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A HIGH RELIABILITY BATTERY MANAGEMENT SYSTEM

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SUMMARY

Over a period of some 5 years Canadian Astronautics Limited (CAL) has developed a system to autonomously manage, and thus prolong the life of, secondary storage batteries. During the development, the system has been aimed at the space vehicle application using nickel cadmium batteries, but is expected to be able to enhance the life and performance of any rechargeable electro-chemical couple.

The system handles the cells of a battery individually and thus avoids the problems of over, and under, drive that inevitably occur in a battery of cells managed by an averaging system. This individual handling also allows cells to be totally bypassed in the event of failure, thus avoiding the losses associated with low capacity, partial short circuit, and the catastrophe of open circuit. The system has an optional capability of managing redundant batteries simultaneously, adding the advantage of on line reconditioning of one battery ,while the other maintains the energy storage capability of the overall system.

As developed, the system contains a dedicated, redundant, microprocessor, but the capability exists to have this computing capability time shared, or remote, and operating through a data link. As adjuncts to the basic management system CAL has developed high efficiency, poly phase, power regulators for charge and discharge power conditioning.

A number of the units comprizing the system were developed to the level of qualification hardware, including a fully redundant discharge converter.

BASIC CONCEPT

CAL undertook a series of contracts under the sponsorship of the Canadian Department of Communications, to design, develop, manufacture and test a concept for the improvement of life expectancy of spacecraft nickel cadmium batteries. It was clear from the body of work carried out to determine the life limiting factors of nickel-cadmium cells and batteries, and was well summarized in the NASA 'Sealed-Cell

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Nickel-Cadmium Battery Applications Manual', that good control of a small number of key operating modes should bring about a significant improvement in useable life and capacity.

These controls are:-

- Prevention of voltage reversal.
- Minimise overcharging.
- Eliminate secondary effects of open, or short, circuiting a cell.
- Provide facility for reconditioning cells.

On developing this short list it is clear that all these parameters relate to single cells rather than to complete batteries and that the secret to the improvement needed was to be able to control individual cells, rather than entire batteries.

The basic concept,then, was fairly simple, to provide each cell with a controllable by-pass system, and this was made feasible by the introduction of the high current, vertical D-MOS power MOSFET transistor.

The basic circuit for a cell by-pass circuit is shown here (Fig 1). It consists of a relay controlled shorting switch and a logic operated, controlled current, by-pass transistor. The logic operating the bypass transistor includes a d.c. isolator, such that the control logic can operate at a common reference level. Providing a logical ON command to a by-pass input, enables a multivibrator oscillator. The output of the oscillator is transformer coupled, providing d.c. isolation, and rectified into a preset voltage divider to provide the controlled gating voltage to operate the by-pass transistor.

The shorting switch actually consists of two sets of relay contacts in series so the the accidental closure of one relay will not cause a catastrophic short circuit across the cell.
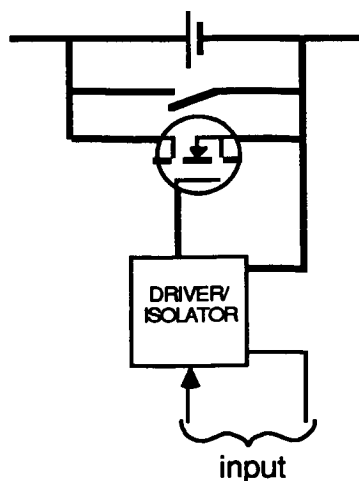

Figure 1. BASIC CIRCUIT

input

306

The MOSFET transistor contains an inherent diode between the source and drain which tends to prevent a cell from being driven too far into voltage reversal during a deep discharge. In normal operation this feature is not required since, as soon as it is determined that the cell has been drained of energy, the shorting switch is closed. This prevents any voltage inversion occurring within the cell, and prevents the depleted cell's internal impedance causing unnecessary power loss.

The by-pass transistor is set up such that when it is operated only the normal trickle charge current flows in the cell. Consequently, when an individual cell is adjudged to have reached its 'top of charge', its current can be reduced to a maintaining level while the cells in series with it continue to accumulate charge to their individual full capacity.

