Journal of Power Sources, *18* (1986) 169 - 176

SELF-DISCHARGE CHARACTERISTICS OF SPACECRAFT NICKEL–CADMIUM CELLS AT ELEVATED TEMPERATURES

S W DONLEY, J H MATSUMOTO and W C HWANG
The Aerospace Corporation, P O Box 92957, Los Angeles, CA 90009 (U S A)

Summary

It is shown that thermal runaway can occur from self-discharge of sealed Ni–Cd batteries at elevated temperatures The process can be fast enough to rupture cells in batteries and cause physical damage to surrounding areas Therefore the temperature of a charged battery must be limited for safety reasons even on open circuit; the temperature limit will depend on the particular thermal environment.

Little is known concerning the self-discharge and heat generation in nickel–cadmium cells when they are subjected to temperatures far in excess of ambient. It is known that, in general, the rate of chemical energy loss from the cells in the form of heat increases with temperature and that thermal runaway is a likely result at sufficiently high temperatures, even with cells on open circuit Actual conditions promoting thermal runaway have heretofore not been established. The work reported here provides such data in tests performed on open-circuited Ni–Cd cells, fully charged, when such cells were heated externally to temperatures from 44 to 118 °C.

The objective of this paper is to relate the effects of heat generation in spacecraft nickel–cadmium (Ni–Cd) cells during high temperature storage on open circuit. When nickel–cadmium batteries are open circuited in the charged state, chemical reaction(s) provide a means of self-discharge and heat-generation. The rates of self-discharge and heat-generation are relatively low at normal spacecraft operation temperatures (—5 to 30 °C); however, the rates and possibly the complexity of the reactions increase with temperature. There are little data available concerning capacity losses via self-discharging in Ni–Cd cells due to elevated temperature (above 40 °C) exposure. Such data could be useful in space programs, as temperatures in the range 80 - 100 °C may cause the batteries to become thermally unstable. Additional heating generated by battery self discharge may drive the batteries into catastrophic failure with consequences for the integrity of the spacecraft and its contents. The testing described here was designed to determine the extent to which battery thermal stability is a valid concern, at temperatures of exposure (externally effected) between 44 and 118 °C.

0378-7753/86/$3 50

The Ni–Cd cells selected for testing were from General Electric with 35 A h nominal capacity, catalog number 35AB11 It is expected that the results obtained with these cells can readily be extended to other Ni–Cd spacecraft batteries.

The cell test apparatus is shown in Fig. 1, which is not drawn to exact scale in order to show some of the details. The cells were enclosed in an insulating container (Fibrothal (Reg.), Kanthal Furnace Products Co.) The large faces of the cell were supported by 0.25 in aluminum restraints which were held together by 4 screws (not shown in the drawing) The cell and restraints were designed to slip into the aluminum liner along with the heater and aluminum shims to provide a snug fit. All sliding pieces were coated with silicone heat conducting compound. The liner was bonded to the glass foam insulation with a high thermal conductivity RTV compound Empty spaces within the glass foam insulator (top, bottom and small faces of the cell) were filled with glass wool Thermistors were mounted at the top and bottom of the cell, on the outside of the cell restraint opposite the heater, on the inside of a small face of the liner, on two outside surfaces of the foam insulator, and at the bottom of the foam insulator A strain gauge was placed on either the cell top or bottom in order to monitor any possible bulging of the cell case. The insulated test assembly was operated inside an environmental chamber

