropriate for the study and was replaced with the MEV-2 vehicle which was being pursued on the DOE/Ford MEVP program.

This task focused primarily on liaison with Ford Motor Company since two of the four vehicles were Ford projects and since the definition of the MEV-2 vehicle was not as well established as the other

vehicles. Definition of the TeVan and G-Van dimensions and battery requirements did change during the program, and these are reflected in the data shown in the following section.

Technical contacts were identified for each vehicle within the appropriate organizations:

Vehicle	Company
ETX-II	Ford Motor Company
MEV2	Ford Motor Company
G-Van	Conceptor Industries Inc.
TeVan	Chrysler Motor Corp.

2.2 BATTERY SPECIFICATION

The final battery requirements are summarized in Table 4 and Figure 4. Sandia produced some changes from those contained in the RFQ: (1) reductions in target calendar life from 8 to 5 years; and (2) reduction in target service life from 2000 to 1000 cycles.

Table 4. Sodium/Sulfur Battery Requirements for Electric Vans

REQUIREMENTS/GOALS	VEHICLE			
	ETX-II	MEV2	G-Van	TeVan
Manufacturer/Developer	Ford	Ford	Conceptor	Chrysler
PHYSICAL SPECIFICATIONS				
Maximum Weight (kg) (Dimensions on Diagram)	500	400	500	500
PERFORMANCE REQUIREMENTS				
Energy Availability Goals	SFUDS	SFUDS	SFUDS	SFUDS
- Driving Cycle	45	40	60	50
- Beginning of Life, kWh	36	32	48	40
- End of Life, kWh				
Peak Power, kW (30s pulse above Minimum Voltage at 80%)	65	65	48	60
Continuous Power, kW (for at least 40 minutes)	35	30	42	35
Nominal Working Voltage, V	342	342	216	180
Minimum Load Voltage, V (at Peak Power)	250	250	160	145
Heat Loss, W	400	400	400	400
Calendar Life, years	5	5	5	5
Service Life, cycles	1000	1000	1000	1000
ECONOMIC GOAL				
Selling Price (\$/kWh)	<150	<150	<150	<150

The battery requirements definition was frozen in the first quarter of 1991 to allow specific cell and battery design tasks to be progressed. The specifications were reviewed during the program by Beta Power and CSPL personnel.

Specific Vehicle Comments

ETX-II Van. During the program the main change to the ETX-II battery specifications accommodated a request from Ford to increase the system voltage. The use of a nominal system voltage of 342V rather than the 200V specified in the RFQ standardized the 75hp and 100hp MEVP vehicles. Minor changes in battery envelope dimensions occurred due to the difference between "as measured" and the original figures.

MEV-2 Van. The requirements and goals for this vehicle were evolved during the program by dialogue with staff at Ford. This vehicle was distinctly different in many ways in its requirements when compared with the other three vans. The battery space was specified as two separate envelopes. The target Peak Power:Energy Ratio was also high when compared to the other vans.

G-Van. The main modification to these specifications concern dimensions. These were obtained via Chloride Electric Vehicle Systems and were consistent with a data sheet issued by Conceptor Industries Inc., giving battery pannier dimensions. This sheet also confirmed the original voltage levels specified in the RFQ. Other aspects of the specifications remained unchanged. An independent check of under vehicle space in G-Vans at Electrotek by CSPL personnel also confirmed the battery dimensions specified in Figure 4.

TeVan. The main modification to these specifications concerned dimensional change. The later data was obtained from Chloride Electric Vehicle Systems and was consistent with diagrams provided by Chrysler Industries Inc. defining battery pannier dimensions. Chrysler also proposed that the target battery height be reduced from an original value of 270mm to 220mm in order to fit the battery under the vehicle without modifying the vehicle suspension. Chrysler also proposed an increase in minimum load voltage from 135V to 145V, which made the voltage window of 180V to 145V very narrow and the delivery of peak power more difficult.

General Comments on Requirements and Goals

Dimensional Specifications. When establishing battery envelope dimensions, one has to be careful that the same definitions have been used. The adopted approach assumed that these dimensions allowed for engineering tolerances and clearances due to vehicle and battery support features. They did not include features that the battery developer may feel are necessary for batteries, such as cooling ducts, control boxes. The issue of whether batteries are split within the envelope was addressed in the detailed battery designs tasks.

3.0 ANALYSIS OF BATTERY REQUIREMENTS

3.1 CELL AND BATTERY MODEL DEFINITION

Preliminary analyses using established programs developed at CSPL showed that there was a danger of losing sight of some important sensitivities. These programs are based to a large extent on characterizing cells and batteries using state of the art cell and battery components.

Examples of this loss in design flexibility are: the assumption that a particular type of seal was being used for the cell; and that a particular type of construction methodology was being used for the battery. It was also difficult to translate these software programs into other cell configurations without producing apparent trends which were due largely to the "fixed hardware" assumptions.

A fresh approach was adopted which combined a "Cell Up" method with a "Battery Down" method. The "Cell Up" part of the study minimized the number of assumptions regarding cell design while incorporating the major parametric factors. The "Battery Down" part of the study sought to specify some of the key goals that the cell should meet in order to satisfy some of the battery requirements.

When cell designs were established in more detail, a further "Cell Specific" model was used to calculate more comprehensive cell performance characteristics at various points in the cycle. When battery designs were established in more detail, their characteristics were examined in greater depth using an existing CSPL "Battery Performance" model.

3.1.1. The "Cell Up" Method

A QuickBasic computer program was written which examined tubular central sulfur, tubular central sodium and flat plate configurations. The program made no assumptions about length or design related components such as seals and, instead, treated the cell as a unit length of an infinitely long tube or as a unit area of a flat plate cell. The sulfur electrode of each configuration was modelled using the transmission line network models developed by Brennan [1]. These predicted the nominal resistance of an electrode in the single phase region.

Despite this greatly simplified approach, several assumptions had to be made in order to generate basic trends. These included the following:

1. A structured sulfur electrode was assumed.
2. A deliverable capacity of 85% of theoretical capacity available at the end of discharge to 1.76V open circuit was assumed.
3. An allowance was made for component tolerance variation in the sodium and sulfur electrode compartments.

4. An expansion allowance was made in the sulfur compartment to accommodate the full reaction of sodium and sulfur.
5. An allowance was made for excess sodium for wicking of the β'' alumina surface at the end of discharge.

SULFUR ELECTRODE MODEL

Relatively thin sulfur electrodes are required by vehicle battery cells to achieve the overall power requirements. This type of cell will be reasonably free of polarization problems and will have a relatively predictable performance. The sulfur electrode was modelled to reflect dimensional parameters such as electrode thickness or diameter.

A dominant aspect of this model was the effect of varying sulfur electrode thickness. Work on this topic is well documented by Sudworth [2], Jacquelin and Pompon [3] as well as Brennan. Since it was key to the study, a model was utilized with the properties assumed in the program. Figure 5 shows the relation of specific resistivity of flat plate electrode, central sulfur and central sodium electrodes. The resistivity, calculated at 310°C , is expressed as a unit of the sulfur electrode/ β'' alumina interface area. As an example of state of the art electrode characteristics, an interfacial diameter of 30mm was chosen for the tubular designs. When relatively thin electrodes are used, then minimal difference is seen between configurations. The flat plate resistivity increases approximately linearly with an increase in thickness. The central sulfur resistivity, however, increases significantly as the thickness exceeds about 7mm, because the electron collection is funnelled into an increasingly smaller diameter. As an extreme, if the thickness equals the tube radius, the radial resistivity will tend to infinity. In contrast, the resistivity of the central sodium configuration will always be lower than the flat plate because an increasing area for electron collection is presented as the outer diameter increases with thickness.

These are general trends and are not necessarily true if differences exist between electrode structures or materials of different configurations. Different curves would have been produced for the tubular configurations if another diameter had been selected. In general, for the range of thickness considered, the trends will become more exaggerated with smaller diameters and will tend towards the flat plate values as diameter increases.

Figure 5. Sulfur Electrode Resistivity vs. Configuration

GENERAL DESIGN RULES

The models for tubular cells have more implied design rules because, unlike a flat plate cell, the diameter is associated with each design case. As diameter changes, then other key parameters such as electrolyte and metal component thicknesses also change. One could produce a range of specific values for these parameters, but this would be ungainly since it would produce a huge matrix of different thickness and diameter combinations. Instead, linear relationships between diameter and thickness were assumed for metal tube components and β'' alumina tubes; these algorithms are defined in Figure 6. Thinner β'' alumina tubes than those currently manufactured were defined by altering the

Figure 6. Tube Thickness Variation

gradient of thickness:diameter to provide a comparison between "State of the Art" and "Thin" tubes.

FLAT PLATE CELL DESIGN DESCRIPTION

Since a unit area of an infinite plate was being considered, these calculations were relatively straight forward. A 8" alumina thickness was input, and a range of sulfur electrode thicknesses was then examined automatically. A schematic diagram of this cell is shown in Figure 7. Maximum similarity was applied between the model for the flat plate and tubular cells, except that no dimensional dependence was built in at this stage. In the case of the tubular model, a diametral dependency had to be

Figure 7. Schematic Diagram of Flat Plate Cell

assumed from the beginning. Suitable quantities of sodium, sulfur, felt etc. were allocated; a single membrane was assigned for the cell (a bi-polar stack was assumed); and a table of specific cell performance was generated for a reasonably wide range of sulfur electrode thicknesses.

CENTRAL SULFUR TUBULAR CELL DESIGN DESCRIPTION

The methodology used for the central sulfur cell design was to start by selecting, from a reasonably wide range, a specific interface diameter between the electrolyte and the sulfur electrode. A range of sulfur electrode thicknesses was then generated which extended from 5% to 95% of the tube radius. Once again, suitable quantities of sodium, sulfur, felt, etc. were allocated, and an outside diameter was calculated which was consistent with containing all the cell components and reactants, as shown by the model depicted in Figure 8. A two dimensional matrix of cell properties was generated which included a wide range of electrolyte diameters and electrode thicknesses. As discussed earlier, the wall thicknesses of the tubular components was varied according to a built-in relationship.

CENTRAL SULFUR MODEL

Figure 8. Diagram of Central Sulfur Cell

The sulfur electrode only partially occupied the available space inside the electrolyte. The volume could be left empty or filled with a solid material; but, in this case, the space was enclosed with a metal tube. This could be a matter for detailed design later; but, at this stage, the tube was considered to provide an adequate form of current collection without penalizing the cell weight.

CENTRAL SODIUM TUBULAR CELL DESIGN DESCRIPTION

The methodology applied to the central sodium cell was very similar to that of the central sulfur cell. Once again, a two dimensional matrix of cell properties was generated which included a wide range of electrolyte diameters and electrode thicknesses. The main difference between the two models, apart from a reversal of the electrodes, was that provision was made for the external storage of sodium outside the main body of the cell. The reason for this feature was because, with the range of sulfur electrode thicknesses selected, it was possible to specify more sodium than is capable of being stored inside the electrolyte. The sodium reservoir formed is assigned the same diameter as the cell case; the resulting cell remains as a single cylinder as shown in Figure 9. The length will, in these circumstances, be more than a unit long.

IMPROVING THE INTERPRETATION OF RESULTS

Due to the number of computer runs which were required to generate the necessary data base, the

CENTRAL SODIUM MODEL
Figure 9. Diagram of Central Sodium Cell

information was stored in files. These files were written in a suitable format for spreadsheet input; but, particularly in the case of the tubular cell designs, it was necessary to interpret the results in a more efficient way than just scanning row after row of numbers. To assist this procedure, another QuickBasic program was written which scanned a specific column of a selected file looking for an assigned value. Once a row was found containing the value in that column, the row was written to a second file. It was more likely that the "look up" value would be bracketed on either side by a pair of rows; in this case, a value was interpolated for the row, which was then written to the second file.

This program was useful because a particular parameter, such as the Peak Power:Energy Ratio, could be selected and the whole source file condensed to contain only the rows of interest. This could be repeated automatically for a number of values, the second file comprising only the rows of interest for specific Peak Power:Energy Ratios.

This file was also in a spreadsheet format where further features such as sensitivity to various cell burdens could be evaluated. For example, seal weight and volume could be included within the spreadsheet. This approach was also more adaptable for graphical output rather than having to produce graphs directly from a QuickBasic program.

3.1.2. The "Battery Down" Approach

At this stage it was critical to understand where battery requirements can drive some of the cell goals. It would have been counter-productive to instigate a sensitivity study of a specific battery design approach which may be inappropriate to a different cell design.

From a performance aspect, the main question was "can we satisfy the power and energy requirements within the dimensional, mass and thermal constraints?" It is not always appreciated that many of the performance parameters are highly interdependent and that many of the battery and cell requirements are implicit directly from these values.

The cell resistance is key to obtaining a particular power level. The cell resistance, coupled with the relatively heavy power demand of a typical electric vehicle duty cycle, is also the main factor causing temperature rise in the battery.

Although battery designers seek to maximize gravimetric energy density, this can penalize the battery from a thermal viewpoint. A reduction in mass will cause a corresponding reduction in thermal mass which, in turn, will cause increased temperature rise when the same heat is being generated.

A spreadsheet was written which quantified these relationships and used them to set the goals for the cells and batteries. The spreadsheet incorporated several of the vehicle specific battery requirements and, using some relatively simple relationships and assumptions, examined sensitivities and allowed performance goals to be set for the cell.

