DOE/AL/54303--T1

SODIUM SULFUR ELECTRIC VEHICLE BATTERY ENGINEERING PROGRAM

FINAL REPORT

FOR THE PERIOD

September 2, 1986, through June 15, 1993

Prepared For

U.S. Department of Energy

Albuquerque Operations Office

Contract No. DE-AC04-88AL54303

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Silent Power
ENERGY STORAGE TECHNOLOGY

DISCLAIMER

EXECUTIVE SUMMARY

In September 1986 a contract was signed between Chloride Silent Power Limited (CSPL) and Sandia National Laboratories (SNL) entitled "Sodium Sulfur Electric Vehicle Battery Engineering Program". The aim of the cost shared program was to advance the state of the art of sodium sulfur batteries for electric vehicle propulsion. Initially, the work statement was non-specific in regard to the vehicle to be used as the design and test platform. Under a separate contract with the DoE, Ford Motor Company was designing an advanced electric vehicle drive system. This program, called the ETX II, used a modified Aerostar van for its platform. In 1987, the ETX II vehicle was adopted for the purposes of this contract. This report details the development and testing of a series of battery designs and concepts which led to the testing, in the United States, of three substantial battery deliverables.

The program was structured to directly incorporate the state of the art cell technology being developed under complementary CSPL and CSPL/SNL contracts. A description of this "core technology" program and the PB cell itself is given in Reference 1. The advances made with respect to the cell technology during this time were significant. For example, in September 1986, CSPL was producing cells at a rate of 100 per week, and by the end of the contract period this rate had been expanded to several thousand per week. Performance and reliability were also dramatically improved. Over the same period the technology was transitioned from laboratory testing of small numbers of cells to extended vehicle trials, independent battery/vehicle trials and substantial destructive safety testing of complete batteries.

The first test unit was an intermediate deliverable battery (IDB) intended to demonstrate CSPL technology, ahead of a commitment to a full scale vehicle battery build. This battery was statically tested by the Argonne National Laboratory (ANL). A full size (50 kwh) battery, the "ETX II", was then constructed and delivered to the US for test first at Ford Motor Company and then Idaho National Engineering Laboratory (INEL). In-vehicle tests were conducted, including the use of a dynamometer. The battery was eventually tested for 18 months and spent 13,000hrs at temperature at the various test centres.

The major objective of the initial (ETX II) phase of the programme was a proof-of-concept demonstration of sodium sulphur EV battery technology. In order to satisfy this objective, many compromises were made during the design and build of the battery. In particular weight, volume and thermal performance were sacrificed in order to employ well proven technology. No attempts were made to miniaturise the control and instrumentation systems either internal, or external to the battery. An additional problem was that the insulation system and enclosure construction techniques were still quite new when the battery was assembled. The weight of the first ETX II battery had gradually risen as compromises were made at the design and particularly its rebuild stages (the battery was rebuilt after suffering damage in transport to the US). It was recognised that significant weight could be removed by respecifying component materials and designing out weight from the heaviest components.

The third deliverable battery represented an advance upon the ETX II particularly in regard to its weight. Significant improvements were made in this second generation system although a shortage of funding prevented the construction of the second of two identical modules required to power the vehicle. This final deliverable was known as the ETX IIs battery. The stated objective of the ETX IIs phase of the program was the manufacture of a lower weight battery. This was accomplished as the half battery weighed 230 kg, an improvement of 14 kg over the predicted weight. This should increase the gravimetric energy density to around 105 Wh/kg. If the performance and reliability of the cells extracted from the actual build are replicated then a substantial improvement in the overall technology can be anticipated.

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NOMENCLATURE

ANL	Argonne National Laboratory.
AWP	Adhesive wall polyolefin. A heat shrink electrical insulation.
BEDFORD CF	The Bedford 3.5 ton delivery van. Also known as the Griffon in the USA.
BEDFORD QUARTER BATTERY	A 56 volt, nominal 18kWh made by CSPL, which forms a quarter of the drive pack of the Bedford CF Electric
CSPL	Chloride Silent Power Limited
C-RWE	The company formed in a venture between the German Utility Company, RWE and Chloride Group plc.
FUDS	The Federal Urban Driving Schedule. A standard velocity-time profile used by auto and regulatory industry that was adopted for use with electric vehicles. See also SFUDS, below.
DoE	The Department of Energy of the US Government
DURATEC	A proprietary electrical insulation material.
EoL	End of Life
ETX II	An advanced electric drive train development for the DoE by Ford and General Electric. It was designed for testing in a Ford Aerostar minivan. In this document the term is also applied to the battery designed for this vehicle.

ETX IIs	As above, but the lightweight battery version of the subject contract.
ETV-1	
EV	Electric Vehicle.
G-VAN	Full size (4.5ton) van using General Motors glider.
IDB	The 960 cell Intermediate Deliverable Battery of the subject contract. This was the proof of concept battery and was tested in the USA by ANL.
IDSEP	Improved Dual Shaft Electric Propulsion Vehicle. Concept based on DSEP vehicle developed by Eaton Corp.
INEL	Idaho National Engineering Laboratory.
J227aD	US Society of Automotive Engineers drive cycle.
J227aC	As above.
LBM	A proprietary material used by CSPL to make light weight bank plates.
LCL	Lower Confidence Limit. In this document this refers to the 95% statistical confidence interval.
MICROTHERM	A proprietary thermal insulation.
NOVAFLEX	A proprietary thermal insulation.
PTA	Post Test Analysis

QB	The prefix represents Quality Bank, normally a 120 cell, 8 volt unit of 30, 4-cell strings. It forms the basic battery building block of the Bedford Quarter Battery. It is also known as a "module", "bank", or "monobloc" and the terms are used synonymously. This unit became a standard test unit at CSPL.
QC	Quality Control
Rc	The resistance of a cell or test battery on charge, taken at 2 volts open circuit, normally after a 10 second dwell period. The temperature is 350°C unless otherwise noted.
Rd	As above but the discharge value.
RWE	The German Energy conglomerate which now owns CSPL.
SFUDS	The Simplified Urban Driving Schedule, a standard battery test profile which includes regenerative breaking and is based on the FUDS for the IDSEP vehicle.
SNL	Sandia National Laboratories Albuquerque, New Mexico.
UCL	As LCL above but this is the lower confidence value.

WEIBULL CHARACTERISTIC	A two parameter statistic function which relates both the location of the population and the rate of failure. The Characteristic is the location parameter and is equivalent to the mean of the normal distribution except that it is located at the 63 percentile. It is usually allocated the Greek symbol alpha and in this document has units of hours or electrical cycles. In the document it is calculated by maximum likelihood estimating and the most likely value is preceded by the lower 95% estimate and followed by the upper 95% estimate.
WEIBULL MODULUS	As above but this is the parameter which defines the rate of failure of the population. It is also known as the "shape parameter" and is most usually symbolised by "m" or Greek beta.

1.0 INTRODUCTION

In September 1986 a contract was signed between Chloride Silent Power Limited (CSPL) and Sandia National Laboratories (SNL) entitled "Sodium Sulfur Electric Vehicle Battery Engineering Program".[1] The aim of the cost shared program was to advance the state of the art of sodium sulfur batteries for electric vehicle propulsion. A chronology of the important events during the span of the contract are listed in Appendix A.

Initially, the work statement was non-specific in regard to the vehicle to be used as the design and test platform. Under a separate contract with the DoE, Ford Motor Company was designing an advanced electric vehicle drive system. This program, called the ETX II, used a modified Aerostar van for its platform. In 1987, the ETX II vehicle was adopted for the purposes of this contract.

In a program lasting until January 1993, the most tangible products were three battery deliverables. Figure 1-1 summarises the design, build, and test of these batteries. The first was an intermediate deliverable battery (IDB) intended to demonstrate CSPL technology, ahead of a commitment to a full scale vehicle battery build. This battery was statically tested by the Argonne National Laboratory (ANL). A full size (50 kwh) battery, the "ETX II", was then constructed and delivered to the US for test first at Ford Motor Company and then Idaho National Engineering Laboratory (INEL). In-vehicle tests were conducted, including the use of a dynamometer.

The third deliverable battery represented an advance upon the ETX II particularly in regard to its weight. Significant improvements were made in this second generation system although a shortage of funding prevented the construction of the second of two identical modules required to power the vehicle. This final deliverable was known as the ETX IIs battery.

This program was structured to directly incorporate the state of the art cell technology being developed under complementary CSPL and CSPL/SNL contracts. A description of this "core technology" program and the PB cell itself is given in Reference 1. The advances made with respect to the cell technology during this time were significant. For example, in September 1986, CSPL was producing cells at a rate of 100 per week, and by the end of the contract period this rate had been expanded to several thousand per week. Performance and reliability were also dramatically improved. Over the same period the technology was transitioned from laboratory testing of small numbers of cells to extended vehicle trials, independent battery/vehicle trials and substantial destructive safety testing of complete batteries.

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[1] Note: The original contract, numbered SNL 14-0850 was assigned to DoE Albuquerque Operations Office in late 1988 and became DE-AC04-88AL54303.

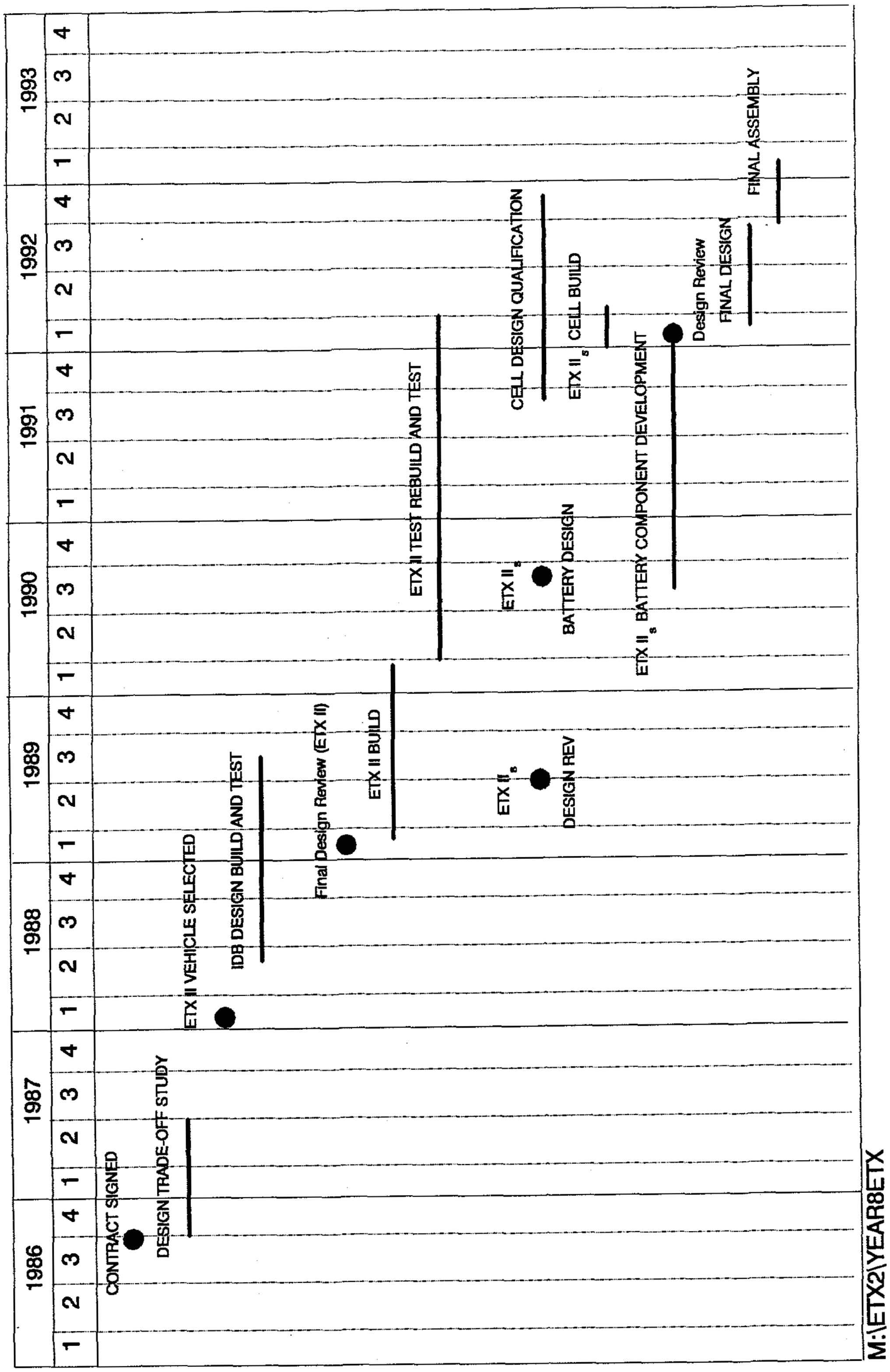


Figure 1-1. Summary Chart of the EV Battery Engineering Program

1.1 TASK STRUCTURE

The Task Structure of the program is outlined below. Task 1 was completed in July 1987 and the award of the remainder of the contract, to complete the other tasks, was contingent on its outcome. The design trade off was a study of two alternative battery systems, one based on the PB cell and a modified Bedford Battery, the other based on either a PB or an XPB cell in a vehicle specific design. The purpose of Task 2.1 was to ensure compatibility with the vehicle manufacturers requirements. Task 2.2 was a large task intended to provide developed and qualified concepts for inclusion in the actual battery system, designed under Task 2.3 and built under Task 2.4. The remaining tasks were documentation, test and commissioning.

TASK 1 DESIGN TRADE-OFF STUDY

TASK 2.1.VEHICLE MANUFACTURER INTERFACING

TASK 2.2.SUPPORTING DEVELOPMENT

Mechanical System
Electronic System
Thermal Management

TASK 2.3.BATTERY SYSTEM DESIGN

TASK 2.4.BATTERY FABRICATION

TASK 2.5.DOCUMENTATION

TASK 2.6.TEST AND COMMISSION

Commission and Test at CSPL
Recommission in the Second ETX-II

TASK 3.PROGRAM MANAGEMENT

1.2 DELIVERABLES

There were three substantial deliverables during the program. The first was a proof of concept battery delivered for test at ANL. The second was a full size battery for the ETX II vehicle, tested at both Ford and INEL. The final battery deliverable was one module of the two required to drive the ETX IIs vehicle. The single module was delivered because of funding shortage at the end of the development program. It was delivered for test at ANL.

2.0 ETX II BATTERY

2.1 DESIGN SPECIFICATION

At the start of the contract, the battery design was not vehicle specific, indeed even the type and size of cell had not been specified. A Design Trade-off Study constituted Task 1 of the contract, with the objective of arriving at an agreed concept for both the vehicle and the accompanying battery technology. Discussions were initiated with Ford and from these, compromises were reached for power demands and heat rejection methodologies. Ford required a continuous output of 35 kW from a battery that was of large plan area but limited height.

Eventually, an agreed concept was reached and an amendment to the contract, to concentrate specifically on a battery for the ETX II vehicle, was submitted on 11th June 1987.

PARAMETER		ORIGINAL	REVISED	NOTES
SYSTEM VOLTAGE	MAX (REGEN)	-	240V	20kW
	MAX (O/C)	180-220V	206V	o/c at 100% SoC
	MIN (LOAD)	150V(40%SoC)	135V (max power at 20% SoC	
POWER	Peak	48kW	65kW	for 20 seconds
	Sustained	21kW	35kW	7% grade @ 30mph
ENERGY		35kWh	50kWh	operation of light van on FUDS
WEIGHT (Target)		570kg	500kg	
EXTERIOR SIZE		1525 x 1065 x 445mm		
VIBRATION		Must meet automotive industrial practices		

The ETX II battery design requirements were more demanding than those previously considered and the changes in the specification are listed in tabular form above.

The battery was intended for installation in the cargo space of the ETX II vehicle although a design amenable to underfloor mounting was a pre-requisite. The plan dimensions, common to both the cargo bay and the underfloor space were 1500 mm x 1065 mm. Initial calculations predicted that 2908 cells was an upper limit assuming a 4-cell high string could be accommodated. It was from these initial specifications that the full design was developed, as detailed in Section 2.3. Section 2.3 also contains a description of the cell string and bank arrangements.

2.2 COMPONENT DEVELOPMENT

2.2.1 Cells

Cell development was not an integral part of this contract. However, the development of the cell and of its performance was of great significance for battery performance, safety and life. The progression of cell designs during the span of the contract is shown in Figure 2-1. This subsection contains a summary of the performance testing that was conducted prior to the build and concurrent with the testing of the ETX II battery. This testing was an important part of the battery development effort because it served to ensure that electrical and safety performance was adequate and to identify any unexpected problems. The option was always available to abort the construction or testing of the battery in the light of the concurrent testing programs.

At the start of the contract the PB cell design that was current was referred to as the MK 2A although it was rapidly being superseded by the MK3SF cell in response to concerns about the safety of the Mk 2A. At the time there was some scepticism about the robustness of the MK3 seal particularly under freeze thaw conditions. A trial was instigated in May 1988 of the MK3SF cell and by November 1988 sufficient confidence had been gained to specify its use in the Intermediate Deliverable Battery ((IDB) see section 2.2.6). There were many process changes ongoing at this time because the MK3 designs were new and in response to continual development findings. However, the pressure to move away from the MKIIA design and introduce additional safety features was such that the new cell was introduced after a relatively limited test and build experience.

DEVELOPMENT OF THE PB CELL

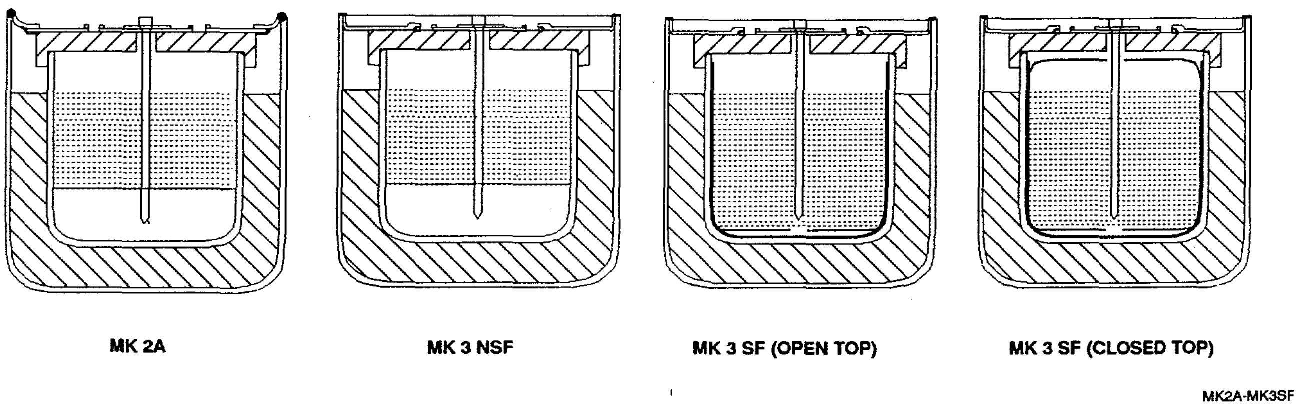


Figure 2-1 PB Cell Designs used During The Contract Period

Intermediate Deliverable Battery

This battery contained the then relatively new MK 3 cells. It was not known at the time of building the battery that a processing flaw had been introduced as a result of the glazing conditions for the alumina header to electrolyte sub-assembly. The nature of the flaw was such that it did not produce any infant mortality and the evidence only became available after the IDB had commenced test. Parallel testing at CSPL indicated that the cells in the IDB should have a Weibull Characteristic of 500 with an associated shape parameter of 2.5.

ETX II Battery

A fraction of all major build populations is selected for Quality Control testing (QC Cells). QC cells receive a standard CSPL test profile (3h discharge, 5h recharge), but many are taken off test to make way for other cells. The testing regimes for other peer groups and "spare" modules were extremely varied making comparative statistical assessment difficult. Much of the data matured concurrently with the testing of the battery and so the comparisons made in this report were not possible as part of a "qualification" process for the cells prior to battery fabrication. The reliability of current technology is such that at least 1 year of testing is required before an indication of statistical life parameters can be obtained. The data presented in this section are thus somewhat out of sequence in the report but it is preferable to analyse the information together. A summary of the cell populations appertaining to the ETX II Battery is shown in Table 2-1.

Table 2-1 Peer Group Testing for ETX II Battery

CELL GROUP	TEST LOCATION	MAX CYCLES	CELL CYCLES	MAX HRS AT TEMP	FREEZE THAW @ CYCLE
QC Cells	CSPL	1728	-	15,700	None
QB 138	CSPL	289	16,600	3,600	@ 3
QB 154	CSPL	674	80,800	7,536	@ 3,and 289
QB 155	CSPL	391	46,900	7,464	@ 3, and 289
QB 177*	ANL	960	115,200	15,336	@ 25 to 160°C
QB 161	Ford/CSPL	836	90,288	10,100	None
Sandia Cells*	SNL	2035	9664	18,816	None
ETX II Battery	CSPL/Ford /INEL	64	184,300	15,000	@ 3

* Provided under Core Technology Contract (SNL 48-8837)

Of the cells listed in Table 2-1 a sub-population of 242 cells was tracked during the life of the ETX II Battery. This consisted of 14 cells (tested as singletons or 4-cell strings), Bank 177 (120 cells) and Bank 161 (108 cells). None of this group had experienced a freeze thaw cycle after extensive electrical cycling. The data were analysed in July 1991 when the ANL tested bank had completed 540 cycles and again when this bank had completed 809 cycles in December 1991, the 14 cells were at a range of cycles depending upon start date. The Weibull statistics are summarised in Table 2-2 and the analysis shows the way that they changed as the population aged.

Table 2-2 Weibull Analysis of ETX II Peer Groups

Analysis		Weibull Statistics	
		Characteristic Life	Modulus
July 1991 QB 161 @ 617 QB 177 @ 540		$_{913}\,1714\,^{3218}$	$_{1.6}\,2.7\,^{4.6}$
December 1991 QB 161 @ 828 QB 177 @ 809	Cycles	$_{1538}\,3369\,^{7381}$	$_{1.1}\,1.9\,^{3.1}$
	Hrs	$_{26,000}\,65,000\,^{164,000}$	$_{0.9}\,1.5\,^{2.5}$

Bank 161 is probably the best indicator of the ETX II population as it was involved in the majority of the incidents suffered by the actual battery. This included commissioning, shipping damage, vibration during transport etc. This bank completed 836 electrical cycles before removal from test, having operated at CSPL from 21-Aug-90 to 10-Oct-91. Resistance and capacity behaviour are shown in Figure 2-2.

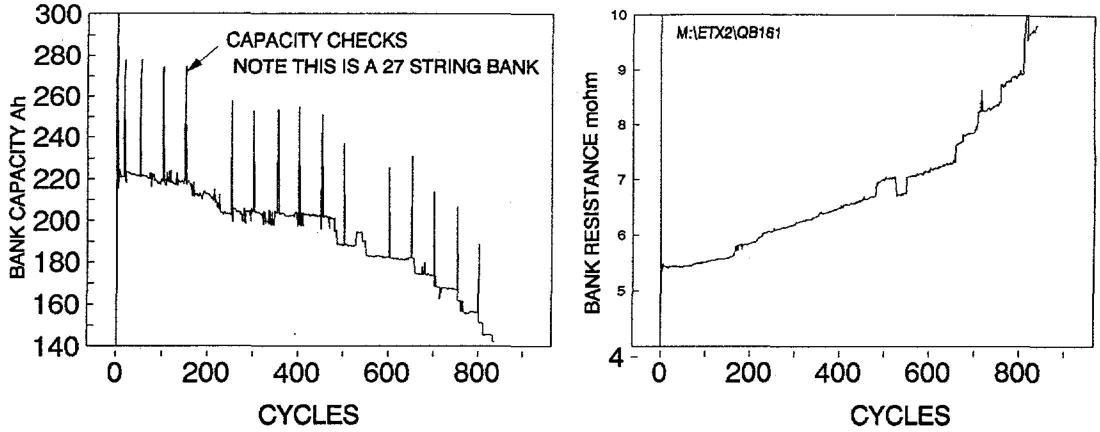


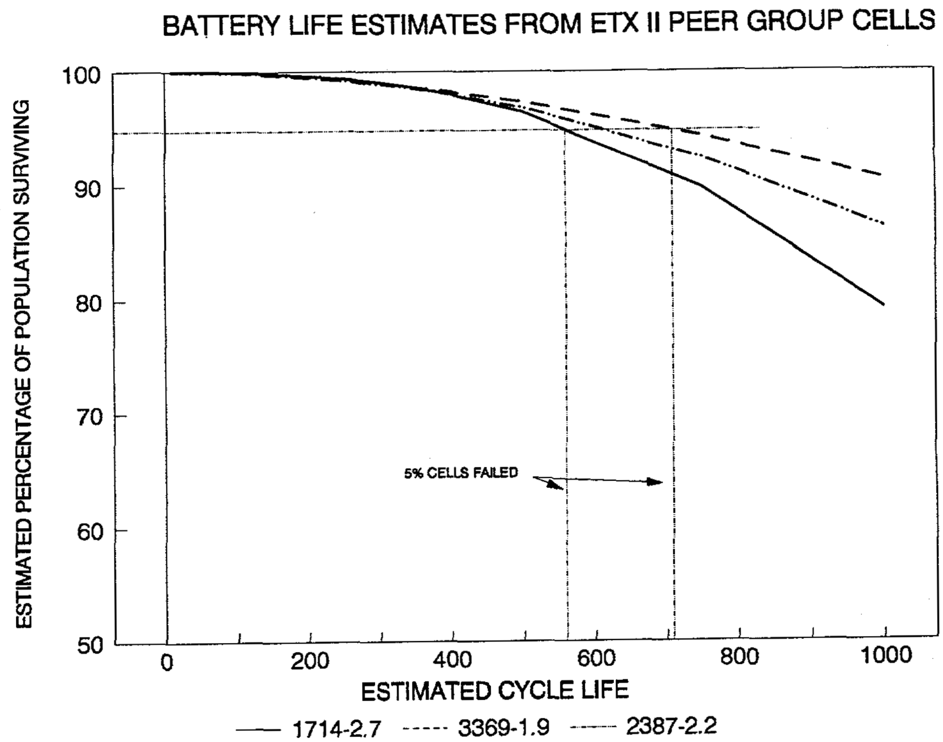
Figure 2-2. Resistance and Capacity - QB 161 (Removed from ETX II on Rebuild)

String failures were observed after 164, 225, 481, 547, 656, 704, 754, 765 and 811 cycles, leaving 18 strings operational at the declared end of life. Analysis of the cycle life data on the bank alone yielded a characteristic life of 2387 cycles (UCL: 5070, LCL: 1124) associated with a shape parameter of 2.16 (UCL: 4.09, LCL: 1.16). At 828 cycles, the bank was providing 145Ah to 8V open circuit (equivalent to 8Ah per operational string) with a resistance of 9.71 m.ohm (equivalent to a cell resistance of 42.2 m.ohm). Based upon an initial bank resistance of 5.5 m.ohm, the resistance rise observed was equivalent to a cell resistance rise of 0.008 m.ohm/cycle. After 800 cycles of test, with 19 operational strings, the bank provided 188.6Ah when discharged to 7.6V open circuit.

The End of life Bank 161 and the two calculations from the 242 cell group are compared in Table 2-3. Note that the sense of the change in characteristic life is always opposite to that of the modulus. Thus in practical terms, the data predicts very similar battery lives as illustrated by Figure 2-3 ie 5% failures at between 560 and 710 cycles. The hours analysis from QB161 is also plotted in the same format and predicts a chronological life of 9000 hours, about 1 year.

Table 2-3 Weibull Estimates of ETX II Peer Groups

Analysis	Characteristic	Modulus
242 Cells July 91	1714	2.7
242 Cells December 91	3369	1.9
Bank 161 EoL	2387	2.2



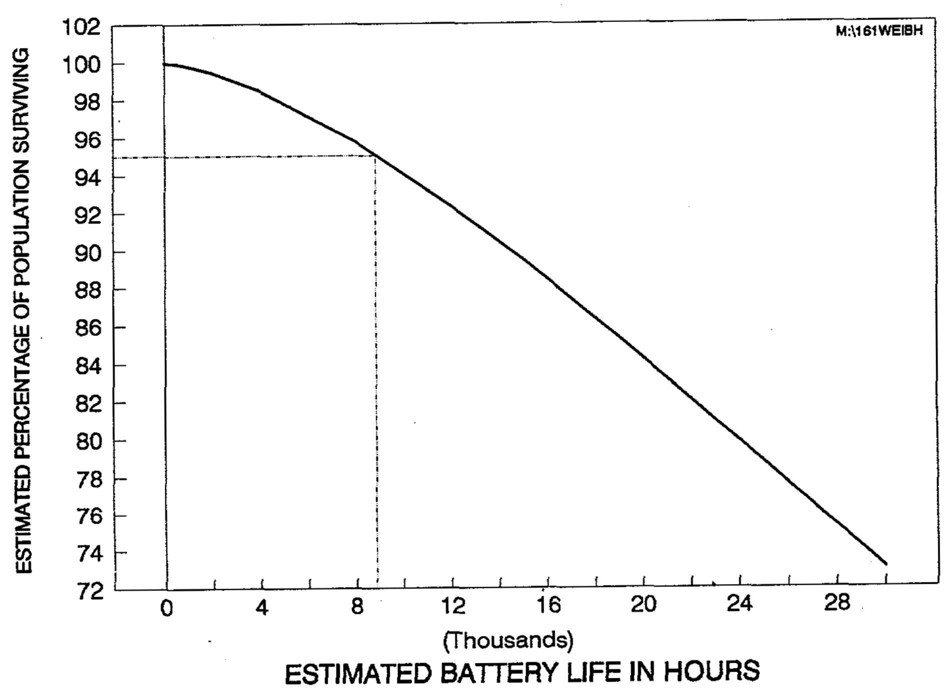


Figure 2-3 Battery Life Prediction for Peer Group Weibull Estimates

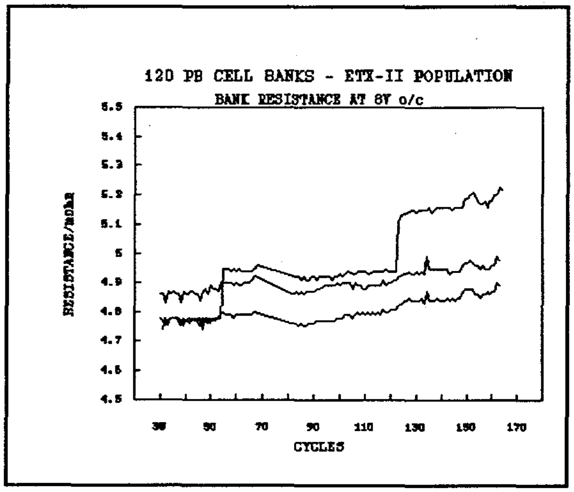
As part of the pre-qualification of banks for the actual ETX II battery, twenty seven 120- cell banks were subjected to 2 electrical conditioning cycles. Twenty four banks were tested in 3 separate groups of 8 banks connected in series. The remainder were later tested individually to provide replacements for 3 banks which had been identified as 'suspect' and excluded from battery construction for the following reasons:

Bank 138 : unstable charge resistance on cycle 2.

Bank 154 : unstable open circuit voltage on cool-down.

Bank 155 : high discharge resistance on cycle 1, but satisfactory performance on cycle 2.

Banks 138, 154 and 155 were connected in series for the first phase of their testing at CSPL.



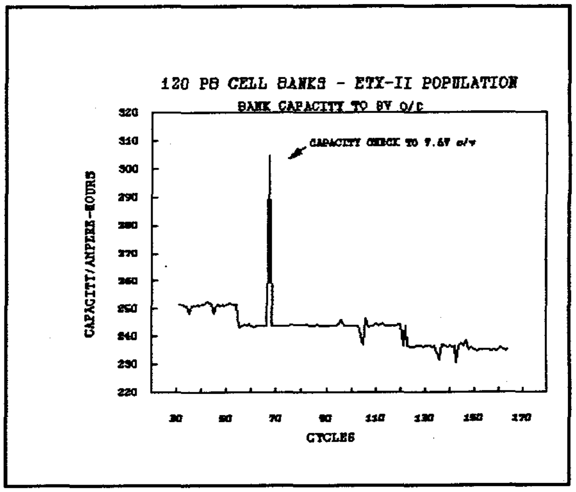


Figure 2-4 Resistance and Capacity - 120-Cell Banks 138, 154 and 155

Bank resistance and capacity behaviour is shown in Figure 2-4 (138 at top, 155 at bottom). Although the resistances of Banks 154 and 155 increased slightly during cycling, there was no evidence of cell failure in these banks at this time. In contrast, 2 cell/string failures were detected in Bank 138, at 55 cycles and 120 cycles. It may be significant that Bank 138 experienced 2 freeze-thaw cycles before testing commenced, whereas Banks 154 and 155 experienced only 1 freeze-thaw cycle.

At 289, cycles the 3 banks were cooled in order to extract Bank 138. The banks were cool for 68 days before testing re-commenced, and at that point, the capacity of the 2 remaining banks connected in series was 235 Ah to 8V open circuit and 296 Ah to 7.6V open circuit. This suggested that two string failures were present in one bank, with one failure probably occurring during the freeze-thaw cycle, as demonstrated by a resistance increase in Bank 155 (see inset in Figure 2-5). No further string failures occurred until cycle 340 was reached, when an accelerated rate of failure was observed, associated with a marked decline in the capacity of the unit. By 353 cycles, the capacity of the 2-bank unit had fallen to 189.6 Ah, and the 2 banks were disconnected for separate testing - Bank 154 continuously and Bank 155 occasionally. Resistance and capacity behaviour for the whole of life for banks 154 and 155 are illustrated in Figure 2-5.