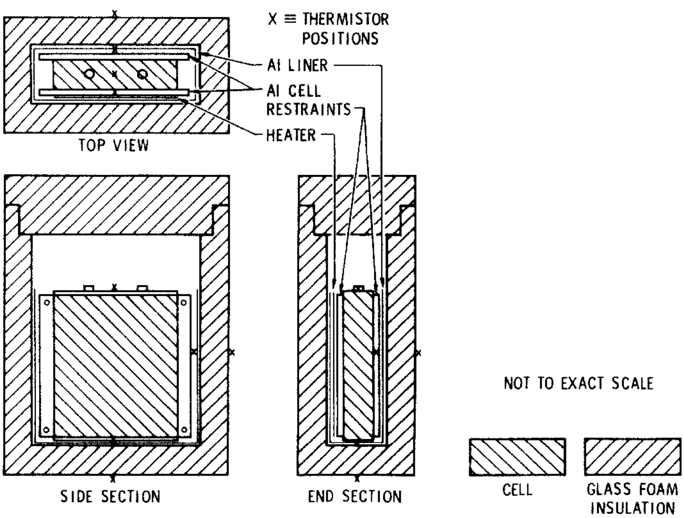

Fig 1 Thermal test assembly

Figure 2 shows a block diagram of the test apparatus. The seven thermistors and the strain gauge outputs were monitored by a computer which also controlled the heater and the temperature of the environmental chamber. Calibrations of the thermistors, specific heat of a cell, specific heat of the test apparatus, and thermal conduction through the test apparatus were made with a solid aluminum "dummy cell" of known spe-

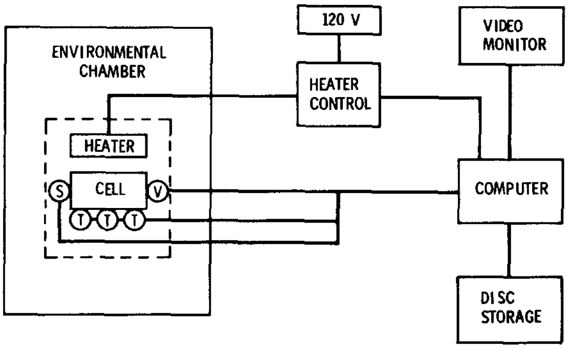

Fig 2 Block diagram of test apparatus

cific heat. At a given environmental chamber temperature, the heater inside the assembly provided sufficient heat for the particular initial internal temperatures.

Measurements of temperature after heating provided the necessary calibration data. While the initial external (environmental chamber) temperature was to be 60 °C, the internal temperatures for the determination were 60, 80, 100, 120, 140, and 160 °C The thermal processes operating in the experimental test fixture during the calibration runs with a dummy cell of known heat capacity (b') are described by the equation:

$$a\int_{t_1}^{t_2} [T(t) - T'(t)]\, dt + c/2[T(t_2) - T(t_1) + T'(t_2) - T'(t_1)]$$

$$= b'[T(t_1) - T(t_2)] \qquad (1)$$

where a is constant for heat loss through the insulator, c is the heat capacity of the insulator, b' is the heat capacity of the "dummy" cell, $T(t)$ is the cell temperature as a function of time, and $T'(t)$ is the chamber temperature as a function of time.

Figure 3 is a computer plot of actual data for selected thermistors from one of the "dummy cell" runs, which were performed in order to determine the heat dissipation rate through the walls of the cell insulating container at various temperatures of the container/contents and the surrounding thermal chamber. In this case, both the dummy cell and the chamber were brought initially to 60 °C, then the cell heaters were disconnected and the dummy cell surface temperatures were monitored for one hour. The dummy cell was then heated to successively higher temperatures, and the temperatures with no cell heating were monitored. The chamber temperature, nominally constant, demonstrated a small upward drift throughout the test, in addition to a significant ripple associated with each cell heating and cooling cycle

The values of the insulator heat capacity, c, and the rate of heat dissipation through the walls of the insulator, a, determined from analysis of