The routine adopted in the spreadsheet used gravimetric energy density as the key variable. The battery internals were assumed to behave as a lumped thermal mass. Given these assumptions, the target energy was used to derive a battery weight and an approximate thermal mass.

A maximum temperature excursion of 50° C was set as a limit during sustained power demand. The period of sustained power demand was represented as a percent of full discharge capacity. In fact, this may be limited in the specified vehicle by non-battery items such as motors and controllers that may have their own thermal limits.

These simple assumptions set an upper limit to the battery resistance for a particular battery voltage. Once this was set, then the peak power capability of a battery with this characteristic resistance was calculated and compared with the actual peak power requirement. As will be seen later, the peak power capability derived from a thermal limit was often well in excess of the performance requirement.

Using the heat loss targets, the time to cool by 50° C was estimated for each battery. In addition,

the heat loss necessary to cool by 50°C over a period of 12 hours without any external power for heating or charging was calculated.

3.1.3. Cell Specific Model

The cell performance model was extended to include the effects of temperature, depth of discharge and rate of discharge. The "transmission line" calculation method developed by Brennan [1] was modified to allow variable electrode properties and to simulate the electrode at various depths of discharge. Electrode properties were corrected for temperature and polarization effects at designated current levels. Using this model, it was possible, for example, to calculate the cell resistance and working voltage against the equilibrated emf at various constant current levels.

3.1.4. Battery Performance Model

The data in an existing computer model developed at CSPL was modified to evaluate the central sodium Conceptual-Cell design. Revised cell characteristics, e.g. resistance, size and weight, were incorporated. The model was a multiple lumped mass system which accounted for entropy, circulating currents within the battery, and temperature effects.

3.2 CELL DESIGN SPECIFICATION DEFINITION

The "Battery Down" model was used to establish the key goals for cell performance. As mentioned previously, a temperature excursion of 50°C was to occur during sustained power demand. The period of sustained power was set to allow discharge to 75% of the rated capacity. It was assumed that no cooling occurred during the sustained power discharge.

The most demanding gravimetric energy density goal of 120Wh/kg comes from the G-Van. The most demanding volumetric energy density goal of 115Wh/litre comes from the ETX-II van. Allowing for a 15% loss due to clearance and to provide some degree of modularity, then a more realistic volumetric energy density goal is 135Wh/litre. Further battery performance targets have been derived from the vehicle requirements and goals in Table 4.

Figure 10 shows the maximum battery resistance that can be tolerated to satisfy either the peak power requirements or the thermal load imposed by

sustained power. When the curves are horizontal, the peak power requirement governs the maximum battery resistance. When the curves are decreasing with energy density, the thermal demands of sustained power determine the maximum battery resistance. For the G-Van, because of the relatively low peak power requirement, thermal demands are the only driver for battery resistance. With the other vehicles, peak power requirements drive the resistance until an energy density of typically 120Wh/kg is reached. After that point, an increasingly lower resistance battery is required to stay within the thermal limits during sustained power demand as the energy density increases. The resistance requirements for the ETX II and MEV-2 are generally higher than that for the G-Van and TeVan

Figure 10. Battery Resistance Requirements

because of their higher nominal voltage. Thus, the sustained power requirements can be the main driver rather than a peak power demand from the vehicle.

The peak power capabilities of the batteries are shown in Figure 11. Figure 11a shows the peak power capability staying within the specified voltage limits to 80% DOD. Figure 11b shows the peak power capability normalized such that the load volts is $2/3$ of the open circuit voltage at 80% DOD.

When thermal demand drives the specification of maximum battery resistance, a comparison of Figure 11a with Table 4 shows that peak power capability exceeds the requirement.

Comparison of Figure 11a and 11b shows that the range of allowable voltage can significantly limit the peak power capability of the vehicle. The range is a function of the controller used in each vehicle. In the case of the TeVan, where a narrow voltage range of between 145V and 180V is specified, peak

Figure 11. Peak Power Capability

power could be increased typically by 50% by increasing the differential voltage range from 35V to 60V. At the battery level the peak power capability, normalized to $\frac{2}{3}$ ocv, has been divided by the nominal energy requirement to produce a Peak Power:Energy Ratio. This parameter is one of the main cell design guidelines, and values are shown in Figure 12. An energy density goal of 120 Wh/kg (specified for the G-Van) will need a battery Peak Power:Energy Ratio of about 2.1 to satisfy a full discharge at the sustained power rate and still stay within the set temperature rise of 50°C. For the TeVan, a Peak Power:Energy Ratio of 2.1 is also required to satisfy the peak power demand within the specified voltage range. In order to extrapolate requirements down to the cell level, an allowance of 10% can be made for battery level factors such as interconnect resistance. Thus the cell Peak Power:Energy Ratio should be 2.3.

When battery design details are scrutinized for potential areas of improvements, demanding but critical goals for medium term batteries are: that the ratio of cell weight:total battery weight should be at least 70%; and that the cell volume: total

Figure 12. Peak Power:Energy Ratio

battery volume should be at least 60%. These levels have been set to allow advanced battery performance targets to be satisfied without an inordinate demand on achieving high cell energy density. These goals will produce a necessary emphasis on a reduction in weight, volume and cost overheads associated with battery components. When these goals are adopted, the cell level energy density can be set directly from the battery level energy density goals. Thus, the battery level goals of 120Wh/kg for the G-Van and 135Wh/litre (including an allowance for modularity) for the ETX-II van translate to 170Wh/kg and 225Wh/litre at the cell level.

The key cell performance goals can be stated:

Specific Energy	170Wh/kg
Energy Density	225Wh/l
Peak Power:Energy Ratio	2.3

As the energy density increases to a long term goal of 180Wh/kg, then the battery must become much lower in resistance. The Peak Power:Energy Ratio at the battery level would now need to be up to 3.5 for the G-Van (i.e. 600W/kg peak) to limit temperature excursion during sustained power demand. It should be noted that heat is generated by i^2r effects and by entropy effects. Sodium/sulfur batteries have an exothermic entropy term which, over the two phase region, is equivalent to about 5% of the capacity. This term is a function of chemical change during discharge and, as such, generates energy which is effectively independent of rate of discharge. The value also increases quite dramatically as the battery is discharged into the single phase region. The low value of entropy over the two phase region has been used in the spreadsheet.

As the energy density becomes much greater, then the thermal mass is less; and correspondingly less heat is needed to establish a particular temperature rise. Since the heat of entropy is constant, disproportionately less heat is permitted for i^2r effects; and the allowable battery resistance must be correspondingly less. The implication is that, if a major increase in energy density is achieved without a corresponding decrease in resistance, the battery design may be forced towards active cooling or latent heat cooling for some applications.

Using the 400W heat loss goal, the time for the batteries to cool 50°C after a sustained power discharge was calculated. These results are shown in Figure 13a. No allowance has been made for the recovery of the heat of entropy on re-charge or for the heat generated by a charge current. Batteries with an energy density of about 100Wh/kg would require a time of between 12 and 15 hours to cool from 380°C to 330°C. This is uncomfortably close to the time available between working days.

Figure 13b shows the maximum heat loss target which would provide a time of 24 hours to cool from 330°C to 280°C without a supply of external power being available to provide heat. It can be

Figure 13. Cooling Time and Heat Loss

seen that advanced batteries with high energy densities have more of a thermal problem since their lower thermal mass also causes more rapid heating and cooling.

Clearly the need to cool a battery before the next working day and the need to provide a reasonably long stand period without overcooling the battery are in conflict. This conflict becomes more critical with batteries having high energy density; and, for some EV applications, the provision of a more efficient thermal enclosure may have to be offset by providing some form of active cooling.

3.3 BATTERY SPECIFICATION REFINEMENT

Early in the program the effort assigned to this task was re-assigned to sub-tasks 2.1 and 2.2. The "Cell-Up" approach to cell modelling, together with generic definition of battery derived requirements, ensured a high probability of meeting the battery requirements. The high cell performance achieved with the central sodium Conceptual-Cell design made further refinement of the specifications unnecessary in order to proceed with the conceptual battery designs. Consequently no activity is reported in this sub-task.

3.4 CELL AND BATTERY DESIGN EVALUATION

The cell performance model was used to predict the resistance of the conceptual central sodium cell design and the secondary option, central sulfur cell.

Figure 14 shows the fully relaxed cell resistance which would be measured if, at any time during a 4.4A constant current discharge, the current was interrupted and the cell open circuit voltage allowed to fully recover. A typical urban EV duty cycle consists of a series of peak power pulses; and, for this type of duty cycle, polarization will be less evident. To allow for this, the figure also shows the cell resistance which can be used to predict the cell peak power capability. Both cell designs use the same electrolyte, and the figure shows clearly that the central sulfur cell has a higher resistance than the central sodium cell.

The battery model was used to predict the thermal response of batteries utilizing the central sodium conceptual design cell operating at the various load

Figure 14. Predicted Cell Resistances of Central Sodium and Central Sulfur Cells

profiles. The results for the MEV-2 battery are shown in Figure 15 for (i) the SFUDS; (ii) sustained power; and (iii) 3 hour discharge without cooling. It is shown that the battery can be discharged at the specified sustained power of 30kW and also at the 3 hour rate without exceeding 380°C. However, discharge under the SFUDS cycle with the peak power set at 65kW will heat the battery up to 390°C. It should be emphasized that this temperature response was calculated on the basis of the battery weight shown in Table 4. Thus, the figure of max peak power/battery weight used for the analysis was 190W/kg, which is rigorous when compared with the strictly applied value of about 90W/kg commonly used in test regimes.

It is evident, then, that the further reduction in weight of battery level components that is anticipated, together with further demands for increased power likely with passenger car applications, emphasize the need for active cooling.

Figure 15. Thermal Response of MEV-2 Battery

4.0 CELL DESIGN STUDY

4.1 CELL CONFIGURATION STUDY

4.1.1. Introduction

Over several years of sodium/sulfur development, the main developers have converged on a tubular "Central Sodium" cell as their chosen configuration for pilot commercialization. This configuration uses a tubular β alumina electrolyte and stores the sodium inside the tube. For some time, CSPL was developing another, "Central Sulfur", tubular configuration where the sulfur is stored inside the tube. Some developers built laboratory scale "Flat Plate" cells where the β alumina electrolyte is produced as a planar sheet, while others produced "Multi-Tube" cells using fine bore glass tubular electrolyte. Component development on sub-assemblies of multi-tube α alumina headers and β alumina tubes have also been produced. These multi-tube cells all have a multiplicity of tubes which are shared in parallel within a cell. Conceptual sketches of the cell configurations are shown in Figure 16.

One requirement of this study was to re-visit the choice of configuration for the sodium/sulfur cell and to re-examine some of the technical issues in the light of the most recent advances in the technology. The formal objectives were:

- o to identify sodium/sulfur cell configurations that satisfy the requirements of the electric vehicles intended for use on the public highway;
- o to select two cell configurations for further analysis and design, having the constraint that they must be qualified within a three year period. One configuration should offer low technical risk and the other a moderate risk.

The next two sections of the document, "Stress Analysis" and "Operational Factors", compare stresses and operational features between the chosen cell configurations. These sections are key since they deal with some fundamental issues relating to technical risk. Following these is a section, "Performance Analysis", which deals with topics such as energy and power levels achieved with the chosen cell configurations.

Figure 16. Diagrams of Cell Configurations

The six main cell configurations considered were:

- Single Cell Tubular: (a) Central Sulfur
and (b) Central Sodium
- Multi-Tube: (c) Central Sulfur
and (d) Central Sodium
- Flat Plate Bi-Polar: (e) Single Membrane
and (f) Ribbed

4.1.2. Summary of Results and Conclusions

The most significant finding from this study was that the central sodium mono-tube cell configuration provides the highest overall performance of all the configurations. The projected levels of performance are also consistent with the high performance, long term goals of the USABC (US Advanced Battery Consortium). This configuration also has the largest data base of testing and development and offers the lowest development risk. Realistic goals for central sodium, cell level performance are 260Wh/kg, 400Wh/litre, 650W/kg and 1000W/litre.

These can be compared to the USABC long term battery level performance goals of 200Wh/kg, 300Wh/litre, 400W/kg and 600W/litre. Thus, the remaining challenge is for improvements in battery packaging, which would require a demanding 75% of the battery weight to be cells and 60% of the battery volume to be cells.

When the cell configurations were fully burdened with seals and functional features, the specific energies projected for the cells were 260Wh/kg, 237Wh/kg, and 220Wh/kg for the central sodium tubular, ribbed flat plate and central sulfur tubular configurations, respectively. These values can be compared with 160Wh/kg achieved with state of the art cells.