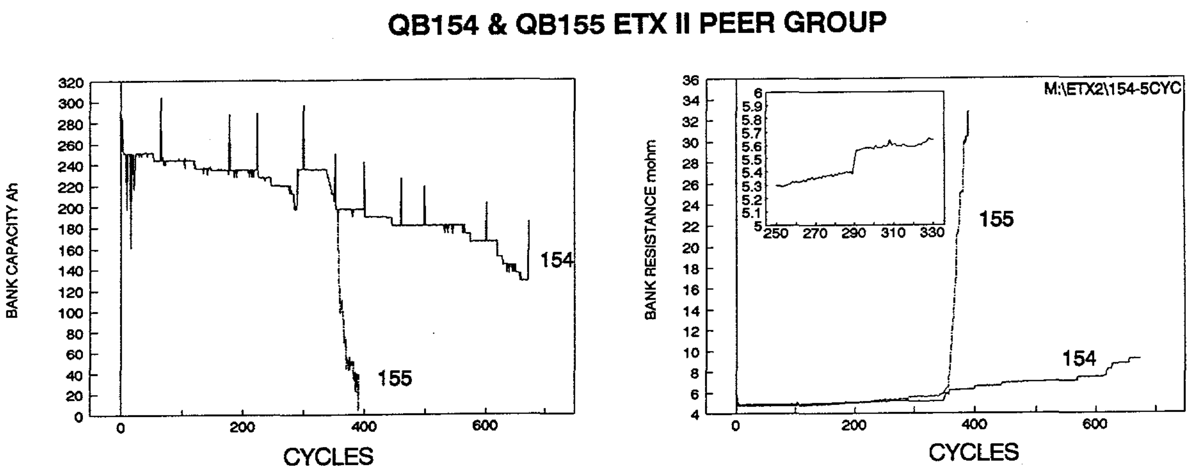


Figure 2-5. Performance of ETX II 154 and 155 Banks During Series Connection

Bank 154 commenced test as a single bank after 353 cycles at a resistance of 6.3 m.ohm and a capacity of 197.2 Ah to 8V open circuit (242 Ah to 7.6V open circuit), suggesting the presence of 6 or 7 failed strings. Further string failures were observed at 401, 445, 565 and 574 cycles, and the bank was providing 166 Ah to 8V open circuit (203 Ah to 7.6V open circuit) after 608 cycles. The resistance of the bank, which by then had 10 or 11 failed strings, had increased to 7.5 m.ohm.

Bank 155 commenced test as a single bank at a resistance of 8.6 m.ohm and a capacity of 128.3 Ah (i.e. almost 50% of strings apparently failed). After that the bank was cycled only at weekly intervals but the resistance increased markedly (to 30 m.ohm) with a corresponding decline in capacity to 40 Ah. The bank completed 387 electrical cycles and, along with Bank 154, was removed for post test analysis.

The change in the rate of cycling is illustrated in Figure 2-6 and in order to make a comparison, the bank capacities are plotted against both cycle life time and chronological life time in Figure 2-7. The rate of resistance rise of the bank due to cell failure is very apparent and the increased failure rate following an incubation period after the freeze thaw cycle is an effect which was confirmed by other testing in parallel programs and led to the introduction of more robust cell design features specifically addressing this issue.

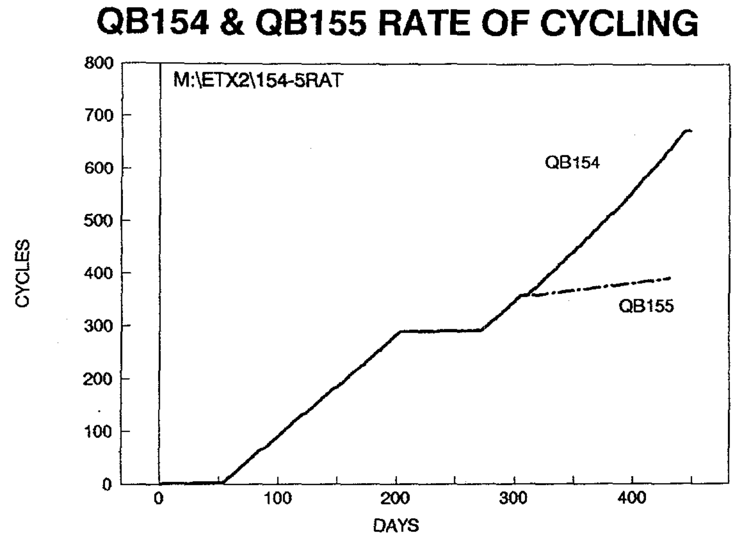


Figure 2-6 Rate of cycling of Banks 154 and 155

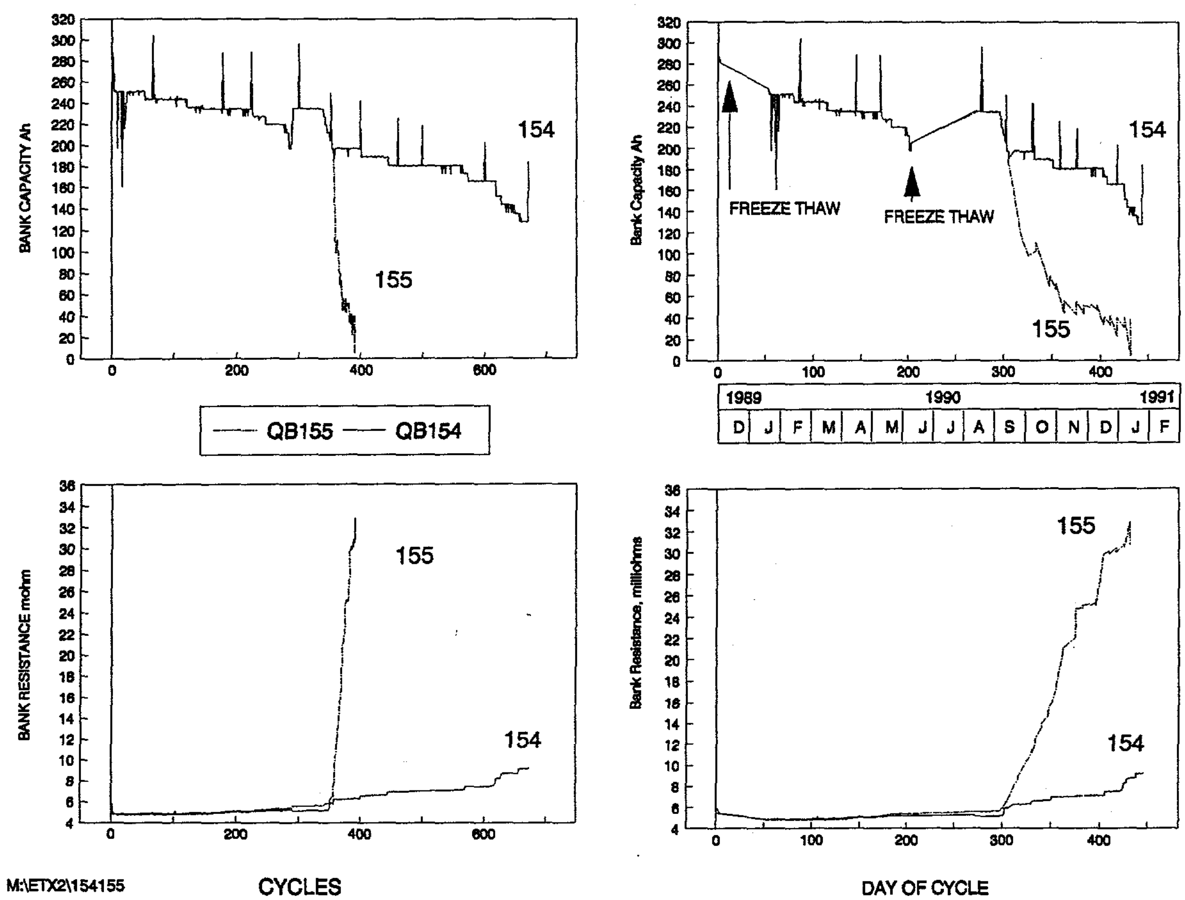


Figure 2-7 Comparison of Capacities and Resistances of Banks 154 and 155 for cycles and chronological time

Summary

As related at the start of this section on testing, much of the information shown was not available at the time of committing to construction and testing of the actual battery. Nevertheless, the available data was sufficient to indicate that a useful life could be obtained from the battery and the program was allowed to proceed to the testing phase. The mature peer group data was available for the subsequent ETX IIs program and the findings were acted upon for that design.

2.2.2 Module Hardware

Only a small amount of module hardware development was conducted in the initial part of the contract as the designs utilised were those developed previously in an internal CSPL program for a Bedford CF Electric van battery. An outline of the actual design is given in the Final Design section of this report.

2.2.3 Module-bus System

The module bus system was based on the "Armadillo" concept developed in the internal CSPL program. A full description is also given in the Final Design section.

2.2.4 Thermal Systems Development

The control of the battery temperature is of primary importance when designing a battery to operate efficiently. If the battery temperature is low this results in high initial resistance whilst if the battery temperature is high this effects its life. The generally accepted operating range for the battery is 320°C to 380°C and CSPL chose to operate with a minimum temperature of 330°C and a target maximum of 370°C. Testing of other CSPL batteries during the initial part of the contract demonstrated the importance of thermal uniformity within the cell matrix since, if the variation in temperature throughout the battery was high, a large proportion of the available operating temperature range was lost. Conversely, an even temperature distribution meant that the average battery temperature could be close to the minimum. Calculations showed that for some of the designs, lower initial operating temperature would allow the deletion of the active battery cooling system.

The thermal response of the ETX II battery was mathematically modelled as an aid in developing an effective thermal management system. The calculation of rate of heat generation as a function of discharge profile, temperature and state of charge was based on results obtained from cells and test banks. The analytical model used related to the performance of a single average string within the battery and modelled the string behaviour during discharge and charge. Values for thermal capacity based on the location of the individual cells, (end or centre), thermal conductivity within the string and at its vertical extremities, and heat generation were all derived from test results or theoretical analysis. The maximum battery temperature at the start of discharge was taken as 330°C and the model took into account the variation of cell resistance with temperature. All the analysis was carried out assuming the cells were discharged to the equivalent of 1.9 Voc and delivered 10 Ah, corresponding to 80% of the theoretical capacity. The general assumptions about the thermal properties of the cell and ETX II battery are shown in Table 2-4.

Table 2-4 Assumed Properties for Thermal Analysis

Vertical thermal conductivity	3 W/m°K
Enclosure insulation value	0.009 W/m°K
Cell Thermal Capacity	150 Joules/°K
Case Thermal Capacity (per end cell)	60 Joules/°K
Intermediate Cooling Rate	1000 W/m^2
Maximum Cooling Rate	3000 W/m^2

The rate of heat generation per cell during a 35 kW constant power discharge is shown in Figure 2-8 where the effect of reduction in cell resistance as the cells increased in temperature was taken into account. The curves clearly show the effect of the initial higher cell resistance, the reducing resistance as the cells heated up and the effect of entropy as the cells became discharged.

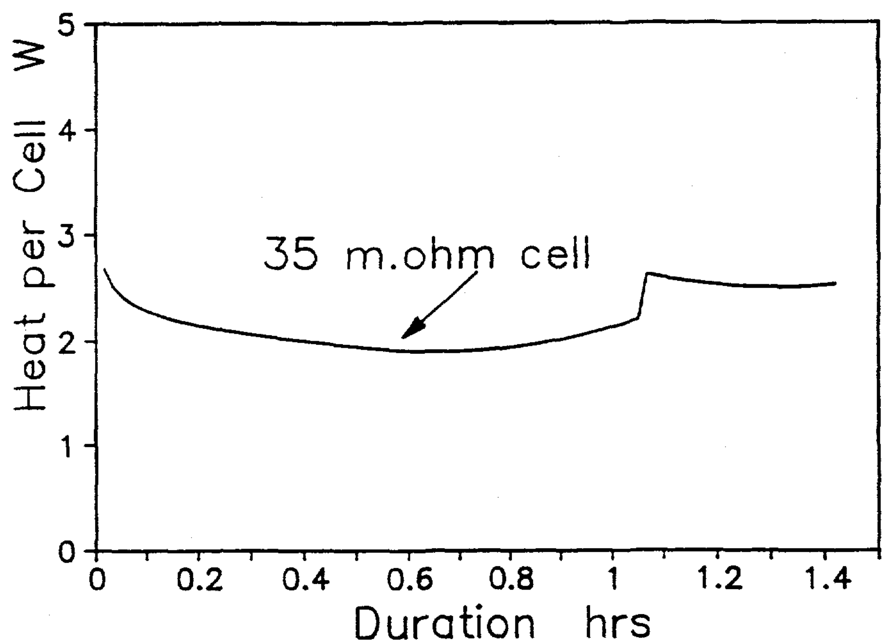


Figure 2-8. Heat Generation per Cell During 35 kW Discharge

As can be seen from Figure 2-9, the calculated temperature rises during the 35 kW discharge to a predicted value of 390°C without cooling and this could have caused significant reduction in battery life. The effect of cooling is shown in Figures 2-10 and 2-11, where the effectiveness of the plenum cooling chambers can be clearly seen (see section 2.2.4.2). An intermediate cooling rate did promote as great a temperature variability throughout the battery as the maximum cooling rate, though the maximum temperatures were higher. The effect of the thermal isolation of the centre cells was clearly shown on the cooled batteries where temperature variations of up to 20°C were predicted. In practice, since the hot and cold cells in the string were in series, the temperature variation in the vertical direction would not have contributed to current imbalance within the battery. An element of self-compensation was also present, where the hotter cells in the string generated less heat than the cooler ones. In all the cooling simulations, the cooling was initiated when the temperature reached 340°C. This reduced the heat removal rate required and minimised the temperature differences within the string. One of the objectives for constructing and testing the Intermediate Deliverable Battery was to determine the cooling philosophy for the ETX II and subsequent batteries, and to define the bounds under which active cooling would be necessary.

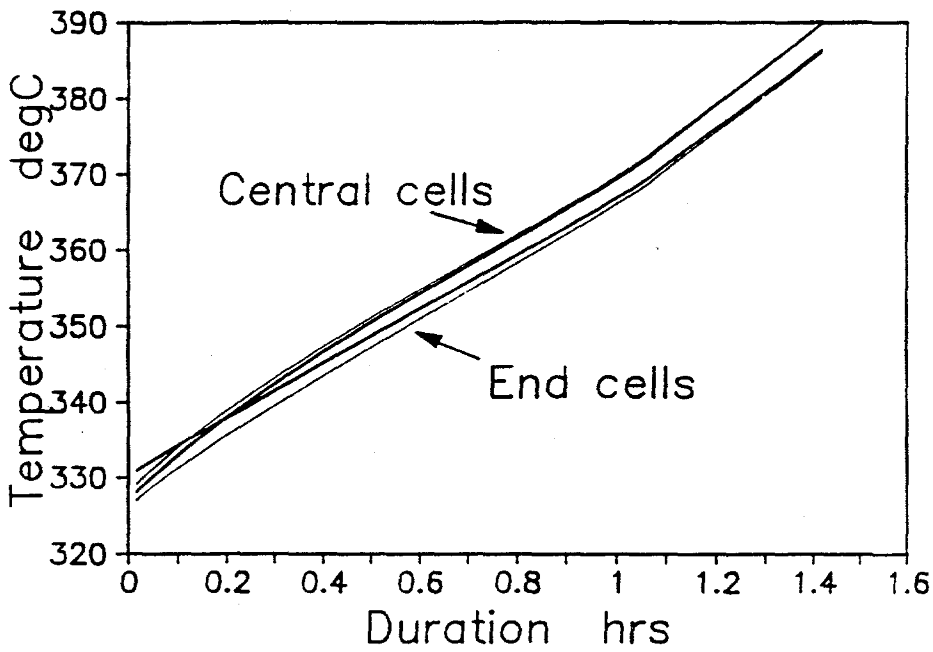


Figure 2-9. 35 kW Discharge, no cooling

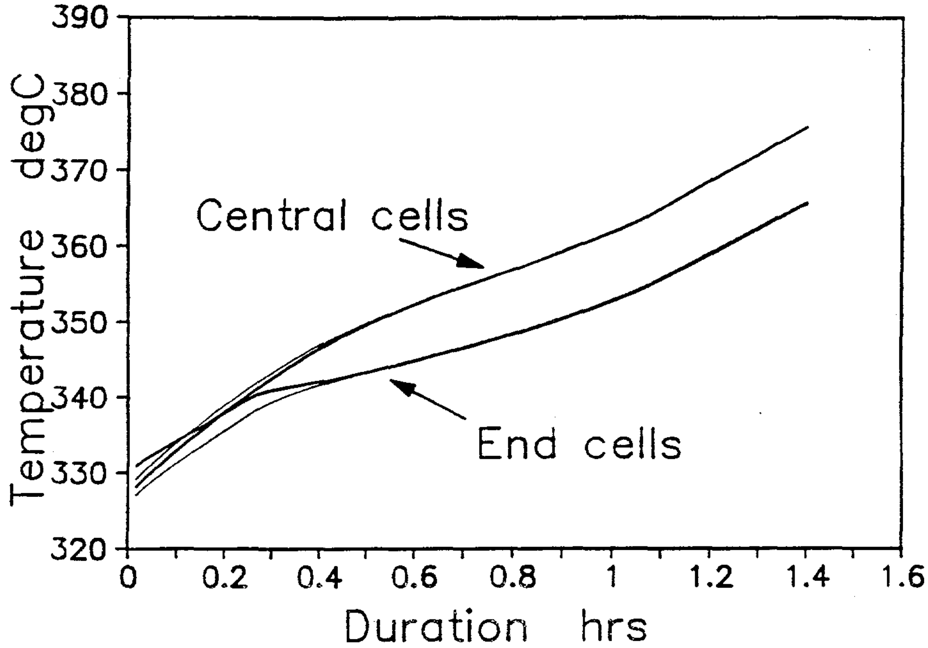


Figure 2-10. 35 kW Discharge, intermediate cooling

Comparable figures for discharge under the SFUDS cycle showed that the heat generation was less and that the temperature rise lower. The predicted thermal performance during SFUDS, with no battery cooling, is shown in Figure 2-12. The maximum predicted temperature was 368°C.

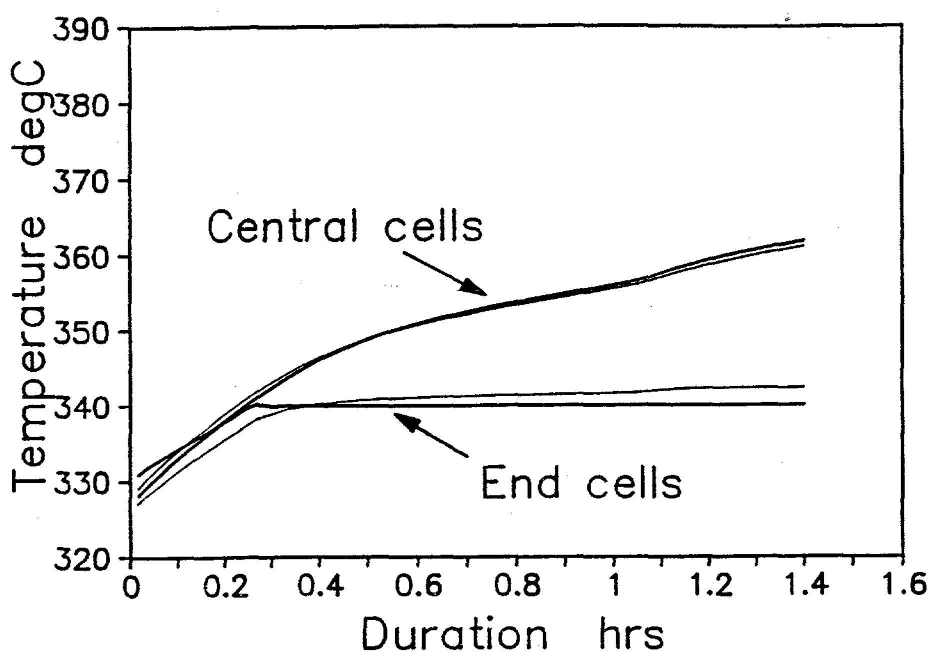


Figure 2-11. 35 kW Discharge, maximum cooling

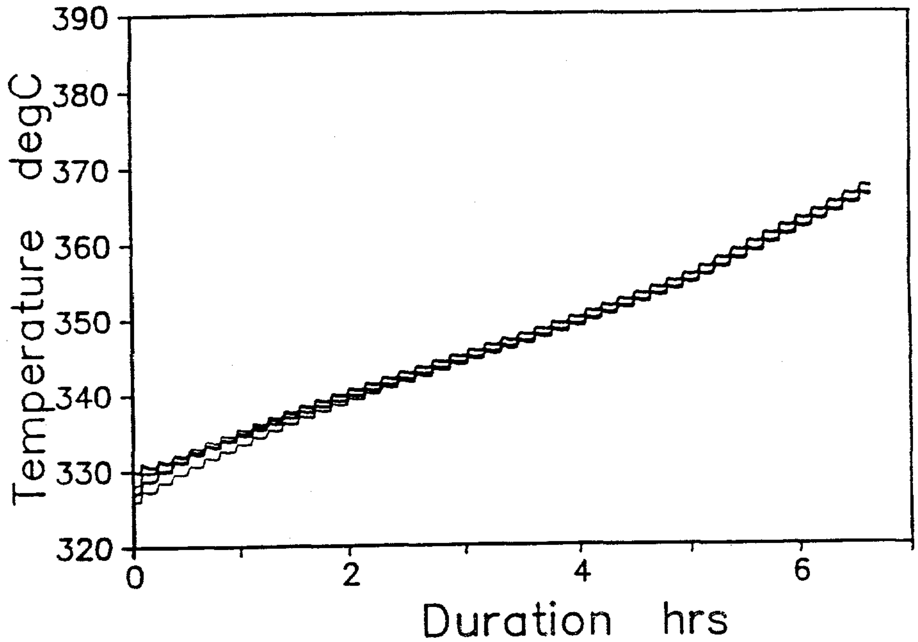


Figure 2-12. Predicted Temperature Rise During FUDS Cycling, no Cooling

The operating temperature specification for the ETX II battery was reduced as the program advanced because early tests with the Mk2A cells had shown a reduction in cell reliability and cell life at higher temperatures. The temperature targets for ETX II battery operation were revised downwards therefore, with the heaters set to maintain an initial temperature of 330°C. The target maximum temperature during discharge was 365°C, with a horizontal temperature variation throughout the battery of no more than 10°C. Test banks had been operated by CSPL at over 500°C for short periods. In practice, the temperature distribution target, with the isolated air cooling philosophy, was a difficult one and could not be met with the design proposed. Temperature distribution across each bank was predicted to be less than 10°C and no problems with current sharing were anticipated.

2.2.4.1 Battery Heating System

Extended Heater Plate

Previous designs of heating system for the battery had been manufactured from a 6 mm thick aluminium plate with the heater elements recessed into the plate. The plate would only provide heat to the base of the battery. To compensate for heat losses associated with battery terminals and instrumentation leads, the heater plate design was modified to extend up the side of the battery at the ends.

Testing of this design of heater plate was carried out using the same battery as used for the interbank conductor tests (see Section 2.2.4.3). For this test, the thermal insulation assembly was improved to reduce losses at the corners of the battery. The results showed the variation in temperature between the top and bottom cells in each string was between 15°C and 20°C, reflecting the low vertical thermal conductivity of the battery, though the overall temperature variation between the hottest and coldest cell was reduced to 27°C.

Global Heater Element

For the ETX II battery the aluminium heater plate arrangement was modified to overcome some of its disadvantages that had been revealed. The problems with using aluminium heater plates were first identified after the June 1988 design review when it was requested that a study be carried out to identify ways of reducing the weight of the ETX II battery. One recommendation of this study was that the 35 kg of aluminium could be saved by attaching the heater element to the inner container. A second advantage of attaching the heater element to the inner enclosure is that heat can be applied to all 6 faces of the battery. Therefore the ETX II battery was designed with independent heaters attached to the top, the bottom and sides of the inner container to give more control of battery temperature uniformity. Testing of this heater arrangement was used to confirm thermal analysis.

2.2.4.2 Battery Cooling System

General Principles

A number of forms of active cooling were considered including phase change materials to store excess heat, switching heat pipes which change from a thermally insulating to thermally conducting mode of operation over a 5°C input temperature change, and air cooling. Of these, air cooling appeared to be the most attractive in the short term because heat exchanger techniques of this type were well known. Nevertheless, the other two temperature management concepts were extremely attractive for long term production designs.

CSPL considered a number of different air-cooling based systems. Eventually the use of sealed plenum chambers located immediately above and below the banks was selected. Direct air cooling of the cells was not considered as attractive because of concerns with undesirable gas product release in the event of seal failures. The thermal conductivity of the cells in the vertical direction was such that, with a top and bottom plenum chamber, temperature variations between the centre cells and the outside cells without vertical thermal conductivity enhancement could be as much as 30°C under conditions of continuous 35 kW output. Such a temperature difference could be supported because the cells were in series and unequal current sharing as a result of temperature variability between strings would not have occurred.

The test apparatus illustrated in Figure 2-13 was developed to evaluate plenum cooling options. This rig was designed to have the same thermal properties as the battery (i.e. vertical thermal conductivity 1 W/m°K, thermal capacity 0.7 J/gram/°C) and was capable of generating 2500 W internally in a model of one third of the ETX II battery.

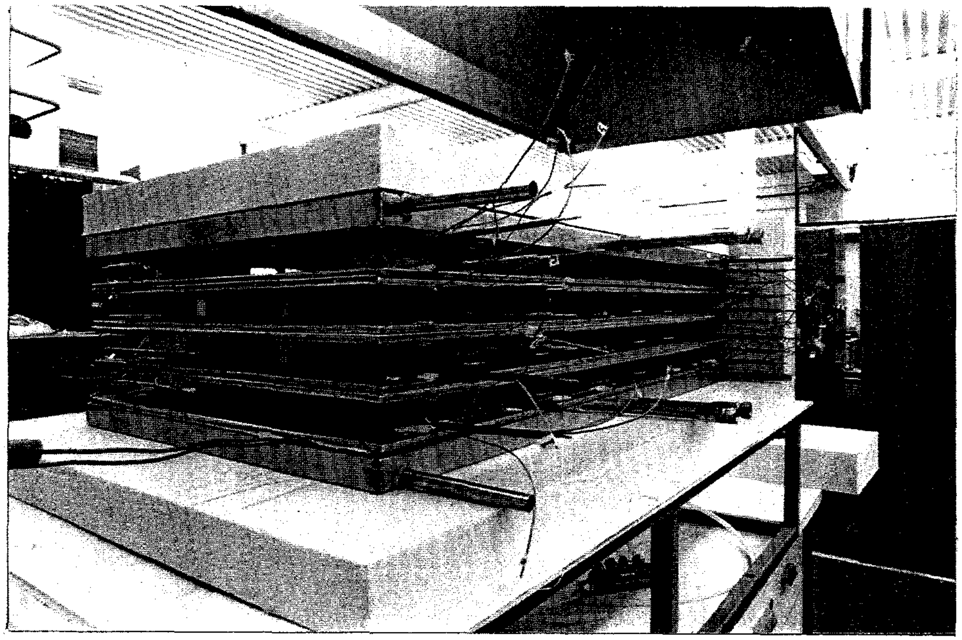
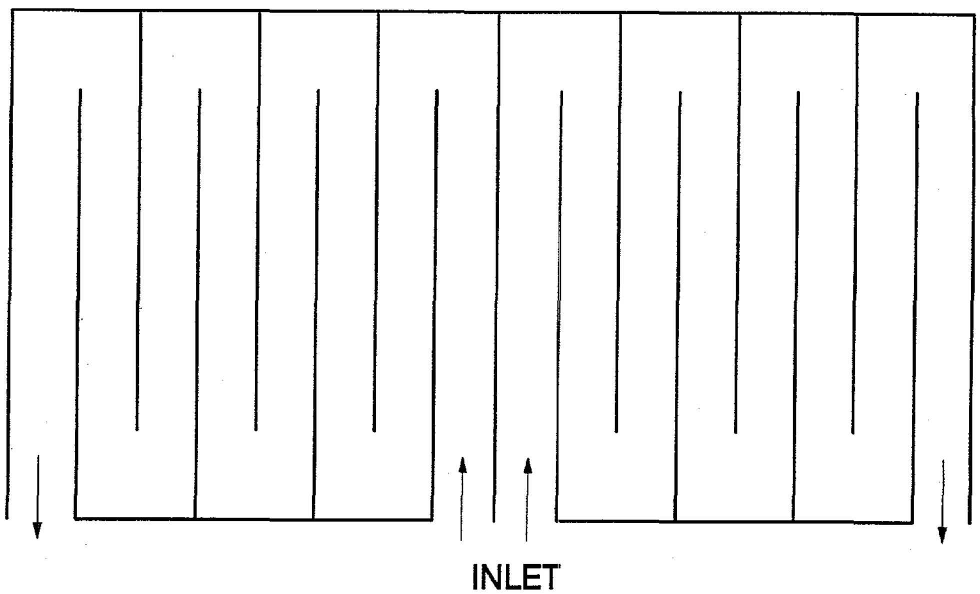


Figure 2-13. Photograph of Plenum Test Rig

The rig was manufactured from 8, 6-mm thick stainless steel plates with each plate having two heater elements attached. At least 5 thermocouples were attached to each plate, with the top and bottom plates of the model had 15 thermocouples attached. The plates were grouped into two's representing each layer of cells. The stainless steel plates were separated by 32 blocks of aluminum which gave the rig an effective thermal conductivity of 1 W/m°K. The rig was assembled with an arrangement of electrical insulation above and below the stainless steel plate stack similar to that used in the batteries and also included the base heater plate. The rig was surrounded by Microtherm insulation 50 mm thick top and bottom and 100 mm thick on each side.

Single Pass Plenum Test Results

First, a simple, single pass plenum was constructed. Without any heating at the point of air entry, the stainless steel plate temperature fell to 240°C which was unacceptable for a sodium sulfur cell. The temperature in the centre of the model showed little change when the cooling was applied. Figure 2-14 shows the ducting layout and the base plate temperature profile.



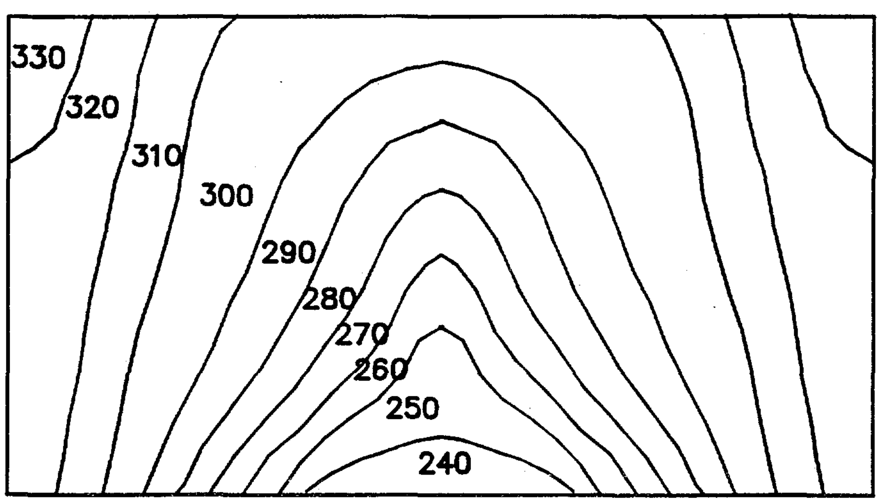
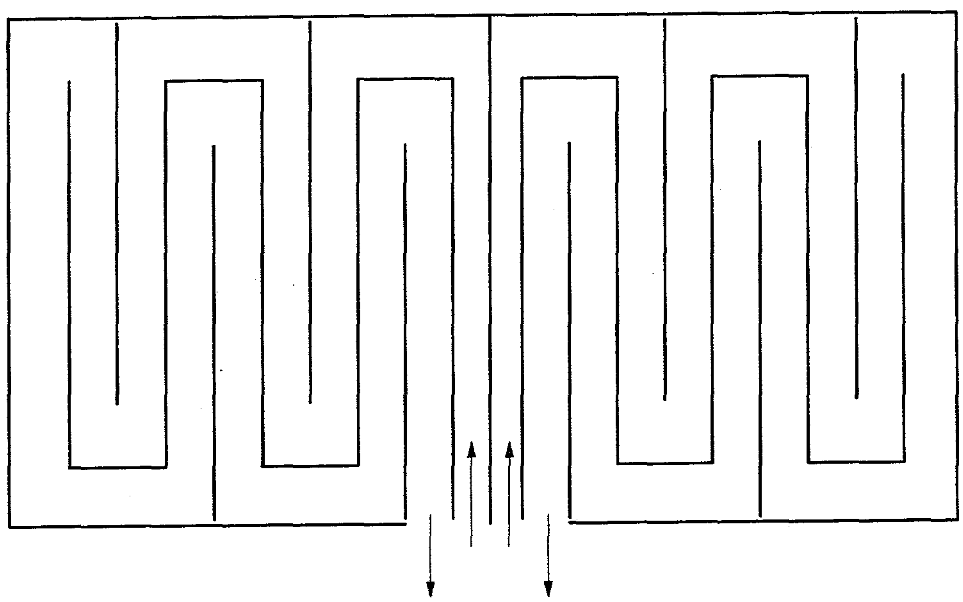


Figure 2-14. Single Pass Design Base Plate Temperatures

Re-entrant Plenum Test Results

This design used the air exiting the plenum to pre-heat the inlet air. This tended to reduce the effectiveness of the plenums at removing heat but the temperature was increased around the inlet ports to above 280°C (dependent on flow rate). Figure 2-15 shows the ducting layout and the temperature profile for the re-entrant design baseplate.



