

BATTERY DEVELOPMENT AND TESTING AT THE EUROPEAN SPACE AGENCY

JEAN VERNIOLLE

*Energy Storage Section, European Space Research and Technology Center,
European Space Agency, Postbus 299, 2200 AG Noordwijk Z-H (The Netherlands)*

Summary

The principal activities of the Energy Storage Section of the Space Research and Technology Center (ESTEC) of the European Space Agency are presented. Nickel-hydrogen and fuel cell systems development are reported. The European Space Battery Test Center (ESBTC) facilities are briefly described along with the current test programs and results obtained.

Introduction

Whereas nickel-cadmium batteries have been used for the vast majority of past ESA spacecraft, the enormous diversification in energy storage requirements for future missions such as COLUMBUS (the European contribution to the U.S. space station), HERMES (the European Space Transportation Vehicle) and deep space scientific missions, has led to a rapid increase in development activities for new energy storage systems.

The majority of test programs in the ESBTC involves nickel-cadmium batteries but the situation will change as prototype hardware from the new system developments is delivered for evaluation.

ESA battery development activities

The main activities are summarised in Table 1. Nickel-hydrogen and fuel cell systems development will be described in more detail.

The growing interest in deep space missions has led to studies of suitable primary power sources. Work has started on the adaptation of lithium-sulfur dioxide cells for such applications.

The high energy density prospects, coupled with encouraging lifetime and reliability data, caused ESA to start feasibility studies on using sodium-sulphur batteries for various types of mission.

TABLE 1

Main ESA electrochemical power sources development programs

Item	Type	Development	Applications	Prime/Sub contractors
Ni-H ₂	GEO	30 - 50 A h IPV + one piece sleeve	Telecom. satellites	SAFT/Aerospatiale (F) under CNES management
		40 - 50 A h battery E.M.	Telecom. satellites	BAe (U.K.)/SAFT (F) Elektronik Centralen (DK)
Ni-H ₂	LEO	50 A h CPV 80 V, 3.3 kW battery module	COLUMBUS IOC	Marconi/Harwell (U.K.)
RFCS	LEO	Trade-off design studies KOH (mobile- immobile) SPE	20 kW module COLUMBUS AOC	Dornier system (D)
FCS	Vehicle		4 kW module HERMES	
Li primary	Deep space probes	10 A h D-size cell 8 years shelf life C/4 rate	TITAN probe (Cassini)	BTC venture (U.K.)
Na/S	LEO GEO	Evaluation	Basic development	To be chosen

Ni-H₂ IPV cell development for geostationary applications

ESA is supporting, in certain areas, the Ni-H₂ individual pressure vessel (IPV) cell development for GEO applications headed by the French national space center (CNES) under a substantial Research and Development program with SAFT.

The key features of the Ni-H₂ cell developed by CNES are presented in Table 2 and Fig. 1. The cell, which operates at a maximum pressure of 75 bar and covers the capacity range 30 - 50 A h, is notable for the one-piece sleeve. This is an integral part of the mechanical cell design contributing to the high safety factor of 4. The sleeve is, of course, an integral part of the cell thermal design as well. This sleeve concept also offers a small mass saving over the conventional split-sleeve design.

The nickel electrodes are fabricated by the aqueous electrochemical impregnation process, the reproducibility of which has been improved by greater control of the impregnation bath parameters. Individual electrode capacity is 1.90 A h at 20 °C in flooded KOH which gives a value of 0.146 A h g⁻¹ and 0.044 A h cm⁻². The 50 A h cell has an energy density of 50 W h kg⁻¹ and a volumetric energy density of 70 W h l⁻¹.