There is considerable scope for improving the power performance of the state of the art central sodium cell configuration. Realistic targets for cell performance are a specific peak power of 650W/kg and a peak power density of 1000W/litre; this is compared to state of the art cell values of 205W/kg and 415W/litre. Other conclusions were:

- 1) The analyses performed and presented in this document show strongly that only the single tube configurations satisfy the program objectives. The remaining configurations have been rejected on the grounds that they present too high of a level of technical risk without offering definite performance improvements.
- 2) The central sodium tubular cell was chosen as the lowest risk option; furthermore, it also offers the highest overall performance. The cell performance levels predicted from the study are consistent, when realistic battery volume and weight burdens are applied, with long term performance targets specified by the USABC and are a significant improvement over state of the art cells.
- 3) The central sulfur tubular cell was chosen as the medium risk option which, based on CSPL test data, may provide for a longer cell life (albeit with typically 15% lower specific energy than the central sodium configuration).
- 4) The multi-tube configurations were rejected on the grounds of the high risk associated with inherent difficulties concerning cell failure modes.
- 5) The flat plate configurations were rejected due to the high risk associated with their technical shortcomings. An exceptional feature of sodium/sulfur cells is the hermetic separation of the two electrodes by the solid electrolyte. Thus, pressure differences can be established across the electrolyte, and the stresses generated may cause poor reliability. The ability to manufacture the preferred ribbed, thin membrane electrolyte to the high tolerances required may also be very difficult. From a performance viewpoint, the potential for high performance from flat plate cells using ultra-thin electrolyte is seriously compromised by the need to provide structural support and a seal around the perimeter. Fully burdened, ribbed flat plate cells have a specific energy which is only marginally ($\approx 10\%$) lower than that achievable with the central sodium configuration.

4.1.3. Stress Analysis for Generic Design Comparison

Different cell design configurations or key dimensional changes can modify stress patterns and levels of stress even though the same loading conditions

have been applied. These, in turn, can affect the ability of a cell to survive manufacturing processes or operating conditions. Thus, stress analysis is a key aspect when comparing cell configurations and should be performed as a part of any cell optimization process.

A detailed stress analysis of the different configurations and their dimensional parameters encompassing an exhaustive study of stress mechanisms is beyond the scope of this contract, but a comparison was made of two critical design areas:

- a) the ability of the electrolyte to withstand pressure differences; and
- b) the ability of the electrolyte to withstand thermal mismatch relative to the alpha alumina frame.

Differences between flat plate cells, derivatives of the flat plate cells and tubular cells were also examined.

4.1.3.1. Allowable Stresses in β'' Alumina

β'' alumina has a high intrinsic mechanical strength which approaches 300MPa where the stressed area is small. As with all components made from a brittle material, the actual stress level needed for fracture depends on the size and shape of the component and its surface and microstructural consistency. Design stresses for these components are invariably lower than the intrinsic strength of the material. In the case of β'' alumina used in sodium/sulfur cells, the situation is much more complicated since ionic flow through the material takes place on charge and discharge and this may influence the effect of applied stress. Experimental work by Anil Virkar of the University of Utah [4] suggests that levels of applied stress as low as 50MPa (either tensile or compressive) can seriously degrade the upper limit of current carrying ability of β'' alumina on charge. Undocumented work at GE/CSPL has also suggested that stressed areas can act as a funnel for corrosion products on the sulfur side.

The underlying concern is that stress levels that are significantly lower than the intrinsic strength of the material may degrade reliability and jeopardize the batteries' ability to achieve commercial battery life targets.

A value of 50MPa was chosen because it is close to the breaking point of a typical glass as well as for

the factors discussed above. It is not intended to be necessarily a "safe" number but rather a maximum design stress which would have to be fully qualified with each design.

4.1.3.2. Stress Mechanisms

Some mechanisms which produce stress in the electrolyte have been analyzed, and these include: pressure difference across the electrolyte and thermal mismatch between components.

STRESSES DUE TO PRESSURE DIFFERENCE

Usually, the sodium/sulfur cell has a solid β alumina (the electrolyte) which divides the two electrodes into two separate, gas-tight compartments. In this situation, it is inevitable that pressure differences will be produced across the electrolyte. These can be created by a variety of conditions:

1. The leak-tightness of the sub-assembly is important, and all conventional high calibre leak-testing methods rely on creating a pressure difference of typically 0.5 to 1 atmosphere across the potential leak path. During component testing, the β alumina is being stressed at ambient temperature and without the presence of complicating factors such as molten sodium or ion flow. In this situation, higher values of stress may be tolerable in the β alumina. However, the design stress limit of 50MPa should still be avoided in the region of the glass seal since critical cracks could be produced.
2. As the operating cell temperature increases above 300°C, then the vapor pressure of sulfur increases sharply, as shown in Figure 17. Non-uniform temperatures within the battery can be caused, for example, by higher discharge through particular strings of cells. Battery malfunction can also develop an excessive temperature rise before fail-safe trips become functional.

Neither case should result in a sudden failure of large numbers of cells. Thus, it seems prudent to allow for operating abuse or malfunction by specifying a design level which provides for these temperature excursions. Allowing for a pressure differential of at least one atmosphere corresponds to a maximum battery temperature of 440°C.

Figure 17. Sulfur Vapor Pressure

3. There is considerable evidence to support the view that it is important, from a safety aspect, that the pressure on the sodium side should always exceed the sulfur side pressure. Thus, the sodium side pressure should ideally be at least one atmosphere at the upper design limit of temperature. When the cell is discharged into the single phase region, the pressure in the sulfur compartment can be close to zero since the vapor pressure of sodium polysulfides is one or two orders of magnitude lower than sulfur. In this case, a pressure differential of one atmosphere will be produced across the β alumina from the sodium side.

All the above considerations support a design principle which accommodates a pressure difference of at least one atmosphere (normally acting from the sodium side). This design level must not be allowed to adversely affect the long term operation or reliability of the cell.

THERMAL MISMATCH OF COMPONENTS

The stresses set up by thermal mismatch can be very complicated to calculate and will depend very much on the seal geometry, materials and the type of sealing processes. Calculation is further complicated, when metal components are considered, by their ability to develop plastic regions and thus depart from relatively simple elastic analysis. It is imperative that, when seal development reaches the detailed design phase, a suitably rigorous stress analysis be performed.

Relative sensitivities of various cell geometries and dimensions are assessed, and simplified situations are considered which are typical cases.

4.1.3.3. Tubular Electrolyte Stress Analysis

For the tubular cell configurations, it was assumed that the electrolyte was glazed to a relatively rigid α alumina component as shown in Figure 18. Stresses were calculated at the open end of the tube and through the body of the electrolyte for state of the art thickness of electrolyte and for "thin" electrolyte as defined in Figure 6.

Figure 18. Schematic Design of Tubular Cell

BENDING STRESS ANALYSIS DUE TO PRESSURE DIFFERENCE

Hoop stresses in the body of the electrolyte and maximum bending stresses at the fixed open end were calculated for a range of electrolyte diameter and a pressure difference of one atmosphere. The results are shown in Figure 19 and indicate that the stress levels are low (typically 3MPa or 3Nm^2) at the open end of the tube and even lower in the body of the electrolyte.

Figure 19. Stresses in Tubular Electrolyte due to Pressure

BENDING STRESS ANALYSIS DUE TO THERMAL MISMATCH

Bending stresses in the region of the open end of the tube have been calculated for 20mm and 30mm diameter electrolyte. The results are shown in Figure 20 and indicate that the stress levels are significantly higher than those due to pressure difference but are still low. Regardless of diameter,

Figure 20. Stresses in Tubular Electrolyte due to Thermal Mismatch

a maximum stress of 28MPa occurs at the open end of the tube. The stresses quickly attenuate and typically fail to less than $\pm 4\text{MPa}$ at a distance greater than 3mm from the open end fixing point.

4.1.3.4. Flat Plate Membrane Stress Analysis

A schematic diagram of a typical cell design is shown in Figure 21 where a relatively thin membrane of solid β'' alumina ceramic is glazed into a ring of α alumina ceramic. Relatively thin metal seal rings are bonded to the α alumina ring with an intermediate sealing ring which is deformable at the bonding temperature.

A circular flat plate design has been analyzed, although, in general, many conclusions will apply to rectangular plates of the same area (these typically have 25% higher stress than the circular plates).

BENDING STRESS ANALYSIS DUE TO PRESSURE DIFFERENCE

Assuming that the edges of the electrolyte disc are built in, the stresses due to the pressure were calculated; Figure 22 shows a typical bending stress

Figure 21. Diagram of Flat Plate Cell

distribution across the surface of a disc. Two components of stress are shown: radial bending, which produces circumferential cracks in areas of tension; and tangential bending, which produces radial cracks in areas of tension. The maximum value of tensile stress always occurs on the outer edge of the disc on the same side as the most positive pressure. A region of comparable levels of radial and tangential bending stress also exists in the central zone of the disc on the opposite side to the most positive pressure. These calculations were based on a pressure difference of one atmosphere, and stress levels of $\pm 35\text{MPa}$ at the center and $\pm 50\text{MPa}$ at the outer edge are shown. Using these equations to calculate the maximum stress up to 50MPa , a range of disc diameters and thicknesses were examined. The results are shown in Figure 23. Compared to the equivalent stress level in a tubular sodium/sulfur cell (e.g. 30mm dia x 1mm thick) of about 2MPa , this represents a significant increase over the stress levels produced in state of the art cells.

Figure 22. Typical Stress Distribution In Plate

BUCKLING OF A THIN DISC

Buckling can be caused by expansion mismatch between β'' and α alumina which set up compressive stresses in the β'' alumina. The stress analysis can be complicated by the presence of bonded metal rings which, depending on the expansion coefficient of the metal, can either make these stresses more or less compressive. For simplification, the situation analyzed was a sub-assembly comprising an α ring and β'' alumina disc which has just been cooled after being glazed together.

The effects of buckling are estimated by predicting when it occurs and what may happen afterwards. It is noted that a perfectly flat disc was assumed and that minor built-in distortions will promote the

FLAT PLATE BENDING STRESS -CIRCULAR ELECTROLYTE (N/Sq.mm.)

Figure 23. Variation of Maximum Stress with Diameter and Thickness

onset of buckling at lower loads. Typical material values which were used to perform the analysis are: an expansion difference of $0.2 \times 10^{-6}/^{\circ}\text{C}$ between α and β'' alumina; a Young's Modulus of $0.2 \times 10^6 \text{MPa}$; and a temperature difference of 600°C . This produces an upper limit for the onset of buckling and determines a minimum electrolyte thickness to diameter relationship which is shown diagrammatically in Figure 24. For the simplified case of a perfect disc, the stresses in the β'' alumina will all be equally compressive (in the radial and tangential directions) until buckling occurs. When buckling occurs, however, the disc suddenly becomes much more flexible in the radial direction; and all of the radial strain produced by thermal mismatch must be absorbed by lateral deflection of the plate.

Figure 24. Upper Limit for Minimum β'' Alumina Disc Thickness (to prevent Buckling)

Unlike a classic beam with constant critical loads, there is a finite limit to the in-plane deflection (produced by the expansion mismatch), and the plate won't necessarily collapse.

POST BUCKLING DEFLECTIONS AND STRESSES IN THE DISC

The bending stresses which occur in the disc following buckling were estimated by comparing the buckled shape of the disc to a strip with built-in ends. A further simplification was that the shape over this length was an arc rather than a cosine shape. (It can be shown that this is accurate within 1%.) Derived equations show that the deflection of the disc is inversely proportional to diameter and also that the bending stress is inversely proportional to diameter. These relationships were combined, and the maximum stress after buckling is calculated to be 173MPa.

This is a high level of stress to apply over much of the β'' alumina surface, which typically has a maximum strength of 300MPa. Conventional glasses only have a typical strength of about 60MPa. Thus it is likely that, once buckling occurs, damage to either the electrolyte or the glass seal would follow.

4.1.3.5. Ribbed Flat Plate Electrolyte

The analyses described above imply that cells using an unsupported flat plate electrolyte may be restricted in area. The introduction of supporting ribs for the electrolyte may offer the possibility of increasing the net cell area without exceeding the design stress of the electrolyte. A typical schematic of a ribbed electrolyte is shown in Figure 25, where ribs have been provided as an integral part of the sulfur

Figure 25. Schematic Diagram of Ribbed β'' Alumina and Cell

side of the electrolyte. In this case, the analysis is limited to bending stress caused by the pressure difference across the β'' alumina.

The maximum stresses arise in the two zones, "a" and "b", as shown in Figure 26:

- along the edge between the ribs and the membrane. This stress is a result of the sagging of the membrane between the ribs.
- at the upper and lower extremities of the ribs where they join the perimeter. This stress is a result of sagging of the ribs between the external supports (i.e. the perimeter seal support).

To meet the EV battery requirements specified for this design study, a sulfur electrode thickness of 4mm is appropriate. Furthermore, it was assumed

Figure 26. Positions of Calculated Stress

that a rib with this depth would be allowable. Using this dimension, together with the design stress of 50MPa, the maximum width between ribs and the maximum rib length for various membrane and rib thicknesses were calculated. These calculations provided a maximum active area for each rib which was then applied to a cell having approximately a square plan area. Figure 27 shows the maximum active area and the utilization of total cell area for various membrane and rib thicknesses. From these results, as an example, one may select a rib thickness of 3mm to give reasonable utilization of about 80% and a total active area of between 70 and 90

Figure 27. Maximum Active Area and Area Utilization of Ribbed Cell

sq.cm for 1.4mm and 0.6mm thick membranes, respectively. The significant reduction in total active area shown for the cases of 0.6mm and 1.0mm thick membranes with 1mm wide ribs reflects the constraint of specifying a square cell. In these particular cases, the differences between these points and corresponding points on other curves was caused by a reduction in the number of allowable ribs/cell. If a rectangular plan is allowable, then additional ribs can be incorporated as required to increase the cell active area. In this instance, engineering tolerances and distortions would have to be maintained to suitable levels. Further information was compiled as shown in Figure 28 for cells of various membrane thicknesses using ribs which are 3mm thick. As an example, a cell having a membrane thickness of 0.6mm would require three ribs which are 3mm wide and 4mm high. The width between ribs would be 20mm and the rib length would be 95mm.