IMPLEMENTATION

The figure below (Fig. 2) represents a implementation of the basic system outlined above, expanded to the level of a power sub-system, having a solar array source, and providing a coarsely stabilised output.
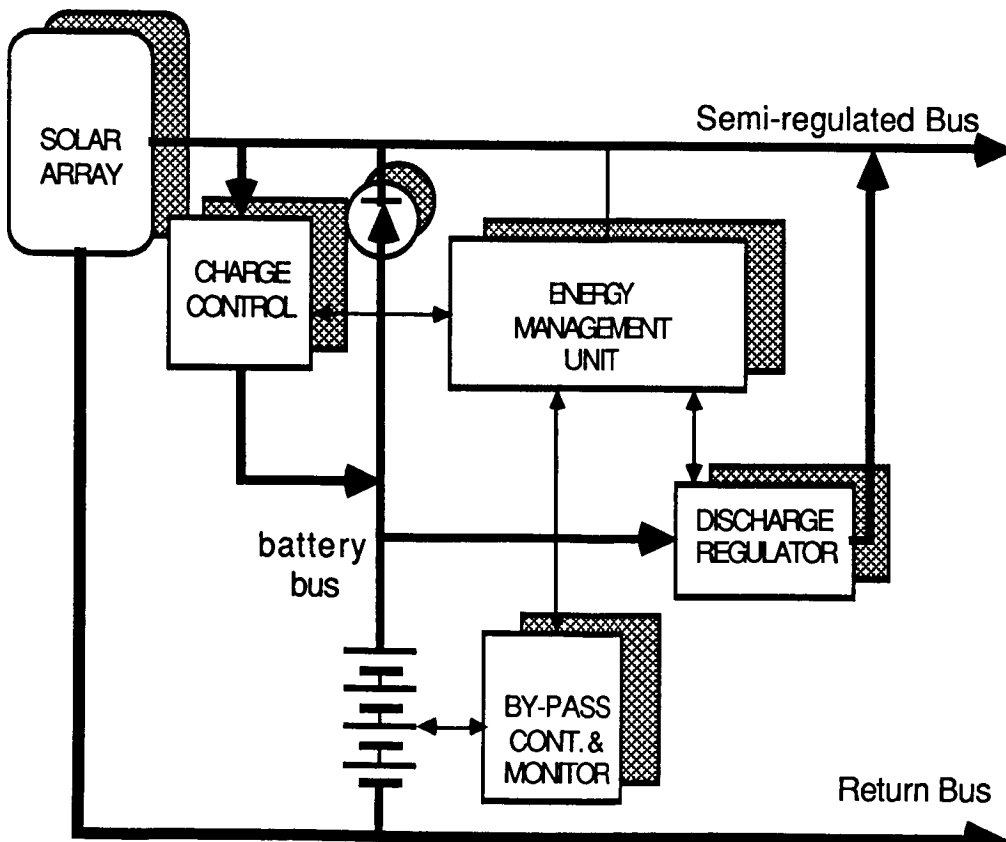

Figure 2. BASIC SYSTEM BLOCK DIAGRAM

It is assumed that the solar array is provided with a shunt regulator, and that during insolation periods, the solar array will maintain the semi-regulated bus. The energy management unit monitors the voltage of this bus, and , providing its voltage is high enough, it directs the charge control regulator to provide power to the battery for the storage or maintenance of charge. The energy management unit is also monitoring the state of charge of the cells in the battery and so knows if the charge current required is for a full charge or for a maintaining (trickle) mode. When the demand on the semi-regulated bus exceeds the capacity of the solar array to the point where the bus voltage falls below some predetermined level, the management unit disables the charge control regulator, switches off any active by-pass circuits, except those around permanently failed cells, and enables the discharge regulator. So as the semi-regulated bus voltage falls to the predetermined output level of the discharge regulator the loading transfers gracefully from the solar array to the battery. A similar, but reverse, process is followed at eclipse emergence.

This graceful change-over is possible because eclipse entry and emergence are slow compared with the processing speed of a computer. There exists, however the possibility of a sudden demand on the bus; either by design, or as a fault clearing pulse. In this case the energy management unit requires some milli-seconds of grace, and this is provided by connecting the 'top' of the battery to the semi-regulated bus through a high current diode.

Within the system designed and implemented at CAL, the energy management unit played a purely passive role during battery discharge.This was because the aim was to demonstrate life improvement on a battery, but the capability is present to monitor the discharge against a predetermined profile and to take interventionary action, in the form of load shedding, if required. In the system as implemented, however, the management unit maintained a count, per cell, of the energy being removed, and if any cell became fully discharged, shorted it out, and stopped incrementing the AHr count on that cell.