ESA has been in charge of the development of a thermal model of the cell-sleeve assembly. A 59-node computer model (SINDA program) has been developed by Aerospatiale which indicates that a 5 °C maximum temperature

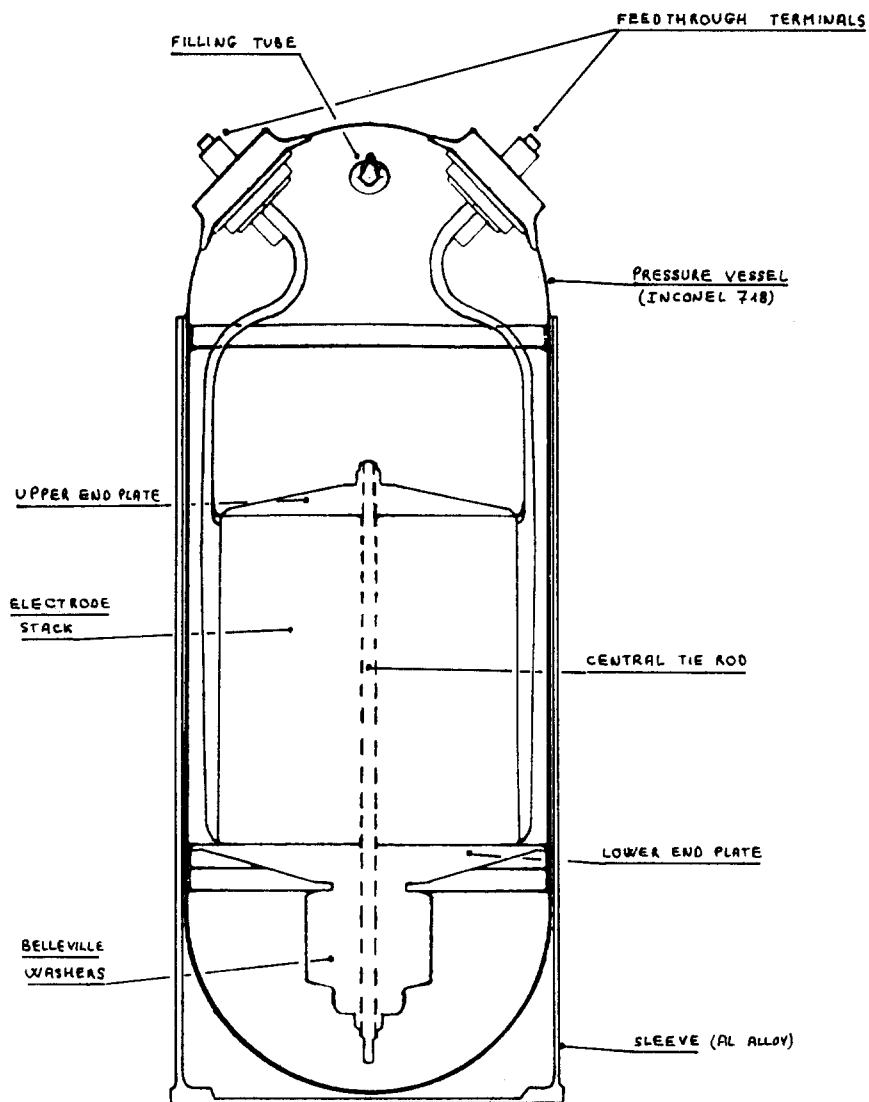


Fig. 1. CNES-SAFT 50 A h Ni-H₂ cell.

gradient between cell stack and inside pressure vessel will exist during 70% DOD geostationary cycle conditions with a recharge factor of 1.2. A thermal vacuum test will be carried out to validate this result.

This test is part of a large CNES validation test program on the 50 A h cell, due to be completed by December, 1987. The final step will be a qualification program to be finished in mid 1988.