Figure 28. Key Dimensions of Cells with 3mm Thick Ribs

4.1.3.6. Summary of Stress Analyses

Tubular electrolyte should be relatively stress free under conditions of differential pressure across the electrolyte. Thermal expansion mismatch between the electrolyte and a rigid α alumina component could induce a peak stress of about 20MPa at the open end at operating temperature; this stress level quickly attenuates to less than 4MPa within 3mm from the open end.

Buckling and pressure induced stresses can cause significant levels of stress in the vicinity of the glass seal in single membrane, flat plate electrolyte. These stresses are an order of magnitude higher than those existing in tubular cells. Although β alumina is quite strong (up to 300MPa), there is a serious concern that an imposed stress will interact adversely with cell reliability. Most operational failure mechanisms for β alumina invoke some form of crack propagation. These cracks may accelerate in the presence of superimposed tensile or compressive stress, and a general increase in stress level by an order of magnitude will require a significant level of qualification and feed-back into the design process.

In order to have a reasonable chance of achieving the necessary reliability, the stresses should be maintained below 50MPa. In this case, cells using single membrane electrolyte are likely to be limited in area to about 25sq.cm. (5.6cm diameter) for

1.4mm thick electrolyte and to about 4sq.cm.(2.25cm diameter) for 0.6mm thick electrolyte.

Flat plate cells could be designed to minimize these stresses by incorporating built-in flexibility, or to cope with stress levels by using shaped electrolyte. An example of a shaped electrolyte is one having ribs at intervals along the length of the electrolyte. Analysis shows that the active area of this type of electrolyte can be extended up to 90 sq.cm. with a membrane thickness of 0.6mm for cells having a square shape. Further increases in active area could be obtained by using rectangular shaped, ribbed cells. These designs would, again, demand an ability to withstand an order of magnitude increase in stress at operating temperature when compared to state of the art tubular electrolyte. Significant development effort and feed-back into the design process would be necessary to qualify these designs. This is unlikely to be achieved within the three year period that was one of the screening criteria for the design study.

4.1.4. Operational Factors

4.1.4.1. Multi-Tube Cell Configuration

A schematic diagram of a central sulfur multi-tube cell, Figure 29, shows that the multi-tube configurations share one or the other of the electrode

Figure 29. Central Sulfur Multi-Tube Configuration

compartments. This effectively connects the tubes in parallel with each other electrically. The failure mode of the sodium/sulfur cell is inconsistent; it can fail initially with a low resistance, develop high discharge resistance and then break down to a low resistance under various operating conditions, such as re-charge. This is particularly onerous because the tubes in these multi-tube cell designs are connected in parallel; and a single low resistance, low open-circuit voltage tube failure can self-discharge

the whole cell. In order to prevent this phenomena, the multi-tube cell design use would have to be combined with a low cost, highly reliable device connected to each tube which would induce a high resistance failure.

An additional problem with the central sodium multi-tube design concerns a potential failure mechanism specific to this configuration. There will be significant variation in resistance between tubes due to differences in wall thickness and temperature. This will lead to a variation in the amount of charge that each tube wants to accept and discharge that each tube wants to deliver. It is very likely that, over many electrical cycles, some tubes will accept more charge than others. Over prolonged periods of operation, there is a probability of over-filling of sodium and subsequent hydrostatic failure of the tube.

Multi-tube cells also pose significant problems in terms of maintaining adequate engineering tolerances. Because the tubes share the same housing, then build up of tolerances from tube to tube must be considered as part of overall sizing of the cell. Meticulous design would be necessary in order to prevent an erosion of any benefits in energy density.

In view of these difficulties, the development risk is judged to be very high; and both of the multi-tube configurations were rejected without performing any further analyses.

4.1.4.2. Flat Plate Cell Configuration

A schematic diagram of a typical cell design using a single membrane electrolyte is shown in Figure 30. Ideally, the cells would be assembled together in "bi-polar" stacks as shown in Figure 16 where the metal dividing plate would be shared between adjacent cells. This stacking arrangement offers good utilization of space and the sharing of cell components with correspondingly good energy and power densities. The main attraction of this cell design is the possibility of using very thin β alumina which, if realized, would reduce the cell resistance and increase power.

This advantage would be negated if thicker β alumina was necessary in order to minimize stress levels. Radical designs are probably necessary to allow the use of an electrolyte which is significantly thinner than a tubular design. Because of the major development required to overcome the problems of

Figure 30. Schematic Diagram of Flat Plate Cell

high stress levels and the improbability of solving these issues within the three year qualification period, the flat plate cell configuration was also rejected.

4.1.5. Performance Analysis

4.1.5.1. Tubular Cells

Tubular cell designs of the central sulfur and central sodium were analyzed using the routines described in Task 2.1. It is important to appreciate that appropriate cell burdens of mass and volume were included to account for components such as seals. Relative performance of the configurations are shown in Figure 31, which shows the specific energy of both the central sulfur and central sodium configurations with state of the art and thin walled electrolyte tubes. Figure 32 also compares the relative energy densities.

THE ROLE OF ELECTROLYTE THICKNESS

Electrolyte thickness is an important design parameter which affects cell resistance and peak power capabilities. While its relation to power is apparent, the interaction with energy and optimum diameter is less obvious. Before the process of choosing an optimum diameter for each configuration is discussed, the various sensitivities to electrolyte thickness will be illustrated by choosing an arbitrary fixed electrolyte tube having a 3cm internal diameter. Another important factor is the match of performance with the requirements of the application. To ensure that this is achieved, the Peak Power:Energy Ratio has been set at 2.5.

Comparing configurations, i.e. Figure 31a with Figure 31b and Figure 31c with 31d, it is seen that, with an internal tube diameter of 3cm, an increase of typically 10% in specific energy is achieved with central sodium cells. In fact, as will be explained later, the sensitivity to configuration is more important as tube diameter is optimized.

A thinner family of electrolyte tubes produces a more significant shift in performance. By comparing Figure 31a with Figure 31c and Figure 31b with 31d it is seen that, with an internal tube diameter of 3cm, an improvement of more than 30% is achieved with the use of thinner tubes.

While the arbitrary 3cm diameter is not an optimum for the target Peak Power:Energy Ratio, since factors such as energy density or cost have not been considered, the figures demonstrate the critical nature of electrolyte thickness in the optimization process. In determining an optimum cell design for electric vehicles, it will be assumed that the thinner family of electrolyte tubes will be utilized in the development process.

OPTIMUM TUBE DIAMETER

When it comes to optimizing the cell diameter, other factors such as utilization of cell volume must be considered. Figure 31 shows the specific energy of the two configurations together with state of the art and thin walled electrolyte tubes. Marked on the figures are the energy densities achieved with the arbitrary internal diameter of 3cm and a Peak Power:Energy Ratio of 2.5. It is seen that the energy densities are far from the maximum achievable. This implies that space is being wasted within the cell. This situation arises because, in order to obtain the correct match of energy and power, the sulfur electrode is thinned down to increase power and to decrease energy.

For a particular vehicle application which targets a specific peak power and range, it can be appreciated that the Peak Power:Energy Ratio is a key parameter. In fact, a value of 2.5 is a realistic target which not only satisfies most prospective applications but also gives reasonable thermal response characteristics. In order to optimize the diameter, the specific energy and energy density need to be maximized.

By using Figure 31 and selecting a diameter which achieves close to maximum energy density, the

Figure 31. Specific Energy of Tubular Cells

Figure 32. Energy Density of Tubular Cells

performance is maximized for a given Peak Power:Energy Ratio. In the preferred cases using thinner electrolyte, the optimum electrolyte diameter for both the central sulfur and central sodium configurations is 20mm inside diameter (0.8mm thick). This gives energy densities of 405Wh/l and 440Wh/l for the central sulfur and central sodium configurations, respectively. The specific energies achieved are 210Wh/kg and 255Wh/kg for the central sulfur and central sodium configurations, respectively.

Thus, without invoking differences of design detail between the two configurations, one can expect a 20% improvement in specific energy with the central sodium cell. In fact, the nominal energy of a central sulfur cell will be much less than that of a central sodium cell. This is due to the additional volume in the sulfur compartment, which is required to accommodate the formation of polysulfides, being located inside the electrolyte for the central sulfur configuration; also, this volume must accommodate a tubular current collector. Consequently, radial space is tighter, which may increase the difficulty in

designing compact seals. In view of this, the control of cell burdens in central sulfur cells is more demanding, and the differentials in specific energy may be worse than stated.

4.1.5.2. Flat Plate Cells

Flat plate and derivative cell designs were also analyzed using the routines described in Task 2.1. It is difficult to make a direct comparison between flat plate and tubular cells because, for the latter, assumptions had to be made regarding diameter : thickness relationships before the analysis could proceed. These assumptions could be made more readily for tubular cells because of the data base generated over several years of development. Similar assumptions need not be made for the flat plate cell analysis to proceed, although ultimately they must be included in order to arrive at realistic cell designs. As an example, Figure 33 shows a comparison of the specific energy of "unburdened" cell configurations; highlighted on this figure is Peak Power:Energy Ratio of 2.5. It is seen that the flat

Figure 33. Basic, Unburdened Comparison of Tubular and Flat Plate Cells

plate configuration has a potential cell specific energy of 340Wh/kg, whereas the corresponding figures for the tubular configurations are 300Wh/kg and 260Wh/kg for central sodium and central sulfur respectively. As discussed before, the tubular designs have already been partially burdened by including diameter dependent component thicknesses. When the cell designs are equally fully burdened by factors such as seals, and in the case of the flat plate cell, ribbed electrolyte, conclusions are changed as shown in Figure 34. This figure shows that more realistic targets for cell specific energy are 260Wh/kg, 237Wh/kg, and 220Wh/kg for the central sodium tubular, ribbed flat plate and central sulfur tubular configurations, respectively.

Figure 35 shows a comparison of energy density for the flat plate and tubular configurations with appropriate burdens applied to the cell design. These curves show that, with a Peak Power:Energy Ratio of 2.5, there is little difference in energy density between the configurations and that each achieves a value of about 400Wh/l.

Thus, the apparent initial advantage in performance of flat plate cells is eroded when more detailed design considerations are included, and a central sodium tubular design emerges as the best performer for applications requiring a Peak Power:Energy Ratio of 2.5.

Coupled with this is the high risk of developing the flat plate configuration to deal with the problems associated with stress mechanisms and the probable need for complex electrolyte shapes.

4.2 UNKNOWN/RISK DEFINITION

4.2.1. Electrolyte Wall Thickness

A conclusive feature to emerge from the analyses was the importance of electrolyte wall thickness and its major influence on preferred cell diameter.

4.2.2. Central Sulfur

The analyses showed that the central sulfur configuration suffers from a significant gravimetric energy

Figure 34. Burdened Comparison of Tubular and Ribbed Flat Plate Cell

Figure 35. Burdened Comparison of Tubular and Ribbed Flat Plate Cells

density penalty compared to central sodium cells when identical design rules are applied. The main incentive for adopting this configuration is the possibility of higher durability (longer life).

Central sulfur cells are still the most long lived demonstration of sodium/sulfur technology at CSPL. The safety of central sulfur cells had already been demonstrated at a reasonable level before the development of this configuration was discontinued at CSPL; note, however, that large populations had not been safety tested.

Very little freeze-thaw testing had been conducted, but it has been argued that central sulfur cells may be more vulnerable to freeze-thaw damage. This would have to be disproved before central sulfur cells could be adopted as a viable configuration for electric vehicle applications.

4.2.3. Improved Performance with Small Cells

Apart from improved performance associated with the use of thinner electrolyte, further improvements can be made at the cell level by minimizing the burdens associated with component design and process requirements. At the same time, the risk of

specifying a smaller diameter electrolyte tube, for example, should not be underestimated. It is essential that the relative size and mass of components, such as seals, should be minimized in order to reduce the burden on the cell.

4.2.4. Improved Battery Packaging

An analysis of state of the art batteries showed that only 50% of a battery mass is due to cells, the rest being attributable to battery packaging. Similarly, only 40% of the battery volume consists of cells. Obviously, there is opportunity for improvement in this area, but a major departure from established battery design concepts incurs possibly high levels of risk and requires thorough qualification.

4.2.5. Summary

These considerations raise the following risks:

- the use of thin-walled electrolyte
- freeze-thaw survivability of central sulfur cells
- the life benefits of central sulfur
- the relative safety characteristics of central sulfur compared with central sodium

- e) those which may surface as a result of maintaining or lowering component and process associated cell burdens
- f) those which may result from radically different battery designs, employed to improve packaging

4.3 SUPPORTING R&D PROGRAM

The objective of this task was to explore and to attempt to resolve, by experimental development, any issues relating to configuration or major design assumptions evolved elsewhere in the program.

4.3.1. Seal Technology

Two options were identified, and evaluated, which aimed to dispense with the need for a separate alpha alumina component, reducing the cell component burden.

One option employed electric field-assisted bonding in an attempt to form an insulating, leak tight film between β " alumina and various metals. This activity built on work first reported by Dunn [5]. Trials were completed under a variety of test conditions, and seals were evaluated for strength, leak tightness and electrical resistance. No effective seals to Cu, Mo, Zr and Ti were achieved, even though their electrical behavior during the sealing operation were similar to aluminum. Bonds to aluminum were made which had excellent strength and fair leak tightness, but the electrical resistance in the foil negative mode was too low to prevent an accumulation of sodium at the seal.