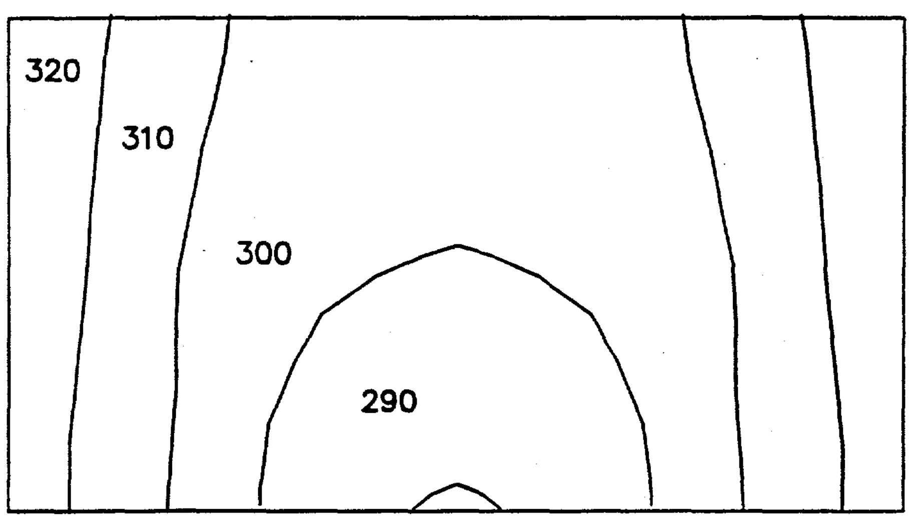


Figure 2-15. Re-entrant Design Base Plate Temperatures

Central Input Plenum Test Results

This design fed air to the centre of the plate at the hottest point in the battery. The air exiting the plenum tended to spread the heat from the centre to the edge where the outlet was located. Figure 2-16 shows the ducting layout and the temperature profile of the base plate.

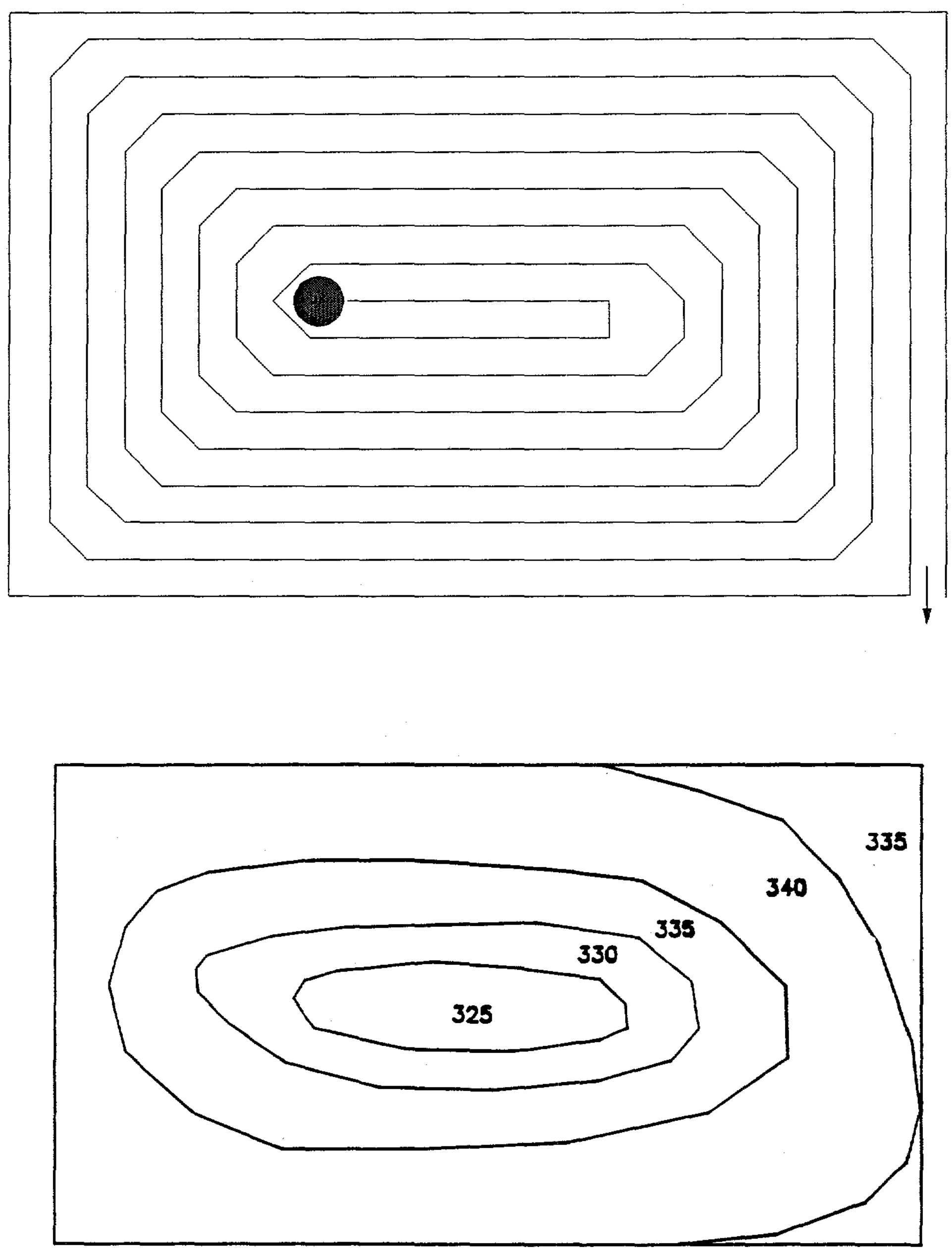


Figure 2-16. Central Input Design Base Plate Temperatures

Conclusions

A summary of the analytical results is presented in Table 2-5. The smallest temperature variation of 21°C was recorded using the central input plenum design. Testing at various flow rates and heat generation rates showed the design to be far more effective than the re-entrant design at removing heat and gave an 11°C reduction in base temperature variation. Although the reduction in overall temperature variation (difference between central temperature in the model and base temperature at the air inlet) was 43°C, this was due to the low vertical thermal conductivity of the model. A higher battery vertical thermal conductivity reduced this value significantly.

Table 2-5. Comparison of Cooling Plenum Results

	Single Pass Plenum	Re-entrant Plenum	Central Input Plenum
Temperature Variation over Base-plate	85°C	32°C	21°C
Overall Temperature Variation	93°C	61°C	43°C
Heat Generated in Model	1800 W	1800 W	1800 W
Air-flow rate per Plenum	100 l/min	100 l/min	100 l/min

2.2.4.3 Battery Thermal Uniformity

Initial battery tests identified the vertical thermal conductivity to be of the order of 1 W/m°K. The effects of this low conductivity could be seen in the poor cooling and temperature uniformity. In order to improve the thermal conductivity of the battery several design options were studied.

Thermal Conductivity

The first design study looked at the reasons for the poor thermal conductivity of cell strings. The conclusion of the study was that the thermal contact resistance associated with the cells and the cell separators was the major contributing factor. To improve thermal contact, cell strings could have been mechanically loaded via the busbar plates but this idea was rejected on the grounds that the forces required would have damaged the cells.

A second study looked into different materials to manufacture the cell separators and in particular the trilobe shaped spacers, used to separate 4-cell strings. Although some materials were identified (eg vitreous enamelled steel) but cost constraints, weight penalties and manufacturing difficulties ruled out their use.

Interbank Conductors

The third design approach was based on fitting material of high thermal conductivity between the banks. These experiments were carried on seven 120 cell banks as shown in Figure 2-17, with the battery open circuit but with the primary base heater active.

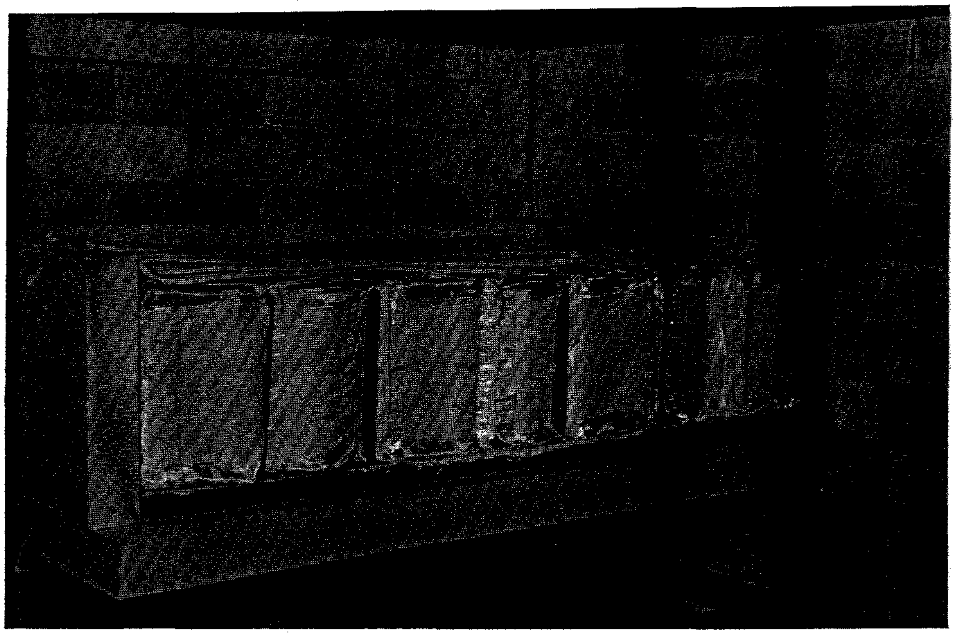


Figure 2-17. Assembled Battery in Test Bunker

The two readily available materials compatible with the battery and which have high thermal conductivity were copper, (nickel plated to minimise corrosion) and graphite. Both of these materials were tested on the seven bank battery. Three banks were wrapped in nickel plated copper (0.8 mm thick) and four banks were wrapped in graphite (2 mm thick). The arrangement of graphite and copper increased the effective thermal conductivity of the battery to 3.5 W/m°K. Each bank was fitted with 12 thermocouples to monitor the battery temperature.

The results of this test showed that the variation in temperature between the top and bottom cells in each string was between 7°C and 10°C and that the overall temperature variation between the hottest and the coldest cell was 38°C. Although a large portion of this 38°C variation was due to problems with the fit between adjacent insulation panels, heat losses associated with the thermocouple leads contributed to the higher than expected temperature variation. Ultimately, the concept was discarded because the thermal performance did not justify the high technical risk associated with having electrical conductor in such close proximity to the ends of each bank plate. A further constraint was the increase in overall battery length associated with the increased bank spacing.

Thermal Conduction Rods

In order to overcome the penalties associated with the interbank conductors with respect to battery length, it was decided to develop conduction rods capable of fitting within the banks. These are shown schematically in Figure 2-18.

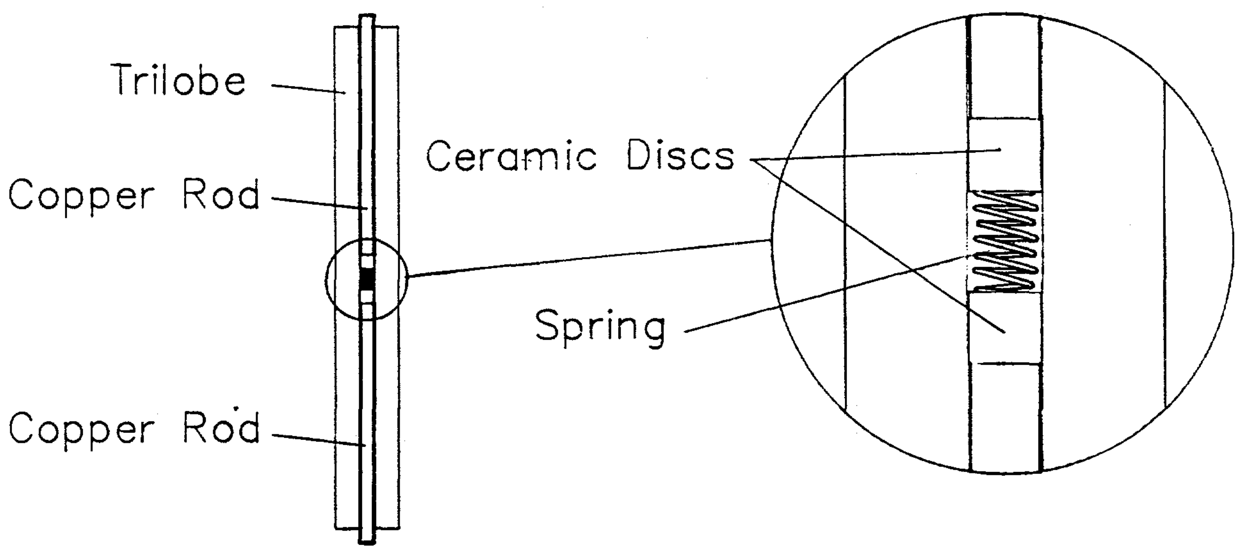


Figure 2-18. Thermal Conduction Rods

An 840 cell, 7-bank battery, containing the rod conductors, was completed and tested. This battery was used to calibrate the thermal analysis model which predicted a top to bottom string temperature variation of 10°C. Following these trials the concept was employed in the ETX II Battery build.

2.2.4.4 Thermal Enclosure

Thermal Insulation Development

Excellent results were obtained from a number of fibreglass-based insulations. Their performance was measured using an in-house thermal conductivity rig. The development was not advanced enough to employ these insulations in ETX II. Development of the insulations into a suitable load bearing form without seriously effecting their thermal properties still needed more work at that time. In addition, the conductivity of glass fibres was shown to be more pressure dependent than the Microtherm product which was thwe standard at the time. That is small increases in vacuum pressure caused large increases in thermal conductivity. However, the potential of these insulations to reduce losses to below 250 W, combined with their lower weight, meant that their eventual adoption was very attractive.

Thermal Preparation

For the ETX II, Microtherm insulation was used with in the thermal enclosure for the reasons noted above. This was operated in a vacuum at pressures below 0.05 m.bar but in time, due to outgassing from the containers and insulation, the pressure was expected to rise. As the pressure rises to 50 m.bar, the heat losses were predicted to increase from an initial value of 450 W to 500 W. In an attempt to extend the life of the vacuum, trials were carried out on an enclosure which had undergone thermal preparation. This involved heating the enclosure both internally and externally for 24 hours to 175°C to remove all the water vapour trapped in the insulation. Gas absorbing getters fitted within the insulation, and capable of maintaining the vacuum pressure for much longer periods, were tested. The results suggested thermal preparation and the use of gas absorbing materials would extend the life of the enclosure to over 12 months.

2.2.5 Electrical Control and Peripherals

2.2.5.1 Electronic System Design

Introduction

In principle, the battery was be designed for operation in the Ford ETX II vehicle and the electronic system was be based on this premise. Battery testing off the vehicle was considered separately because the discharge and regenerative voltage limitations were set by the vehicle controller itself. The electronic system included the necessary power supplies to drive the electronics and, where necessary, interfaces with the vehicle and the charger took place through appropriate electrical isolation barriers. The system itself contained and supported the thermal monitoring equipment, the heater switching circuits, the by-pass electronics, the cooling system power supply and the cooling fans. The thermal monitor was powered from the 12 V auxiliary system or from the charger cabinet via the heater cables as appropriate. The by-pass electronics were self powered from each individual bank and optical isolation of the output was provided. The cooling system power supply was the full battery voltage with a simple contactor, powered from the 12 V system, to energise the cooling fans.

The control cabinet required a three phase (380V) supply. Internal connections gave some security of heater operation should the main heater phase have become inoperative. The major power drain by the unit was caused by the charger. The main and stand-by heaters were connected to separate phases and had power ratings of 990 watts.

The instrumentation was designed to protect the battery from being accidentally operated in potentially damaging regions of its performance envelope. The systems were designed to be "invisible" during normal battery operation and would not protect the battery from deliberate abuse, though warnings would have been given to the ETX II controller/computer system when any out of limit condition was exceeded. These warnings were given via optically isolated signals to ensure minimal interaction with external control gear.

Battery Charging System

An effort was undertaken to develop an inexpensive , yet effective charger for the ETX II battery. Tests using rectified mains power and high frequency charging systems demonstrated that the CSPL NaS battery technology appeared insensitive to the waveform of the charging current and work was performed to confirm that there were no long term adverse effects. The battery charger supplied was based on a conventional, three phase rectified, lead-acid battery charger with the appropriate modifications to the methodology for terminating charge. The charger delivered a substantially constant current charge until the charge termination point was detected where upon the charger current was reduced for a period of about 30 minutes, following which, it would be disconnected. The charger was rated to recharge the battery within 8 to 10 hours and the nominal charge current was 34 A. Most of the charge was provided at this constant current. The charger also had a pre-set load voltage limit of 230 V, ensuring that, even if other limits failed to operate, the maximum voltage that any cell within the array would see was less than 10 V. The desired maximum is 2.8 V/cell. It would have been necessary to discharge the battery carefully following such a system failure, because the battery would have an abnormally high resistance for the first part of the discharge. The specific details of the charger control are described in the next paragraph.

The voltage across each bank was continuously monitored and, as soon as the first bank reached top of charge as measured by its voltage, charger cut-back was initiated. Charge current would then be reduced and the battery continued to be trickle charged. Bank by-pass electronics limited the maximum voltage which appeared across any bank to a safe level and a timing system was used to terminate charge completely. The principles of bank by-passing and the by-pass circuit are shown in Figure 2-19. The function of the bypass units was to allow current from the main charge to be routed around banks which were at nominal "top of charge" so that others that might have been at a lower state of charge could themselves be fully charged. When the voltage on the bank rose to 8.6V, the device started to pass current, which rose non-linearly to approximately 3 A at the working voltage of 9.0 V. Higher voltages then caused a linear increase in current, limited by the series resistance of the bypass circuit. The bypass device was rated at 6 A by the power dissipation limits of its resistors. Since a short circuit failure in the bypass output transistor would cause a continuous drain on the bank, the circuitry was arranged to open-circuit the bypass devices while the battery is either open circuit or on discharge. In this way a small amount of differential charge was returned to lower capacity banks to keep the whole battery in balance. The bypass devices remained ostensibly open circuit with a nominal drain on the bank of less than 2 mA during most of the battery operation, on both discharge and charge. In practical terms, this current drain had negligible effect on the battery capacity but did, if anything, improve the initial response of the battery to discharge current after charge termination.

In normal circumstances, the amount of battery imbalance was anticipated to be very small because it was assumed that cell reliability would be high and that deterioration of capacity and performance would be gradual. In practice the system was never required as the battery maintained balance throughout its life.

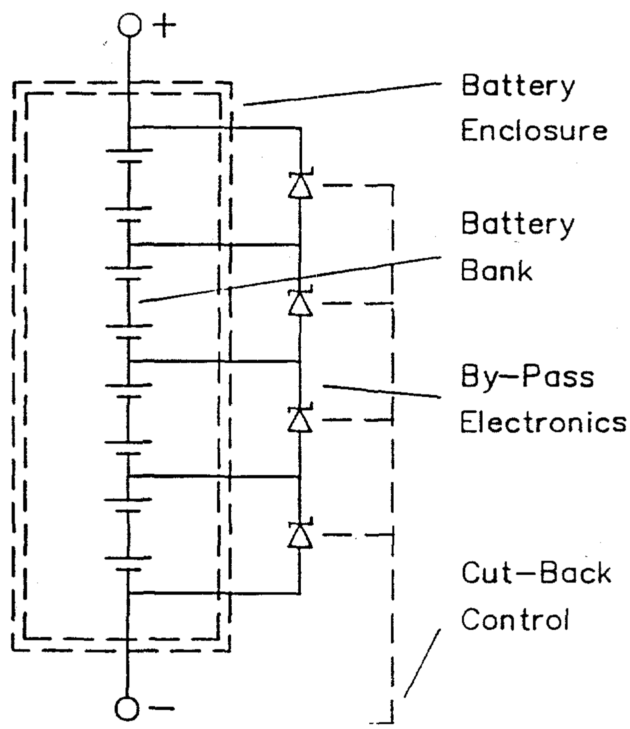


Figure 2-19. Bank By-Passing and By-Pass Electronics for each of 3, 8-bank sections of the ETX II Battery

Battery To Vehicle Interfacing

There were 3 interfaces between the battery system and the vehicle. These were the main power cables which also supplied the charging current, the bank voltage signals and the 12 V power supply for the temperature monitor. The 12 V supply could be disconnected from the vehicle when the charger was plugged in, using a mains powered relay on the battery, energised by the heater supply cables.

The Ford vehicle system controller was designed to accept detailed information from the battery via an RS 232 interface. Rather than carry out an internal development program on such a system, CSPL purchased and adapted a general purpose interfacing unit to meet this requirement. The information that the battery controller needed to send to the vehicle was limited to the cutback signals for charge (regenerative braking), discharge and over-temperature. A production sodium sulfur battery would not necessarily need such a sophisticated unit for this purpose and CSPL would normally have supplied a simpler system.

The interfacing between the three main systems i.e. vehicle, battery and charger is shown in Figure 2-20.

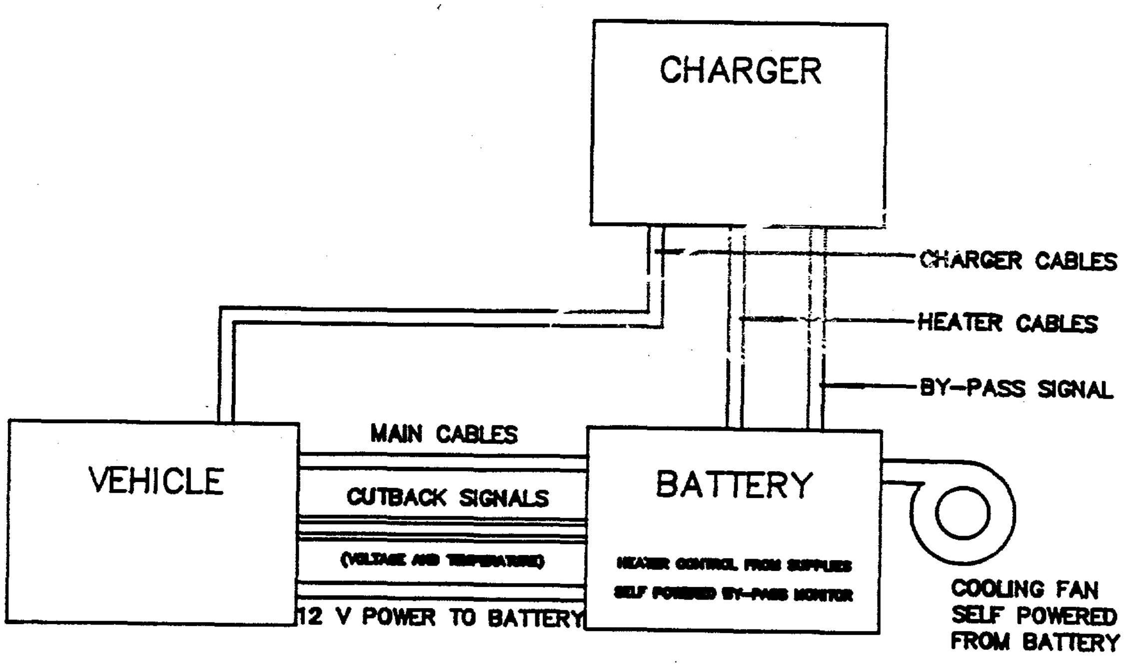


Figure 2-20. Vehicle, Battery and Charger Interfacing

Battery To Charger Interfacing

Three separate interfaces were required between the battery and charger: the charger cables, the heater cables and the by-pass signalling cables. In principle, the heating could have been carried out using the DC supply, making the heater cables as a separate entity, redundant. In practice, the charging and heating systems was considered separately because under some circumstances, the charger was disconnected from the battery electrically (i.e. when the battery is fully charged it was considered preferable to interrupt the charging current at the charger rather than at the battery). Since the heater switching circuits were located on the battery, it was feasible to use the heater supply cables to provide the power for the thermal monitoring system under these conditions. The charger cables were routed via the vehicle electronics so that the state-of-charge could be deduced in accordance with a CSPL algorithm.

Protection System

The success of this program depended as much on the battery protection systems and vehicle interfacing as it did on the battery design itself. It was not possible to ensure that the vehicle would always be driven in the most carefully monitored fashion and it was essential that the battery system be self protecting against accidental and deliberate abuse. At the design stage, it was unlikely that all possible damaging modes of operation had been foreseen and care was still required to ensure that the battery was adequately protected. A typical abuse which the battery system design was unable to address, for instance, was where the battery is not recharged after use and is left discharged for long periods or allowed to go cold.

The electrical protection system was based on bank voltage. Excessive bank voltage due to either battery charging or regenerative braking, would be signalled to the charger or the vehicle controller as appropriate. A simple option of initiating a hard cut-back and reducing the regenerative current immediately to zero was provided. Reduction of regenerative power to zero in this fashion would be unacceptable in a production vehicle and alternative electronic systems were considered. Ideally, the regenerative current could be adjusted to maintain the individual bank voltage to its maximum level while gradually reducing the current. In practice, the characteristics of the sodium sulfur cell made it unlikely that excessive regenerative voltage was seen because, under normal circumstances, the capacity withdrawn during discharge was more than the capacity returned during regenerative braking. The adverse situation described could only have arisen if the vehicle, when fully charged, was allowed to regenerate down a hill. This is a practical possibility in production EV's and the ETX II was not designed to absorb energy under these conditions.

The over-discharge protection was based on bank voltage which protected an equivalent bank open circuit voltage level of 7.5 V. The circuit operated by multiplexing the bank voltages in turn to an analog multiplication circuit which performed the calculation

$$V_{oc} = V_l + IR$$

The calculation assumed that the bank resistances were approximately equal and resistance values were preset on initial test. The limit of 7.5 V was chosen so that testing could be performed to the normal termination conditions of 7.6 V equivalent, without interference from the protection electronics. This system operated at zero battery current, in which case the trip voltage was be independent of bank resistance. Low voltage sensed by the unit sent several warnings to the vehicle controller though the actual time interval before final shutdown warning was governed by the number of banks displaying over-discharge conditions. Some flexibility was provided to override this shutdown temporarily, provided that the protection electronics was assured (by an external controller system) that over-discharge was intentional. This would allow the testing to continue should the battery be high resistance on initial discharge or if one bank had an anomalous resistance.

Thermal Control

It was assumed that the only time the test battery would be disconnected from the charger was during discharge. Thus, no features were included to make it possible for the battery to stand for long periods of time away from a charger, relying on its own internal energy to maintain temperature. The battery heating system was therefore powered via the charger and the temperature maintained in accordance with signals from the temperature measuring systems within the battery. Battery cooling was operational only while the battery was being discharged and was not enabled as the temperature rose but switched on in response to a battery temperature high signal.

The ETX II battery had a total of eight separate thermal controllers, three for the main heaters, three for the backup heaters, one for the cooling system and one over-temperature controller. In all cases, battery temperature sensing was by means of thermocouples and two sets of control thermocouples were used. One group of three thermocouples was used as the main temperature control, the second independent group acted as standby. The temperature was averaged between these thermocouples by passive components and this provided the input for each controller. The over- temperature controller thermocouples were positioned in the most likely hot zone of the battery and, in the event of the battery temperature reaching 400°C, the temperature controller was arranged to request emergency shut-down to the vehicle controller.

The thermal controller utilised proprietary equipment supplied by "Eurotherm" Ltd. The two independent heating systems, the "main" and the "standby", differed only in the positioning of their control thermocouples and their electrical interlocks. Each temperature controller also controlled temperature on a programmable "ramp" allowing either to be used to give a controlled warm-up or cool-down. Each controller was connected to its own heater in the battery via separate thyristor power regulator units. The primary and stand-by heaters were of the same power and were sufficient to keep the battery warm independently. The primary and stand-by controllers were set to operate at different control temperatures, with the "standby" temperature setting being lower than the "main" temperature setting. This ensured that, if there was a failure in the main control system, the standby controller would maintain the temperature at a low but operational temperature. The main and standby heater systems were powered from separate phases to protect the battery from the effects of a single phase failure.

The main and standby heater control over-temperature limits were also interlocked to both heater supplies, preventing accidental overheating of the battery if either output thyristor pack malfunctioned. A further interlock was provided by the reserve heater controller which, if under-temperature was detected, would disable the fan and prevent accidental overcooling.

A third controller, was set to operate when the battery temperature exceeded a pre-set value, is used for the cooling fan. The fan was also activated if either of the heater control systems gave an alarm over-temperature, to act as a backup for the fan controller. When the fan was activated, the main heater system was inhibited to prevent interactions between the heater controls and the cooling control. The cooling fan contactor was interlocked with the main heater supply so that the main heater did not try to compensate for the cooling. The backup heater was not interlocked with the cooling system but, since the control temperature of this was set lower than that of the main heater, interaction between the backup heater and the cooling system was not anticipated.

The final part of the temperature control system was a simple over-temperature detector, with alarm. This was independently powered by a small rechargeable power supply and would operate in the event of a general power failure, open circuiting the battery from all heaters and possibly the load or charger system. It also provided a loud audible alarm, regardless of the power supply availability.

State-of-charge Measurement

Measurement of state-of-charge of the sodium sulfur battery is particularly straightforward since the faradaic efficiency is 100%. During the lifetime of the vehicle however, the state-of-charge gauge must be updated in response to gradual deterioration of capacity of the battery. The following proposal was adopted for the initial trials of state-of-charge gauge measuring systems.

The state-of-charge was defined as zero when the open circuit voltage of the lowest capacity bank reached 7.6V (ie 1.9 V/cell). When this occurred, the state-of-charge gauge was re-set to zero and discharge cut-back was initiated. When the battery was new and charged, the state-of-charge gauge responded to the Ah returned and was set to read 100%. As the battery aged and capacity decreased, the state-of-charge gauge, which was updated at bottom of discharge, read less than 100% at top-of-charge. The state-of-charge gauge also displayed that the battery had been fully charged. In this way it was intended that the driver was provided with an accurate and continuously updated statement of the true battery capacity and would not be misled into attempting longer journeys than were actually possible.

2.2.6 Component Qualification

2.2.6.1 Intermediate Deliverable Battery Design

A battery, called the Intermediate Deliverable Battery (IDB), was designed and fabricated midway through the ETX II phase of this contract for two purposes. Firstly it was to qualify many of the individual component developments. Secondly it was intended to prove the conceptual feasibility of the ETX II design. Its features were established as a result of discussion and collaboration with SNL and Ford. It was desirable to make the battery a reasonable portion the complete design and one third was eventually selected. The standard bank or 'monobloc' being developed by CSPL at the time consisted of 30, 4-cell series strings connected top and bottom by mild steel bus plates. Initially, 7 banks of 120 cells were specified, but when the design of the ETX II was more firm, this was changed to 8 banks so that it represented one third of the 24 in the design.

Electrically, the battery consisted of 960 cells arranged to deliver 300 Ah at 56 volts. The working capacity was set at 80% DoD (250 Ah). The design was similar to the ETX II proposed design for bank configuration (with the exception of thermal conduction rods), electrical performance, thermal performance and electronic systems; it differed in insulation system and protection electronics. The salient dimensions were as follows:

Overall length	1340 mm
Overall width	660 mm
Overall height	375 mm
Insulation thickness	60 mm
Cooling Plenums (total thickness)	40 mm (2 @ 20mm)
Weight	309 kg

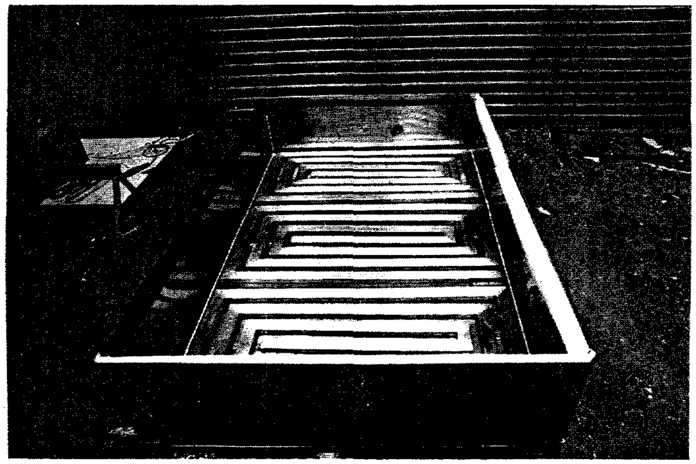
Cooling plenums were provided on the top and bottom plan areas. They were designed to remove 1500 W from the battery and were refined with the aid of lumped mass analytical models and a physical model.

2.2.6.2 Battery Build

Manufacture of the cells for the IDB was completed in November 1988. The cells were manually shim welded into 4 cell strings prior to bank assembly. Assembly of the IDB is illustrated in Figure 2-21. The construction of the side bus-plates was new at the time and has come to be known as the armadillo construction. This method of construction was originally scoped in April 1988. Thermal enclosure development was not sufficiently advanced for the desired double skin vacuum method to be employed and thicker conventional insulation was substituted. This enabled a simple removable lid to be used.