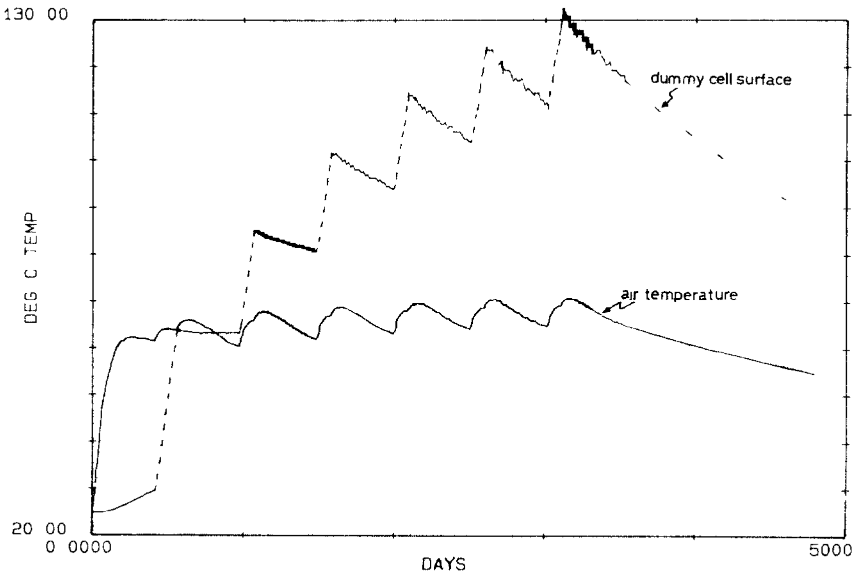

Fig 3 Calibration curves, 60 °C initial temperature

the thermistor data during the periods of active heating and by determining the cooling rates (heaters off), respectively, are shown in Table 1. The heat capacity (b) of the actual 35 A h cells that are the subject of this paper were determined by calculation from the materials of construction of the cells The value obtained for a fully discharged cell was then adjusted by calculation to account for the differences in the heat capacities between the charged and discharged active cell materials A value of ΔH (cell) of 0.235 W h $°C^{-1}$ (202 cal $°C^{-1}$) was derived from this calculation, in good agreement with data found in the literature [1]

TABLE 1

Thermal parameters

Heat dissipation rate	0 126 W $°C^{-1}$
Cell heat capacity	0 235 W h $°C^{-1}$
Cell restraints heat capacity	0 216 W h $°C^{-1}$
Insulation heat capacity	0 156 W h $°C^{-1}$

In the cell testing, fully charged cells were fastened between restraining plates, fitted with thermistors, etc , and inserted into the insulating housing in the same way that the dummy cells were treated earlier. The experiments were performed with fully charged cells at initial internal and external temperatures of 44, 64, 82, 85, and 118 °C The temperatures following the initial heating were monitored for up to 48 h and provided the data necessary for calculating the self-heat generation of these Ni–Cd cells in this temperature range. The same two cells were used for the 60 °C tests that were tested at 40 °C, after recharge. Otherwise, fresh cells were used in each cell temperature test. The testing procedure was to heat the test chamber to the preset test temperature, then to heat the cells to approximately the same temperature via timed resistance heaters contained inside the insulators, in contact with the cell surface, at the rate of ~2 °C min^{-1}. Table 2 shows the actual cell wall temperatures achieved at the completion of the heating period and also the maximum temperatures achieved.

TABLE 2

Cell temperature data summary

No of cells tested	*Initial temp* (°C)	*Cell temp achieved at end of test* (°C)	*Environmental chamber temp* (°C)
2	~44	42	36 - 38
(2)*	~64	64	58 - 59
2	~82	85	70 - 72
2	~85	> 166**	72 - 79
1	~118	230	121 - 129

*Same cells as in 40 °C test
**Cells were fully discharged

One hour after the chamber reached the setpoint temperature, the cell heaters were fed a predetermined amount of energy calculated from the cell constant, sufficient to bring the cells and other contents of the insulating containers to the setpoint temperature Thereafter the chamber temperature was maintained and both chamber and cell temperatures were monitored. As in the earlier calibration runs each cell had five thermistors attached to it, and three thermistors were attached to the outside surface of the insulator The thermistor readings were monitored at intervals throughout the test and the data stored on floppy disks. Values of all the cell surface temperatures were averaged prior to the succeeding calculation of self discharge rates, as were the chamber temperatures Sample cell and chamber actual temperature data (for simplicity not all thermistor outputs are shown) appear in Figs. 4 -6.

The calculation of cell self discharge rates assumed that all cell capacity and energy losses were converted entirely to heat and that the heat dissipation rate through the walls of the insulator and the cell thermal capacity derived earlier are valid at all testing temperatures. The cell discharge rates, q, at various temperatures were calculated from actual time/temperature data, and the slopes of the time/temperature plots were derived from the following equation:

$$q(t) = \left(b + \frac{c}{2}\right) \frac{\mathrm{d}T(t)}{\mathrm{d}t} + \frac{c}{2} \frac{\mathrm{d}T'(t)}{\mathrm{d}t} + a[T(t) - T'(t)] \quad (2)$$