The second option employed a proprietary coating on β " alumina. Strong bonds were made to aluminum during bonding trials, but sub-surface fracture of the β " alumina prevented evaluation of leak tightness and other seal properties.

On the basis of this work, the prospect of dispensing with the alpha alumina component is still considered to be speculative. Both cell designs proposed in Task 3.4 include provision for an α alumina component.

4.3.2. Corrosion Resistance

A literature survey on the corrosion resistance of aluminum and aluminum alloys in polysulfides was conducted. CSPL and ABB have used aluminum successfully and demonstrated excellent cell durability; however, the technical literature has produced

conflicting results. Battles and Brown [6] reported corrosion of aluminum in sodium tetra-sulfide while Hartmann [7] listed aluminum as corrosion resistant in sodium tetrasulfide. The reason for this variance between the reported results may be due to differences in the nature of the surface, the atmosphere in the sulfur electrode (eg. moisture and oxygen levels) or differences in test procedures. Further experimental work is needed in this area to provide clearer guidance.

A corrosion test cell was constructed (after a design by Mikkor [8]) which enables characterization of candidate materials and coatings using cyclic voltammetry. The cell consists of a sealed glass test tube with two working electrodes of the sample material immersed in sodium polysulfide. A third electrode was included in later designs which is normally electrically inactive but which was periodically subjected to a single electrical cycle. This allows a comparison between effects due to electrical cycling and static corrosion or passivation. Several tests have been progressed, including a baseline test using chrome plated 446 stainless steel where current levels of typically 50mA/sq.cm. were applied in the anodic and cathodic modes. Sample coupons have areas of about 10 sq.cm. each, and tests have been conducted for periods of up to 60 days, with equivalent accumulated half cycle charge of up to 22Ah/sq.cm. This work has provided a convenient method of screening the corrosion behavior of candidate materials.

4.3.3. Battery Packaging

Screening of potential schemes was completed; a preferred, proprietary option was evaluated in small battery sub-assemblies. This option has potential for improved battery packing efficiency and good structural characteristics consistent with advanced battery requirements. Risks associated with departure from known battery packaging technology will require major qualification of battery parameters such as vibration resistance, electrical insulation, safety and thermal characteristics.

4.3.4. Freeze-Thaw Durability of Central Sulfur

Freeze-thaw characteristics of the central sulfur configuration were evaluated in XPB electrolyte/sulfur electrode sub-assemblies. These sub-assemblies were vertically oriented in a bath of silicon oil which

simulated as the sodium electrode and acted as a heating and cooling medium.

When the sub-assemblies were heated and cooled at normal rates of between 5 and 10° C/hour, fracture consistently occurred on the second warm up. This was associated with the phase change of β sulfur to α sulfur at temperatures in the range 119 to 125° C. In these assemblies the sulfur solidified towards the base of the electrolyte, and no relief was available when sulfur in this region experienced the 5% increase in volume attributable to the phase change.

A limited amount of testing suggested that a faster heating rate of 30° C/hour or more may suppress this failure mechanism and allow freeze thaw to occur without fracture of the electrolyte. One explanation for this may be due to suppression of the α to β phase change until the sulfur electrode is at least partially liquid. It may also be due to a shift in the thermal characteristics which would encourage expansion of liquid sulfur into a free void and the creation of a liquid film between the electrolyte and the bulk of the remaining solid sulfur electrode.

Limited testing with a larger diameter, aluminum pole allowed a total of three freeze thaw cycles to occur without fracture of the electrolyte. This would tend to support the view that the thermal characteristics of the assembly, with a good thermal conductor in the center of the sulfur electrode, are key for the central sulfur cell to obtain good freeze thaw durability.

4.3.5. Thin Walled Electrolyte

Manufacturing runs have been conducted outside this program to determine the manufacturability of thinner walled, 30mm diameter electrolyte. The results indicate that thinner electrolyte can be produced without a significant effect on manufacturing yield. This result validates one point on the thickness to diameter relationship of thin walled electrolyte which was assumed in Task 2. Effects on reliability must be resolved; this will involve extensive qualification.

4.3.6. Analysis of Central Sulfur Safety

A mathematical analysis of the safety characteristics of central sodium and central sulfur cells was completed by CSPL. The model, which used code

adapted from Lawrence Livermore, analyzed transient temperatures resulting from sudden release of heat around the periphery of the electrolyte. This model was intended to simulate the sudden shattering of the electrolyte, but where the amount of sodium available for reaction is limited to that contained in the annulus between the electrolyte and the safety can. Results compare well with worse case XPB cell measurements during safety testing. The results also show the differences in thermal response between a single cell and cells assembled in a battery. The results show conclusively that significantly lower temperature exotherms (a reduction of up to 50° C) should be produced in central sulfur cells, compared with central sodium cells, when the electrolyte is severely shattered.

4.4 CELL CONCEPTUAL DESIGN

4.4.1. The Central Sodium Conceptual-Cell Design

The primary aim of this task was concerned with specifying a conceptual design of a cell suitable for the US van applications. In the Cell Configuration Study, Task 3.1, the central sodium cell configuration was identified as having the lowest development risk, yet capable of meeting or exceeding the van application requirements. The methodology employed to evolve the cell design was to use the curves generated in Task 3.1 to specify cell diameter, to select a suitable cell length based on the battery dimensional requirements, and then to progress with a detailed cell design using the design skills and experience embodied at CSPL and Beta Power. Finally, a comparison was made between the detailed cell performance and that projected from the generic cell study in Task 3.1.

4.4.1.1. Selecting Electrolyte Diameter

To initiate the design, a layout of a central sodium cell with an electrolyte having an internal diameter of 3cm, which is the diameter of the electrolyte for the CSPL PB and XPB cells, was produced. When this cell was fully loaded with reactants, an impressive energy density of about 300Wh/kg was produced, but the match of Peak Power:Energy was too low. To achieve the target of 2.5 for the cell, either the power had to be increased and/or the energy had to be decreased. Unfortunately, this was most readily achieved by effectively "de-energizing" the cell by under-filling with sodium and supplying correspondingly less sulfur in a thinner sulfur electrode. The latter measure produced a lower cell

resistance with an accompanying improvement in power. The net result, however, was to significantly reduce the cell energy density.

A decision was taken to choose a cell design that could meet the Peak Power:Energy battery target of 2.1, while maximizing the volumetric energy density. At the cell level, the target Peak Power:Energy Ratio was set at 2.5, and, from Figure 31d, an external electrolyte diameter of 2.16cm was selected which provided close to maximum energy density. With the physical attributes ascribed to the cell for this study (i.e. electrolyte thickness, etc), the cell volumetric energy density should be maximized while achieving close to optimum specific energy. Figures 30d and 31d show that values of 255Wh/kg and 440Wh/l are predicted from the generic cell performance curves when the cell was discharged to 1.76V o/c. With a Peak Power:Energy Ratio of 2.5, a cell specific power of 638W/kg and a cell power density of 1100W/l are predicted. It must now be demonstrated that these values, predicted by the generic cell design, can be realized in a detailed conceptual-cell design.

4.4.1.2. Selecting Cell Length

The choice of cell length is an important parameter which must be decided before proceeding with a specific cell design. Since the cell diameter was effectively set by the target Peak Power:Energy Ratio, the length will establish the cell capacity. The length must be consistent with battery packaging considerations, such as complying with any battery height constraints. An overriding consideration in this selection is the program objective to propose design concepts which could be qualified within three years. At Beta Power and CSPL it is believed that a "small capacity" cell of about 10Ah has demonstrated reasonable system reliability for EV batteries when connected in 4 cell series strings. Furthermore, the majority of this battery experience is based on vertical cell orientation. In considering these factors, the cell length chosen for the central sodium cell was 6cm which, in the vertical orientation, can be shown to give good packing efficiency for the four vans. The cells can be arranged vertically three cells high to meet the height requirement of about 250mm for the ETX-II, the G-Van and the TeVan batteries. The cells can be arranged vertically four cells high to meet the MEV-2 battery height requirement of 320mm.

4.4.1.3. The Conceptual-Cell Design

A schematic diagram of the Conceptual-Cell design, shown in Figure 36, incorporates the assumptions which were built into the spreadsheet utilized in Task 2.1. Using technology and improvements in design and processes currently under development at CSPL and Beta Power, the cell has been subjected to a detailed design study. The projected performance and details of this cell are defined as follows:

Cell Details:

Outside Diameter	32.8mm	Length	62mm
Weight	85g	Volume	50.7cc

Cell Performance

Resistance (at 350° C)	17.5mΩ
Capacity (to 1.9V o/c)	10.9Ah
Energy (at 3h rate)	21.4Wh
Peak Power(at 80% DoD, load volts = 2/3 ocv)	52W
Peak Power:Energy Ratio	2.4
Cell Specific Energy	250Wh/kg
Cell Specific Power	600W/kg
Cell Energy Density	420Wh/l
Cell Power Density	1010W/l

Figure 36. Conceptual Design of Central Sodium Cell (dimensions in mm)

4.4.1.4. Comparison with Generic Cell Design Predictions

The cell Peak Power:Energy Ratio of 2.4 achieved with the Conceptual-Cell design is close to the value

of 2.5 predicted from the generic cell design. The cell specific energy achieved with the Conceptual-Cell design of 250Wh/kg, specified to 1.9V end of discharge open circuit voltage, actually exceeds the prediction of 255Wh/kg since the latter was specified to 1.76V. There is about 20% difference in capacity when the cell is discharged to 1.76V compared to 1.9V. Similarly, the Conceptual Cell achieves an energy density of 420Wh/l, specified to 1.9V end of discharge open circuit voltage, which exceeds the prediction of 440Wh/l.

These comparisons confirm that the curves produced in the Cell Configuration Study, Task 3.1, can be used to select key cell parameters. The comparisons also show that the predicted values can be translated to detailed cell performance projections with good agreement.

4.4.2. The Secondary Central Sulfur Conceptual-Cell Design

The secondary aim of this task was concerned with specifying a conceptual design for a central sulfur cell suitable for the US van applications.

This task evolved a reasonably detailed, conceptual design of a central sulfur cell which was the medium risk cell option identified in the Cell Configuration Study, Task 3.1. The terms of reference for the cell design were similar to the central sodium Conceptual-Cell design; i.e., the cell length was about 6cm and the design was optimized to maximize the volumetric energy density with a Peak Power:Energy Ratio of about 2.5.

4.4.2.1. Selecting Electrolyte Diameter

From Figure 31c an internal electrolyte diameter of 2cm was selected which approached the maximum energy density and, with the physical attributes ascribed to the cell for this study (i.e. electrolyte thickness, etc), achieved close to optimum specific energy. Figures 30c and 31c show that values of 210Wh/kg and 405Wh/l are predicted from the generic cell performance curves, discharged to 1.76V o/c. With a Peak Power:Energy Ratio of 2.5, a cell specific power 525W/kg and a cell power density of 1010W/l are predicted.

4.4.2.2. The Secondary Conceptual-Cell Design

A schematic diagram of the Secondary Conceptual-Cell design, shown in Figure 37, incorporates the as-

sumptions built into the spreadsheet utilized in Task 2.1. Using technology and improvements in design and processes currently under development at CSPL and Beta Power, the cell has been subjected to a detailed design study. The projected performance and details of this cell is defined as follows:

Cell Details:

Outside Diameter	32.8mm	Length	62mm
Weight	66g	Cell Volume	36.3cc

Cell Performance:

Resistance (at 350° C)	31.2mΩ
Cell Capacity (to 1.9V o/c)	6.2Ah
Energy (at 3h rate)	12.5Wh
Peak Power(at 80% DoD, load volts = 2/3 ocv)	30W
Peak Power:Energy Ratio	2.4
Cell Specific Energy	190Wh/kg
Cell Specific Power	456W/kg
Cell Energy Density	344Wh/l
Cell Power Density	825W/l

Figure 37. Conceptual Design of the Central Sulfur Cell

4.4.2.3. Comparison with Generic Cell Design Predictions

The Peak Power:Energy Ratio of 2.4 achieved with the Secondary Conceptual-Cell design is very close to the value of 2.5 predicted from the generic cell design. The cell specific energy achieved with the Secondary Conceptual-Cell design of 190Wh/kg, specified to 1.9V end of discharge open circuit

voltage, actually exceeds the prediction of 210-Wh/kg since the latter was specified to 1.76V. Similarly, the cell energy density achieved with the Secondary Conceptual-cell design of 344Wh/l, specified to 1.9V, actually exceeds the prediction of 405Wh/l specified to 1.76V.

Once again, these comparisons confirm that the curves produced in the Cell Configuration Study, Task 3.1, can be used to select key cell parameters for central sulfur cell configurations. The comparisons also show that the predicted values can be translated to detailed cell performance projections with good agreement.

5.0 BATTERY DESIGN STUDY

5.1 MODULARITY INVESTIGATION

An objective of this task was to examine the feasibility of using common battery modules for the specified US vans. If this approach were successful, the modules would be capable of accommodating variations in voltage, capacity and dimensions between the vehicles' battery specifications.

The study was intended to determine the fundamental feasibility and differences between two basic modularization approaches which were considered for this study:

- a) sub-battery modularization — where an optimized number of cells were packaged within their own thermal enclosure; and
- b) bundled cell modularization — where an optimized number of cells were built together as a sub-assembly. Several sub-assemblies were then connected together before packaging the whole assembly within a thermal enclosure.