TABLE 2
CNES-SAFT Ni-H₂ cell key features

Mechanical	Electrochemical
<i>Pressure vessel:</i> Thin walled 81 mm in diameter with 2 hemispherical end caps	<i>Positive electrode:</i> Nickel-plated perforated steel substrate. Ni(OH) ₂ electrochemically impregnated on sintered Ni powder
<i>Material:</i> Inconel 718 heat treated	<i>Negative electrode:</i> Expanded Ni grid substrate. Porous layer of active C with Pt catalyst. Hydrophobic porous PTFE
<i>Stack:</i> Back to back circular with flats supported on a central tie rod and two rigid end plates. Belleville washers to accommodate stack expansion	<i>Separator:</i> Non-woven polyamide felt extending to vessel wall
<i>Terminals:</i> Ceramic feedthrough with Ni-plated braze. Both located at one end cap	<i>Gas screen:</i> Woven nylon
<i>Filling tube:</i> 45° off-set	<i>Electrolyte:</i> KOH 7.3 N
<i>Hydrogen pressure:</i> 5/P/75 bars	
<i>Sleeve:</i> One piece Light Al alloy	
<i>Safety factor:</i> 4 atm for cell + sleeve 2.5 min. for cell only	

GEO Ni-H₂ battery engineering model development

The geometry of nickel-hydrogen cells requires that careful consideration be given to thermal and structural battery design. Furthermore, due to the volumetric energy density disadvantage compared with Ni-Cd, particular attention is required to maximise the packing density of the cells into the battery assembly. Finally, the battery mass to total cell mass ratio has to be kept as low as possible.

ESA has a development contract with British Aerospace (U.K.) and SAFT (F) for the manufacture and testing of a battery engineering model designed to a European communication spacecraft specification. The design concept is presented in Fig. 2. The cells are bonded to an Al thermal sleeve (either of a split or one piece concept) mounted via a flange to a light support base plate, to the opposite side of which is mounted a thin radiator plate. A cavity is provided in the thickness of the base plate so that the

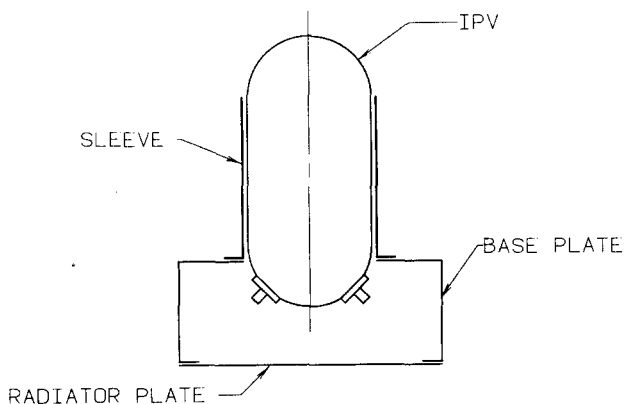


Fig. 2. Ni-H₂ battery design concept.

cell, with its terminals positioned downwards, partially projects into it. Protection by-pass diode circuitry using the base plate as heat sink is provided for each cell. This packaging concept couples good thermal design with a very short harness length. The design accommodates SAFT 81 mm dia. cells in the 40 - 50 A h range.

Ni-H₂ CPV development for LEO applications

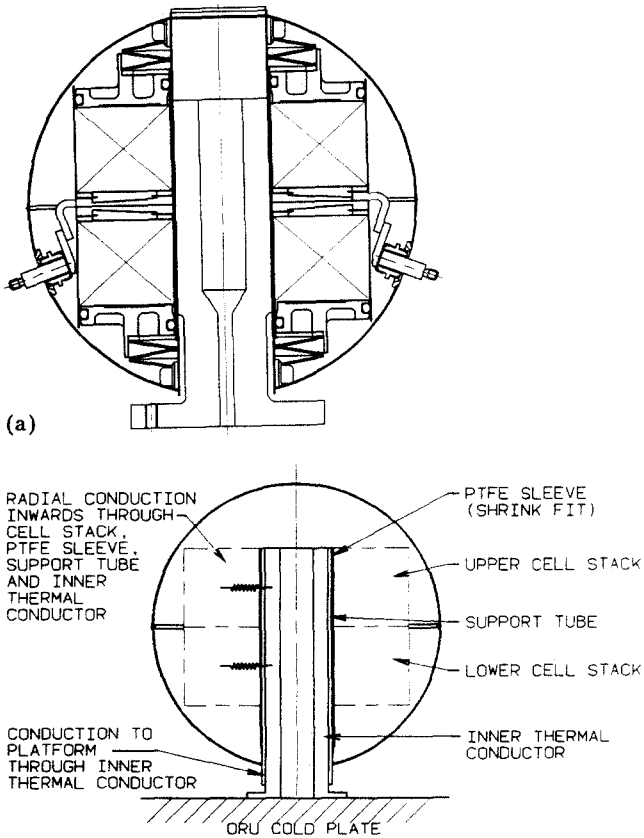
ESA secondary batteries for current LEO spacecrafts such as ERS-1 and EURECA are based on Ni-Cd technology. Qualified cells up to 40 A h are now available in Europe. Nevertheless, a 50% saving in battery mass might be expected if nickel-hydrogen cells were used instead.