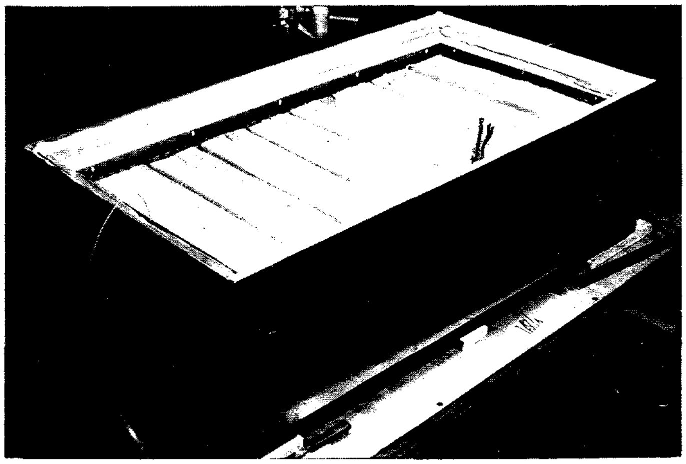
In common with all batteries built with the armadillo busplate construction, the bottom busplate - sideplate welds were made with the modules inverted. The sub-assemblies were then sequentially loaded into the inner-outer box assembly for final side-busplate welding. Figure 2-21 illustrates this process being undertaken. The insulation boards were made from Microtherm encased in sheaths of fibreglass and were placed in the space between the inner and outer boxes.

Naked Bank Assembly



Enclosure with Cooling Plenum

Welding of Bus-side Plates



Battery before placement of Top Lid

Figure 2-21 Battery Build - Intermediate Deliverable

2.2.6.3 Battery Evaluation

The battery was dispatched to Argonne National Laboratory in January 1989. The results of the testing have been reported elsewhere by De Luca et al[2] but are summarised in Figure 2-22 which covers the first 220 of 237 cycles. At the time, the battery achieved the highest specific energy of all the technologies tested by ANL. A weight of 232 kg was employed for the calculations based on a projected ETX II battery weight of 696 kg. The actual weight of the IDB was 309 kg.

ANL conducted a comprehensive series of tests which included the following:

- verification of rated capacity
- Available energy v. constant power discharge rate
- Available peak power v. depth of discharge
- Self discharge losses v. stand time
- Sustained hill climb capability
- Projected ranges for various vehicles and driving schedules

The reliability of this battery, as measured by its capacity history, is shown in Figure 2-22 for the first 220 of an eventual 237 cycles. Its electrical performance is summarised in Table 2-6 as projected range.

Table 2-6 Summary of ANL Simulated Vehicle Range Results

Driving Schedule	**SFUDS 79**	**J227aD**	**J227aC**
Vehicle	IDSEP	ETV-1	G-VAN
Assumed Battery Weight kg	695	488	1180
Av Speed, mph	19	28.3	15.1
Peak Power, W/kg	79	48	36
Av Power, W/kg	9.9	12.0	7.3
Projected Range (miles)	**148**	**182**	**135**

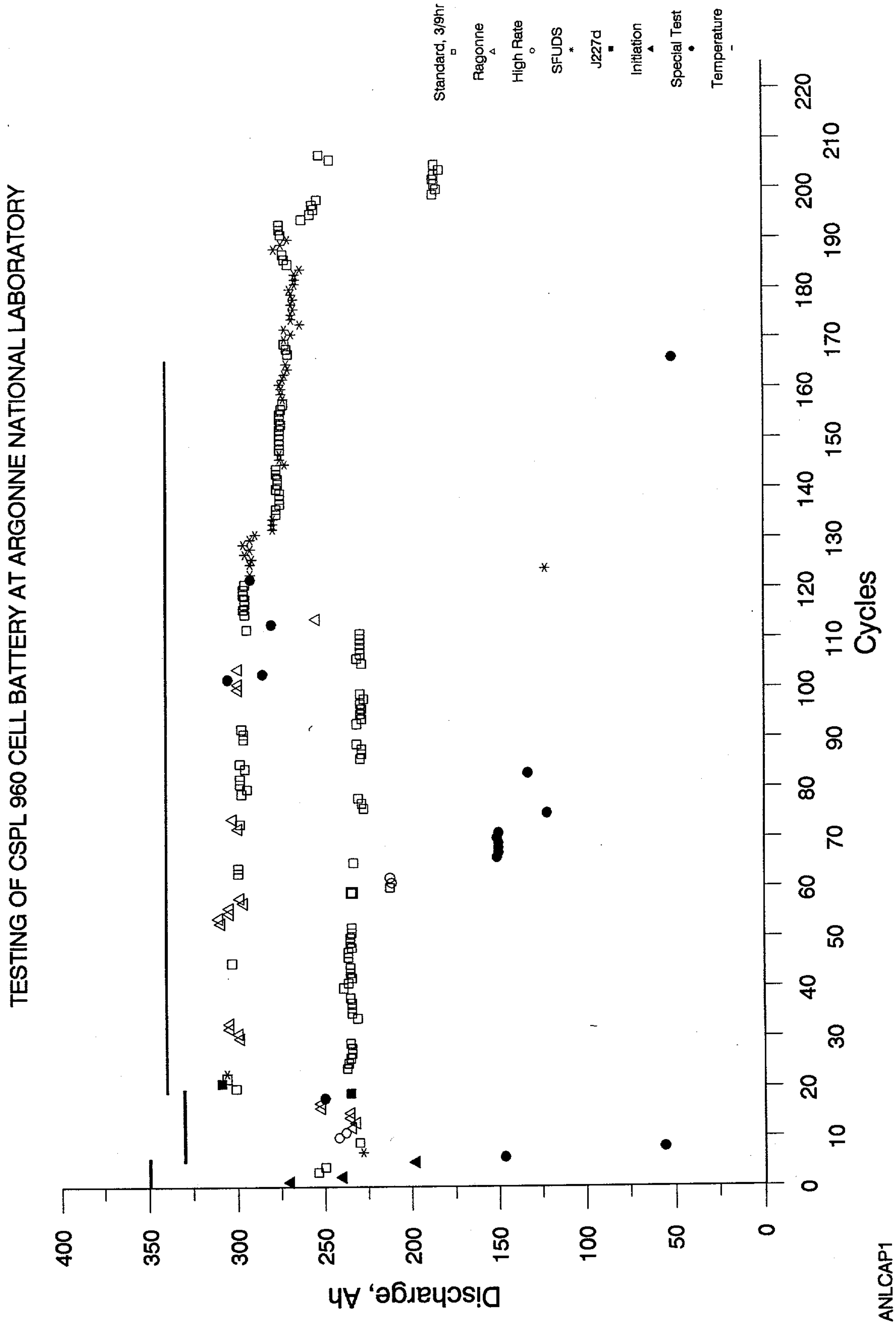


Figure 2-22 Discharge Capacity - Intermediate Deliverable Battery

Although the battery life was reduced by the quality of the cells (refer to Section 2.1), the unit nevertheless achieved its original design life and provided a confidence boost for the technology in this first independent test of a NaS battery. The range values computed by ANL were between 2 and 3.5 times those of the contemporary lead-acid figures and well in advance of the competing technologies at the time.

The life obtained from the IDB was higher than that predicted by the peer group cell testing data (section 2.1). The battery network and the statistical data were used to compute the probability that about 240 cycles would have been achieved. Using the most likely estimate of characteristic life and modulus (500,2.5), a battery of 960 cells in 8 x 120 banks would only be expected to have a life of 200 cycles even at the 2% probability level (ie 2 batteries in every 100). This suggests that the data from the peer group cells was biased low.

Post test analysis of the battery was conducted both at ANL and CSPL. The capacity loss had been 92Ah and Bank 3 was believed to be limiting the capacity of the battery. After strip-down, the cells were radiographed. The radiographic information is summarised in Table 2-7 and diagrammatically in Figures 2-23 and 2-24. The failures include those detected whilst the battery was operating and those which occurred during cool down.

Table 2-7. Distribution of Cell Failures in IDB

Bank Number	No. of Failed Strings	No. of Failed Cells	LOCATION OF CELL FAILURES Cell 1*	Cell 2	Cell 3	Cell 4**
1	7	8	4	2	2	0
2	7	9	4	4	0	1
3	8	9	2	5	2	0
4	8	8	4	2	2	0
5	1	1	1	0	0	1
6	8	9	5	0	3	1
7	3	4	1	0	2	1
8	2	3	1	1	0	1
TOTAL	**44**	**51**	**22**	**14**	**11**	**4**
% OF TOTAL			**43**	**27.5**	**21.5**	**8**

* Base Cell ** Top Cell

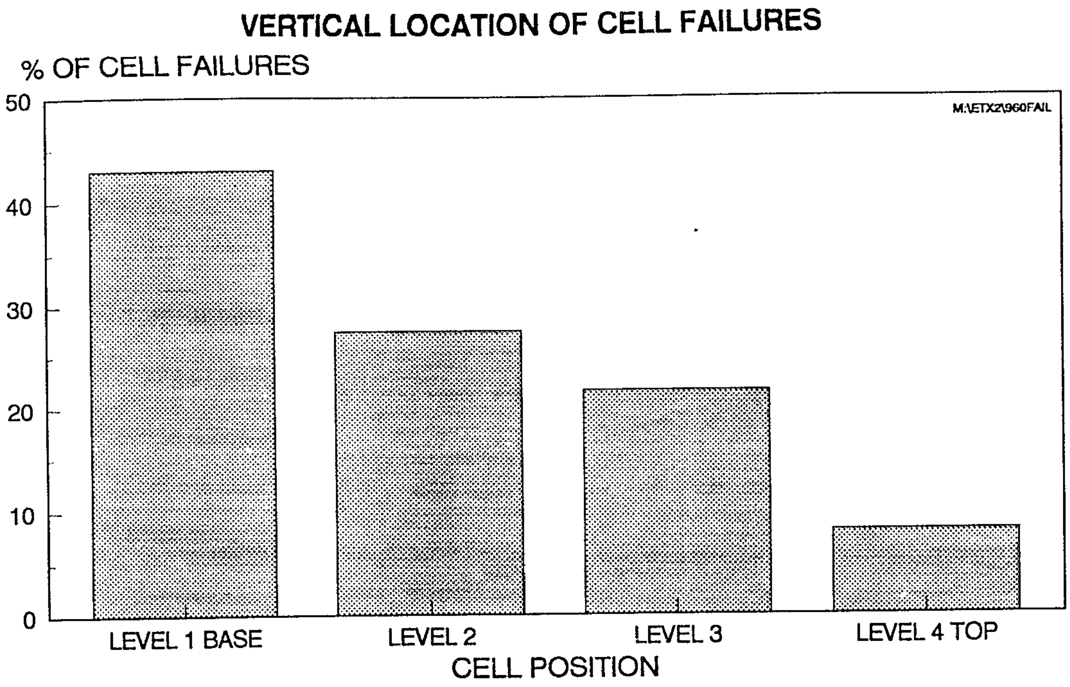


Figure 2-23 Location of Cell Failures - IDB

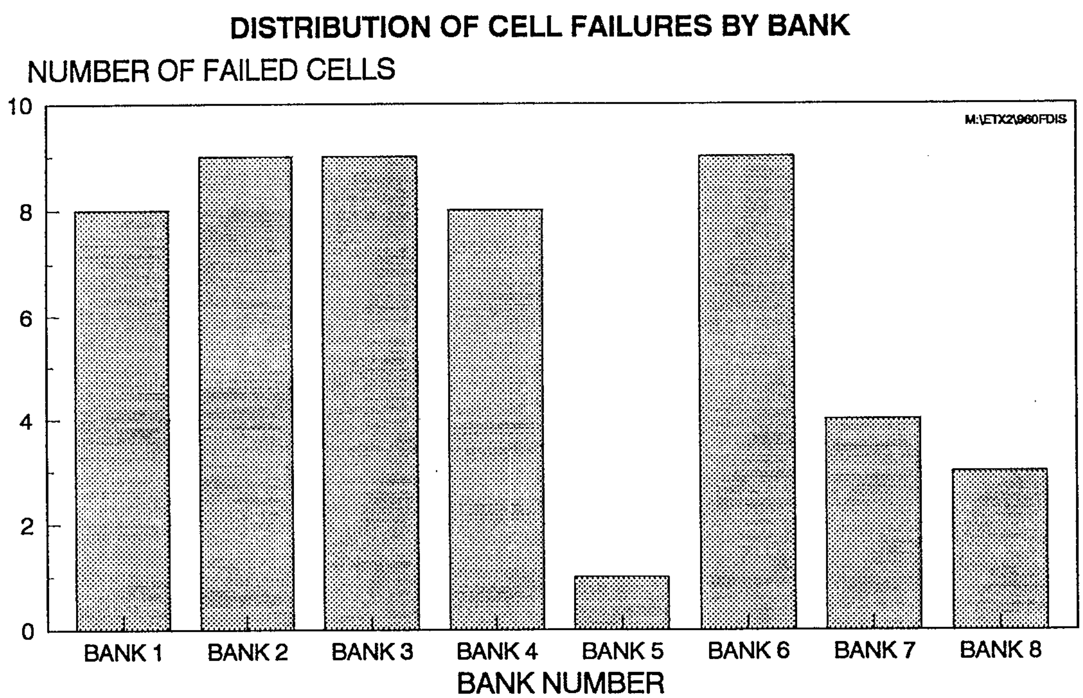


Figure 2-24. Distribution of Cell Failures - IDB

Major observations from post test radiography were as follows:

(a) Almost all cell failures were associated with the glass seal, consistent with the failure mode observed on other cells of the same generation.

(b) The distribution of cell failures was not random, but appeared to be temperature and position dependent.

(c) The majority of the cell failures (43%) occurred in cells situated at the base of strings (Figure 2-23), as compared with 8% of failures in cells situated at the top of strings. Possible sources of the increased failure rate were the higher temperature of base cells due to their proximity to the heater plate or an increased level of mechanical stress owing to the weight of the other 3 cells in the string. The latter reason is not likely as the ceramic spacers were specifically designed to prevent such loadings from occurring.

(d) There appeared to be a lower incidence of cell failure in banks which were located close to the battery terminations and leadthroughs (Banks 7 and 8), the coolest part of the battery (Figure 2-24).

(e) Six banks included strings with 2 cell failures and in 5 instances, the failures were observed in adjacent cells.

Conclusions

The Intermediate Deliverable Battery served its purpose in demonstrating that the NaS technology was capable of creating a battery system that could be delivered for outside testing and provide meaningful data. The constructional features of the battery were translated to the full size ETX II battery. Although heating was demonstrated to be unnecessary it was included in the initial design of the ETX II battery.

2.3 ETX II BATTERY - FINAL DESIGNS

It is important to note that the final design of the ETX II Battery which formed the primary deliverable of this contract consisted of two iterations. The battery was contained in a single box as illustrated in the artists concept Figure 2-25. The illustration depicts many of the components to be discussed in this section. It was delivered to Ford for initial testing. This battery was damaged in transit and only limited testing was performed before it was shipped back to CSPL for repair. At this time it was decided to capitalise on the considerable experience that had been acquired and to re-package the battery in three separate thermal enclosures, and also to dispense with active cooling. Almost identical battery internals were employed although one 120-cell bank was removed and replaced. To effect this change, the battery enclosure was dismantled and three new enclosures were built. Into each, an array of 8, 120-cell banks was placed.

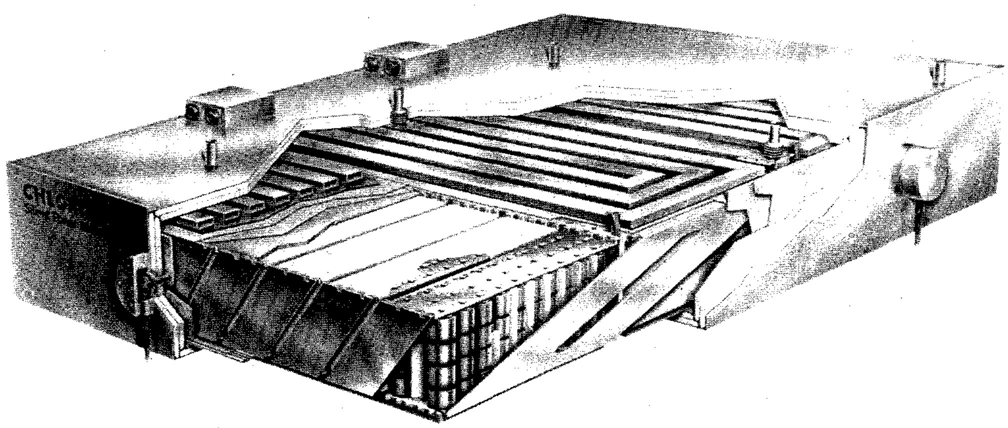


Figure 2-25 Artists Sketch of the First Single Box ETX II Battery Design

2.3.1 Mechanical Design

2.3.1.1 String Design

The basic building block of the 120-cell banks was the four-cell series string (Figure 2-25a). Each cell case was electrically insulated from the next by a cordierite spacer.

The electrical connection between cells was provided by a nickel shim, spot welded to the sodium seal washer of the lower cell and to the outer case of the upper cell. Each spot weld was electrically checked against a standard as it was made and any welds which did not meet an acceptable standard were rejected. In practice, multiple welding at each joint was used and this cell interconnection was an exceptionally reliable feature of the battery system design. The shim was designed to be collapsible to prevent the possibility of shock loadings being transmitted through the shims to the cell seals.

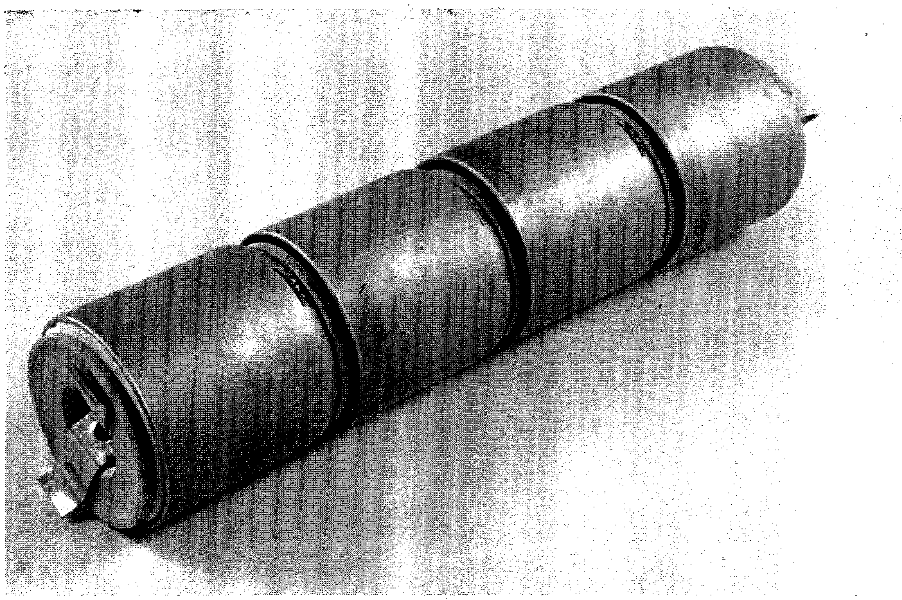


Figure 2-25a. Four-Cell String

2.3.1.2. Bank Design

The bank design adopted for the Intermediate Deliverable and ETX II batteries consisted of 30, 4 cell strings, arranged in a 3 x 10 matrix, connected in parallel. A typical bank is shown in Figure 2-26. The strings were electrically connected by the upper and lower busbar plates, which were manufactured from 2 mm thick mild steel. The top and bottom cells in each string were connected to the busplates by nickel shims which were spot welded to the plate. Cells were prevented from electrically touching at points other than the positive and negative string terminations by an insulated separator called a trilobe, manufactured from cordierite. The trilobe also provided a high degree of mechanical support for the cell strings within the bank.

The top and bottom busbar plates were mechanically connected by five bolts arranged in a 'W' along the length of the plates. The bolts were electrically insulated from each plate.

The tolerances associated with the four cell string led to a variations in string length as large as 2.75 mm. In order to ensure each string fits accurately between the top and bottom busbar plates, packing rings were used to take up the variations in height. The packing rings were manufactured from glass fibre felt. This component was also designed to provide some protection to the cells from shock loads during road trials.

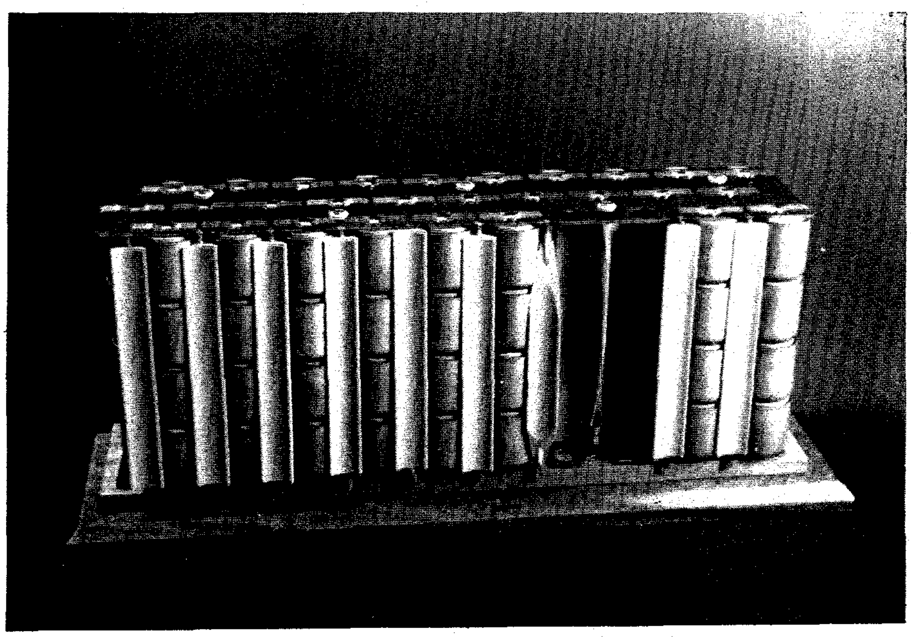


Figure 2-26. 120 Cell Bank

2.3.1.3. Bank Interconnection

The batteries themselves were built from a series array of banks, with the top plate of one bank being connected with the bottom plate of the next. Bank interconnection was achieved via side plates manufactured from 2 mm thick mild steel, connecting banks from top to bottom along their short edges. Mechanically, this arrangement was robust and contributed to the rigidity of the complete bank structure. This arrangement was also relatively easy to manufacture and assemble. It is shown in Figure 2-27.

This method of interconnection had a number of advantages, associated with the prevention of cross contamination between banks in case of cell leakage. In previous designs, bank interconnection was carried out within the cell matrix via insulated aluminium rods, which proved very difficult to electrically isolate in the unlikely event of a cell breach. This could result in soft electrical shorts between banks. The side plate design allowed a much better isolation system to be adopted, reducing the possibility of such current leakage even if cells did leak. The side plate design was adopted for the Intermediate Deliverable Battery. The design was taken a stage further in the ETX II battery where, instead of welding the side plates to the lower busbar plate, they are were an integral part of it. Each side plate was welded to the upper bank plate by five spot welds.

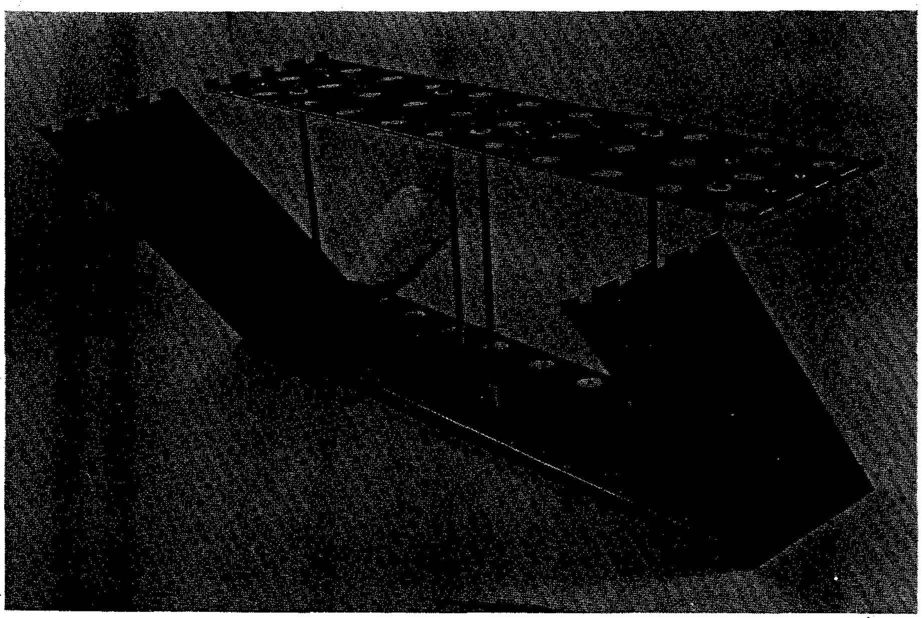


Figure 2-27 Bank Side Plates

After assembly, the banks were wrapped in a layer of glass fibre cloth, intended to absorb the reactants in the event of a cell do. The glass fibre also provided the first layer of electrical insulation. A wrapped bank is shown in Figure 2-28.

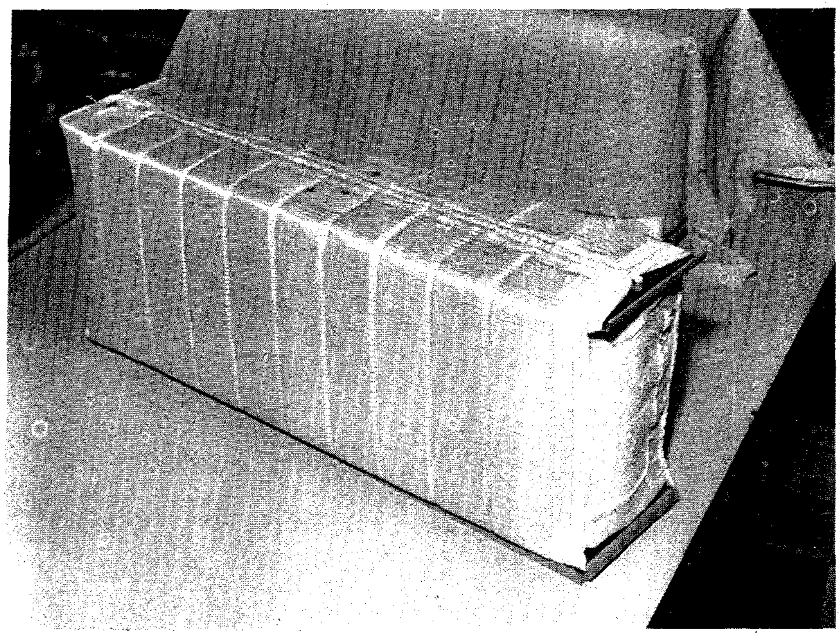


Figure 2-28. Bank Wrapped in Glass Fibre Cloth

2.3.1.4. Battery Internals

The space available in the ETX II vehicle, combined with the electrical requirements, resulted in an arrangement of 24 banks grouped in three rows of 8. Each row of 8 banks was interconnected by an end plate manufactured from 2 mm thick mild steel. The end plate formed an integral part of the lower bus plate of the end bank and was spot welded to the upper busbar plate of the adjacent rows end bank.

Considerable effort was used to ensure electrical isolation would be maintained over the life of the battery. Electrical insulation consisting of 2 layers of 6 mm thick Duratec insulation (compressed calcium aluminium silicate) and 3 layers of 1 mm thick filamic insulation (muscovite mica paper) was placed between each row of 8 banks. On the outside of the banks (long side), another 6 mm thick layer of Duratec insulation was fitted. Surrounding the entire battery core between the outside of the banks and the thermal management system was another layer of 1 mm thick filamic insulation. As well as the glass fibre cloth surrounding the banks, a sheet of Novaflex insulation 0.4 mm thick was used to separate each bank to provide an additional electrical barrier.

2.3.1.5. Battery Terminals

CSPL developed a number of main terminal designs to connect the battery with the vehicle. Early designs, based on spiral weld aluminium rods were technically satisfactory but proved difficult to manufacture and assemble. A straight-through design using stainless steel rod was adopted. The diameter of the rod was 14 mm and the anticipated maximum operating temperature under worst case conditions cannot exceed 700°C. The heat loss during standby conditions and the resistance under normal operating conditions were predicted to be 15-20 W and 0.3 m.ohms per terminal respectively. An important feature of the terminal design was to provide adequate maximum temperature capability. Otherwise, there was a potential danger that thermal runaway would occur under the very heaviest load conditions, leading to failure of the terminal. For this reason, the terminal was sized for maximum rated power.

2.3.1.6. Instrumentation

The battery instrumentation consisted of by-pass leads, voltage monitoring leads and thermocouples. There was one voltage monitor and one by-pass lead associated with each of the 24 banks, plus one voltage monitor attached to both the negative and positive ends of the battery. Each lead was spot welded to opposite ends of each top busbar plate.

The voltage monitors and by-pass leads were identical in design and manufactured in four pieces. First, a short section of stainless steel was welded to a nickel tag which, in turn, was welded to the top of the busbar plate. A length of aluminium (3 mm diameter) was friction welded to the stainless steel to provide a low resistance section. A second length of 3mm stainless steel was used were the lead passed through the thermal enclosure to minimise heat loss. The leads were electrically insulated by two layers of Adhesive Wall Polyolefin (AWP) sleeving. The leads passed between the rows of banks and the enclosure along the top of the duratec insulation. The thermocouples were positioned throughout the battery to provide temperature monitoring for the thermal management system and to provide data on battery temperature uniformity. The thermocouples were located in ceramic tubes adjacent to the cell at various heights in the battery. The tubes electrically insulated the thermocouples without significantly effecting the accuracy of the readings. The thermocouples ran across the top of bank plates then along the top of the duratec sheets to the opening in the enclosure in the same manner as the by-pass leads.

The three 8-bank sections of the battery were treated independently for the by-pass system design, each section had its own set of by-pass terminals and by-pass electronics. The by-pass electronics were connected to the battery via high-grade plugs and cabling to allow the electronics to be placed in the most convenient place in the vehicle.

2.3.1.7. Enclosure

CSPL pursued a number of enclosure designs, both with lids removable and permanently sealed. While technically adequate for experimental purposes, the lidded designs (shown in Figure 2-29) proved to be difficult to manufacture and gave rise to serious thermal non-uniformity.

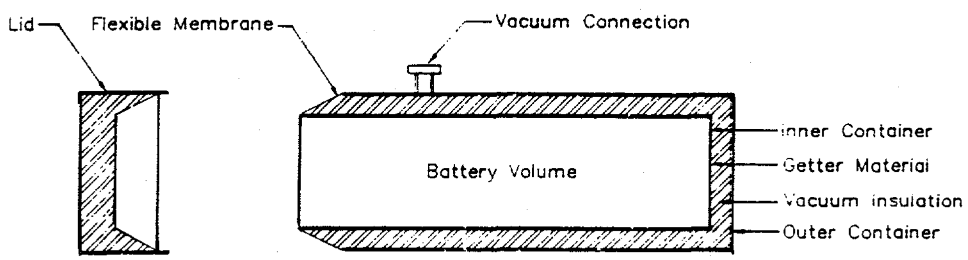


Figure 2-29. Lidded Design of Enclosure

Later work confirmed the technical superiority of the double skinned lidless enclosure which could be fabricated rapidly and accurately. The interconnection philosophy adopted by CSPL makes servicing unnecessary and the absence of a lidded enclosure was not perceived as a disadvantage in this respect.

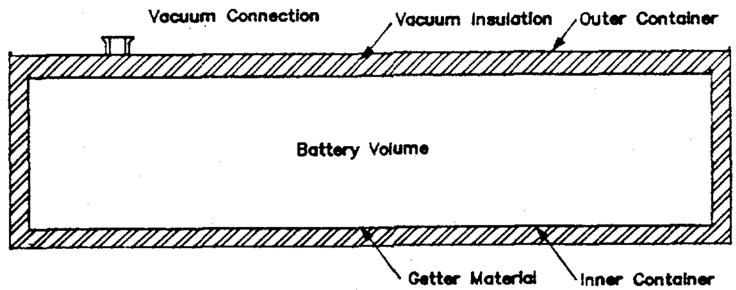


Figure 2-30. Lidless Design of Enclosure

The enclosure, shown in Figure 2-30, consisted of an inner stainless steel container into which the battery banks fitted. Around the sides of this container was a 30 mm thick layer of microporous insulation. This insulation was chosen for its excellent load bearing and vacuum properties. Surrounding the insulation was the outer container, manufactured from 0.9 mm thick stainless steel. The main terminals, instrumentation wiring and battery cooling system passed through the enclosure via flexible bellows which provided a vacuum seal between the two containers and minimised conductive heat losses. Two resealable ports were provided to initiate the vacuum between the containers.

Each of row of banks had its own cooling system that was based on the concept described in Section 2.2.4.2. Each component was positioned above and below the battery. Associated with this cooling system were 6 inlet ports and 6 outlet ports located on the upper and lower surfaces of the enclosure. The battery heating system also used an independent vacuum lead-through positioned on the top surface of the enclosure. The battery instrumentation had 4 vacuum lead-throughs, positioned on the top surface of the battery. The main battery terminals were positioned on the sides of the enclosure at opposite corners.

2.3.1.8. Battery Handling And Support Frame

The enclosure was not designed to be inherently self-supporting. CSPL designed a separate battery support, based on the experience and expertise derived from support of lead acid batteries using lightweight tray systems.