This bypassing of a cell is considered, by the system, to be an acceptable part of normal operation and, assuming the cell continues to fully discharge prior to the end of discharge, the cell will continue to be used in each successive charge/ discharge cycle, finishing each discharge in a shorted state.

The reasoning behind this is that while the cell is capable of storing some useful energy it might as well continue to be used. This cannot be

allowed in a system which manages a battery as a whole, because the low capacity cell becomes a power waster and a hot spot.

There is a manual overide, via. telecommand, which allows the operator to make the short circuit permanent after the next time the shorting switch closes. The exception to this is in the rare case of an open circuit cell, where the management unit immediately closes the shorting switch, and will only reopen it on telecommand.

Eclipse emergence is detected by a rise in the semi-regulated bus voltage, and at some predetermined voltage, the charge control regulator is turned on and the discharge regulator turned off. The management unit now opens all non-permanent shorting switches and sets up conditions for a full charge current to be applied to the battery, counting AHrs into each cell. As this process continues, the management unit monitors each cell for any indication of a fault condition by checking for; (a)falling cell voltage,(b) rapidly rising temperature, or (c) a voltage in excess of 1.6V, which would indicate gassing within the cell. The occurrence of any of these malfunctions causes that cell to be immediately put into the maintaining mode (by-passed), and the monitoring algorithm to lower the point at which this cell is adjudged to have reached top of charge.

The point at which each cell has reached top of charge (TOC) is determined by its voltage. At fixed intervals the charge current is turned off momentarily and the terminal voltage of all cells is read. These voltages are compared with a list of calculated TOC voltages and consequently the cell is either by-passed or returned to full charge for a further period. The calculated TOC voltage is automatically reviewed, by a control algorithm, at the completion of each charge cycle, and revised to maximise cell voltage at TOC, and charge efficiency, simultaneously.

CONTROL ALGORITHM

As mentioned earlier, the management of the battery is based on operating each cell in its most efficient mode, and this requires an algorithm which is tailored to the cell and can adapt to changes as the cell ages. The algorithm is structured to attempt to maximise cell voltage and charge efficiency simultaneously. This is an impossible task, but it will lead to the cell being operated in its optimum range. An explanation of this is best understood after examining the typical curves of charge input vs. cell voltage, and charge efficiency, shown in Fig.3.

It should be noted that the normal definition of charge efficiency is; the ratio of total charge input to total charge extractable, at any instant,

but that CAL uses a modified definition, i.e. charge last input divided by charge previously extracted, starting from, and finishing at TOC. This is to provide a simpler mathematical definition to the algorithm.
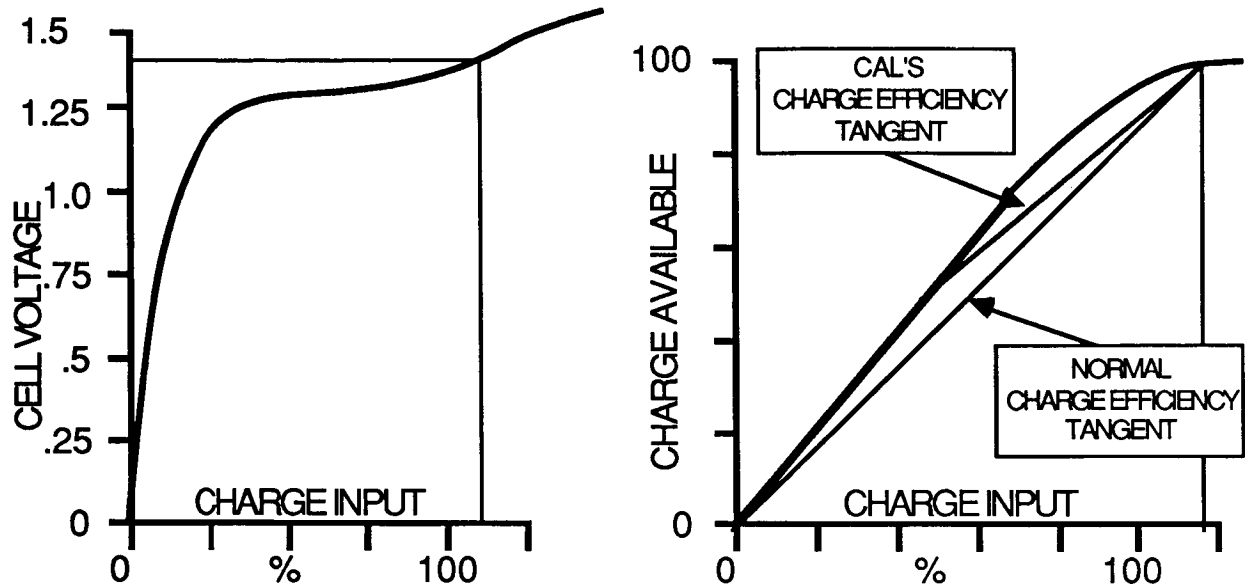
NB: All charge parameters expressed as a % of rated capacity