ESA Ni-H₂ technology development for LEO applications is primarily driven by the COLUMBUS project where power levels in the range 5 kW - 20 kW are required. An investigation of alternative Ni-H₂ technologies (IPV, CPV, Bipolar) that could satisfy COLUMBUS needs was performed by Harwell (U.K.) [1] and led to a preference for Ni-H₂ CPV (Common Pressure Vessel) cell option.

A contract for the design and validation of a complete 80 V, 3.3 kW CPV Ni-H₂ battery module including integral active thermal management and with a lifetime requirement of 18 000 - 30 000 cycles, was awarded to Marconi Space System (U.K.) with Harwell (U.K.) as a subcontractor.

An initial design trade-off study led to the selection of a battery based on a spherical, 50 A h dual-stack CPV cell. The cell design is shown in Fig. 3(a). The final choice had been between this concept and a more conventional cylindrical 2-stack CPV design (Fig. 4(a)).

Both cells operate at 40 bar maximum with an Inconel 718 pressure vessel and incorporate LEO and CPV design requirements. Concentric current collectors are used which, in conjunction with the end plates, fully



(a) Spherical CPV cell design; (b) spherical cell thermal design concept.

centrally cooled cell stack thermal design (WITH PASSIVE COOLING)

contain each stack. This containment is mandatory to avoid any electrolyte bridging or electrolytic corrosion of the pressure vessel. Water transfer, caused by migration of free oxygen, is controlled by recombining any oxygen within the cell from which it was produced. The electrode expansion during cycling is accommodated by a system of Belleville washers. The stacks include electrolyte reservoirs. A good thermal link is provided between the two stacks in order to have isothermal stacks, and the stack thermal design is such as to maintain a temperature difference between the stack and the pressure vessel at less than 8 °C.

The geometrical difference between the two designs arises from a radical change of the thermal design (Figs. 3(b), 4(b)). In the cylindrical design the stack is cooled at its outer periphery, via a hydrogen gap, through the pressure vessel wall to the thermal sleeve. In the spherical design the