2.4 BATTERY BUILD

The first ETX II cell was completed on 15th July 1989, and the final cell was completed on 25th September 1989. The cells were MK3SF PB cells (CSPL drawing ref. P530\A3\1212\A, see Figure 2-1, closed top), which were sulphur limited cells with a theoretical capacity of 11.8 Ah to an open circuit voltage of 1.9V. Nearly 3500 cells were made and were used as follows:

38 single cells tested	38 cells
38 single cells archived	38 cells
15 strings tested	60 cells
12 strings archived	48 cells
3 banks tested	360 cells
24 banks delivered	2880 cells
Total number of cells =	3424 cells

The cells assigned for single cell testing represented 1% of production. For each bank, 31 strings were assembled, the 31st string being alternately assigned to test or archive. In this way the single cells and strings were representative of the battery as a whole.

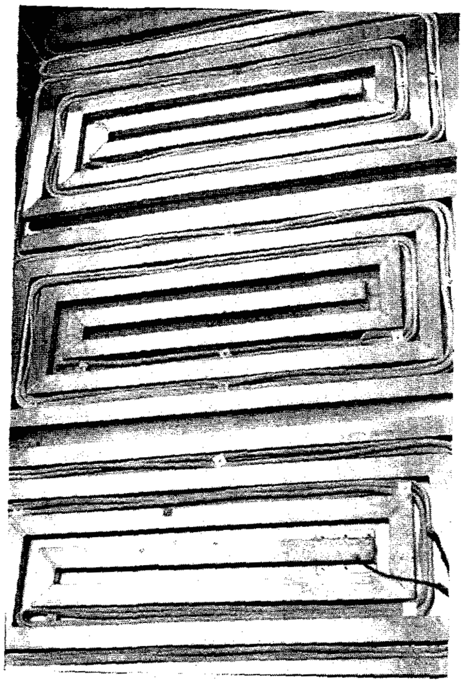
At CSPL, each 120-cell bank is given a unique number. The ETX II population consisted of banks 138 to 161 inclusive. After electrical qualification of the banks, three were withdrawn from the battery build and replaced.

Bank 138 was replaced with bank 171
Bank 154 was replaced with bank 170
Bank 155 was replaced with bank 164

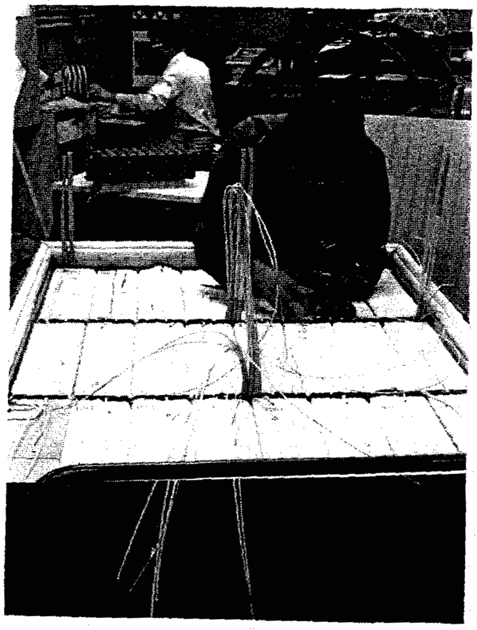
The replaced banks were retained for testing in-house as a series connected three bank battery. The reasons for the replacements were as follows: Bank 138 was replaced because it had undergone two freeze-thaw cycles and previous experience had suggested that string life may be degraded by freeze-thaw cycling. Bank 154 exhibited unstable open circuit potential on cool-down after the break-in cycles. The resistance of bank 155 on its first cycle showed two step-wise increases suggesting that at least two strings had "dried-out". Normal behaviour was observed on subsequent cycles. Subsequently, an additional 120-cell bank (#177) was built as a deliverable for the SNL "core technology contract". This was tested at ANL as described in section 2.2.1.

Construction of the battery proceeded when all 120 cell banks were satisfactorily commissioned (October 1989). On 20th November 1989, the final assembly process began. Some re-arrangement of the CSPL battery assembly area was required to accommodate the size and weight of the battery. Welding of the thin gage battery box was a persistent problem which needed continuous development to achieve the required hermeticity. Distortion of the large panels under welding stresses and subsequent vacuum stresses was also evident but a sound construction was completed in time for delivery to Ford on 31 January 1990.

The captioned photographs in Figures 2-31 and 2-32 show the battery during various phases of assembly.

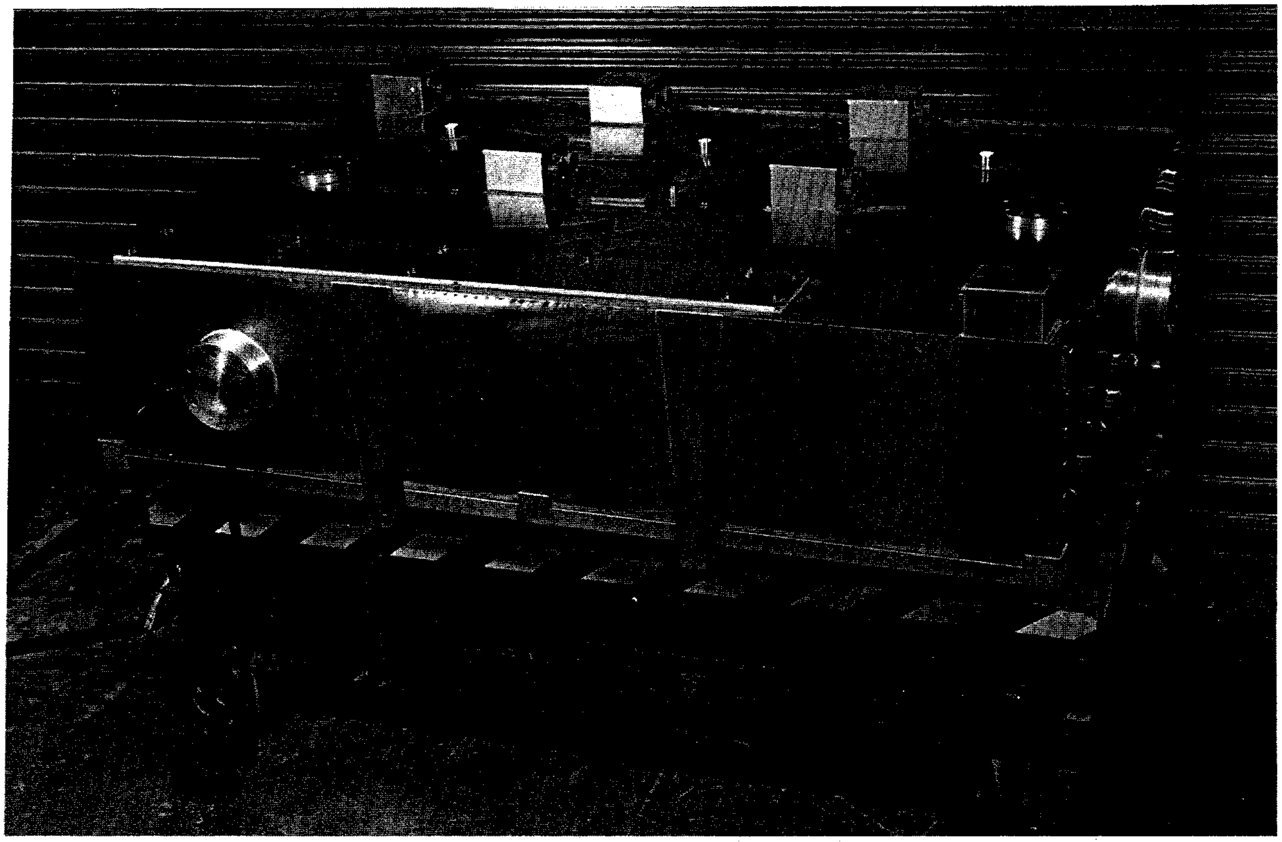


Cooling Array



Packing Insulation

Thermal Conditioning
Figure 2-31 ETX II Battery Build



The Completed Battery Before Delivery

Figure 2-32 ETX II Battery Build

2.5 BATTERY TEST

The ETX II deliverable battery was delivered to Ford in late January 1990. However, the battery and associated equipment appeared to have suffered shocks during transit, since many of the acceleration "tell tale" devices had been triggered and the wooden crates were damaged. When the equipment was un-crated, some parts had broken loose from their mountings, causing slight internal damage to the vacuum system and heater controls. Furthermore, the enclosure had lost its vacuum and subsequent re-evacuation revealed that damage to the battery box had caused the vacuum leak. Several attempts were made to seal the leak temporarily, but all were unsuccessful.

After examination and electrical checks on the battery, warm-up was nevertheless commenced. During warm-up, a high resistance fault developed between the battery cell matrix to the inner case. Similar high resistance paths had been observed in the past due to water condensation, and the fault did increase in resistance as the battery warmed, completely clearing at one stage. Large amounts of water were also expelled from the battery during warm-up. However, when the battery had achieved its working temperature, the fault had re-appeared (remaining variable), and the initial discharge of the battery caused an equipment trip due to loop currents. This was in part because the Ford discharge equipment had a fault to earth which interacted with the battery fault. Subsequent investigations revealed that the battery fault was associated with the bank plate between Banks 16 and 17.

The battery fault required the battery case to be allowed to float from earth potential for electrical testing to continue. The battery case was at 130V relative to ground, providing a potential hazard to personnel. Ford considered that this posed a sufficient safety hazard to prevent vehicle testing and only allowed a static testing programme to be carried out, supervised by the CSPL personnel. An abbreviated test program was implemented to show that the battery performance specification could be met.

The initial discharges indicated that the battery closely approached predicted resistance and provided expected capacity (300Ah). However, the temperature distribution in the battery was unacceptable (range: 53°C) owing to the differential distribution of the main heaters. This was remedied by trim heating and cooling adjustments, reducing the temperature variation to an acceptable level (20°C) for the majority of the testing. Most of the testing program involved operation at high discharge rate and use of a FUDS profile to illustrate that the battery would meet the performance criteria set by Ford.

The specification for high rate discharge required 35 kW to be provided for 40 min. without exceeding the upper operating temperature limit of the battery. Although Ford had specified that active cooling should be provided to achieve this target, CSPL had predicted that cooling would be unnecessary and that the battery would operate for approximately 1h without exceeding the maximum temperature limit. Figure 2-33 shows the actual performance of the battery during 35 kW discharge. As predicted, the battery provided 35 kW for 1h, during which period the maximum temperature rose to 375°C from an average starting temperature of 325°C. Current and voltage remained substantially constant during the discharge, with a slight fall in voltage/rise in current towards the end of discharge. Active cooling was not used during this test.

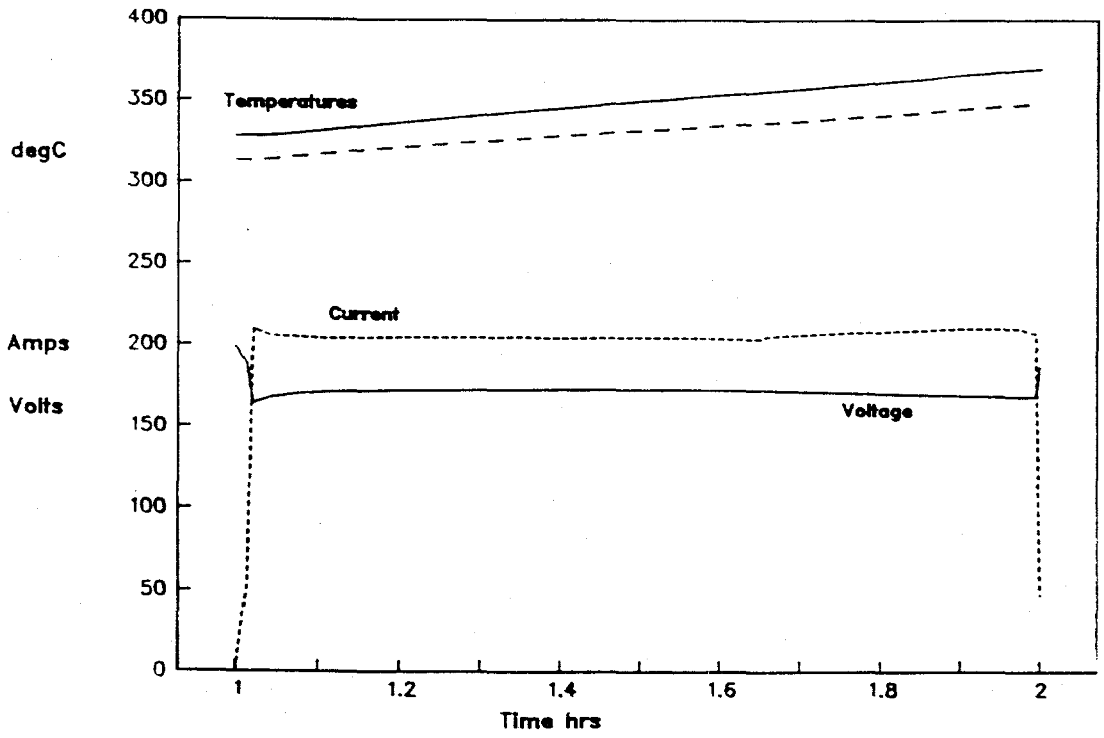


Figure 2-33. 35 kW Discharge of ETX II Battery

During FUDS cycle testing, the battery achieved 20 full 21 min. FUDS cycles before discharge was complete, which is equivalent to a vehicle range of approximately 150 miles. The temperature distribution obtained on FUDS cycling is shown in Figure 2-34. Over the 8h discharge period, the maximum temperature reached was less than 350°C, although the spread of battery temperatures increased significantly. The large spread of battery temperatures at the end of discharge was partially due to the deterioration of the vacuum insulation during discharge. Continuous evacuation was impossible because the ground fault would have caused the battery case to be earthed via the pumping system.

The ancillary equipment associated with the battery performed well, without major problems.

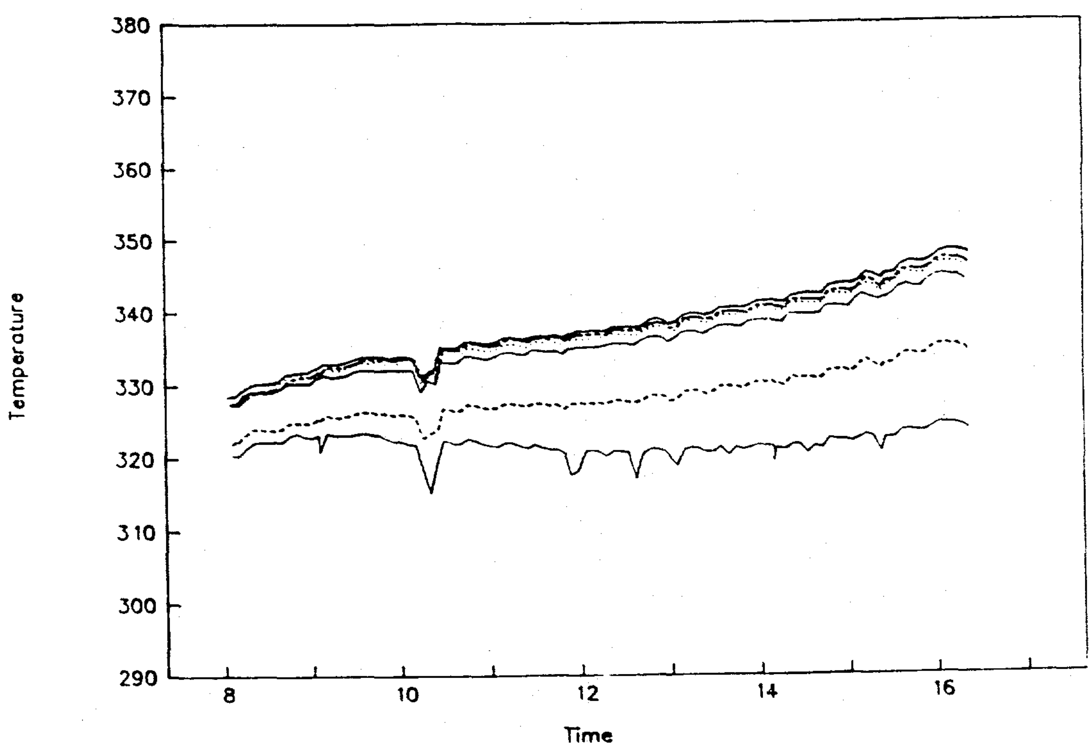


Figure 2-34. Temperature Distribution - FUDS Cycling (each line represents a different thermocouple)

2.6 BATTERY REBUILD

Following the short test programme at Ford, the battery was returned to the UK for examination to investigate and correct the cause of the ground fault. Detailed discussions with Ford resulted in an agreement that the battery would be re-constructed without active cooling, and with the battery housed in 3 separate enclosures, each containing 8 banks, as illustrated in Figure 2-35. This redesign and refurbishing was performed entirely at CSPL's expense.

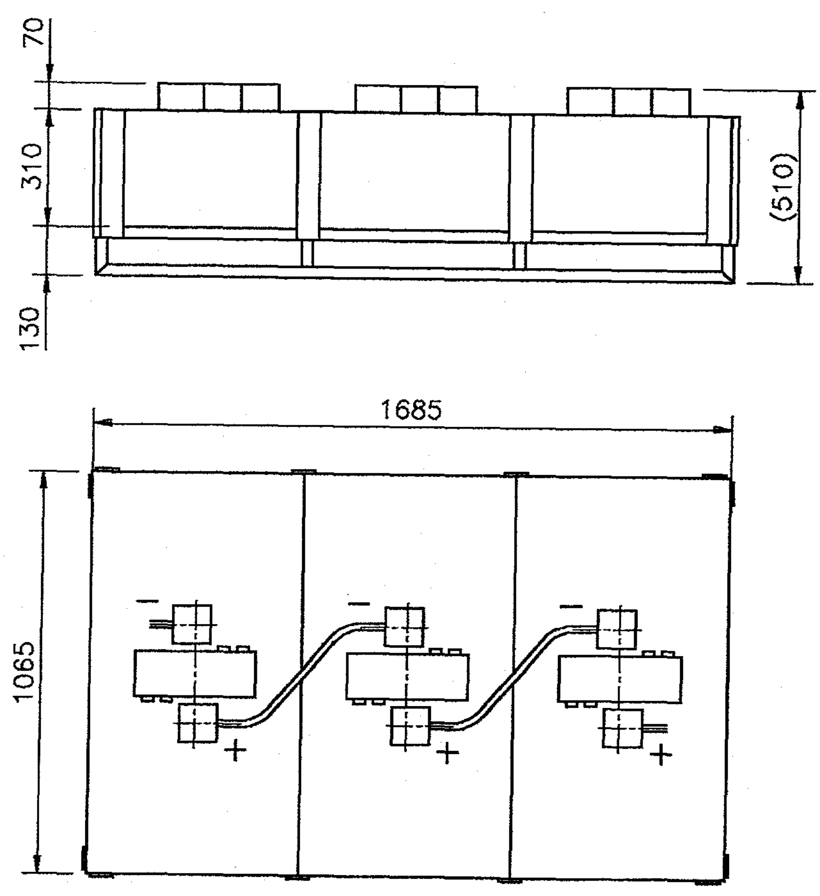


Figure 2-35. ETX II Battery Re-Packaging

The modifications to the battery packaging also necessitated corresponding modifications to interconnections, cabling and heater control systems, to be compatible with a 3-unit battery. Since the temperature distribution in the original battery was poor, requiring temporary trim heating to be introduced, additional trace heating was included in the exposed long sides of the 2 outer batteries. The instrumentation wiring was also re-configured to enable Ford to operate the battery with minimum instrumentation during road test, using only the battery controller. The most serious delays in the rebuild program resulted from an inability to produce hermetical enclosures. These were solved by patient attention to detail and slowly gained experience. As jigging and automation were increased the problems lessened. For the final product, a compromise was made in that thicker Microtherm insulation was used than desired. This material, as discussed in Section 2.2.4.4, has superior thermal resistance if un-evacuated, compared with glass fibre board. Therefore, in the event of a non-hermetic enclosure, insulation would be adequate, but not optimum. This compromise also slightly increased the size and weight of the battery.

2.7 CONTINUATION OF BATTERY TESTING

The re-built battery was returned to Ford in July 1990 and successfully warmed-up. A failure of the Ford active load rig limited initial cycling of the battery. Following repair, the battery showed comparable behaviour to that obtained when it was first tested in the US in a single enclosure. This result indicated that all cells survived the re-build and re-warm.

The performance on high rate cycling without the cooling structures included in the original battery unit confirmed that these were unnecessary. In fact, the performance without cooling was somewhat better than the original battery since the 3-box design allowed the initial temperature variation across the battery to be controlled to tighter limits. During FUDS cycling, the battery again achieved 21 cycles, equivalent to a range of approximately 150 miles. Problems with the vehicle drive system prevented a rolling road test, which in turn left the vehicle/battery controller interface untested.

The vacuum performance of all 3 enclosures was initially poor. However, during the testing, as more of the volatiles in the battery insulation burnt off, the vacuum on the enclosures improved. When CSPL staff left Ford, the vacuum performance was still improving and it was decided to leave the enclosures continuously pumped.

The ETX II battery and vehicle was demonstrated to US DoE Management at a meeting at Ford, and the DoE officials were driven the vehicle. A final contract review was held on 23rd October 1990 and the battery was officially accepted as conforming to contract requirements.

The DoE decided that the final phase of testing should be conducted at INEL and the battery was transported in the hot condition, by truck. The two day journey was accomplished using portable generators to keep the battery warm. The testing at INEL was conducted under DoE Contract DE-AC07-761IDO1570. The details of the INEL testing were reported by Burke in report EGG-EP-9688 and will not be repeated in this document. Figure 2-36 is a summary of the history of the ETX II testing program through to March 1991. Table 2-8 is a summary of the dynamometer testing on the INEL equipment. The rebuilt battery was maintained at operating temperature from August 1990 until February 1992. Including the first version of the battery, the time at temperature was about 20 months. During this period the battery was cycled about 60 times.

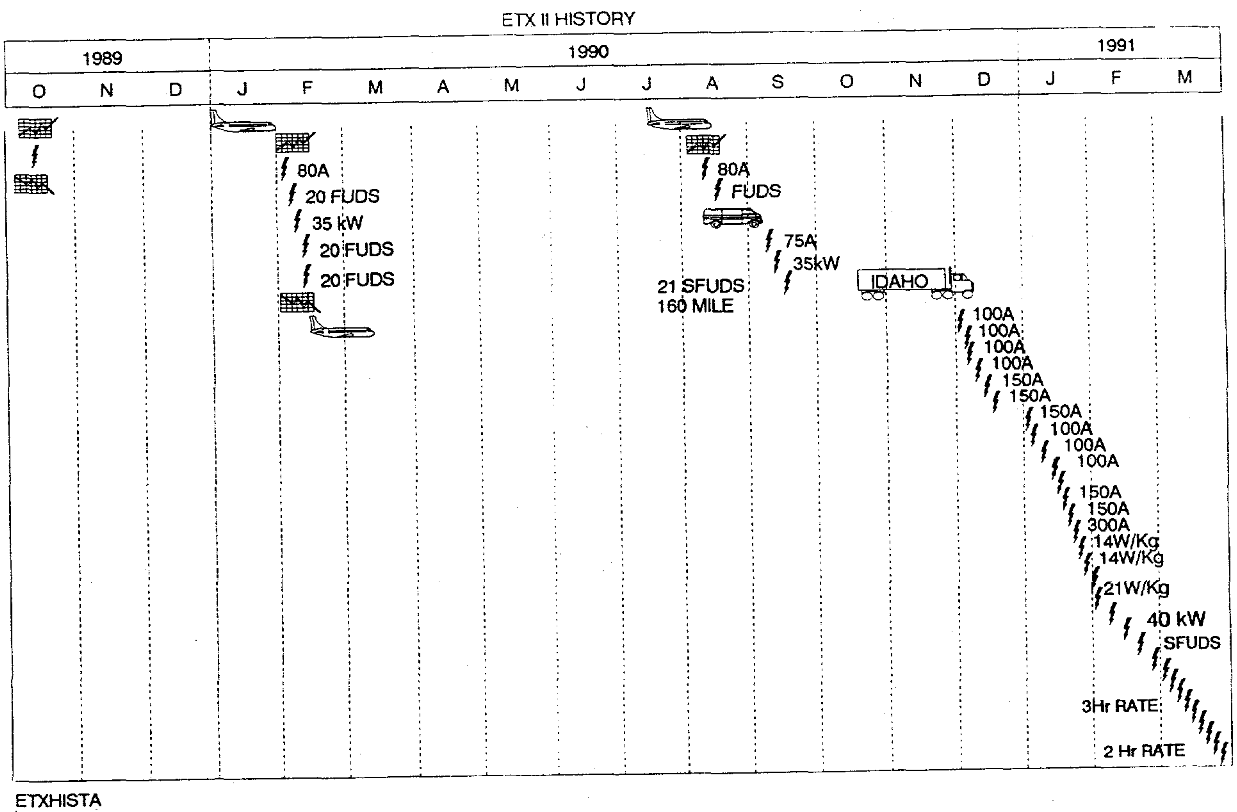


Figure 2-36 Partial Summary of ETX II Test Program

Table 2-8 Summary of INEL Dynamometer Testing

Driving Mode Constant Speed (km/h)[1]	Energy Consumption (Wh/km)
56	150
72	172
88	218[3]
96	242
Cycles [2]	
FUDS	233 (212)[4]
SAE J227aC	218 (196)[4]
[1] Test done with CSPL NaS Battery [2] Tests done with sealed lead acid battery [3] Measured range of 185 km [4] Gross(net) consumption	

2.8 DATA ANALYSIS AND PARALLEL TESTING

Mainly because of test procedure restrictions at INEL, and difficulties with equipment at Ford and INEL the battery was exercised very infrequently and direct comparisons with CSPL statistics are not possible. However some interesting comparisons can be made with regard to calendar life and the effect of extended stand periods at open circuit, at temperature. The battery was held on open circuit whilst awaiting discharge equipment and in order to minimise degradation, CSPL recommended that it was cooled to 300°C during the hold period.

After being on open circuit for 5 months, the battery was discharged at the 100A rate to ascertain its condition. A capacity of 221Ah was obtained and an analysis was conducted on the INEL data in order to predict the condition of the individual banks in the battery. These data were then compared with a cell failure pattern predicted by Monte Carlo simulation of 100 batteries. There was reasonably good agreement between the predicted number of failures in each 120 cell bank and the number of failures estimated from the battery data. These are summarised in Table 2-9.

Table 2-9 STRING FAILURES PER BANK

NUMBER OF STRING FAILURES/BANK IN A 24 BANK BATTERY	PREDICTED RANDOMLY	PREDICTED FROM BATTERY DATA
0	0	0
1	1	1
2	3	2
3	4	5
4	5	3
5	5	9
6	3	4
7	2	0
8	1	0

The test data also enabled predictions of bank capacities remaining in the battery before and after its stand period. These are summarised in Table 2-10.

Table 2-10 Predicted Capacities Before and After 5 Month Open Circuit Stand at INEL

	Before Stand		After Stand	
Bank Number	Predicted Capacity	No. of Strings Failed	Predicted Capacity	No. of strings failed
1	263	4	227	7
2	265	4	239	6
3	255	5	227	7
4	276	4	236	6
5	274	3	244	6
6	274	3	252	5
7	263	4	228	7
8	254	5	232	7
9	271	3	239	6
10	273	3	252	5
11	256	4	227	7
12	274	3	254	5
13	273	3	235	6
14	273	3	245	5
15	254	5	234	7
16	262	4	236	6
17	262	4	238	6
18	266	3	240	6
19	243	6	220	8
20	253	5	227	7
21	273	3	252	5
22	271	3	254	5
23	241	6	220	8
24	295	1	256	4

Although there were failures within the battery during the stand, the battery showed a remarkable consistency in failure numbers for each bank, and strongly supported the philosophy of deliberate sequencing of cells into battery build. That is the ETX II was the only battery built, up to that time, where specific cell lots were distributed into different banks (as opposed to building banks with one lot of production cells). The characteristics of the battery after the open circuit hold indicated that there was no detrimental effect on battery resistance. There was concern at the time that the hold might have led to some form of resistance change.

At 18 months on test, the battery had been at temperature for 13,000hrs. Using the statistics shown in the cell section of this report, 231 failures were predicted. This compares with 94 actual failures at that time. This significant reduction is attributed to the low temperature of the open circuit hold period.

2.9 CONCLUSIONS ARISING FROM ETX II BATTERY DEVELOPMENT

The major objective of the initial phase of the programme was a proof-of-concept demonstration of sodium sulphur EV battery technology. In order to satisfy this objective, many compromises were made during the design and build of the battery. In particular weight, volume and thermal performance were sacrificed in order to employ well proven technology. No attempts were made to miniaturise the control and instrumentation systems either internal, or external to the battery. An additional problem was that the insulation system and enclosure construction techniques were still quite new when the battery was assembled. The weight of the first ETX II battery had gradually risen as compromises were made at the design and rebuild stages. It was recognised that significant weight could be removed by respecifying component materials and designing out weight from the heaviest components.

As noted in section 2.6, the final iteration of the ETX II battery weighed 750 kg compared to an original design estimate of 550 kg. The weight of the single box design was 697 kg which included an air cooling system. Removal of this cooling system when the 3 box rebuild took place did not compensate for the extra enclosure hardware and reverting to an aluminium plate heating system.

Despite these restrictions the feasibility of the technology was demonstrated in an independent test centre and the battery met its performance goals. The reliability was good and had the battery been exercised regularly and routinely predictions show it would probably have delivered around 60,000 miles equivalent range.

The acceptance of the above findings was reinforced by the DoE decision to fund a follow-on programme phase to develop an improved, second generation battery the ETX IIs.

3.0 ETX IIs BATTERY

3.1 CONCEPTUAL DESIGN

Recognising that the primary deficiency of the ETX II design was its total weight, the contract was extended in July 1990 to develop and fabricate a lightweight system suitable for underfloor mounting in an ETX II vehicle. This second generation, lightweight battery is referred to as the "ETX IIs" battery. An important consideration from the rebuild of the single enclosure ETX II battery was that an active cooling system would again not be needed.

3.1.1 Layout

The space constraints of the ETX IIs battery were fixed by the necessity to mount the battery in the underfloor pannier. This pannier, shown in Figure 3-1, was capable of accepting box/battery combinations 75 x 30 inches. Some compromise was available on the 10 inch preferred height. Modifications to the vehicle suspension system allowed a possible 12 inch head clearance. The available spaces are shown in Table 3-1.

Table 3-1 Pannier Inside Dimensions

OPTION	LENGTH	WIDTH	HEIGHT
PREFERRED	75"	30"	10"
	1905mm	762mm	254mm
MAXIMUM	75"	30"	12"
	1905mm	762mm	305mm

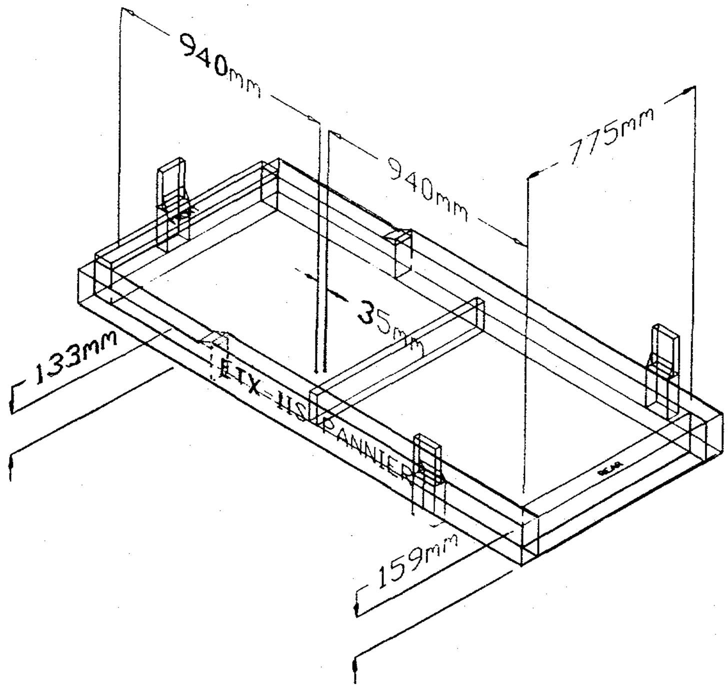


Figure 3-1 ETX IIs Pannier Arrangement

The stiffening bar in the middle of the pannier meant that a two box layout was the most obvious choice. This was also in line with CSPL design concerns about the dimensions of vacuum based systems. The majority of CSPL experience at that time was with the 18 kWh Bedford Quarter Battery which was of the same order of size.

The design had to incorporate an optimum bank (monobloc) configuration and account for the way that this would influence the terminal positions and the inter-box electrical connections.

The handed layout shown in Figure 3-2 was eventually selected, an arrangement in which the box designs and internals were nearly identical but handed to suit the interconnects.

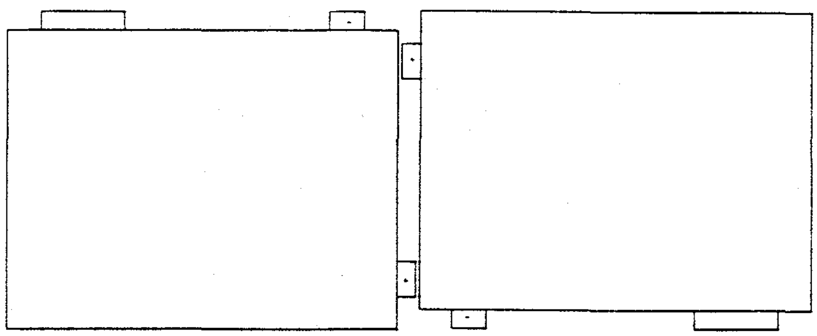


Figure 3-2 Layout of ETX IIs Battery (Top View)

3.1.2 Electrical Network

Experience with a variety of battery designs and builds led to the development of preferred approaches to interconnect banks and minimise the voltage differences between closely spaced, but electrically isolated components. The electrical layout was designed in accordance with this established protocol and reviewed by a sub-committee of independent engineers from CSPL with experience in electrical design.