The schematic diagrams shown in Figure 38 illustrate the differences between the approaches. The majority of the modularity investigation was conducted before the Conceptual-Cell design had been specified; therefore, the decision was made to use the PB cell as the baseline cell design.

The study was also conducted before the battery requirements had been frozen. The dimensional

Figure 38. Modularization Approaches

envelopes available at the time differed significantly from the dimensions specified in the frozen battery requirements. However, they still served to demonstrate some fundamental differences between the approaches and to support the findings of this task.

5.1.1. Sub-Battery Modularization

A sub-battery modularization approach to battery design is attractive for many reasons which include manufacturing and assembly considerations. Modules which could be applied to several different vehicles would have the benefit of extending the range of common components right through the battery to the thermal enclosure. This would improve the economy of scale, allow simpler build-up of sub-assemblies and extend the application of automated assembly operations. All these factors would have potential cost benefits.

A further benefit of this approach may be possible improvements in battery maintenance. As failures occur, it is likely that one or more sections of the battery would limit the overall life. A battery constructed of many modules could potentially be repaired by replacement at the discrete module level.

A spreadsheet was prepared which determined the dimensional fit of a wide range of cell arrays within the specified plan areas. Suitable provision was made for electrical and thermal insulation. The

question of how the cells were to be connected electrically to provide system voltage was not addressed in detail at this stage.

In this way, a self-contained battery module was identified which fit reasonably well within the battery envelopes of the ETX-II, G-Van and Te-Van. The resulting battery schemes are shown in Figures 40, 41, and 42, respectively.

Figure 39. Sub-Battery Module

It was clear from the study that the MEV-2, with its different height and with the split battery compartments specified, could not be accommodated with this modular approach. A provisional modular arrangement was included for this battery, which is shown in Figure 43, to demonstrate the difference between this and the other battery schemes.

Having determined the maximum possible number of cells that can fit inside the specified dimensions, provision then had to be made for suitable electrical connection. The final electrical layout had to provide close to the specified voltage and energy while being accommodated within the specified cell array. Figure 39 shows the chosen sub-battery module arrangement used for the ETX-II, G-Van and TeVan batteries.

5.1.1.1. The ETX-II Van

The battery arrangement for this vehicle is shown in Figure 40. The specified voltage for the ETX-II van of 342V is provided by 5 sub-battery module voltages of 68.4V. For an open circuit cell voltage of 2.076V, the number of cells in series in each module must be about 33. Since there are a maximum of 408 cells in each module, the number of strings in parallel in each module must be 12.

One configuration which fits reasonably well electrically is an arrangement of 8 banks with 12, 4 cell series strings connected in parallel. This provides a total of 384 cells in each module as compared to a maximum possible of 408. If the plan array of each module is examined, it is seen that there are 14 rows of 7 cells and an extra 4 cells. These must be subdivided to provide groups of 12, and it will be appreciated that this does not fit conveniently within the actual array. The final result is a battery module which has to be configured internally to suit and which does use not all of the available cells.

The deliverable battery energy for this configuration is 39kWh against a target of 45kWh at a nominal voltage of 324V compared with a target of 342V.

5.1.1.2. The G-Van

The battery arrangement for this vehicle is shown in Figure 41. The specified voltage for the G-Van of 216V is provided by 8 sub-battery module voltages of 27V. For an open circuit cell voltage of 2.076V, the number of cells in series in each module must be about 13. Since there are a maximum of 408 cells in each module, the number of strings in parallel in each module is 31. One configuration which fits reasonably well electrically is an arrangement of 3 banks with 32, 4 cell series strings connected in parallel. This provides a total of 384 cells in each module as compared to a maximum possible of 408. As before, the plan array of each module must be subdivided, this time to provide groups of 32, 4 cell series strings; it will be appreciated that this also does not fit conveniently within the actual array. Again, the layout of the battery module is one which has to be specially configured internally and which does not use all of the available cells.

The deliverable battery energy for this configuration is 63kWh against a target of 60kWh at a nominal voltage of 199V compared with a target of 216V.

5.1.1.3. The TeVan

The battery arrangement for this vehicle is shown in Figure 42. The specified voltage for the TeVan of 180V is provided by 6 unit sub-battery module voltages of 30V. For an open circuit cell voltage of 2.076V, the number of cells in series in each module should be about 14. Since there are a maximum of

Figure 40. Sub-Battery Module Layout for ETX-II

408 cells in each module, the number of strings in parallel in each module is about 29.

This vehicle has a very narrow voltage window, and it is important to maintain the nominal voltage close to, or higher than, the specified 180V. A choice of

14 or 15 cells in series is suitable for meeting this nominal voltage requirements. Unfortunately, these numbers do not lend themselves to match the physical constraint of 4 cell high stacks.

It is difficult to define an arrangement which fits reasonably well electrically for this application. A

Figure 41. Sub-Battery Module Layout for G-Van

Figure 42. Sub-Battery Module Layout for TeVan

complicated arrangement of connecting cells in series and parallel in each of the four vertical planes may be required. Again, the resulting battery module layout is one which is configured internally to suit the requirements of this particular van.

The deliverable battery energy for this configuration is a maximum of 50kWh against a target of 50kWh; after electrically configuring the modules in the battery, the energy is likely to fall short of the target.

5.1.1.4. The MEV-2 Van

The battery arrangement for this vehicle is shown in Figure 43 and, as mentioned before, uses a specific module design. The specified voltage for the MEV-2 of 342V is provided by 4 unit sub-battery module voltages of 85.5V. For an open circuit cell voltage of 2.076V, the number of cells in series in each module should be about 41. A convenient multiple is 42; and, since there are a maximum of 408 cells in each module, the number of strings in parallel in each module is 9.

The deliverable battery energy for this configuration is 31kWh against a target of 40kWh at a nominal voltage of 349V compared with a target of 342V.

5.1.1.5. General Comments on the Sub-Battery Modularization Approach

Having completed a sub-battery modularization study, it was concluded that, although modularization may be a worthy target, it is unlikely to be

achieved for the specified US van applications. Despite having defined a common physical unit for the three vans, when the battery designs were extended to include an attempt to satisfy electrical requirements, the approach was significantly weakened. The target energy was not met for the MEV-2, TeVan and ETX-II vans.

All of the batteries required significantly different internal restructuring to produce the correct voltage. There would, of course, be a resultant loss in standardization of battery components and assembly at this level.

The thermal enclosures which extended around each sub-battery module comprised a significant fraction of the available space. On average, only 55% of the area was used by the cells.

An additional concern was the disproportionate amount of plan area occupied by the thermal insulation. This will have a negative impact on cost and energy density.

The conclusion of the sub-battery modularization study was that, unless US van battery specifications can be made more consistent, the sub-battery approach to modularization is not viable.

5.1.2. Bundled Cell Modularization

A bundled cell modularization approach to battery design retains many of the attractions of modularization but has much more flexibility in battery packaging. The benefit of extending the range of

Figure 43. PB Sub-Battery Layout for MEV-2

common components right through the battery sub-assemblies would still improve the economy of scale, allow simpler build-up of sub-assemblies and extend the application of automated assembly operations. All these factors would have potential cost benefits.

Once again, a spreadsheet was prepared which determined the dimensional fit of a wide range of cell arrays within the specified plan areas. Suitable provision was made for electrical isolation and thermal insulation. The question of how the cells were to be connected electrically to provide system voltage was not addressed in detail at this stage.

In this way, the cell bundle shown in Figure 44 was identified as one which fit reasonably well within the battery envelopes of the ETX-II, G-Van and TeV-an. The resulting battery schemes are shown in Figures 45, 46, and 47, respectively.

Again, the study concluded that the MEV-2 with its different height could not be accommodated with this modular approach. Figure 48 shows a provisional modular arrangement illustrating the differences between it and the other battery schemes.

Having determined the maximum possible number of cells that would fit inside the specified dimensions, provision then had to be made for suitable electrical inter-connection which would provide

close to the specified voltage and energy while being accommodated within the specified cell array.

PLAN VIEW
OF
BUNDLED CELL
MODULE

Figure 44. PB Cell Bundle

5.1.2.1. The ETX-II Van

The battery arrangement for this vehicle is shown in Figure 45. It has 28 bundles of 20, 4 cell high stacks for a total of 2240 cells. The specified voltage for the ETX-II van is 342V; therefore, there needs to be at least 165 cells in series. One arrangement

Figure 45. Bundled PB Cell Layout for ETX-II

which fits reasonably well electrically has 40 banks comprising 14, 4 cell series strings connected in parallel; these 40 banks are connected in series.

Thus, the number of useable cells in the battery matches the maximum possible. The electrical subdivision of 14 does not fit the physical array of 4x5, and the battery has to be configured internally to suit.

The deliverable battery energy for this configuration matches the target of 45kWh; the nominal battery voltage is 332V compared to the target of 342V.

5.1.2.2. The G-Van

The battery arrangement for this vehicle is shown in Figure 46. It can accommodate 39 bundles of 20, 4 cell high stacks for a total of 3120 cells. The specified voltage for the G-Van is 216V, and the total number of cells in series in the battery therefore needs to be about 104.

One arrangement which fits reasonably well electrically has 26 banks of 30, 4 cell series strings connected in parallel. Thus, once again, the number of useable cells in the battery matches the maximum

Figure 46. Bundled PB Cell Layout for G-Van

possible. The electrical subdivision of 30 does not match the physical array of 4x5; the battery would have to be configured internally to suit.

The deliverable battery energy for this configuration is 62kWh compared to the target of 60kWh; the battery nominal voltage is 215V compared to the target of 216V.

5.1.2.3. The TeVan

The battery arrangement for this vehicle is shown in Figure 47. It can accommodate 32 bundles of 20, 4 cell high stacks for a total of 2560 cells. The specified voltage for the TeVan is 180V; therefore, there needs to be about 87 cells in series.

As mentioned before, this vehicle has a very narrow voltage window; and it is important to keep the nominal voltage close to, or higher than, the specified 180V.

One arrangement which fits reasonably well electrically has 22 banks comprised of 29, 4 cell series strings connected in parallel. These banks would be connected in series. For this layout, the number of useable cells in the battery is 2552 compared to the maximum possible of 2560, and 8 cells would not be used. The electrical subdivision of 29 does not match the physical array of 4x5; the battery would have to be configured internally to suit.

The deliverable battery energy for this configuration is 51kWh against a target of 50kWh; the battery nominal voltage is 182V compared to the target of 180V.

5.1.2.4. The MEV2 Van

The battery arrangement for this vehicle, shown in Figure 48, uses a specific bundled cell module design and employs cell stacks which are 6 cells high. The battery has a total of 17 bundles of 20, 6 cell high stacks. The specified voltage for the MEV2 is 342V, and there needs to be about 165 cells in series.

For the MEV2 van battery, the situation is complicated by the need for an appropriate electrical arrangement which can be sub-divided to suit the three separate compartments; one at the front of the vehicle, one in the middle, and the third in the rear.

One arrangement which fits reasonably well electrically has 28 banks comprised of 12, 6 cell series strings connected in parallel. These 28 banks are connected in series. In this case, the number of useable cells in the battery is 2016 compared to the maximum possible of 2040, and 24 cells would not be used. All the unneeded cells would be in the front battery compartment. The 28 banks would be divided into three groups of 3:20:5 in the front, middle and rear compartments, respectively.

Figure 47. Bundled PB Cell Layout for TeVan

Figure 48. Bundled PB Cell Layout for MEV2

The deliverable battery energy for this configuration will be 41kWh against a target of 40kWh; the battery nominal voltage is 348V compared with a target of 342V.

5.1.2.5. General Comments on the Bundled Cell Modularization Approach

Having completed the bundled cell modularization study, it was concluded that a reasonable degree of modularization within the batteries is possible for three of the specified US van applications.

All of the batteries required significantly different internal electrical schemes to produce the correct electrical configuration but, in all cases, a good match of energy and voltage was achieved. This emphasizes the superior packaging ability of this approach compared to the Sub-Battery Modularization Approach. Also identified is the need for a scheme which is flexible enough to allow electrical inter-connection within each battery to suit requirements.

The conclusion drawn from this part of the study is that the bundled cell approach to modularization is appropriate to the ETX-II, the G-Van and the TeVan. The MEV2, with its significantly different height, could achieve a degree of modularity albeit with 6 cell high stacks instead of the 4 cell high stacks that were used with the other van batteries.

5.2 CONCEPTUAL-CELL BATTERY DESIGN

Once the Conceptual-Cell design had been specified, the conceptual designs of the batteries was progressed using this cell design. It became apparent that the MEV2 van battery required a separate approach relative to the other vans, and a separate task was created, Task 4.6, Conceptual-Cell Battery Design for the MEV2, to perform this activity.

Meanwhile, the battery requirements had changed since the "Battery Modularity Study" was initiated. The revised requirements were frozen, and the Conceptual-Cell battery designs were now directed to satisfy these requirements. Improvements at the battery level were expected due to the high performance projected at the cell level, but the objective was to achieve a high degree of modularity using the bundled cell approach. After examining the cell array options for the ETX-II, the G-Van and the TeVan, a bundle of 15, 3 cell high stacks was chosen as the preferred arrangement. A plan of this bundled cell module is shown in Figure 49. Conceptual-Cell battery designs were produced for the ETX-II, the G-Van and the TeVan, with single enclosure provided for each of the batteries. A thickness of 25mm was allowed for the thermal insulation, which will limit the heat loss well within the target of 400W.