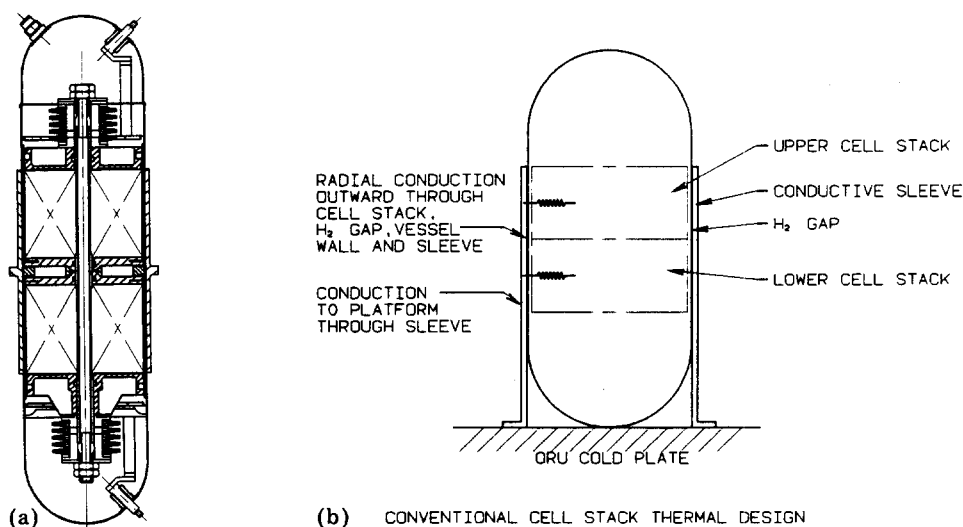


Fig. 4. (a) Cylindrical CPV cell design; (b) cylindrical cell thermal design concept.

stack is cooled via an insulated central support tube, itself supported on a thermally conductive pillar. The rest of the pressure vessel can then be designed for the lightest possible geometry. Although the cooled contact area is smaller than in the conventional design, it is possible to provide a much better thermal contact with the stack. This thermal and mechanical design uses electrodes of a larger diameter (120 mm as opposed to 84 mm selected for the cylindrical cell).

Another feature of the spherical design is that the two contained stacks are independent units, which greatly simplifies the cell assembly. The stacks are attached to the central Inconel tube, which also acts as a tie rod, via the positive inner current collector, and the series connection is completed by connecting the inner collector of one stack to the outer collector of the other, as opposed to the cylindrical design where the central tie rod forms the series connection.

The expected energy density for both optimised designs is around 43 W h kg^{-1} (including the sleeve).

The two cell designs lend themselves to rather different battery packaging schemes:

Cylindrical design. The cell is centrally mounted by a short thermal sleeve, itself coupled to a mounting plate incorporating a fluid loop or heat pipes.

Spherical design. The cells are mounted on either side of a support plate by means of a mounting flange at the base of the thermal pillar. The plate is formed in two halves sandwiching an active cooling loop or heat pipes.

Thermal analysis of the cell and of the mounting plate for both designs at 40% DOD indicates that in order to maintain a maximum cell stack temperature of 20 °C, a mounting surface temperature of 5.7 °C is required for the spherical CPV, which then shows an inside maximal thermal gradient of 6.2 °C, whereas the figures for the cylindrical design are 7.7 °C and 5.3 °C, respectively.

The volumetric energy density is, of course, lower for the spherical CPV cell (32 W h l⁻¹ against 45 W h l⁻¹) but the overall battery volume is about the same for both battery modules because of the lower footprint area of the spherical CPV on the supporting plate, which still leaves room for protection diode circuitry.

FCS and RFCS pre-development

For a manned re-entry vehicle such as HERMES, with mission durations up to 28 days, a primary Fuel Cell System (FCS) is the only realistic choice of power source.

Of the electrochemical secondary power sources that can be considered for longer term high power applications in LEO (such as COLUMBUS AOC (Advance Orbital Configuration), a Regenerative Fuel Cell System (RFCS) appears to be a promising choice. This system consists of O₂-H₂ fuel cells to provide energy to the spacecraft during eclipse periods, and an electrolyser which regenerates the O₂ and H₂ reactants during sunlight periods by electrolysis of the water produced by the fuel cells.

ESA is presently running pre-development studies for both applications. It is intended that the fuel cell system chosen for HERMES will also be used in the RFCS. Design requirements are presented in Table 3.

The different Fuel Cell Systems under consideration are alkaline (with mobile or immobile KOH electrolyte) or acid (with Solid Polymer Electrolyte [SPE]).