A variety of computer-generated solutions were examined before the general network shown in Figure 3-3 was selected. This network required 24-string banks (ie 24 parallel x 4-cell series strings giving a nominal 240 Ah at 8 volts). Twenty four of these banks were to be connected in series, to produce a battery with 192 volts and 240 Ah nominal. The inter-box series connection was designed to be placed at the right hand side of the system and the main power take off points at the left hand side of the system. Such an arrangement spaced the higher voltage components apart, without necessitating long power or interconnection cables to suit the vehicle requirements. The initial sketches of the bank design and terminal arrangements are shown in Figure 3-4, and it was from these that the detailed design and component qualification was progressed. The middle strings in each bank are not shown in Figure 3-4 to allow the delineation of each monobloc to be clearly seen.

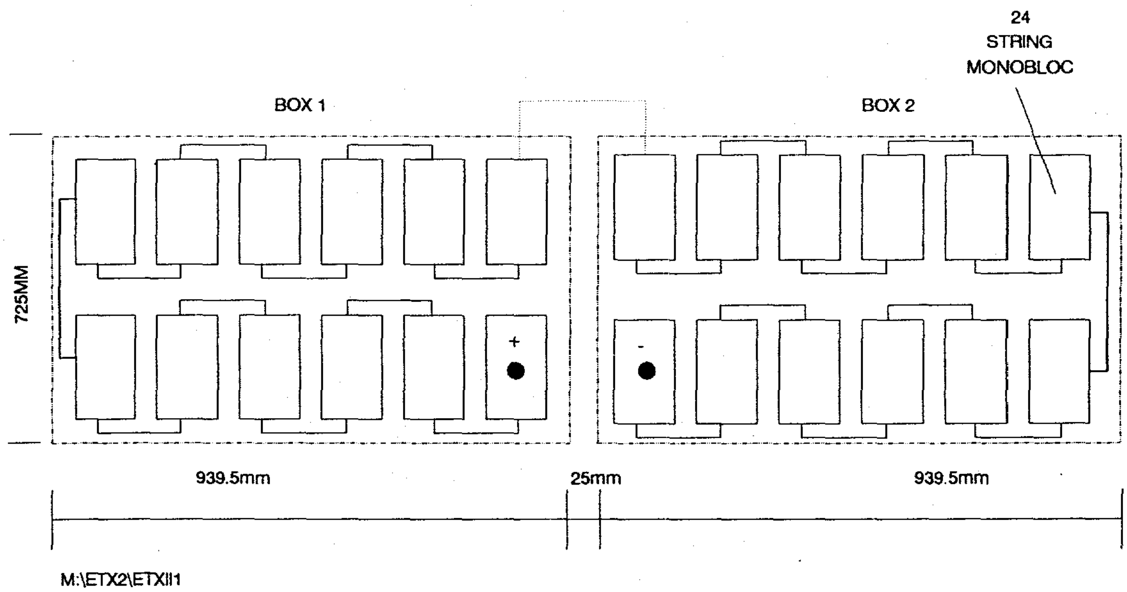


Figure 3-3 Electrical Layout of ETX IIs Battery

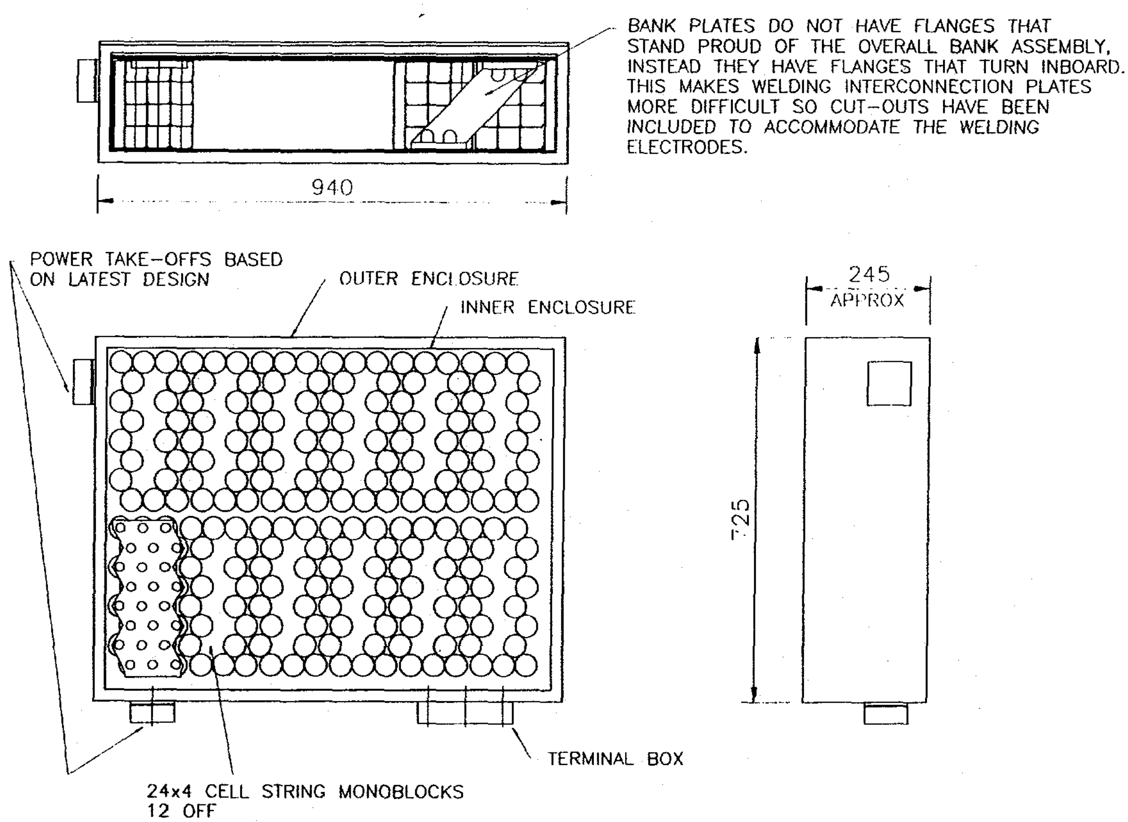


Figure 3-4 Preliminary Sketch of ETX IIs Battery Box Layout

3.1.3 Thermal Analysis

In comparison to the ETX II battery the thermal modelling carried out for designing of the ETX IIs was limited. This arose in part from the decision not to install active cooling, thus removing much of the complexity. The thermal analysis that was conducted was aimed at providing an accurate specification for the lightweight heater design. Figure 3-5 shows a typical thermal profile obtained from the modelling.

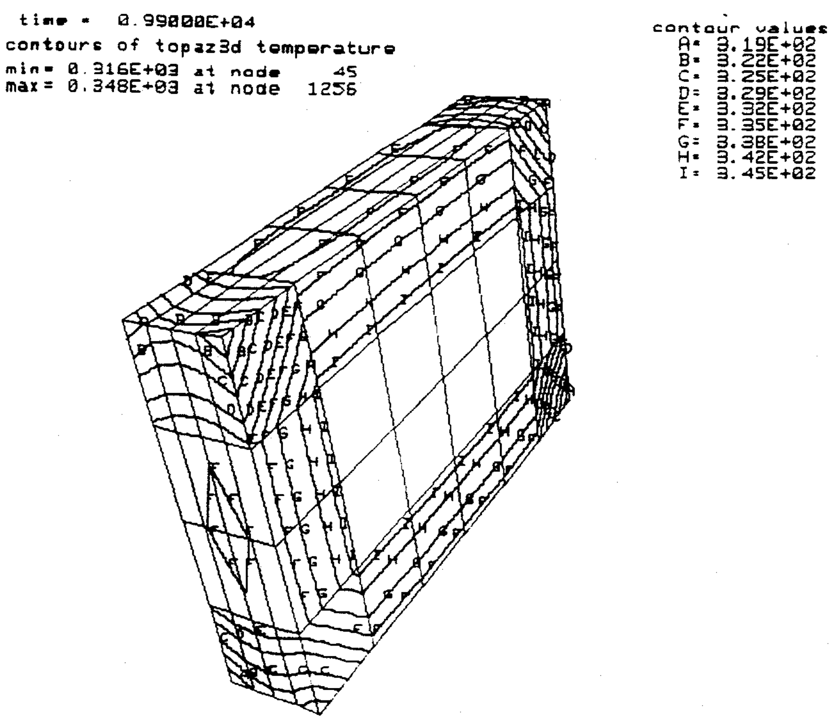


Figure 3-5 Typical Thermal Profile on the Inner Surface of the Container

3.2 COMPONENT DEVELOPMENT

3.2.1 Height Reduction

A key development to reduce the battery height was the thickness reduction of the inter-cell spacer. This insulator is used to separate cells from each other in the same 4-cell string and was normally made of moulded ceramic. For the ETX IIs a mica washer was used to reduce the height of the string, enabling the bank plates to be spaced closer.

The thickness of the heater was drastically reduced by the use of a proprietary mica heater which enabled the removal of the 6 mm aluminium heater plate that was used on the rebuilt ETX II. Reductions were also made in the thickness of the electrical insulation layers without compromising electrical isolation. The upturned welds bank bus-plates in the ETX II battery were converted to down turned plates. A comparison of the overall reduction is shown in Figure 3-6.

Finally, procedures were developed to allow the top lid of the thermal enclosure to be welded without an upturn producing an additional saving in height.

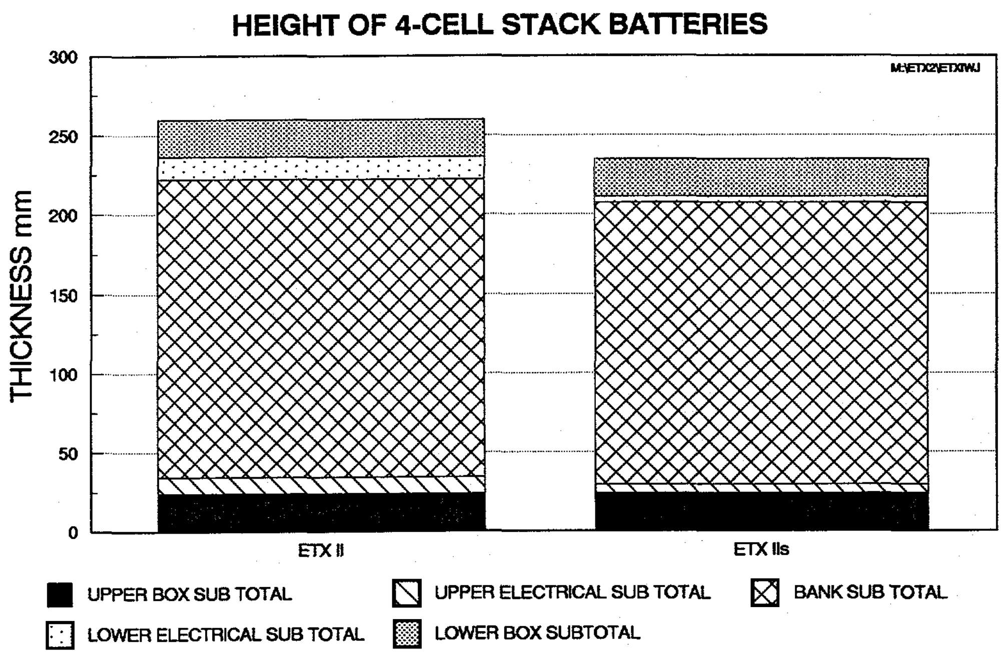


Figure 3-6 Effect of Component Modification on Battery Height

3.2.2 Trilobes

The standard method of construction of CSPL batteries uses ceramic "trilobes" as spacers between individual 4-cell strings within a bank. These electrically, thermally and physically isolate the strings, but with a weight penalty.

Several concepts were explored to reduce the weight and the one which showed most promise initially was a plain mica tube manufactured so that it laterally restrained the cells of the string. A small module of strings was assembled as shown in Figure 3-7 and this was subsequently vibration tested.

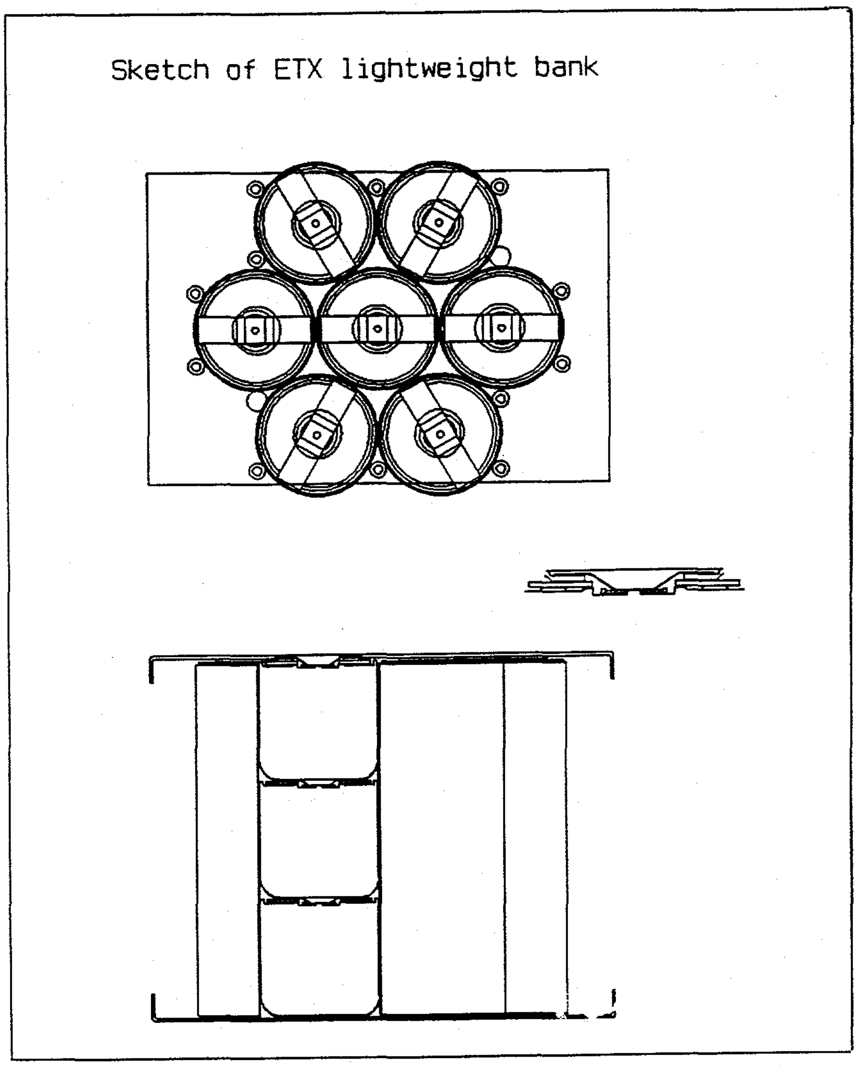


Figure 3-7 Sketch of Mica-Tube Vibration Test Module

Other concepts such as the mica inter-cell spacers were also tested at the same time. The vibration testing revealed several deficiencies in the mica tube concept as the cells abraded the side walls and eventually penetrated. Methods of reducing the weight of the trilobe were also considered. This development was conducted in collaboration with the existing component vendors and a variety of ceramic manufacturing routes were trialled. Details of the design, particularly the lobe length and shape, were altered to suit the manufacturing process. The effort had some success and the selected trilobe weight was eventually reduced by 30.5% to 25 g per trilobe.

3.2.3 Bank Plates

Bank plates are the electrical conductors placed above and below the 4-cell strings to provide the 8 volt bus-system (see Figure 2-26 for an example). They have an electrical and mechanical function and their design must therefore take account of current flow and strength. Mild steel is a useful material because of its cost, weldability and long term compatibility with other components of the module assembly. Its main disadvantage is relatively poor electrical conductivity. Although copper is an excellent conductor it has poor oxidation resistance at operating temperatures and is unsuitable in the un-coated condition. A laminated steel-copper composite had an attractive combination of properties and was eventually selected for use in the ETX IIs battery.

The existing method of welding bank plates to the side plate busbars was to turn the plate up and perform an edge resistance spot weld. This had the disadvantages of requiring approximately 6 mm of upturn and additional insulation to protect the heater plates from damage due to the small protruding edges. Thus the existing design wasted height and increased total weight. The method used for ETX IIs was to form the bank plates and the side plates from a single piece of material and to employ a weld made to a down turned geometry. This reduced the total number of welds required.

The design of the bus plates and their interconnection necessitated a special assembly sequence as described in section 3.2.5

3.2.4 Bank Tie Rods

These components are used to retain the bank plates in position by providing a tensile force between the plates. The rods are attached to both bank plates and must therefore be electrically insulated both from the plates and from the cells they pass between. Absolute security of insulation is vital as any shorting would fail the battery. A new, low profile insulation arrangement was developed for ETX IIs to take account of the reduced height available when down turned banks were used.

3.2.5 Bank Assembly Procedure

The previous procedure in assembling an array of banks is to invert the bank and make the bottom bank plate to side plate weld. The banks are then returned to the upright position and placed in the inner enclosure of the battery. Welding of the top plates to the side plate of the adjacent bank is then carried out in situ.

A new bank interconnection technique was devised for the battery which eliminated the need for the bankplate upturns and downturns normally used for bank-to-bank welding. For the ETX IIs, the battery banks were designed to be built sequentially, such that each bottom bankplate would have as an integral piece, the top plate of the previous bank in the battery. This is illustrated in Figure 3-8.

The first step in bank assembly was to make a bankplate sub-assembly which comprised the bottom bankplate of the first bank, the positive busbar and the positive leadthrough pin. Bank number 1 could then be welded to this bankplate sub-assembly as shown in Figure 3-8 stage 1. A temporary top plate was then attached to the bank using six tie rod screws, as shown in stage 2. Thus, the first bank could be lifted into the enclosure and moved into position with the leadthrough pin through the bellows. Once inside the enclosure and in the correct position, the temporary lifting plate could be removed.

Bank number 2 was then built onto a "Z-shaped" plate (with the bottom shim-to-plate welds made at this stage as with bank 1) and the temporary plate attached as before. This plate was then used to lift Bank 2 into the battery so that the top portion of the "Z-plate" becomes the top bankplate of Bank 1. This is shown in Figure 3-8 stage 3. The shims at the top of Bank 1 were simply folded together and fed through the holes in the upper portion of the Z plate as it was lowered. With the second bank in position the tie rod screws could be replaced in the first bank.

Figure 3-8 Stage 4 shows the first two banks in place in the battery with the temporary top plate removed and ready for the next bank in the sequence.

Bank 3 was built onto a bankplate sub-assembly that featured a bottom plate with a diagonal connection to the top plate of bank 2 as shown in stage 5. As before this bank was lifted into the battery using the temporary plate so that the upper portion of the pre-formed plate was lowered onto the top of Bank 2.

Assembly of the banks into the enclosure continued in this manner, with each bank being built onto a bankplate sub-assembly that included the top plate for the previous bank. No top shim-to-plate welding needed be done until all of the banks were fitted into the enclosure.

The top plate of the last bank was the last bankplate to be fitted into the battery and this had to be welded to the negative busbar and hence the negative terminal of the battery. Prior to this final weld being made, the entire battery could have been disassembled since no shim-to-plate welds had been made.

In order to perform the Bank 12 top plate-to-negative busbar weld in-situ in the battery, a negative leadthrough pin sub-assembly was manufactured. This consisted of the negative leadthrough pin welded onto the negative bus bar. This sub-assembly was positioned in the battery before Bank 12 was lowered in place.

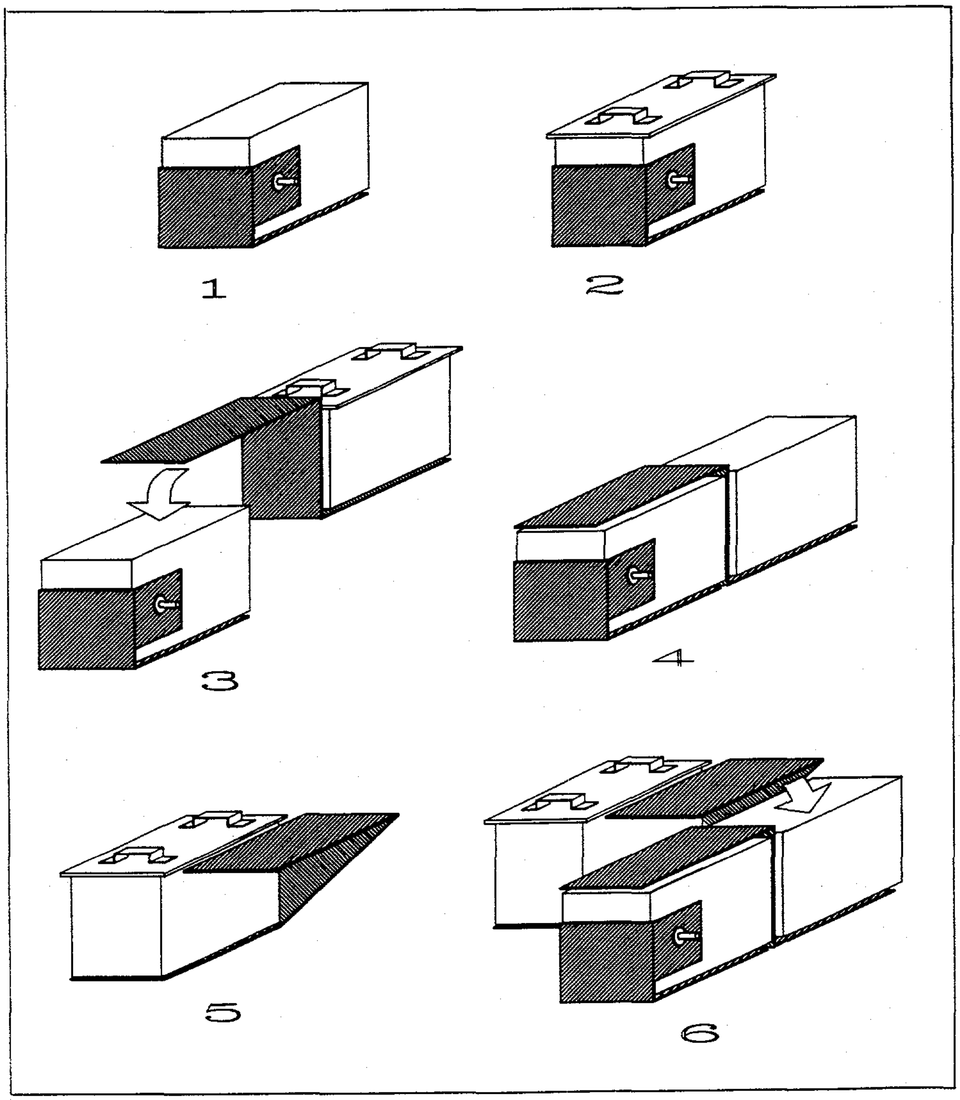


Figure 3-8 Battery Bank-Matrix Assembly Procedure

Thus all bank to bank welding was completed by welding of bankplate sub-assemblies outside the enclosure, apart from the final weld between the negative busplate assembly and the top bankplate of Bank 12. The Z-shaped plate was made as one continuous plate which was folded during manufacture, but the bankplate sub-assemblies containing the diagonal piece were fabricated from three plates which were resistance welded together in an assembly fixture. The final stage was to perform the top cell shim-to-plate welds. This was done with the banks in the enclosure.

3.3 COMPONENT QUALIFICATION

3.3.1 Mechanical

The mechanical performance of new components and designs was qualified by conducting a variety of tests, including:-

- Trial build/assembly
- Weld trials
- Metallurgical analysis of welds
- Peel and tensile weld testing
- Temperature testing
- Vibration testing
- Thermal trials on glass fibre insulation

The qualification testing was performed to prove the suitability of the lightweight designs prior to use in the battery.

3.3.3.1 Trial string assembly

A number of 4-cell strings were assembled using various thicknesses of mica cell separators. Since mica was available in thickness of 0.1mm intervals the string assembly was used as an indicator to assess the suitability of different arrangements. The combination of 0.6mm and 1mm thicknesses was chosen to be the most suitable.

3.3.3.2. Hot Seven String Module Vibration

A-7 string, 3 cell per string module was built with the following features (see Figure 3-7):-

Mica cell separators (as above)
Mica tubes
Lightweight bankplates

The module was vibrated, vertically at 350°C for a period exceeding 100 hours at the following levels:-

10 to 150 Hz swept sine vibration
1g acceleration
1 octave/min sweep rate

After the test, the module was taken apart and examined for signs of wear or damage. It was found that there was no problem evident with the mica cell separators or the bankplates. There was, however, evidence of severe damage to the mica tubes where the vibration had caused the insulation to wear away completely in some places.

3.3.3.3. Trials on Lightweight Bankplate Material (LBM)

As mentioned in section 3.2.3, a laminated steel-copper composite was selected as a preferred candidate material. Initially a resistivity check was made at 350°C. The measured value of resistivity was $1.45 \times 10^{-7}\Omega m$, which compared well with the theoretically derived value of $1.4 \times 10^{-7}\Omega m$. Therefore, a 25% improvement in conductivity using 0.8mm thick bankplates was confirmed.

A series of weld trials on nickel to LBM, mild steel to LBM and LBM to itself were performed in order to simulate cell shim to bankplate, leadthrough pin flange to busbar and bankplate to bankplate welds. These welds were firstly metallurgically examined and peel tested by hand, in order to achieve the best welding parameters possible.

Once optimum weld settings had been determined, trials were conducted on non-heated and heated samples to investigate whether any temperature effects would weaken the weld. The results obtained are shown in Table 3-2.

STRENGTH TESTING WELDS FOR BATTERY BUILD.

M:\ETX2\LBMWELD

TYPE	SAMPLE No	FAILURE LOAD (kg)
LBM:LBM	1	29.0
AS-MADE	2	25.0
	3	28.3
	4	25.9
	5	24.0
	6	27.7
	7	27.5
	MEAN	26.77
	STD(N-1)	1.84

TYPE	SAMPLE No	FAILURE LOAD (kg)
LBM : steel	18	76.7
AS-MADE	19	68.0
	20	61.0
	21	46.0
	22	78.6
	23	82.9
	MEAN	68.87
	STD(N-1)	13.70

TYPE	SAMPLE No	FAILURE LOAD (kg)	
LBM : Ni	34	10.6	Ni TORN
AS-MADE	35	15.1	Ni TORN
	36	14.3	Ni TORN
	37	15.3	Ni TORN
	38	14.4	Ni TORN
	39	13.0	Ni TORN
	MEAN	13.78	
	STD(N-1)	1.76	

TYPE	SAMPLE No	FAILURE LOAD (kg)
LBM:LBM	8	10.2
1 WEEK @ 350 C	9	13.2
	10	15.1
	11	10.1
	12	13.3
	MEAN	12.38
	STD(N-1)	2.17

TYPE	SAMPLE No	FAILURE LOAD (kg)
LBM : steel	24	62.6
1 WEEK @ 350 C	25	56.1
	26	82.6
	27	58.0
	28	62.5
	MEAN	64.36
	STD(N-1)	10.58

TYPE	SAMPLE No	FAILURE LOAD (kg)	
LBM : Ni	40	15.3	Ni TORN
1 WEEK @ 350 C	41	15.6	Ni TORN
	42	16.3	Ni TORN
	43	15.3	Ni TORN
	44	15.5	Ni TORN
	MEAN	15.60	
	STD(N-1)	0.41	

TYPE	SAMPLE No	FAILURE LOAD (kg)
LBM:LBM	13	36.4
1WEEK @ 600 C	14	40.4
	15	47.5
	16	42.4
	17	43.7
	MEAN	42.08
	STD(N-1)	4.10

TYPE	SAMPLE No	FAILURE LOAD (kg)
LBM: steel	29	61.0
1 WEEK @ 600 C	30	65.2
	31	58.0
	32	68.1
	33	59.2
	MEAN	62.30
	STD(N-1)	4.24

TYPE	SAMPLE No	FAILURE LOAD (kg)	
LBM : Ni	45	12.6	Ni TORN
1 WEEK @ 600 C	46	11.9	Ni TORN
	47	11.5	Ni TORN
	48	13.0	Ni TORN
	49	11.0	Ni TORN
	MEAN	12.00	
	STD(N-1)	0.81	

TYPE	SAMPLE No	FAILURE LOAD (kg)
steel:steel	50	340
1 WEEK @ 350 C	51	288
	52	318
	53	355
	MEAN	325.25
	STD(N-1)	29.11

Table 3-2 Results of Bankplate Welding Trials

Table 3-2 includes three sets of figures for each weld type, representing:-

(1) Failure loads for un-heated welds
(2) Failure loads for welds heated for 1 week at 350°C
(3) Failure loads for welds heated for 1 week at 600°C

The results show that in all cases with the nickel to bankplate weld the weld was stronger than the nickel itself (the nickel fractured every time). With the LBM to mild steel welds, only a marginal decrease in average failure load occurred (from 68.8kg to 62.3kg). However, with the LBM to LBM welds, there was a large reduction in weld strength in the samples heated at 350°C (from 26.7kg to 12.4kg). This failure load then increased to an average of 42.1kg on the samples heated to 600°C.

A vibration test was then performed on a sample weld of bankplate steel to LBM deliberately placed under shear stress during vibration. The vibration test was carried out at specified vibration levels for a period of 30 hours at 350°C. A micro-section of the weld was made after the vibration test which was then metallurgically examined. No evidence of vibration induced cracking was found.

This test, combined with the fact that 8, 4mm diameter resistance welds were to be made on each bankplate to bankplate connection gave confidence that the weld strength in all cases would be sufficient.

3.3.3.4. Cold Vibration Test on ETX IIs Banks

When the bank design was fairly firm, a two-bank module was constructed and housed in a vacuum enclosure. The module, illustrated in Figure 3-9, featured:-

Mica cell separators
Lightweight trilobes
LBM bankplates
Representative insulation layers below and above the banks

A cold vibration test was performed on the module at the following levels:-

10 to 150 Hz swept sinusoidal vibration
2g constant acceleration
Sweep rate 1 octave/min
Test duration - 27 hours continuous
Sweep count - 418 completed sweeps

This accelerated vibration test was based on a British Standard (BS 2011 Part 2.1 Fc:1983) for testing of electronic equipment intended for installation in or use by ships, railways or road transport. In this standard, 20 sweeps are called for. IN the test outlined above 418 sweeps were used in order to increase the severity of the test. The British Standard is very similar to a German DIN vehicle standard.

After the test, the module was stripped and examined for signs of wear or damage. No damage was found apart from a small amount of white dust, visible around the trilobes. Also, an electrical check was performed on the outer strings to investigate the effectiveness of the cell separators and trilobes as insulators following vibration. No reduction in electrical isolation was evident.

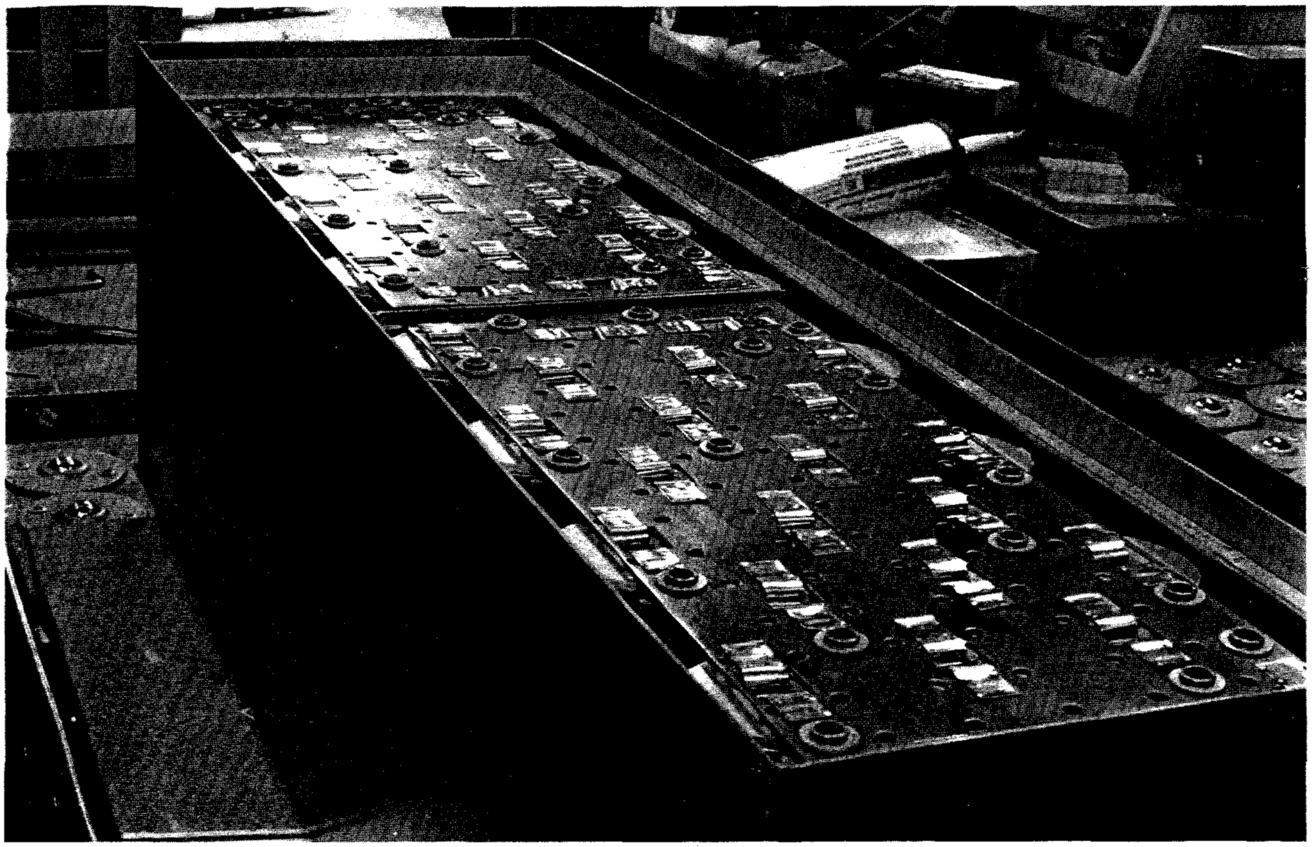


Figure 3-9 Two Bank ETX IIs Test Module

3.3.2 Electrical

3.3.2.1. Tests on Mild Steel Instrumentation Wire

One of the innovations in the ETX IIs Battery was the use of mild steel as an instrumentation wire. Requirements for this wire included low cost, good weldability, and an actual resistance of less than 5Ω. A resistivity check was done on the mild steel wire with the measured resistivity recorded at, $\rho = 1.23 \times 10^{-7} \Omega m$. This value was then used to predict voltage sensing lead resistance for the battery:-

Resistivity adjusted for 400°C, $\rho = 5.24 \times 10^{-7}\Omega m$
Wire dia. = 0.9mm
Area, $A = 6.36 \times 10^{-7} m^2$
Length of longest lead, l = 2m

Therefore, actual resistance = $(\rho l)/A = 1.65\Omega$, which confirmed that the actual resistance would be within the maximum specified resistance of 5Ω.