Figure 3. TYPICAL CELL CHARGING CURVES

An examination of the curves in Fig. 3 reveals that; with increasing charge input the cell voltage also increases, but that this is accompanied by a decrease in the numerical value of the ' charge efficiency', (i.e. the charge available divided by the charge input). If, then, a cell is charged to a predetermined terminal voltage, the charge necessary to do this can be compared to the charge previously removed, and the TOC terminal voltage can be adjusted, to change the 'charge efficiency' on the next cycle. This process may be better understood by examining the flow chart shown in Fig 4.
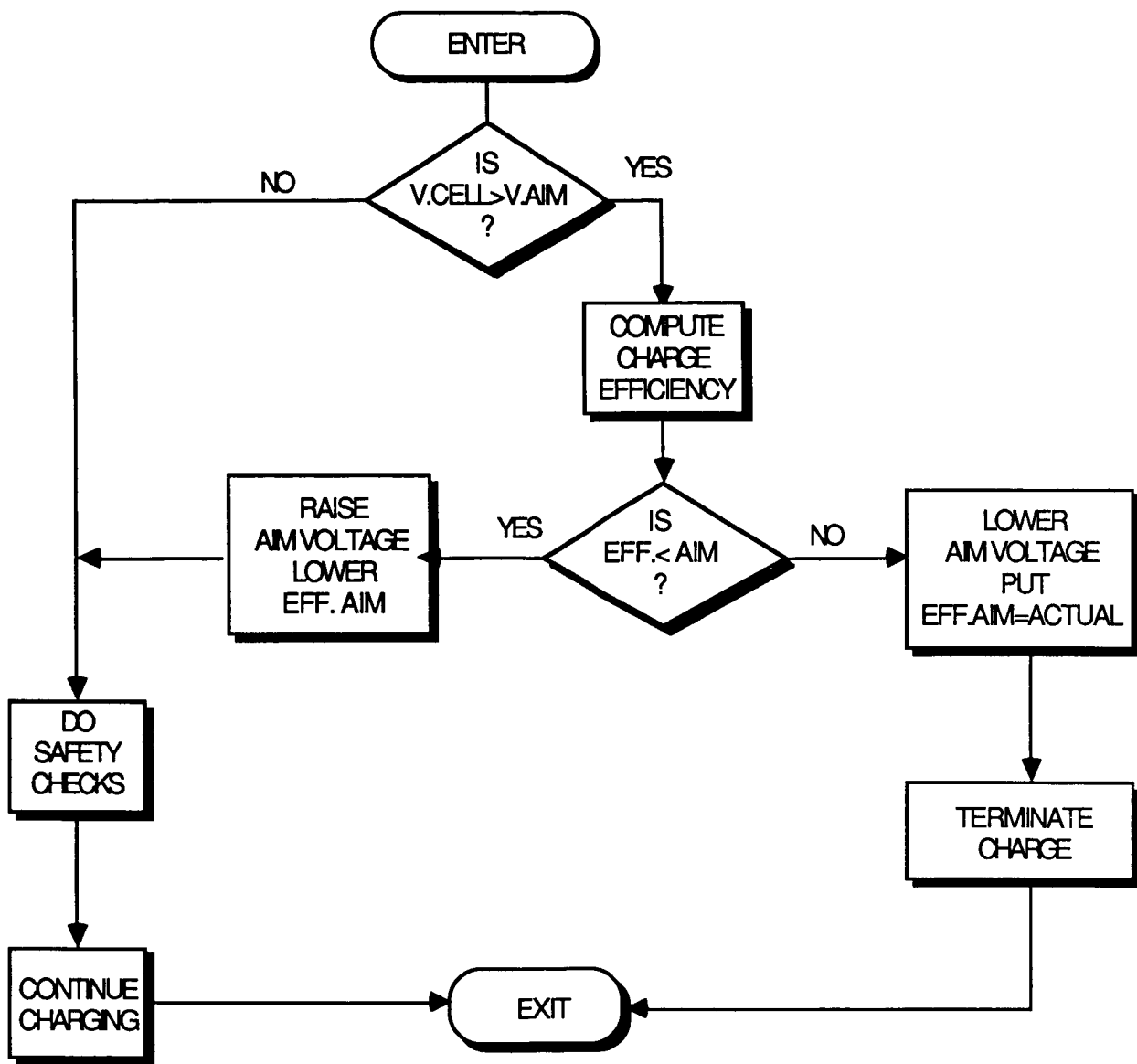
Figure 4. BASIC CELL MANAGEMENT ALGORITHM