TABLE 3

Comparison of main design requirements

	HERMES	COLUMBUS AOC
Average power level (kW)	4	20
Voltage level (VDC)	85 - 135	150
Mission duration	11 (28) days	5 years
Operating time	30 max.	90 min.
between maintenance (days)		
Orbital replacement unit	No	Yes
Operation during launch	Yes	No
Reactant storage	Cryogenic	Pressure tank
Gas/liquid separator	Yes	Yes

For the regenerative fuel cell system, design trade-off studies of these different fuel cell options, coupled with electrolyser and ancillary mechanical sub-systems (gas-liquid separators, reactant storage technologies, pumps), are presently underway. One of the RFCS concepts proposed by Dornier is presented in Fig. 5. This design is based on a mobile KOH system which is representative of the state of the art in Europe. The KOH electrolyte loop participates in the thermal management of both fuel cell and electrolyser and a gas/electrolyte separator is necessary. The reactant gases are stored in pressure tanks provided with electrical heaters to prevent condensation of water.

The main steps in both FCS and RFCS development are as follows:

- Selection of system concept: KOH (mobile-immobile); SPE
- System design trade-offs
- Optimization of the water removal system
- Development of reliable separators for space
- Optimisation of heat rejection concepts
- Selection and testing of materials
- Optimisation of system architecture
- Acquisition of lifetime data.

ESTEC battery test activities

The main test activities are presented in Table 4. These include battery lifetime tests, product comparisons, battery management evaluations, and support to spacecraft projects. All these tests are performed at ESTEC in the European Space Battery Test Center.

In addition to these tests, experimental cell thermal studies are carried out under contract.

European space battery test center (ESBTC)

Commissioned in 1978, the ESBTC is a large, automated test facility designed to monitor up to 100 test stations, with a total capability of 2000 measurement channels [2]. The overall ESBTC test control, data acquisition and data processing systems are presented in Fig. 6. This is based on a dual DEC PDP 11-45 computer which provides test control and data recording on all active test stations.

Measurement channels are scanned as a minimum every 57 seconds. Raw test data are accumulated on magnetic tapes (day tapes) and sent in parallel to an HP-1000F computer dedicated to data processing. Recent data (up to 3 weeks) are stored on large, individual disk files rapidly accessible for checking test progress. Periodic data transfer to magnetic tapes is performed for archiving.

TABLE 4
Present ESBTC main test activities

Test	Type	Battery	Configuration	Objectives
ELAN	LEO	Ni-Cd (SAFT)	20 batteries 12 cell assembly on cold plate	Joint ESA-CNES lifetime assessment program coupled with destructive failure analysis
X-80	LEO	Ni-Cd (SAFT)	1 battery 14 cell assembly in temperature controlled chamber	Lifetime assessment 22 500 cycles completed at 23% DOD EODC cell voltage still above 1 V
TDT	LEO	Ni-Cd (SAFT)	3 parallel batteries 14 cell assembly on cold plate	New charge control method evaluation
ERS-1	LEO	Ni-Cd (SAFT)	1 battery 12 cell assembly on cold plate	Battery management assess- ment for ERS-1 project
METAL-H ₂	LEO	Ni-H ₂ (SAFT) Ni-H ₂ (DAUG) Ag-H ₂ (SAFT)	3 batteries 2 cell assembly mounted on chassis placed in tem- perature controlled chamber	Lifetime assessment product comparison
MARECS	Acc.GEO	Ni-Cd (SAFT) Ni-Cd (G.E.)	2 batteries 12 cell assembly in tem- perature controlled chamber	Support to spacecraft lifetime assessment
ECS	Acc. GEO	Ni-Cd (SAFT)	3 ex-flight models	product comparison
OTS	Real time GEO	Ni-Cd (SAFT)	28 cell assembly on cold plate 1 battery 2 - 14 cell modules in series in two different chambers	High DOD lifetime assessment Real lifetime flight simulation