Weld tests were performed with the mild steel wire to 0.2mm thick nickel (as was proposed for the battery). A repeatable weld was produced that caused a "slug" of nickel to be pulled during peel testing. The weld was also metallurgically examined deemed satisfactory and the wire was subsequently used for the battery build.

3.3.2.2. Mica Heater tests

The aluminium plates which carried the heater element in the ETX 2 battery weighed about 10kg. To reduce this contribution, a series of component tests was performed on thin (0.5mm) mica heaters initially using a component designed for the CSPL Bedford Quarter Battery. These tests included:-

(1) Performance checks at battery operating temperature (25 days continuous testing including operation of both main and reserve circuits simultaneously).

(2) Electrical insulation breakdown testing before and after exposure to temperature.

The only evidence of damage to the heater following exposure to battery temperatures was a slight de-lamination of the area close to the heater joint. This de-lamination was compensated for in the battery design by mechanically clamping this area.

A thermal and vibration test was carried out on a full Bedford Quarter Battery featuring top and bottom mica heating and 0.5mm thick insulation.

The vibration test was performed with the battery at operating temperature and the vibration applied only while the battery was being discharged. The following test regime was applied:-

10 to 150 Hz swept sine vibration
Vibration in vertical direction only
Constant 2g peak acceleration
28 hours total accumulated vibration time (over 12 electrical cycles)

No problems with electrical short circuiting to the battery case arose during or after the test indicating that the use of 0.5mm mica was successful. The mica heater was still operational after the full duration of the test with the resistance of the elements remaining unchanged.

3.3.3 Thermal

A long-term test at operating temperature was performed on an enclosure featuring glass fibre insulation. The thermal insulation was evacuated and monitored over a period of a few months and the levels of vacuum attained were recorded. With the vacuum pump disconnected, a steady loss of 0.006W/mK was produced. This equated to a heat loss of 160W/enclosure if the ETX-IIs enclosure sizes were used.

The full Bedford Quarter Battery, noted previously in section 3.3.2.2, contained glass fibre insulation. No problems of the glass fibre compressing under the weight of the battery occurred during build. During the vibration test, no problems were evident with the thermal insulation and sufficient confidence was therefore gained in the insulation to use it in the ETX-IIs Battery.

3.4 CELL SPECIFICATION

3.4.1 Cell Design

The ETX II was the last battery to utilise the MK3SF PB cells. A new PB cell configuration, designated the Mk 4 was designed to improve the manufacturing aspects of the cell (ie a cell "designed for production"). This cell design was sufficiently qualified for it to be specified for the Pilot Production Facility built for CSPL's first licensee, Chloride-RWE and commissioned in October 1990. Subsequently, the cell has been produced in large quantities for vehicle test batteries.

At the time of writing, a 120-cell bank of cells (QB357) made with product from the C-RWE Plant, had completed 1000 cycles with only a single failure at 656 cycles. This result represents the best reliability that the Mk 4 design has demonstrated to date.

At the time of specifying the cell design for the ETX IIs battery, a variant of the MK4 cell was being tested at CSPL. This cell, which contained a new sealing material, was demonstrating exceptional resistance to freeze-thaw, thermal cycles. The test schedule that had been suggested for the ETX IIs battery envisaged a number of freeze-thaw cycles either deliberate or at least likely due to unforeseen circumstances. It was therefore jointly agreed that the more advanced cell variant should be incorporated in the cell build for ETX IIs battery and that the actual cell population should be qualified prior to final battery assembly.

3.4.2 Cell Qualification

Apart from the cell design issues, there were a number of new processes inherent in the cell build that was proposed for ETX IIs battery. The electrolyte was to be manufactured in the newly commissioned C-RWE plant which incorporated a number of significant process changes. Ahead of the ETX IIs cell build, a group of cells had been earmarked as containing electrolyte from the new plant and these were used as a bench-mark for the new product. At the time of battery delivery (Jan 1993), the 116 cells of the group (designated NWRU) had accumulated 126,000 cell cycles. The average cell life was 1086 cycles and the longest lived cells had completed 1928 cycles in 17,280 h. Two failure had occurred at 230 and 623 cycles. The average cell capacity was 78% of the theoretical value based on the cell reactant volumes. The average cycle status of the 36 cells remaining on test was 1440 and for the 78 cells removed intact was 940 cycles. It is not possible to compute Weibull Statistics for this population, but the reliability is obviously high.

A population of cells containing the new glass formulation proposed for ETX IIs cells was also monitored to provide bench mark qualification statistics. The most important data was derived from a 120-cell bank (QB318). This bank was given two thermal cycles, a partial one at cycle 26 (to 180°C) due to a power failure and a full freeze to room temperature at cycle 737. The hazard plot of the data (figure 3-10) shows that the failure mode initiated by the freeze-thaw in Bank 75 is not evident in Bank 318. Bank 75 was made at the same time as the Intermediate Deliverable Battery tested at ANL and did not contain cells with the improved sealant.

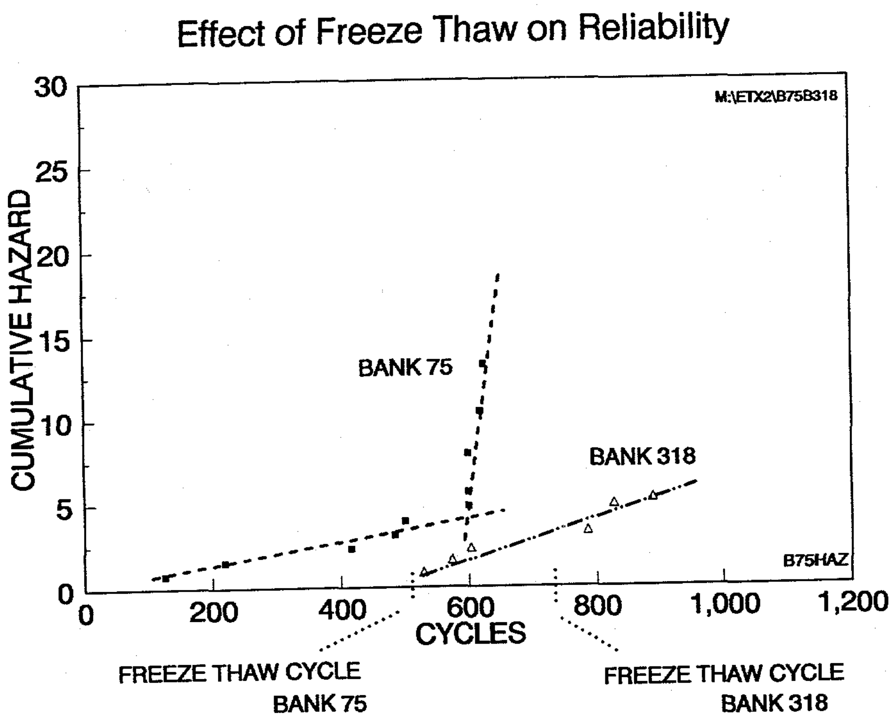


Figure 3-10 Hazard Plot for 120 Cell Bank QB318

During the construction of the battery individual 24 string banks were electrically qualified in dummy bank arrangements. Banks 1 and 14 were rejected from the battery build population and a standard 120-cell bank was built up using all 24 strings from Bank 14 and 6 strings from Bank 1. Further evidence of the improved freeze-thaw survivability of the new cell design is obtained from this bank (QB399).

This unit was electrically tested, but an equipment malfunction caused severe over discharge around cycle 10. Some cells stopped functioning due to loss of negative current collector contact when all of the available sodium was discharged. However, the bank was carefully recovered with a loss of only one string and then continued on cycle testing. On cycle 103, it was given a deliberate freeze-thaw to room temperature. At the time of writing, the bank had recommenced cycling with no obvious deterioration of performance resulting from the freeze-thaw. The graphs in Figure 3-11 show the bank capacity to be affected by the over discharge and slow recovery but unchanged by the freeze-thaw. The progressive re-starting of dried out cells can be seen in the resistance graph.

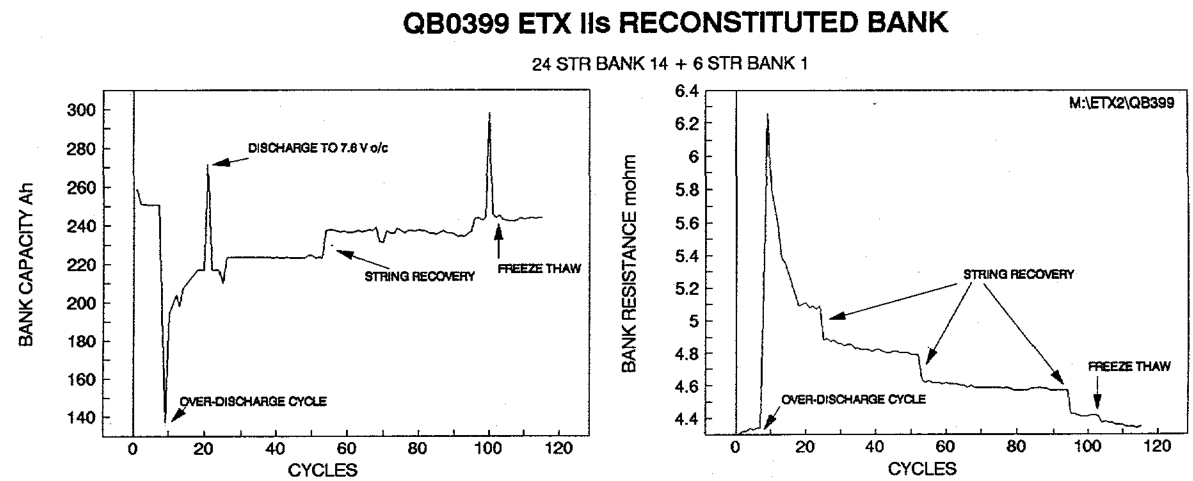


Figure 3-11 Capacity and Resistance of ETX IIs Bank QB399

As with ETX II, the cell build population was monitored by QC cells removed sequentially from the production line. A total of 60 cells were placed on test as single cells or 4-cell strings.

At the time of delivering the battery (January 1993), the population had accumulated 41,950 cell cycles with an average cell life of 699 cycles. Nine cells were removed between 114 and 609 cycles. Of the 46 cycling cells at January 1993, the average cycle life was 811 cycles in 7,300 h. The longest lived cell was cycling at 918 cycles. Five failures had occurred at 17, 292, 539, 540 and 566 cycles. The failure at 292 occurred in a cell that came from a group of cells quarantined because of a glazing furnace malfunction. PTA revealed a failed glass seal, justifying the decision to quarantine the whole batch from which the cell came.

The mean resistance of the cells in January 1993 was 32.3 mohm compared to a mean minimum resistance of 29.4 mohm. The resistance rise was thus 2.9 mohm in about 800 cycles ie approximately 3.6 mohm per 1000 cycles. The average capacity retention of the group was 84.45% for the cycling cells (at an average of 811 cycles each). The longest lived cells all had capacities slightly above the mean value at 85%.

3.4.3 Battery Reliability Prediction

It is difficult to generate meaningful Weibull statistics from the data available. The ETX IIs peer group of 60 cells had only 3 failures at the time of writing if the 292 and 17 cycle failures were censored. PTA identified the cycle 17 failure as an abnormal defect on the electrolyte and it might be anticipated that the pre-qualification procedure applied in the bank build would have screened out any similar defects. One cell did fail from the 1344 tested, supporting this conjecture. The failure at 292 cycles can be justifiably censored on the grounds that it was quarantined, as described earlier.

Other populations that might be used to predict reliability have caveats associated with them, either due to testing differences, cell design differences or process differences. However, in order to make an assessment, three populations have been analysed. The data are summarised in Table 3-3. The chosen data groups are the 60 cell peer group of ETX IIs, the 120-cell bank QB318 and a group of 295 cells which all have the advanced glass seal feature. In order to illustrate the shape of the failure function, hazard plotting was used to create Figure 3-12. QB318 showed an increase in failure rate after 1000 cycles. The ETX IIs 60 cell population had not reached that stage when the analysis was performed and so it was not known if the same effect would occur. The 295 cell population includes cells that operated for more than 2000 cycles without any evidence of an upturn in failure rate.

Table 3-3 Weibull Statistics for ETX IIs Peer Group and Associated Cells

Population	Cycle Status	Weibull (Maximum Likelihood Estimate)		Weibull (Hazard Plot Least Square)	
		Characteristic Life (cycles)	Modulus	Characteristic Life (cycles)	Modulus
QB318	1136	$_{1408}\,1894\,^{2549}$	$_{2.4}\,4.1\,^{6.9}$		
QB318 + 60 cell	810			1900	3.2
	1100			2282	2.7
295 cell Associate Group	Avg 750	$_{1935}\,2648\,^{3624}$	$_{2.4}\,3.3\,^{4.7}$		

<u>Failures</u>

QB318 @ 810 510, 577, 596, 795, 805
@ 1136 856, 1011, 1063, 1064, 1070, 1094, 1096, 1112, 1136

60 Cell 539, 540, 566

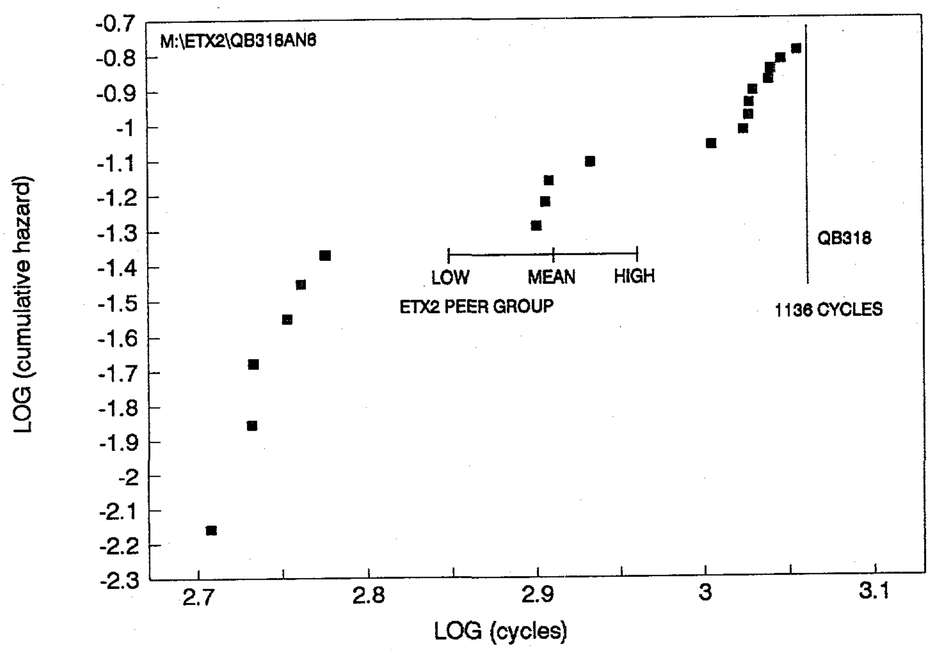


Figure 3-12 Hazard Function for ETX IIs Peer Group Testing

Weibull parameter combinations of 1900/3.2, 1890/4.1 and 2648/3.3 were used to generate the survival probability graphs in Figure 3-13. If 5% cell failures is used as a battery failure criteria, then a life of 750, 900 or 1050 cycles is predicted for each of the three weibull combinations. A 20% reduction in capacity would occur when about 2.7% of cells had failed.

These lifetimes are predictions based upon a two or three cycle per day test regime at 350°C nominal test temperature. The banks were tested at two cycles per day and the cells and strings at three cycles per day. Allowing the battery to idle at 300°C and a reduced cycle frequency rate will probably increase its calendar life expectancy, high power discharges generating higher temperatures will probably decrease the calendar life expectancy.

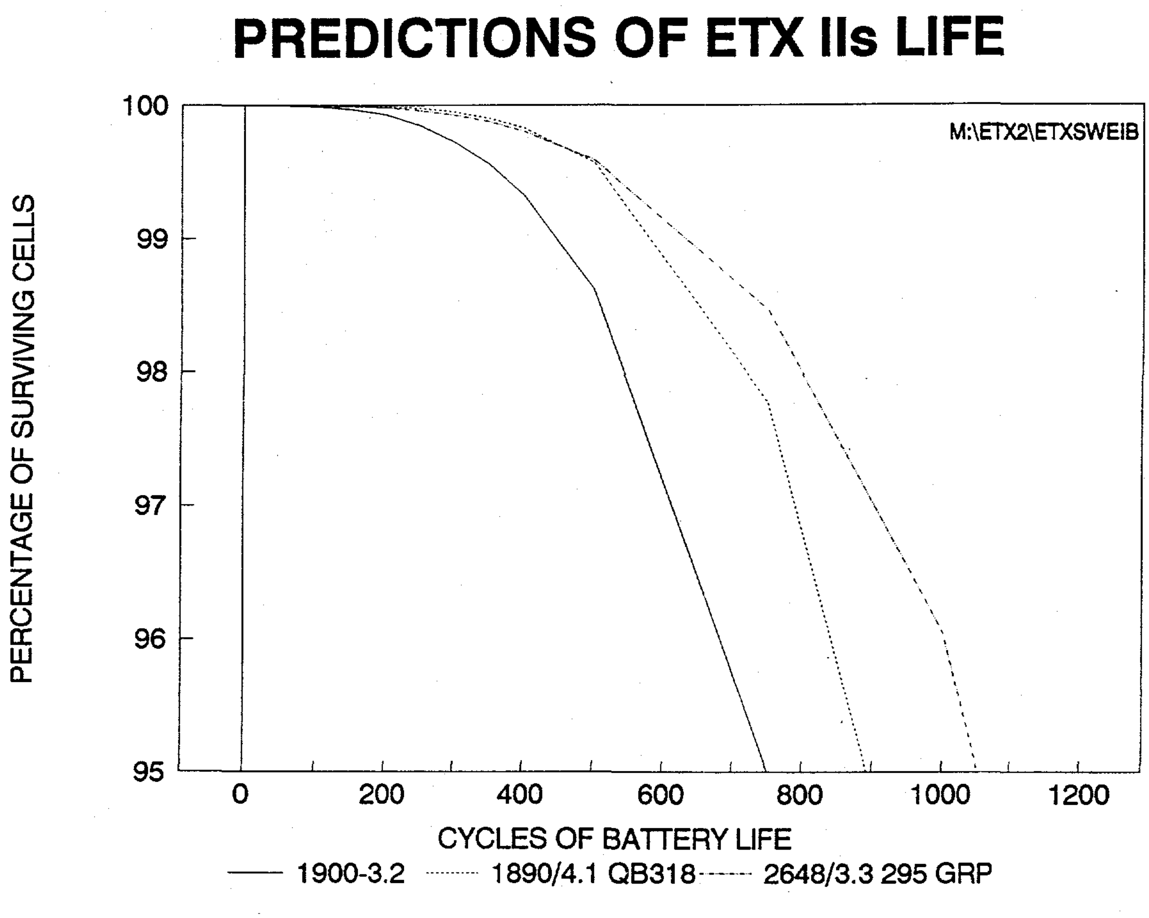


Figure 3-13 Prediction of Two Cycle per Day Lifetime of ETX IIs

3.5 SAFETY TESTING

An objective of the programme was to enhance the safety of the battery. This was accomplished by attention to detail and incorporation of results and experience gained from CSPL-funded parallel programmes. In particular, an extensive programme of destructive testing of 18 kWh batteries has been completed. This included shock tests at 25, 40 and 500g, fire tests (at 5 min and 30 min), short circuit, over voltage, crush testing, impact testing and penetration testing. This comprehensive series of tests was witnessed by external observers and overall was considered very successful. The results gave confidence about the safety characteristics of the ETX IIs Battery.

3.6 FINAL ETX IIs BATTERY DESIGN

The final battery design procedure consisted of taking the qualified concepts, making any necessary, low risk refinements and incorporating them into the detailed engineering drawings required by the production build team. As a result of the lengthy qualification procedures that were implemented, only minor detail changes were required at the final stage. However, because the build up of a battery could not be attempted until the final components were available, some modifications were incorporated at late stages of the build. In the case of bank assembly, new jigging was manufactured at a late stage to circumvent some of the problems encountered.

Final weld off of the outer enclosure lid was the last detail to be finalised. Plans were made to accommodate both a down turned lid and the older design upturned lid. Trials were made just prior to closing the outer enclosure and the neater, smaller, down turned design was employed for the actual battery.

The general arrangement of the battery is shown in Figure 3-14.

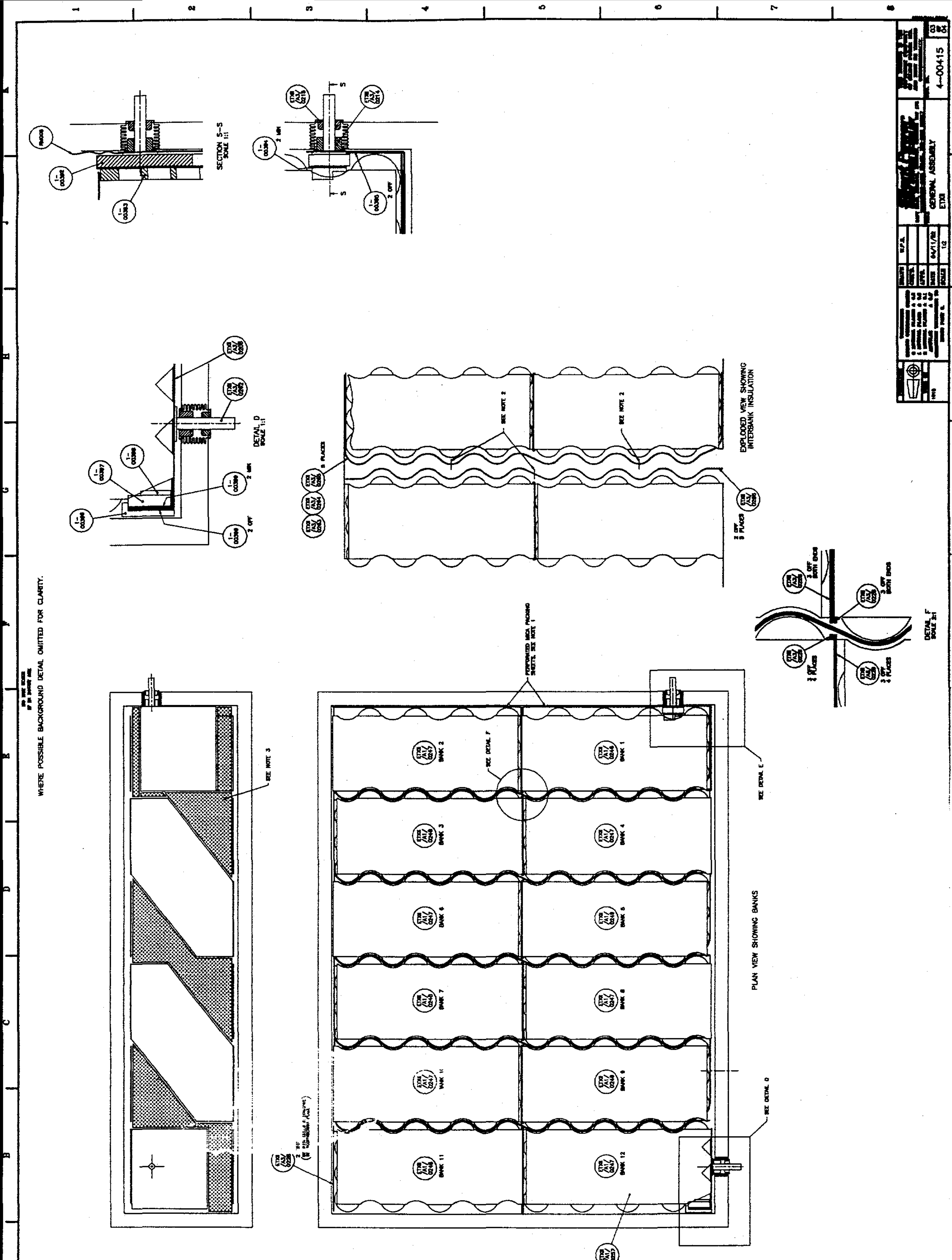


Figure 3-14 General Arrangement Drawing of ETX IIs Battery

3.7 BATTERY BUILD

In order to ensure a sufficient supply of cells to construct the deliverable battery and to provide spares and QC cells, a total of 1514 cells were constructed. The electrolytes and other components were withdrawn from stock. Final assembly of the first cells took place on 3rd February 1992 and the final cells were made on 24th March 1992. Every cell was assigned a unique number. In accordance with cell build procedures in the development production area, full records were kept of the batches employed and process dates.

Each cell was subjected to two thermal proof test cycles before being radiographed. This procedure was a precaution following the failure of a cell at 17 cycles in the 60 cell peer group. After radiography, consecutive cells were welded into 4-cell strings and allocated a string number. A computer randomisation of strings was created for the fourteen, 24 string banks and this number layout was followed by the assembly technicians. The strategy behind this method was to spread any rogue batches throughout the battery but to keep "rogues" in the same string, where the first to fail would have effectively isolated the other three, minimising the effect on the battery. Experience with the ETX II battery had confirmed the benefits of this approach with an even spread of failures throughout the banks of that battery. A criteria applied to the build was that high yields were to be achieved for acceptance of the batch. With the exception of the batch which was glazed during a furnace failure no batches were rejected due to poor yields.

The accepted, numbered strings were assembled into their allocated banks and a dummy top bank plate was welded temporarily so that electrical pre-qualification could be conducted. Figure 3-15 shows the pre-qualification banks in a trial assembly

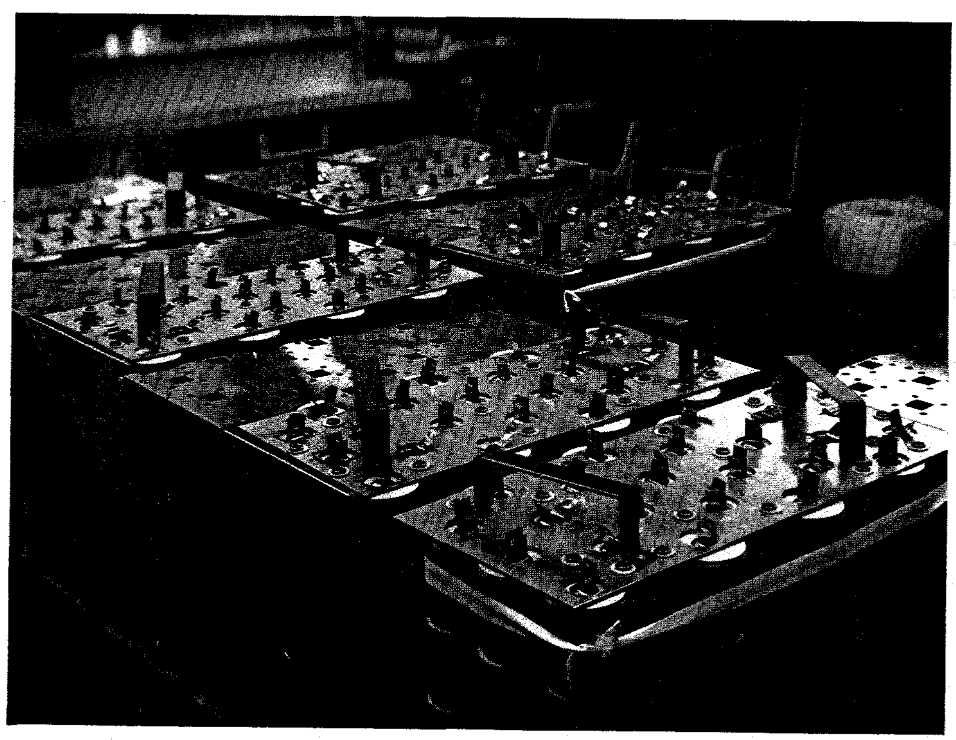


Figure 3-15 Pre-Qualification Banks for ETX IIs

For pre-qualification testing , the banks were tested in two groups, Banks 1 to 7 and Banks 8 to 14. The banks were cycled for 2 electrical cycles to assess the acceptability of the strings for battery construction. Cycle 1 was a discharge at 12A until 240Ah was discharged or until the first bank reached an open circuit voltage limit of 8.0V, followed by recharge at 12A until the first bank reached a load voltage limit of 9.1V. Cycle 2 was a discharge at 48A until 245Ah was discharged or until the first bank reached an open circuit voltage limit of 7.8V, followed by recharge at 24A until the first bank reached a load voltage limit of 9.1V.

Table 3-4 summarises the end of discharge data on cycle 1 of the banks. Discharge terminated when Bank 1 reached the open circuit voltage limit of 8.0V when 226.1Ah had been discharged.

Table 3-4

End of Discharge Data (ETX IIs 1st Group Cycle 1)

Bank Number	End of Discharge Open Circuit (V)	Resistance (mohm)	Temperature (°C)	Predicted Capacity to 7.6V o/c (Ah)
1	7.995	5.99	352	283.6
2	8.065	5.79	355	303.5
3	8.083	5.84	349	308.9
4	8.082	6.15	343	308.6
5	8.079	5.77	354	307.6
6	8.081	5.87	353	308.1
7	8.078	5.99	346	307.2

The final column of Table 3-4 indicates that the predicted capacity of Bank 1 was around 24Ah less than the predicted capacity of the remaining banks, suggesting that Bank 1 included 1 or 2 non-operational strings. Based upon the resistances of Banks 2, 5 and 6 with similar test temperatures to Bank 1, the resistance of Bank 1 with 1 failed string would be expected to be 6.06 mohm.

On cycle 1, recharge terminated at 215.1Ah, a shortfall of 11Ah. The limiting bank on recharge was Bank 7, which reached the load voltage limit of 9.1V first.

Table 3-5 summarises the end of discharge data on cycle 2 of the banks. Discharge was terminated when Bank 1 reached the open circuit voltage limit of 7.8V, after 229.2Ah had been discharged.

Table 3-5

End of Discharge Data (ETX IIs 1st Group Cycle 2)

Bank Number	End of Discharge Open Circuit (V)	Resistance (mohm)	Temperature (°C)	Predicted Capacity to 7.6V o/c (Ah)
1	7.789	5.68	360	251.0
2	7.885	5.37	365	265.2
3	7.887	5.42	359	265.5
4	7.884	5.65	351	265.1
5	7.885	5.43	361	265.2
6	7.887	5.49	361	265.5
7	7.884	5.55	353	265.1

The data indicated that Banks 2-7 inclusive were well-matched, but predicted capacity data and resistance data on Bank 1 suggested the presence of one non-operational string - based on the performance of Banks 3, 5 and 6, the resistance of a bank with a non-operational string would be 5.69 mohm at 360°C.

On cycle 2, the recharge terminated when 227.2Ah had been recharged, a deficit of 2Ah.

Assuming a bank resistance of 5.65 mohm for a completely operational bank at 350°C and a contribution of 10 mohm from inter-cell connections and connections to bank plates, an equivalent cell resistance of 31.4 mohm was calculated for the cell population (The ETX IIs peer group strings gave a mean cell resistance of 30.5 mohm at 350°C after 5 electrical cycles).

Banks 2-7 inclusive operated normally but Bank 1 appeared to include a non-operational string. Bank 1 was segregated and the location of the non-operational string determined. Strings were used to make up QB 399 as described earlier in this report.

The second group of banks was tested in an identical manner. Table 3-6 summarises the end of discharge data on cycle 1 of the banks. Discharge terminated when Bank 8 reached the open circuit voltage limit of 8.0V after discharging 233.2Ah.

Table 3-6

End of Discharge Data (ETX IIs 2nd Group Cycle 1)

Bank Number	End of Discharge Open Circuit (V)	Resistance (mohm)	Temperature (°C)	Predicted Capacity to 7.6V o/c (Ah)
8	7.996	5.75	356	292.9
9	8.014	5.62	356	297.9
10	8.019	5.68	352	299.4
11	8.019	5.88	344	299.4
12	8.014	5.59	357	297.9
13	8.015	5.58	357	298.2
14	8.019	5.80	357	299.4

The final column of Table 3-6 indicates that the predicted capacity of Bank 8 was slightly less than the remainder but the difference was insufficient to be indicative of a non-operational string.