The first decision is taken by examining the terminal voltage of the cell. This is always measured in the open circuit condition to eliminate the effects of different charge current and variations in cell internal impedance. If the cell has not reached the aim point then charging should continue, so, providing the voltage and temperature checks are satisfactory the charge is resumed.

If the cell has reached, or exceeds the aim point then the efficiency of the cell, in CAL'S terms,(i.e. the charge it has been necessary to return in order to replace the charge taken out), is compared to an aim efficiency. If the cell is showing greater efficiency than the aim,(i.e. numerically smaller), then the cell is operating in the more linear portion

of the "charge in / charge out" curve and can usefully accommodate more charge. Therefore the aim voltage is raised and the numerical value of the aim efficiency is lowered. This should result, the next time the measured cell voltage exceeds the aim voltage, in the computed efficiency being lower (i.e. numerically greater) than the aim. If this is not so the process repeats until that condition does occur. When the measured efficiency is found to be numerically greater than, or equal to, the aim, the aim efficiency is revised to be equal to this measured value, and the aim voltage is lowered a little. At this point the cell is said to be at top of charge, and it is switched to the maintaining mode.

It can be seen that the only way to terminate a charge is to have achieved a sufficient terminal voltage and to have absorbed enough energy to assure a full charge. The raising and lowering of the aim points is carried out using a number which is proportional to the difference between the measured and the aim value. This allows rapid 'zeroing in', without significant overshoot, although the values of proportionality must be carefully chosen to minimize oscillation.

Because this system is choosing the operating point for each cell, on the assumption that the cell is operating in a rational, or nominal, mode it is necessary to implement some traps and safeguards which will prevent attempts by the system to operate a faulty cell in a potentially hazardous or unknown operating area. For this purpose the aim voltage is not allowed to exceed 1.6 volts and the efficiency is not allowed to fall (numerically) below 110%. This should assure that the cell doesn't gas in overcharge and that a sufficient charge is always returned for the next discharge. There is no actual lower limit on the operating voltage of a cell except that in a discharge, if its voltage falls, and remains, below 0.5 volts, it is assumed to be drained, and is shorted out.

Recognizing the fact that there is also room for intuition and prediction in a good energy management system, the software also allows partial and total manually operated modes, wherein the aim points can be reset or locked to specific values, the factors of proportionality, governing the magnitude of changes in the aim points, can be changed, or the system can be placed in a passive (monitoring only) mode.

The system does contain one partially predictive algorithm in that, at the end of each discharge, the cell terminal voltage is checked and compared with the previous end of discharge. If the end of discharge voltage is found to be falling the top of charge aim voltage is increased by the same amount. This ensures that in a period of increasing usage, such as the first half of an eclipse season, maximum energy storage is

available, while in a stable or decreasing usage period, the cells are operated at their optimum point.

For the sake of clarity a number of refinements have not been mentioned, e.g. when 'aims' are to be revised the new computed value is 'averaged' with the existing value, before the new aim is set. This helps to prevent system noise, or spurious results, giving rise to significant changes in the operating mode. Additionally all cell voltage readings are scaled, according to the current cell temperature, to prevent cyclic, and long term, temperature effects from biasing the algorithm.