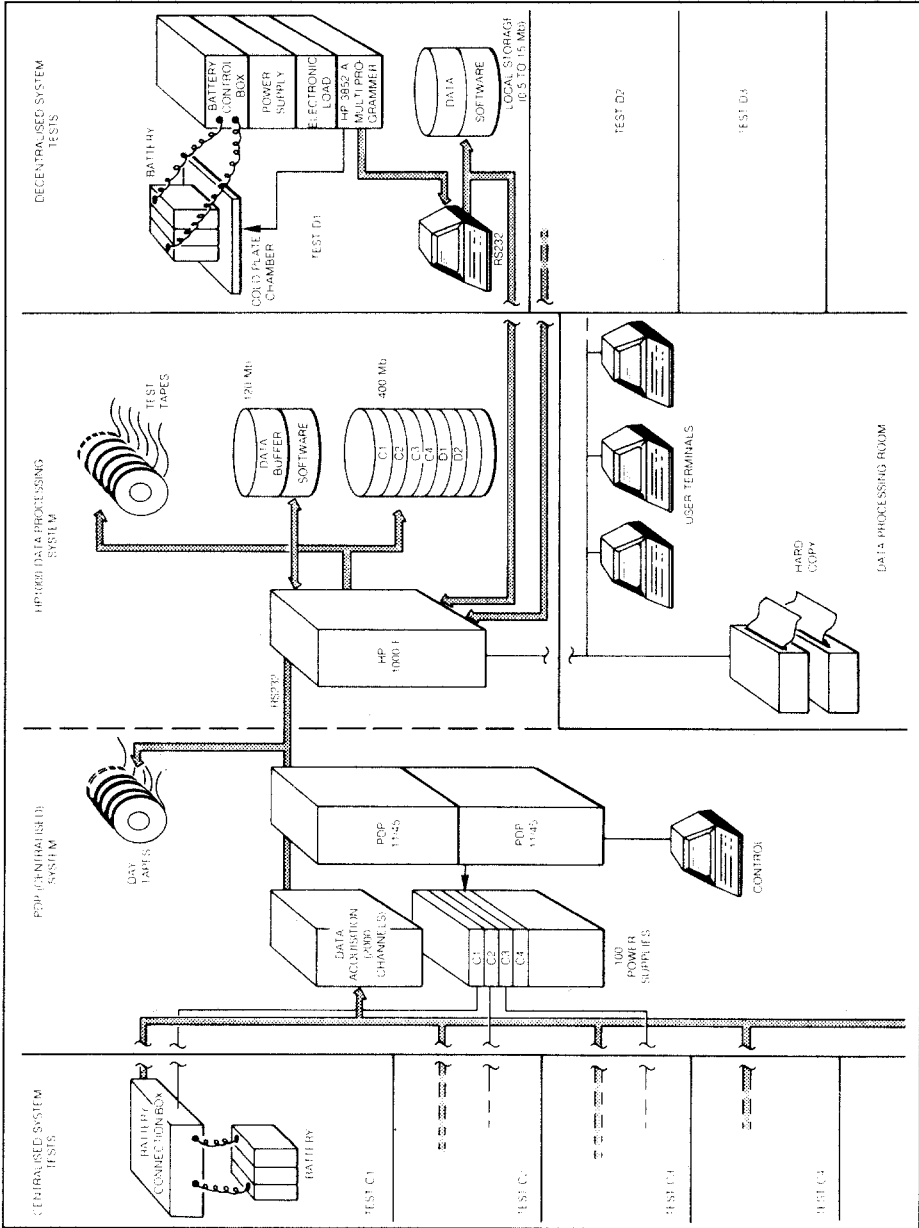


Fig. 6. ESBTC configuration.

In order to obtain the higher level of system flexibility of the system as well as test sophistication now required, the 'centralised' system is in the process of being gradually replaced by a 'decentralised' system. As indicated in Fig. 6, each test station will be under direct control of a dedicated micro-computer and have its own data acquisition unit. The link to the HP1000F system will be conserved, allowing this machine to continue to be used for fast processing and archiving of large data files.