Figure 49. Conceptual-Cell Bundle

5.2.1. Battery Component Design

A key consideration of electric vehicle battery component design is the efficient utilization of space, often in a limited plan form area. The component designs which were evolved packed the cells as closely together as possible, given the burden imposed by necessary assembly components, battery sub-grouping requirements, interconnects, and cell stack isolation. Other concerns were the issues of parts count, component manufacturability, and bank/battery assembly procedures. A primary goal was to keep the number of different components required for battery build to a minimum in order to reduce tooling costs, inventory require-

ments, and assembly complexity. To this end, the battery design utilized four basic stampings, each of which could be reversed in orientation in order to fulfill dual roles within the battery assembly. Also required were basic cell interconnect and spacer hardware elements. The resulting design allowed for a straightforward and relatively simple battery assembly which packed cells into the available plan form area almost as tightly as a simple hexagonal dense packing of cylindrical cells bereft of bank and interconnect hardware.

5.2.1.1. The ETX-II Van

This battery was arranged with 56 bundles of cells in a 4x14 array as shown in Figure 50. In the interest of maximizing the modularity between the three van batteries, the energy for the ETX-II was significantly exceeded; 54kWh is available as compared to the target of 45kWh. This allowed for the bundles to be simply connected in series, whereas, with lower energy, a much more complicated electrical interconnection would have been required.

When this arrangement is compared to the TeVan battery design, it can be seen that they are physically identical. The ETX-II voltage is twice that of the TeVan and half of the capacity. This topic is discussed in more detail under the TeVan heading.

The battery fits comfortably within the available battery envelope and the projected height is 260mm compared with an allowable 270mm.

Figure 50. Conceptual-Cell Layout for the ETX-II
(dimensions in mm; dotted lines indicated max. available size)

Figure 51. Conceptual-Cell Battery Design for G-Van

The nominal voltage is 348V compared with a target of 343V. Design and performance details are summarized in Table 5.

5.2.1.2. The G-Van

This battery was arranged with 72 bundles of cells in a 6x12 array as shown in Figure 51. The G-Van battery's energy is 69kWh compared to the target of 60kWh. The bundles are connected in pairs before being connected in series to provide a system voltage of 224V compared to the target of 216V. The battery fits comfortably within the available battery envelope and the projected height is 260 mm compared with the allowable 260 mm. Design and performance details are summarized in Table 5.

5.2.1.3. The TeVan

As with the ETX-II, this battery was arranged with 56 bundles of cells in a 4x14 array as shown in Figure 52. In this case, though, the nominal target voltage is 180V compared to the target system voltage of 342V for the ETX-II.

When the PB cell was being used as the baseline cell, it was emphasized that the narrow voltage range of 145 to 180V allocated for the TeVan should be utilized to the maximum by choosing a nominal voltage of at least 180V. Using the Conceptual Cell, with its much lower resistance, this was less of a problem, and it was possible to lower the nominal voltage. This has a significant benefit regarding modularization because it allows the TeVan to have exactly half the battery voltage of

the ETX-II battery. Since the energy requirements are similar, this produces a very attractive option where the two batteries are identical except that, for the TeVan, pairs of bundles are connected in parallel before connecting in series. The energy available for this application is 54kWh compared with the target of 50kWh; the nominal voltage is 174V compared to a target of 180V. The battery fits

comfortably within the available battery envelope except that the projected height is 260mm compared to an allowable height of 230mm. This is the only dimension that has not met the US van battery targets and would be a subject for further discussion in the event of further progress of these battery designs. Design and performance details are summarized in Table 5.

Figure 52. Conceptual-Cell Battery Design for TeVan

Table 5. Comparison of Projected Battery Parameters Against Targets

BATTERY DETAILS	VEHICLE			
	ETX-II	MEV2	G-Van	TeVan
Projected Weight(kg)	400	310	496	400
Target Weight(kg)	500	400	500	500
Projected Energy(kWh)	54	43	69	54
Target Energy(kWh)	45	40	60	50
Projected Peak Power(kW)	111	89	145	76
Target Peak Power(kW)	65	65	48	60
Projected Nominal Voltage	348	348	224	174
Target Nominal Voltage	342	342	216	180
Minimum Load Voltage	250	250	160	145
Specific Energy(Wh/kg) Projected	135	139	139	135
Target	90	100	120	100

5.2.1.4. The MEV2 Vehicle

The MEV2 battery van required a separate design approach from that of the other vans. This task was created to develop the battery design employing the Conceptual Cell.

As with the other battery designs, the aim was to achieve a high degree of modularity using the bundled cell approach. A bundle of 12, 4 cell high stacks was chosen as the preferred arrangement.

A single battery enclosure was utilized with the preferred 25mm thick thermal insulation; thus the heat loss should be well within the target of 400W. The approach to the design of battery components was similar to that used for the other battery designs developed for the ETX-II, TeVan, G-Van and MEV2 vehicles.

Figure 53 shows 42 bundles arranged in a 6x7 array, for a total of 2016 cells. The bundles were connected in series to provide a nominal voltage of 349V. Design and performance details are summarized in Table 5 and Table 9.

5.2.1.5. Summary of Conceptual-Cell Battery Designs for the ETX-II, G-Van and TeVan Vehicles

Conceptual-Cell battery designs were completed for the ETX-II, G-Van and TeVan which either met or exceeded the specified battery requirements. The only exception was the height restraint of 230mm for the TeVan, which would be exceeded by an estimated 30mm. This could be a matter for negotiation with Chrysler, given that the ETX-II and TeVan batteries would otherwise be almost identical.

Figure 53. Conceptual-Cell Layout for the MEV2

The projected specific energy for the Conceptual-Cell design batteries was between 135 and 140Wh/kg compared to targets of between 90 and 120Wh/kg. The projected peak power capabilities were well in excess of the targets, even for the TeVan with its narrow voltage window.

All three batteries used standard bundles of 15, 3 cell high stacks; and many of the other battery components such as bank plates, leadthroughs, etc, would also be standard. In the cases of the ETX-II and TeVan, all components were standard apart from those interconnecting components needed to produce the different system voltages.

Heat losses from all batteries were well within the target 400W, provided evacuated glass fibre insulation (or comparable) was specified.

5.3 COST AND MANUFACTURABILITY STUDY

Once the Conceptual-Cell design and Conceptual-Cell battery components were specified, the manufacturability and costs of these designs were evaluated.

Manufacturing techniques, labor and material breakdowns, cost and pricing policies are a very sensitive part of any commercial operation. In order to protect CSPL's and Beta Power's proprietary information, the cost information has been aggregated to show combined values. In addition, a standard costing methodology, developed by George in 1984 on behalf of the Electric Power Research Institute[9], has been adapted to project selling price. Quinn, Symons and Brown [10] also used the George methodology but added items to include battery disposal and license fees.

In order to be consistent with the Quinn et al report, this study assumed that 22,500, 18kWh batteries are made/year; this is equivalent to 421 MWh/year. The choice of an 18kWh battery does not correspond to a battery design addressed in this document but, instead, was chosen for comparison with a specific PB cell based battery design. With 840 cells in each battery, the total number of cells produced per year was 17 million.

The inflation linked items in the costing methodology were updated from the original values quoted at the end of December, 1983, to the end of De-

cember, 1991, by assuming an annual inflation rate of 4%.

The updated labor rate was \$17/hour; the rent was \$7.9/sq.ft/year; and the marketing, warrantee, and miscellaneous expenses were \$7.9/kWh. Other assumptions were: an overhead rate on labor of 150%; an overhead rate of 10% on materials; a battery disposal cost of \$5/kWh; a 3% license fee; and a 10 year, linear period of depreciation.

The topic of the effect on selling price of increasing battery output has not been addressed in this study, although Quinn et al estimated a 9% reduction by doubling the factory production rates.

Where possible, costs were derived from quotation from suppliers of raw materials and components. Quotations were based on annual production rates comparable to the factory size assumed in this study. Existing experience at CSPL, for PB based production techniques and costing studies, was used extensively to estimate levels of direct labor and the use of automated machinery.

The Conceptual Cell may employ alternative manufacturing equipment and procedures to the PB cell. It was outside the scope of this program to conduct a detailed evaluation of these effects and, instead, it was assumed that these items would be comparable to the PB cell. Thus, the capital cost of plant and equipment, the plant area and the manning levels were assumed to be comparable for both cell designs.

The relative levels of cost of energy and power are shown in Figure 54. A significant material cost

Figure 54. Relative Prices

reduction of about 30% is shown for the Conceptual Cell compared to those projected for the PB Cell. Interestingly, the projected selling price of the Conceptual Cell is about 20% lower than the PB cell.

Although one may have expected more of a pro-rata decrease, the reason why this was not achieved is that the levels of labor, investment and plant area have been assumed to be comparable between the two cell designs. Some of the cost assumptions of the methodology, e.g. battery disposal cost, relate to a fixed cost/kWh.

In conclusion, it can be seen that a significant reduction in price of energy of about 20% is projected for the Conceptual-Cell design.

A much more dramatic effect in the price of power of the Conceptual Cell is shown, and the projected price represents a 56% reduction on the price of power of the PB cell.

6.0 ADVANCED PASSENGER EV BATTERY

Worldwide public attention was focused on the US during 1990 when GM demonstrated its progress on a concept electric vehicle passenger car code named the Impact. This vehicle, in an impressive demonstration, dispelled many of the myths about electric vehicles and promoted the feasibility of producing an electric car which would have comparable road performance to gas powered cars in an attractive design package.

The two seat vehicle, equipped with Delco Remy lead acid batteries, accelerated from 0 to 60mph in 8 secs, with a quoted range of 120 miles between charges. The vehicle weighed 1160kg (including batteries), had a very low drag coefficient of 0.19, and a low rolling resistance due largely to the use of lightweight, high pressure tires.

One of the requirements of the extension to this contract was to examine the use of the conceptual sodium/sulfur cell in a battery for an advanced electric passenger car. The vehicle requirements could be hypothetical and not linked dimensionally to a particular vehicle. The conceptual-cell design developed in the main part of the program would, if necessary, be modified to suit the needs of the

passenger car battery. A conceptual battery design would be produced for the selected vehicle.

The USABC long term requirements were not significantly different from the MEV2 battery requirements. The design of a battery based on the Impact requirements became an attractive proposition since it provided a stimulating difference in battery design that was aimed specifically at passenger cars.

Two battery design studies were produced. The first study used the Conceptual-Cell design specified as part of the main contract; the second study used a smaller diameter cell which provided a better match of the original Impact battery specifications. Differences between the two battery designs are highlighted in the following paragraphs and a comparison is made to the lead acid battery physical and performance characteristics.

6.1 DEFINITION OF BATTERY REQUIREMENTS

The Impact fulfilled its task of demonstrating technical excellence and the potential of electric passenger cars. It is likely that an electric passenger car designed for a high volume market will be different in many ways from the Impact. It is likely that, with the increasing use of composites and lightweight materials in the automotive industry, the vehicle weight of an advanced passenger car can be reduced to the levels achieved with the Impact. It is probably unlikely, though, that a car of this type, built for a high volume market, would achieve the low drag coefficient of 0.19 and the low rolling resistance of the Impact.

Based on these comments, it is likely that the power needed to maintain the stated level of acceleration will stay at about 90kW but that significantly higher energy (estimated at 50%) will be required to maintain a range of 120 miles between charges over typical urban driving or steady 50mph driving.

Thus the specifications detailed in Table 6 should be modified by the likely needs of a commercially produced electric passenger car. The data in this table is extracted from a handout from GM/Delco Remy and relate to the vehicle and battery used for the Impact demonstration.

6.2 CELL AND BATTERY DESIGN ANALYSIS

Without knowing the likely driving cycle for this particular application, analyses were performed to estimate the likely thermal characteristics.

A 3 hour discharge rate was chosen for the Conceptual Cell battery to represent an aggressive constant driving cycle. The results are shown in Figure 55 where, without cooling, it is seen that cell temperatures increased from typically 330°C to 380°C throughout the complete discharge of the battery.

For the small diameter cell battery, a 2 hour discharge rate was chosen to represent an equivalent driving cycle to that of the Conceptual Cell battery. The results are shown in Figure 56 where, without cooling, it can be seen that cell temperatures also increased from typically 330°C to 380°C. Although the discharge period was shorter, the thermal mass was correspondingly lower; the net result was a comparable temperature rise to the Conceptual Cell battery.

6.3 CONCEPTUAL-CELL DESIGN

Two battery design studies were completed: the first used the Conceptual Cell; and the second used a

Figure 55. Temperature Rise in Conceptual Cell Battery

Figure 56. Temperature Rise in Small Diameter Cell Battery

Table 6. Impact Electric Vehicle Lead Acid Battery Specifications

Parameter	Specification
Length	2261mm
Width	254mm
Height	366mm
Volume	191 litres
Voltage	320V
Capacity (2h Rate)	43Ah
Energy (2h Rate)	13.7kWh
Power (10s, 50% DOD, 265V)	90kW
Cycle Life (80% DOD) (30% DOD)	500 2500
Recharge time 0-50% SOC 0-100% SOC	30 minutes 4 hours
Price to Replacement Customer	<\$1500 installed

smaller diameter cell. The physical and performance details are summarized in Table 7. The Conceptual-Cell design was optimized on the requirements of four US EV's: the TeVan, the G-Van, the ETX-II van, and the MEV2. The peak power requirements of the cells for these batteries were driven more by thermal aspects than by performance. The combination of target range and vehicle characteristics, such as gross vehicle weight, also demanded a relatively high battery energy. Thus, the Peak Power:Energy Ratio of the Conceptual Cell was approximately 2.4. The Conceptual Cell provided battery performance which is potentially viable and was included in this study as a reference point.