On cycle 1, recharge terminated when 222.3Ah had been recharged, a shortfall of 10.9Ah.

The predicted capacities, the resistances and temperatures for each of Banks 8 to 14 is given in Table 3-7.

Table 3-7

Performance Data (Cycle 2)

Bank Number	End of Discharge Open Circuit (V)	Predicted Capacity to 7.6V o/c (Ah)	Resistance (mohm)	Temperature (°C)
8	7.765	263.3	5.46	362
9	7.762	262.9	5.37	365
10	7.763	263.0	5.42	362
11	7.761	262.8	5.56	352
12	7.760	262.6	5.40	363
13	7.760	262.6	5.32	365
14	7.762	262.9	5.54	359

The resistance data confirms that the banks were well-matched with no evidence of failures. On cycle 2, the recharge terminated when 244.3Ah had been recharged, an excess of 1.1Ah. Predictions of equivalent cell resistance from the bank data are similar to the prediction from the first 7 banks i.e. 31.4 mohm at 350°C.

On the basis of the foregoing data, Banks 2 thru 13 were prepared for final assembly into the battery.

Final Assembly

The unprepared battery box is shown in Figure 3-16. Problems were also encountered with the welding of the bellows, a rare occurrence after a long series of successful box constructions. Figure 3-17 shows the side plate heater and instrumentation panel being positioned and Figure 3-18, the box prior to placement of the banks.

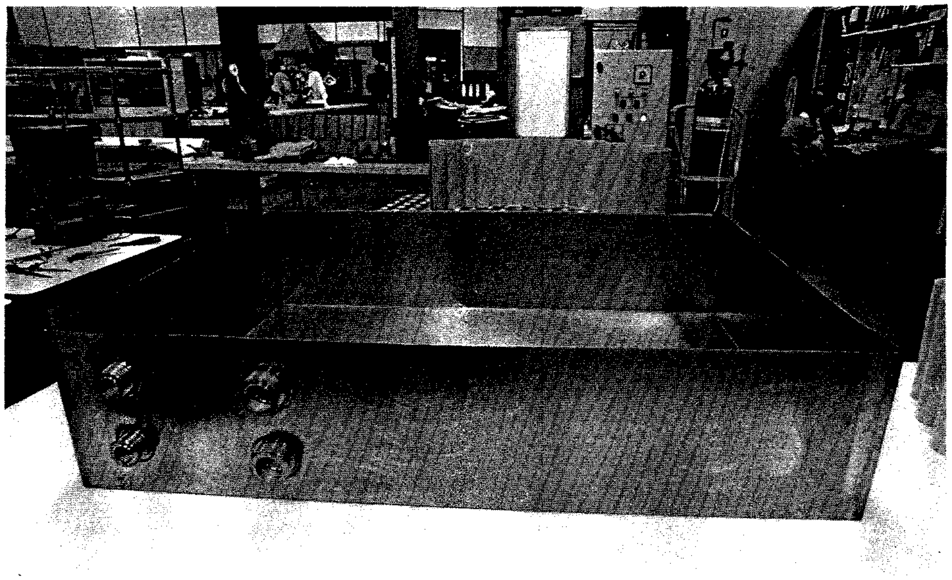


Figure 3-16 ETX IIs Unprepared Battery Box

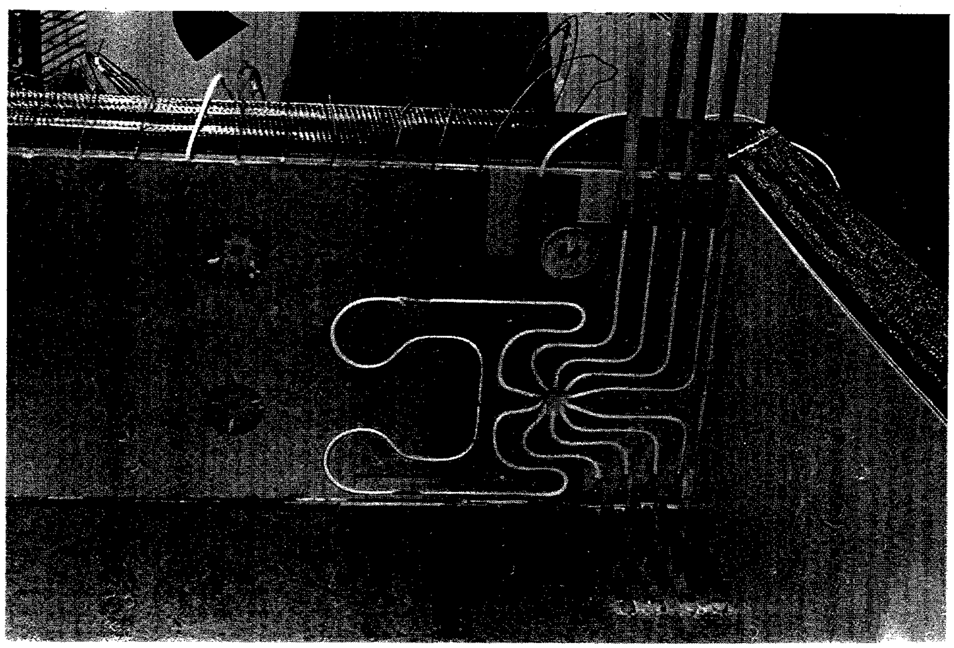


Figure 3-17 ETX IIs Side Plate and Heater Arrangement

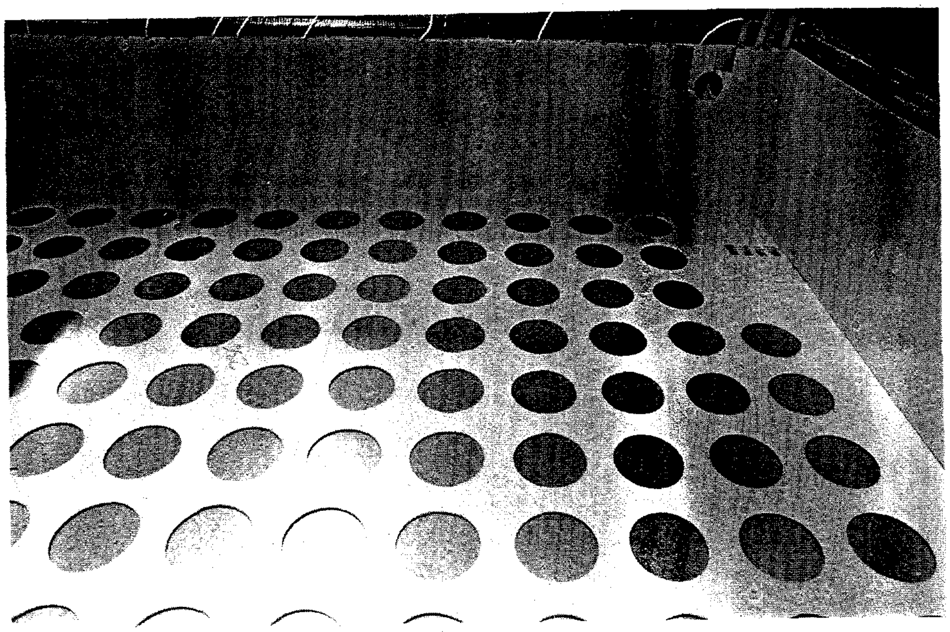


Figure 3-18 ETX IIs Prepared Box Ready for Bank Assemblies

Figure 3-19 shows the start of the assembly of the bank into the box and the moulded inter-bank insulation. The battery just prior to and during termination weld off is shown in Figures 3-20 and 3-21.

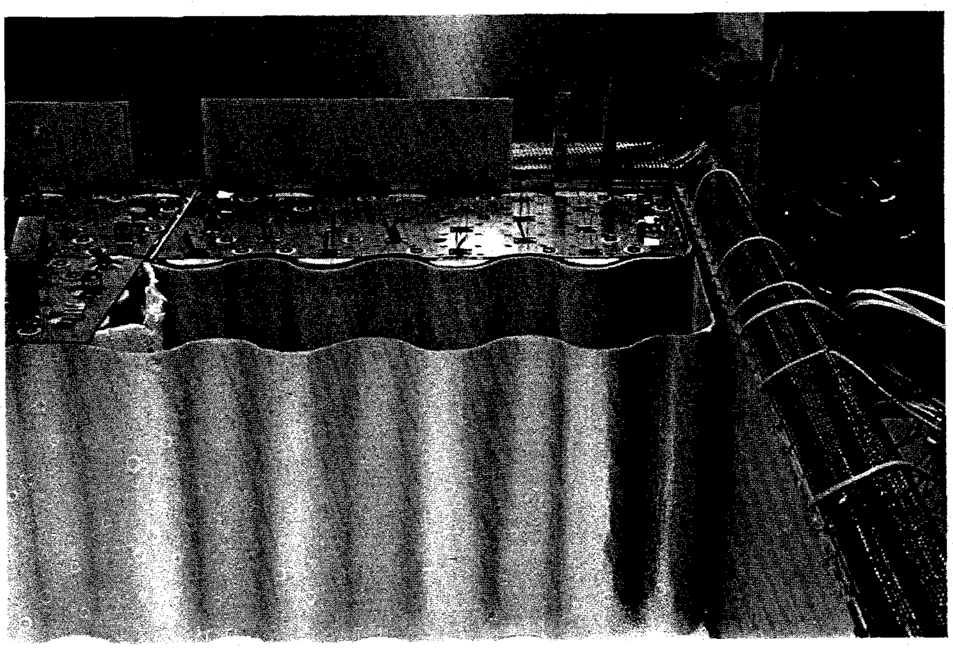


Figure 3-19 ETX IIs Start of Final Bank Assembly

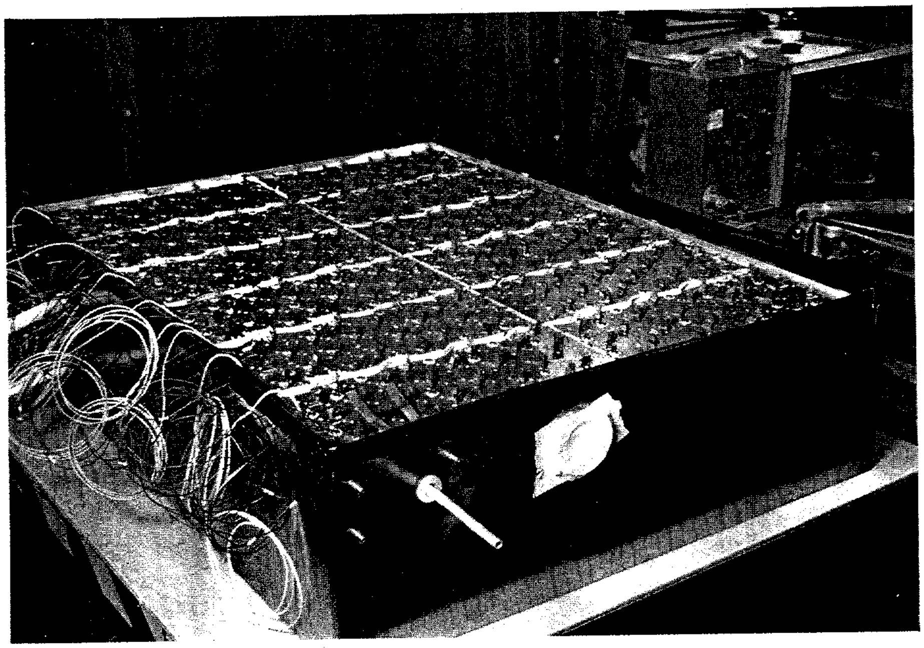


Figure 3-20 ETX IIs Battery with Banks in Place Prior to Termination Weld

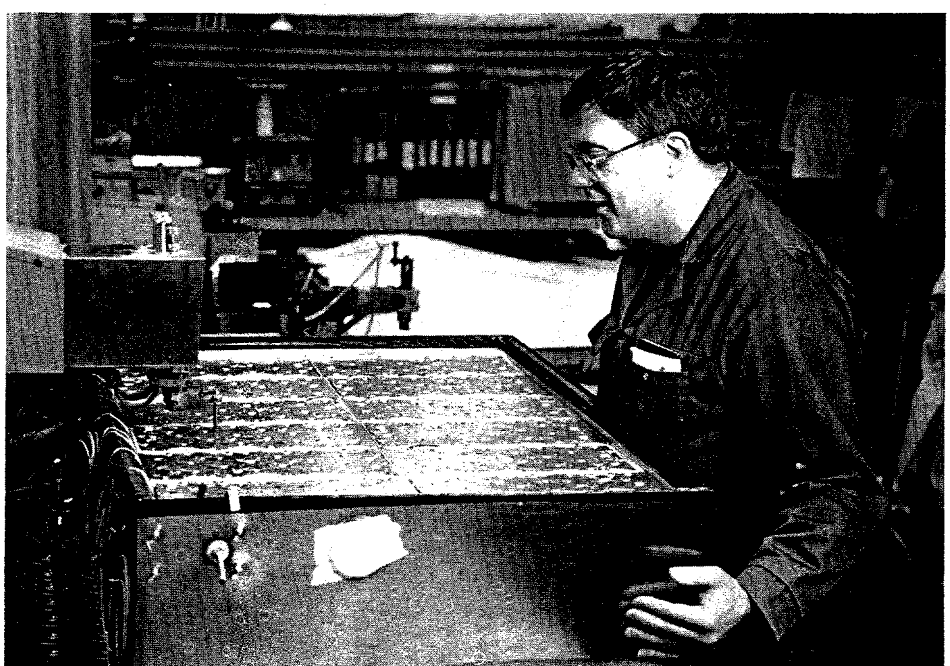


Figure 3-21 ETX IIs Final Termination Weld-off

The battery box was completed by the final electrical checks and welding off. Weld off was performed by an automatic linear welder set up on trial components and then temporarily attached to the actual battery box. The down turned, bank plate configuration was used.

Electrical Pre-qualification

Prior to delivering the battery for testing in the US final electrical qualification and thermal insulation conditioning was performed. The battery was placed in a conventional oven so that external heat could be applied. Evacuation of the enclosure was started prior to warm-up and the enclosure was continuously pumped during warm-up. The external surface of the battery was brought to 180°C while the inner temperature of the battery was increased at the normal rate to 180°C, and then more quickly to 350°C.

No temperature excursions were evident suggesting that all cells successfully warmed up. At temperature, the heaters were re-configured in series and the trace heater operated in series with the top heater. The maximum temperature variation across the cell matrix, prior to the initial discharge was 22°C.

On electrical cycle 1, 255 Ah was discharged at a nominal battery resistance of 70 mohm, (predicted resistance was also 70 mohm). The capacities of each bank were as shown in Table 3-8. At the end of the first discharge, the maximum cell temperature rise from 362°C to 385°C and the distribution in the matrix was 24°C although this reduced to 10°C if thermocouple 8 was ignored. Thermocouple 8 was positioned close to the negative lead-through pin.

Thermal insulation conditioning was performed during the electrical cycling.
With the external temperature at 180°C and an internal battery temperature of 350°C two Argon purges were carried out in order to remove moisture from the glass fibre insulation. The pump was then re-connected .

Table 3-8 ETX IIs First Cycle Bank Capacities

Battery Bank Number	Pre-Qualification Bank Number	1st Cycle Capacity Ah
1	2	257.5
2	3	254.7
3	4	254.6
4	5	254.4
5	6	254.5
6	7	254.4
7	8	254.7
8	9	258.1
9	10	257.6
10	11	258.0
11	12	257.6
12	13	257.1

Figure 3-22 shows the battery resistance during the first cycle charge/discharge. Figure 3-23 shows the individual bank resistances. Figure 3-24 shows the average temperature profile during the first charge-discharge cycle.

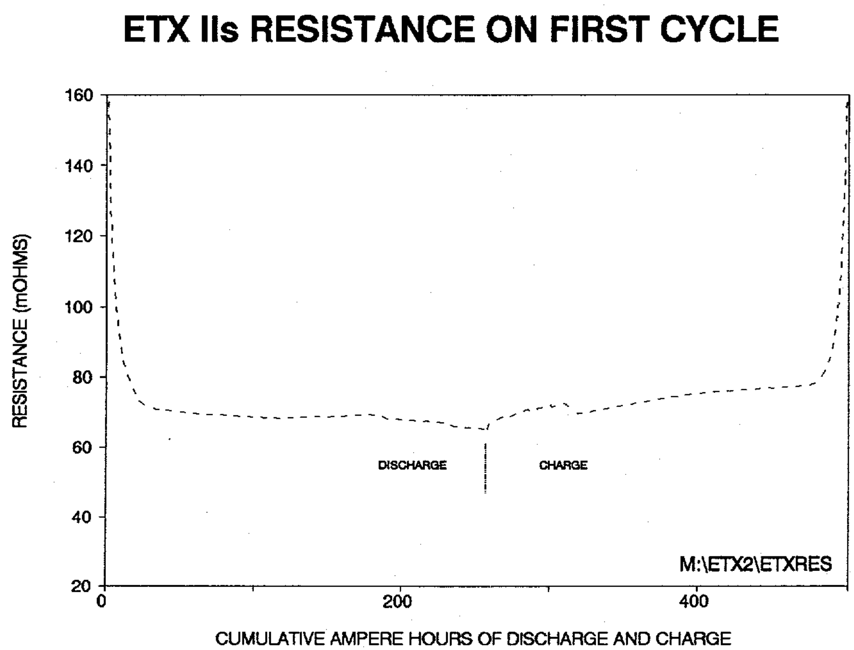


Figure 3-22 ETX IIs Battery Resistance on First Cycle

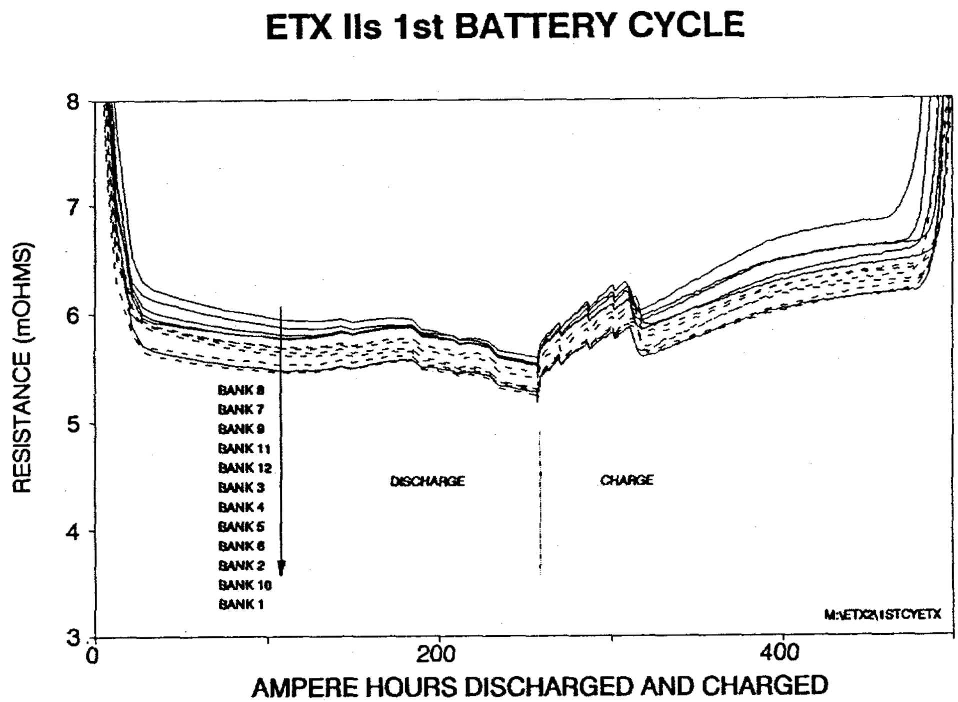


Figure 3-23 ETX IIs Individual Bank Resistances on First Cycle

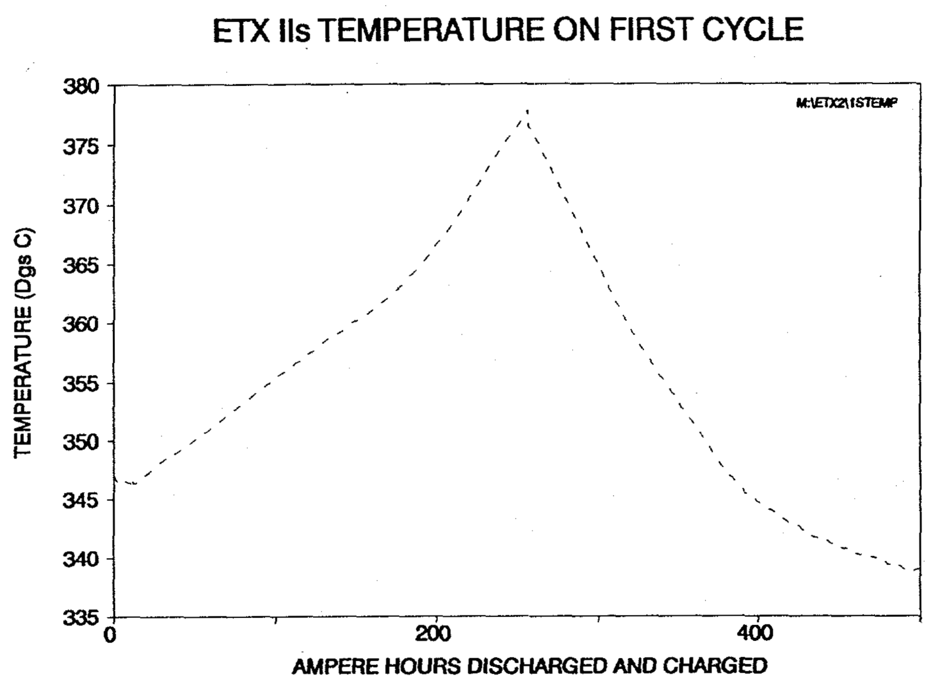


Figure 3-24 ETX IIs Temperature Profile During First Cycle

Final wiring of the terminal, power leads and instrumentation boxes concluded the battery assembly. Considerable progress was made with the control and instrumentation hardware during the time of the contract, substantially on parallel programmes. The profile of the termination box was considerably reduced by the miniaturisation of instrument connections is shown in Figure 3-25.

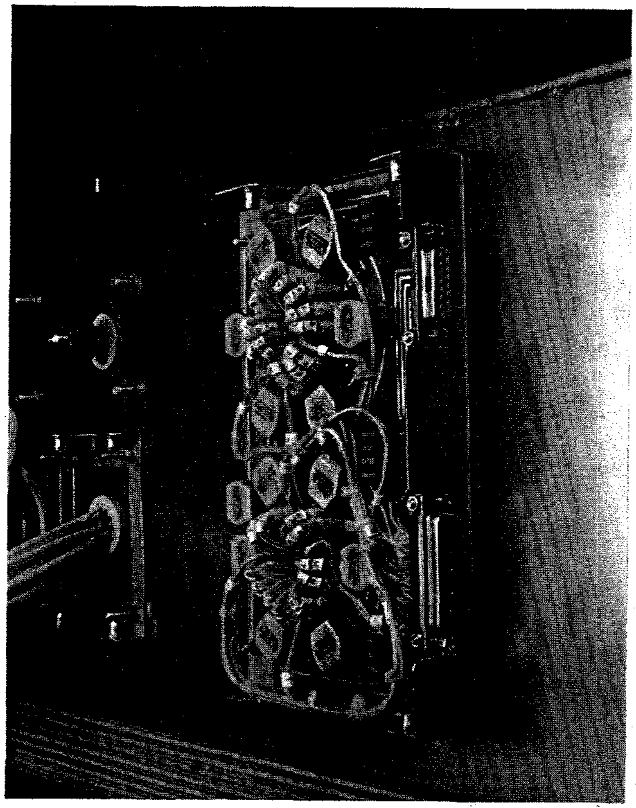


Figure 3-25 ETX IIs Instrumentation Termination Box

The complete battery is shown in Figure 3-26

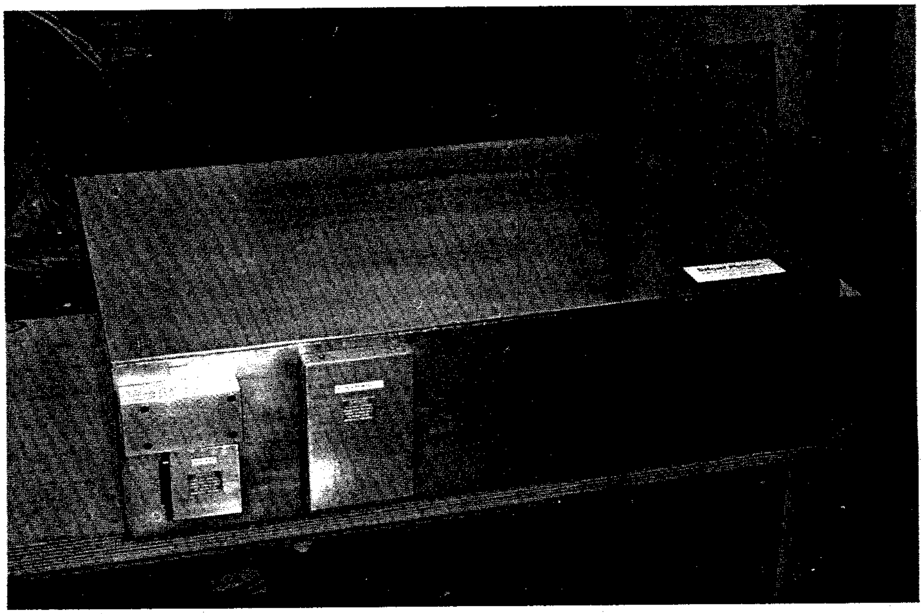


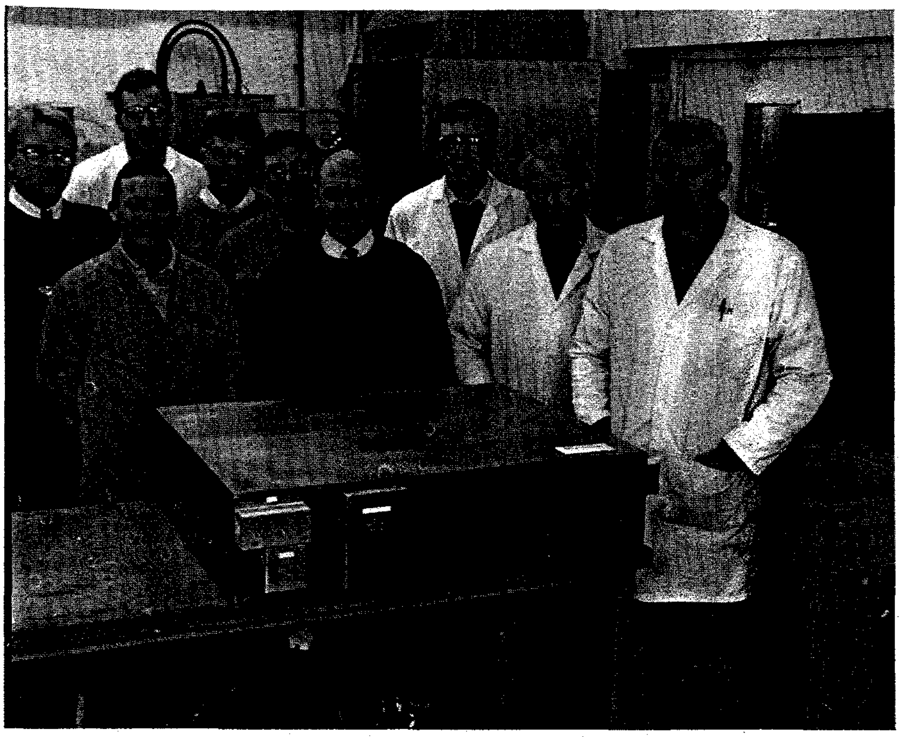
Figure 3-26 The Completed ETX IIS Battery Prior to Dispatch

3.8 SUMMARY

The stated objective of the ETX IIs phase of the program was the manufacture of a lower weight battery. This was accomplished as the half battery weighed 230 Kg, an improvement of 14 Kg over the predicted weight. This should increase the gravimetric energy density to around 105 Wh/Kg. The actual height of the complete battery was 238 mm, the nominally predicted value. With a breadth and width of 710 mm and 927 mm this gave the predicted battery volume of 156.6 l, equivalent to 154 Wh/l. The technology incorporated in the battery was state of the art for the time and providing the predictions from the trials and test cells are replicated there is a reasonable expectation that a worthwhile demonstration will follow from the testing at ANL.

4.0 ACKNOWLEDGEMENTS

The following people and organisations are acknowledged for their input into the program. The scope of the contract was such that the input came from a broad range of US based organisations and naming of individuals would almost inevitably lead to omissions. However the efforts of Dr Jeffrey Braithwaite the Sandia Program Manager, and the CSPL build teams should be specially highlighted. The contract was managed from DoE headquarters, and DoE Albuquerque Field Office. Testing was performed by Ford at Dearborn, the Argonne National Laboratory and Idaho National Engineering Laboratory. Their efforts are duly acknowledged.



The Battery Build Teams

5.0 REFERENCES

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2. WH De Luca, AF Tummillo, JE Kulhaga, CE Webster, KR Gillie, R Hogrefe. Performance Evaluation of Advanced Battery Technologies for Electric Vehicle Applications. Proc. 25th IECEC August 1990.

6.0 APPENDICES

APPENDIX A
PROGRAMME CHRONOLOGY

ETX II PROGRAMME CHRONOLOGY

Sept 86	Original contract signed
Jul 87	Task 1, Design Trade-off completed.
Dec 87	Bedford battery fails. (contained MKIIA Cells). Design of the intermediate deliverable battery nearly complete and specifying 6 or 7 banks of 120 cells.
Jan 88	Programme amended to concentrate on ETX II design.
Feb 88	Intermediate Programme Review. First lidless battery enclosure received by CSPL. 4 top and bottom cooling arrays under construction.
Mar 88	Lidless dummy battery design completes trials. Battery cooling method firmed up.
Apr 88	Side-plate bank interconnection designs being scoped into hardware.
May 88	Vibration of silicone-filled MK3 cells. Fibreglass compression trials commenced in heat conductioning.
Jun 88	Battery Design Review at Albuquerque. Design of the IDB completed. Double skin lidless battery completes 45 days evacuation test.
Aug/Sept 88	Design Review of Intermediate Deliverable Battery. ETX II weight estimated at 550 kg. Weight analysis completed. IDB changed from 7 banks to 8 banks. Tests on Bi-metallic Aluminium Composite plates began. Shock testing of cells initiated. Thermal modelling completed.
Oct\Nov 88	Cells for IBD completed with an average resistance including connects of 37.5 mohm.
Dec 88	IDB completed. Qualification bank completes 35 cycles.
Jan 89	IDB delivered to ANL.

Feb 89	Final Design Review for ETX II Battery. IDB reaches 80 cycles. Qualification bank removed from test at 216 cycles.
Apr 89	IDB completes 100 cycles with no failures. Cause of premature failure of Qualification Bank isolated to glass seal defect.
May\Jul 89	IDB removed from test after 237 cycles. 1000 cells for ETX II completed. First delivery of Lightweight Bank Plate Material (LBM).
Jun 89	Design review for ETX IIs battery.
Aug\Oct 89	PTA of IDB completed and report issued. All banks for ETX II commissioned. Capacity predicted as 300 Ah 115 to 120 mohm. Improved welding techniques for battery enclosures introduced.
Oct 89	Programme Review at Albuquerque.
Dec 89	B138, 154 and 155 placed on test.
Jan 90	ETX II battery completed and delivered to Ford. Ground fault detected and a rebuilt agreed to.
Jul 90	Rebuild complete. Battery returned to Ford. ETX IIs Contract extension signed.
Aug 90	Schematic ETX IIs design created. Weight reduction study commenced.
Sept 90	On board vehicle testing of ETX II battery. Capacity determined at 297 Ah and the vehicle range estimated at 157 miles.
Oct 90	Lightweight bank design developed.
Oct\Nov 90	ETX II battery shipped to INEL.
Dec 90\Mar 91	Preliminary testing of ETX II completed at INEL.
Mar\Oct 91	ETX II battery on O/C hold at INEL.
Nov 91\Mar 92	Limited testing of ETX II at INEL.

Nov 90	Improved lightweight heater development commenced.
Dec 90	ETX IIs layout and Bank Design finalised. Height and weight study completed.
Mar 91	Lightweight module concepts vibration tested.
Apr 91	Mica tube testing completed.
Aug 91	ETXIIs qualification cell designs commence test.
Sept 91	120-cell safety module tested.
Dec 91	QB 318 Completed 445 cycles.
Jan 92	ETX IIs cell build commenced. QB318 completed 600 cycles.
Mar 92	ETX II battery cooled down at INEL. Formal design review ETX IIs battery.
Apr 92	ETX IIs population fore-runner cells reach 150 cycles.
Jun 92	Decision to build and deliver only one of two batteries needed to power the ETX II s system.
Jul 92	ETX IIs QC Cells reach 375 cycles. Average resistance 30.5 mohm. 7 banks for battery prepared.
Aug 92	QB318 completes 1000 cycles including a full freeze-thaw cycle.
Sept 92	ETX IIs final battery assembly commences.
Dec 92	ETX IIs commissioning cycle completed.
Jan 93	Final wiring commences. ETX IIs Battery arrives in USA for life testing at ANL.