SYSTEM CONFIGURATION

As mentioned previously CAL implemented this system into hardware, some of its parts being developed to a level where they were demonstrated to pass qualification test for an STS launch, and GEO orbital environment. In order to provide the most representitive test bed for the management of a battery, the system was designed to emulate the power sub-system of an intermediate size communications spacecraft, say of the ANIK type. During the final testing of the system, the operation of the management system within a spacecraft in geostationarry orbit was simulated. The division of units into which the system was divided is illustrate in Fig 5 below.
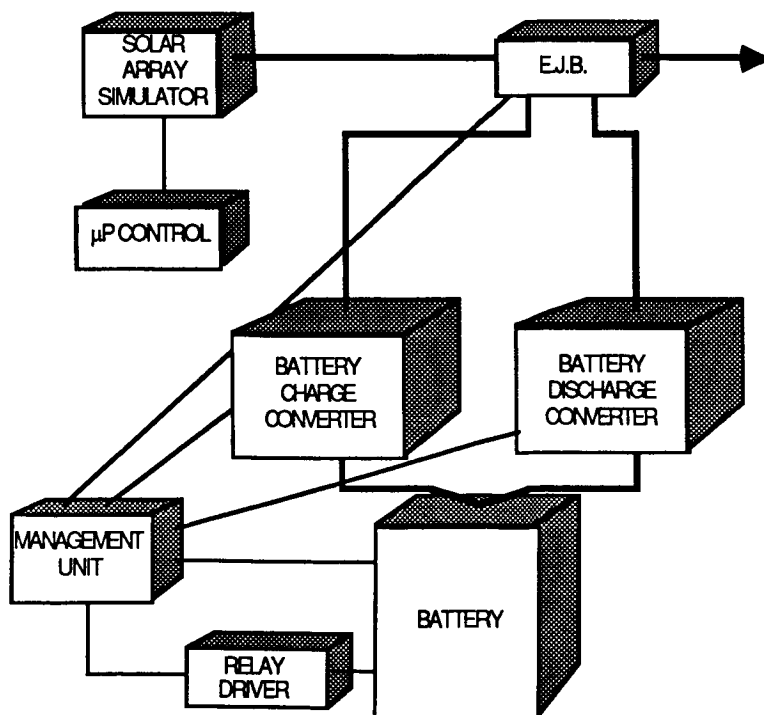

Figure 5. HIGH RELIABILITY BATTERY MANAGEMENT SYSTEM

313

The energy storage unit, or battery, consisted of three or four cell pack simulators and an optional eight cell pack of 37.5 AHr. GE, prismatic NiCd cells. The cell pack simulators were based on a string of 'D' cells, and their capacity was scaled to the desired level by the use of amplifiers and external power supplies. The use of these cell simulators had many advantages, not only in terms of their versatility, but also in terms of the safety advantage of not working with high energy storage cells while developing the system. In all cases the cell by-pass circuitry was housed within each cell pack, adjacent to the appropriate cell.

The solar array was simulated by a commercial power supply, controlled by a microprocessor to simulate eclipse entry and insolation.

Both the charge and discharge regulators use poly-phase, class 'D', switching techniques which give rise to excellent conversion efficiency, and in the case of the unique design for the discharge regulator, the ability to continue operation after the 'first failure'. The discharge regulator was developed to 'flight' hardware standard, and qualified. It was shown to supply 300 Watts at a conversion efficiency of 96.5%, and 600 Watts at a conversion efficiency of 95%, with a line regulation of less than 20mV.

The management unit was built in a breadboard format, but all the parts used were generic to space qualified equivalents. All the circuitry was redundant and dual such that continuous error checking in the management unit could be accomplished. The basic operating algorithm was 'burned' in a EPROM while all the operating variables were held in RAM. A set of start up parameters was also held in ROM. This allowed that the management unit could be completely powered down, but on reapplication of the power, the system would restart in a safe operating condition. The management unit also interfaced with a telemetry/telecommand port, formatting and sending housekeeping telemetry, and looking for commands which it interpreted and actioned, or passed on, as appropriate.

Other interfacing and interconnections were effected within the relay driver unit and the E.J.B. (electrical junction box).

CONCLUSION

Canadian Astronautics Ltd. has developed a microprocessor based system to autonomously manage batteries, particularly nickel cadmium batteries, on a cell by cell basis, which will enhance the life of the battery by ensuring that each cell is charged to its optimum level. The system uses an adaptive algorithm which accomodates changes in each cell's characteristics over life. The system also compensates for, and

protects against, the effects of individual cell failures.

The system was constructed to replicate the power sub-system of an intermediate size communications spacecraft, and a number of the individual units were developed to qualification status, including a 600 Watt poly-phase discharge converter.

ACKNOWLEDGMENT

The author wishes to recognize the skills and dedication of all those at CAL, and in the CRC, who made this project a success.