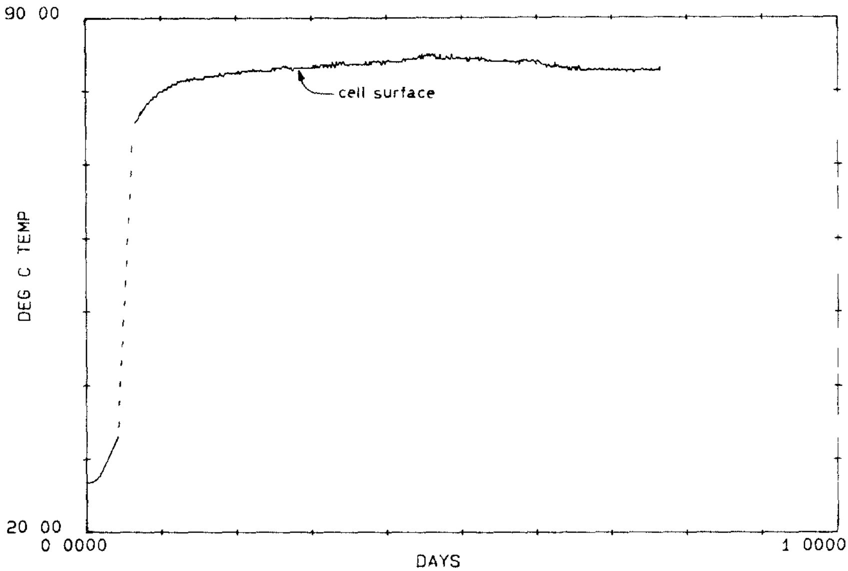

Fig 4 Thermal test, 82 °C initial temperature

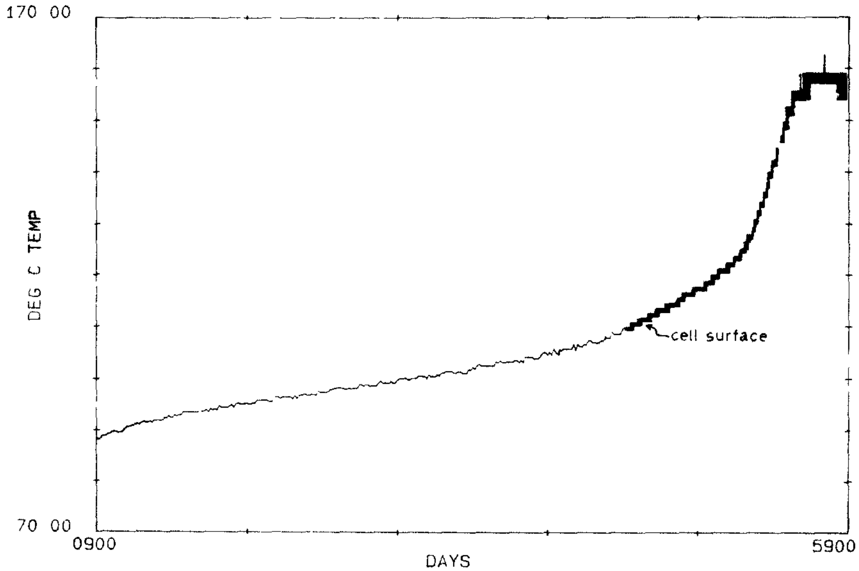

Fig 5 Thermal test, 85 °C initial temperature

The calculated cell heat generation data are plotted (as log q *versus* T^{-1}) in Fig 7 together with error bars. The errors are greater at the lower temperatures because, at these temperatures, the derived heating rates are dominated by the term in the equation requiring the determination of small temperature differences Literature data [2] at 40 °C are shown for com-