The smaller diameter cell was selected to increase the Peak Power:Energy Ratio to greater than 4. This Ratio was been chosen to allow for an increase of about 50% in energy over the lead acid battery while supplying approximately 90kW peak power. Thus, the Ratio is $90\text{kW} / 20\text{kWh}$, or 4.5. This performance match was more in line with the original Impact specifications, but with some significant advantages such as reduced mass and length.

6.4 CONCEPTUAL BATTERY DESIGN

6.4.1. The Conceptual-Cell Battery Design

Modules employing the Conceptual-Cell design fit conveniently into the Impact battery envelope and require only a very simple internal battery network. The full length and width was utilized to provide a maximum number of cells; this is depicted in Figure 57. Four cells were stacked vertically and

were connected in series to provide a networking arrangement well proven at CSPL which offers a way of accommodating cell failures over the life of the battery. Eleven of these strings were connected in parallel in a sub-assembly referred to as a bank, each bank had an 8V nominal voltage and a capacity of 118Ah. Thirty-eight of these banks were arranged in line and were connected in series to provide a nominal battery voltage of 316V. Table 8 summarizes the battery physical and performance details.

The most apparent feature of this battery was the high energy that was stored within the envelope. The 36kWh would, on a pro-rata basis with the 13.7kWh lead acid battery, provide a range of 315 miles. In fact the battery weight was reduced from 396kg to 235kg; this gave a useful 161kg lower gross vehicle weight which would also extend the range to in excess of 350 miles under comparable driving conditions.

The only dimensional difference was the 36mm lower height, which may be of some benefit to the vehicle designer.

The Conceptual Cell battery was capable of supplying a peak power of 85kW over 80% of the discharge range as compared to 50% of the discharge range of the lead acid battery. It must be emphasized that this was estimated based on a minimum load voltage of 210V (2/3 the open circuit voltage) compared with the 265V achieved with the lead acid battery. The minimum load voltage is determined by the capability of the control system, and the

Table 7. Summary of Cell Details

Cell Parameter	Conceptual Cell	Small Diameter Cell
Diameter	33mm	21mm
Length	60mm	60mm
Mass	84g	38g
Resistance (at 350° C)	18mΩ	29mΩ
Capacity (to 1.9V o/c)	10.9Ah	3.7Ah
Energy (at 3h rate)	21.4Wh	7.3Wh
Peak Power (at 80% DoD, 2/3 ocv)	52W	32W

Figure 57. Battery Design for Impact Car Using Conceptual Cells

USABC has specified a load voltage:open circuit voltage ratio of 2/3. This is a critical issue for determining battery performance since, for comparable peak power capability, higher levels of minimum voltage demand reductions in battery resistance. It was assumed, for these sodium/sulfur battery designs, that vehicle controller technology would accommodate the assumed voltage range. If this proves not to be possible then the peak power that can be delivered will be degraded.

6.4.2. The Small Diameter Cell Battery Design

The Small Diameter cell design fits reasonably well into the Impact battery envelope with a very straight forward internal battery network. This battery design is shown in Figure 58. The available width of the envelope was increased slightly so that a sufficient number of cells could be installed to supply an energy of 20kWh. Once again, four cells were stacked vertically and connected in series to provide a well proven networking arrangement. Eighteen of these strings were connected in parallel in a sub-assembly (bank); each of these had an 8V nominal voltage and a capacity of 67Ah. Thirty-eight of these banks were arranged in line and con-

nected in series to provide a nominal battery voltage of 316V. Table 8 summarizes the battery physical and performance details.

The most apparent feature of this battery was the major reduction in length and mass. The energy supplied was 20kWh, and this would, on a pro rata basis with the 13.7kWh lead acid battery, provide a range of 175 miles. In fact, the battery weight was reduced from 396kg to 180kg which would give an even greater reduction of 216kg in gross vehicle weight. This 20% reduction in mass would also extend the range to well over 200 miles under comparable driving conditions.

The major dimensional difference was the 743mm (2.4ft) reduction in length; this will certainly be of some benefit to the vehicle designer since it reduces the tunnel length necessary to house the battery.

This battery was also capable of supplying a peak power of 85kW over 80% of the discharge range, based on a minimum load voltage of 210V (2/3 of the open circuit voltage). All the comments on peak power capability contained in the previous section also apply to this battery. The provision of

BATTERY DESIGN USING SMALL DIAMETER CELLS

Figure 58. Battery Design for Impact Car Using Small Diameter Cells

higher peak power and lower energy was achieved by providing 60% more cells of a smaller capacity, and this will have an impact on cost. On the one hand, much less reactants are supplied to a smaller battery; this will reduce the battery cost. On the other hand, more seals and cell components are

required, which will tend to increase battery cost. Battery level components such as heaters, instrumentation and controllers tend to remain constant. A detailed comparison of all the cost trade-offs possible between the battery and vehicle was clearly beyond the scope of this report.

Table 8. Summary of Battery Details

Parameter	Lead Acid	Conceptual-Cell Battery	Small Diameter Cell Battery
No of Cells:			
In Parallel	1	11	18
In Series	160	152	152
Total	160	1672	2736
Capacity	43Ah	118Ah	67Ah
Nominal Voltage	320V	316V	316V
Energy(2h rate)	13.7kWh	36kWh	20kWh
Peak Power	90kW (at 50% DoD,265V)	85kW (at 80% DoD,210V)	85kW (at 80%DoD,210V)
Mass	396kg	235kg	180kg
Dimensions: (long wide high)	2261x254x366mm	2261x254x330mm	1518x260x328mm
Volume:	210 litres	190 litres	129 litres
Specific Energy	35Wh/kg	153Wh/kg	112Wh/kg
Energy Density	65Wh/l	190Wh/l	155Wh/l

6.4.3. Summary of Results and Conclusions

Both of the sodium/sulfur Impact batteries were capable of supplying more energy, a peak power which was close to the specified 90kW, and a significant reduction of between 40 and 55% in battery weight when compared to the lead acid battery.

The battery using the Conceptual-Cell design used most of the available space but had a potentially useful height reduction of 36mm. The battery energy was much greater, 36kWh compared with 13.7kWh with the lead acid, which, in combination with the weight reduction, would extend the quoted range of the Impact from 120 to in excess of 350 miles.

The battery using the smaller diameter cell had a height reduction of 38mm and a significant length reduction of 743mm (2.4ft). This battery had an energy of 20kWh, which would extend the range of the Impact to in excess of 200 miles.

Benefits associated with the use of sodium/sulfur include: full peak power capability for 80% of depth of discharge (DoD); full capacity delivered almost irrespective of rate, i.e., capacity will not be significantly effected by the way the vehicle is driven; battery performance and life essentially unaffected by ambient temperature; and a prospective calendar life of at least 4 years even under deep discharge cycling.

With a projected price of \$150/kWh, then the battery with the conceptual cells would cost \$5400, and the battery with the Smaller Diameter cells would cost \$3000. Both these figures are much higher than the target of <\$1500, although the latter was linked to a two year battery life. The capability of sodium/sulfur cells has been demonstrated to be in excess of four years, with deep discharge cycle lives of several thousand cycles.

7.0 ACKNOWLEDGEMENTS

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APPENDIX A

1.0 MEV2 PB BATTERY DESIGN

A task was added to complete a detailed design of a MEV2 battery using an advanced PB cell. This design would provide a baseline for the Conceptual-Cell battery designs and to Ford Motor Co. for their use in this DOE-sponsored MEV program. The approach to battery component design, which was developed during the other battery design studies, was also adopted for this vehicle.

The MEV2 battery space allocation was divided into two separate compartments: one large compartment in the middle of the vehicle and a smaller compartment at the rear. The battery design was predicated on meeting the electrical requirements and fitting within the allowable space. The cell design premise was an advanced PB cell with an increased energy of 24Wh as compared to the nominal 20Wh of the state of the art PB cell.

Early on, it was recognized that the peak power requirements would drive the battery designs and that battery design options may exist which would depend on the value of cell resistance that could be achieved in the future.

In preliminary battery design studies, dimensional restrictions were identified as a severe design constraint. The allocated height of 320mm was undoubtedly the most serious dimensional concern. An obvious effect was to limit the number of cells in a vertical stack.

The specified MEV2 battery envelope precluded the use of four cell strings either alone (inefficient packaging) or stacked vertically into an overall eight cell height (insufficient available height). Electrical and dimensional concerns suggested that the most effective designs should specify either three cell strings in a six cell high battery or five cell strings.

In view of these considerations, a number of battery options were developed, each with assumptions regarding cell resistance and the height of cell stacks. The 40kWh beginning of life (BoL) energy requirement and 342V nominal system voltage dictated a module design composed of a minimum of 10 parallel strings. In order to meet the 65kW peak power, while maintaining a minimum voltage above 250 volts, the number of strings in parallel depended on the achievable cell resistance. Thus, the battery design was driven by the MEV2 peak power requirements. A summary of the battery performance and other parameters is shown in Table 9.

1.1 DESIGN A: 6 CELLS HIGH, BOTH BATTERY COMPARTMENTS

This option, shown in Figure 59, investigated an arrangement based on the maximum utilization of space in both the compartments.

This battery has 29 modules of 15, 6 cell high stacks to give a total of 2610 cells; 24 of the modules are

Table 9. Comparison of Projected MEV2 Battery Parameters Against Targets

PARAMETER	Target	Design A	Design B	Design C	Conceptual Cell
Weight(kg)	500	530	396	371	310
Energy(kWh)	40	62	48	43	43
Peak Power(kW)	65	65	65	67	89
Assumed Cell Resistance(mΩ)	-	34	25	24	18
Nominal Voltage	342	361	349	374	348
Minimum Load Voltage	250	250	250	250	250
Specific Energy(Wh/kg)	80	117	121	116	139
Specific Peak Power(W/kg)	130	123	164	181	287

in the middle compartment and 5 in the rear compartment. Each of the modules has 15 strings connected in parallel, with a parallel interconnecting plate provided at the mid-point to subdivide the 6 cell string into 2, 3 cell series strings.

A critical feature of this design is the effect of the combination of height restriction and the use of 6 cell high stacks. As a result, only 13mm of thermal insulation can be incorporated, compared to a preferred thickness of 25mm. In order to meet the target of 400W heat loss, the use of evacuated glass fibre insulation or equivalent is mandatory.

The total deliverable energy of this battery is 62kWh; this is significantly higher than the target of 40kWh. With an equivalent cell resistance of 34mΩ,

the deliverable peak power at the end of discharge is 65kW and the nominal voltage is 361V.

1.2 DESIGN B: 6 CELLS HIGH, MIDDLE BATTERY COMPARTMENT ONLY

This option, shown in Figure 60, investigated an arrangement based on the use of 6 cell high stacks housed in the middle battery compartment only.

This battery has 28 modules of 12, 6 cell high stacks to give a total of 2016 cells. Each of the modules has 12 strings connected in parallel, with a parallel interconnecting plate provided at the mid-point to subdivide the 6 cell string into 2, 3 cell series strings.

Figure 59. Battery Option with 6 Cells High and Both Compartments

Figure 60. Battery Option with 6 PB Cells High and Middle Compartment Only

Again, a critical feature of this design is the effect of the combination of height restriction and the use of 6 cell high cell stacks. As a result, only 13mm of thermal insulation can be incorporated compared to a preferred thickness of 25mm. In order to meet the target of 400W heat loss, the use of evacuated glass fibre insulation or equivalent is mandatory. The total deliverable energy of this battery is 48kWh, still well above the target of 40kWh. With an equivalent cell resistance of 25m Ω , the deliverable peak power at end of discharge is 65kW and the nominal voltage will be 349V compared to targets of 65kW and 342V, respectively. The state

of the art equivalent PB cell resistance is 34m Ω , thus the requirement for a 25m Ω PB cell represents a significant improvement.

1.3 DESIGN C: 5 CELLS HIGH MIDDLE BATTERY COMPARTMENT ONLY

This option, shown in Figure 61, investigated an arrangement with 29 modules of 36, 5 cell high stacks to give a total of 1800 cells. Each of the modules has 10 strings connected in parallel, with all of the cells in each 5 cell stack connected in series.

Figure 61. Battery Option with 5 Cells High and Middle Compartment Only

It is noted that, although the electrical and physical requirements may have been satisfied by reducing the number of strings in parallel to 10, the battery reliability may have been penalized due to the lower level of redundancy. The degree of effect will depend on the cell reliability characteristics.

This battery design, with its shorter cell stacks, allows the thickness of thermal insulation to have the preferred value of 25mm. Thus, the target of

400W heat loss can be easily met with the use of evacuated glass fibre insulation or equivalent.

The total deliverable energy of this battery will be 43kWh, which meets the target of 40kWh. With an equivalent cell resistance of 24mΩ, the deliverable peak power at end of discharge is 67kW and the nominal voltage is 374V compared to targets of 65kW and 342V, respectively.

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