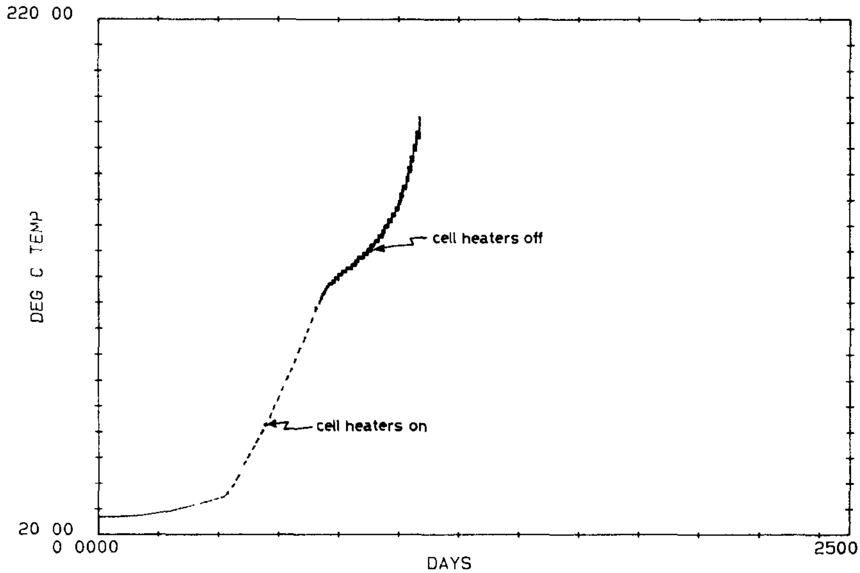

Fig 6. Thermal test, 120 °C initial temperature

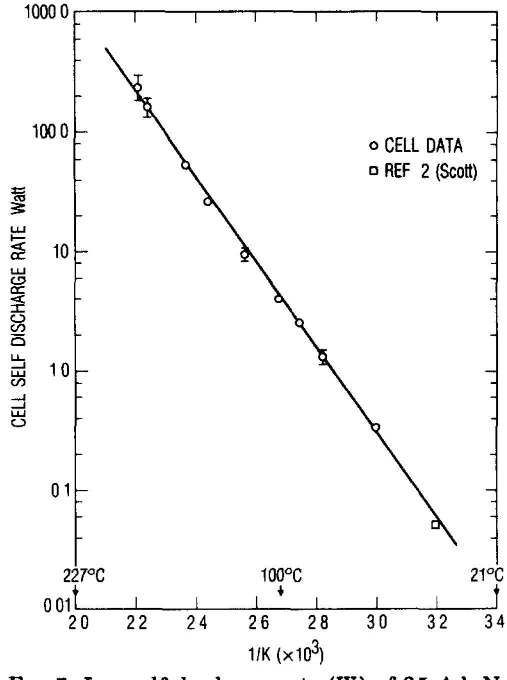

Fig 7 Log self-discharge rate (W) of 35 A h Ni–Cd cells *vs* 1/K ($\times 10^3$)

parison. These data can now be used to evaluate thermal runaway conditions for any battery system with known thermal control properties The data should be scalable to other cell sizes.

We earlier described a cell as having "exploded" at a cell surface temperature in excess of 230 °C With the calculated rate of heat generation (>500 W) a few minutes before the catastrophic event occurred, it is likely that the actual temperature at points within this cell were well in excess of that measured at the cell surface. At these temperatures the separator material fused, allowing the electrode materials to come into intimate contact. Although we do not have information adequate to judge whether an explosion indeed occurred or merely a forceful venting, a distinct odor of organic combustion was detected in the surrounding laboratory area after the event The heavy stainless steel walls of the environmental chamber were bowed outward and the door hinges were bent, in spite of a 4 in dia. hole having been provided for pressure dissipation. The 0.25 in. aluminum restraining plates over the cell faces were bent, but held, while a side panel of the cell was blown free The electrode sinter was covered by black frangible dust which was all that was left of the active material

Conclusion

The conclusions of this study are that thermal runaway can occur from elevated temperature self-discharge of Ni–Cd batteries. Thermal runaway can be fast enough to rupture cells in batteries and cause physical damage in the surrounding area. Thus, temperatures of a charged battery must be limited for safety measures even on open circuit. The maximum allowable temperature depends on thermal management In our particular case battery temperatures above about 80 °C cannot be allowed without adequate provision for heat dissipation

References

1 A Laursen and P H Jacobsen, Analysis and testing of the thermal properties of space battery cells, *European Space Agency Contract No 498/82/NL/JS(SC)*, Jan , 1983
2 W R Scott and D W Rusta, *Sealed-Cell Nickel–Cadmium Battery Applications Manual*, NASA Reference Publication 1052, Dec , 1979, p 101