Ni-Cd LEO lifetime assessment

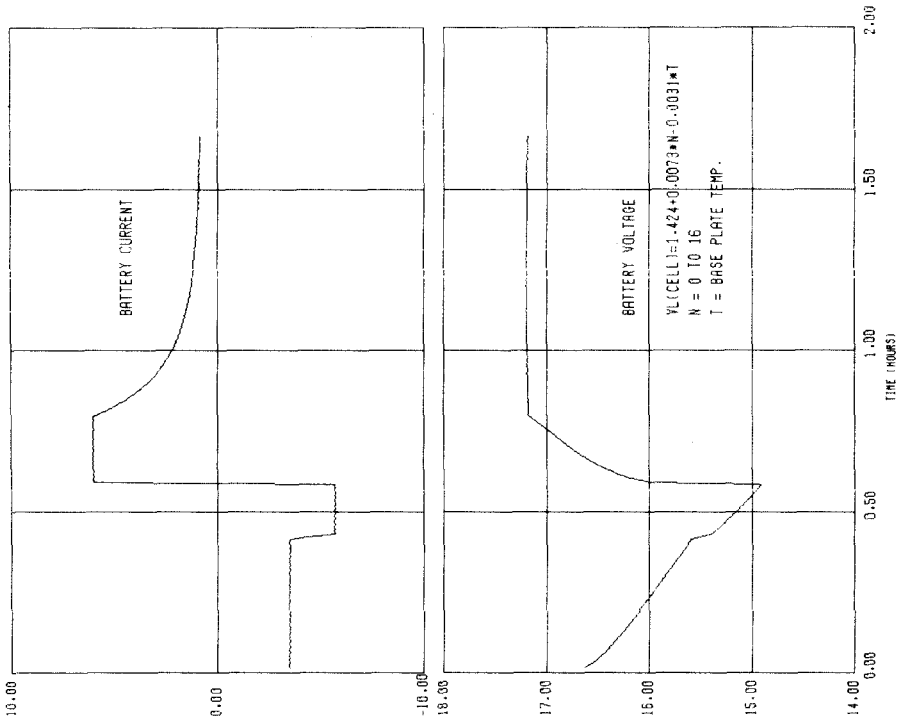
The relative lack of lifetime data for Ni-Cd batteries under LEO conditions led ESA and CNES to initiate a joint five-year test program called ELAN. The program, started in June 1985, includes battery cycling at different depths of discharge and at different temperatures, carried out at the ESBTC, along with destructive analysis of failed cells carried out under contract at an independent laboratory. The batteries are 12-cell assemblies specially designed to be thermally representative of a real spacecraft battery but with the ability to remove individual cells in case of failure.

The matrix of the cycling program, including the test conditions, is presented in Fig. 7(a). Figure 7(b) shows a typical battery cycling profile which derives from the French SPOT earth observation program. A 35 min discharge is performed in two different constant current steps, and a 65 min charge starting at a constant current is terminated at a temperature-compensated constant voltage (tapering technique) which is selectable from 16 different levels to provide control of the recharge factor, K .

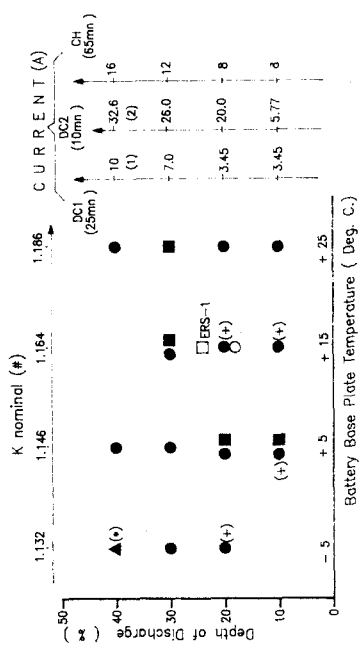
Figure 8 gives the end of discharge (EODC) cell voltages (based on battery voltages) at the end of the second discharge as a function of the number of cycles. Cycling of 40 A h cells has just begun and therefore is not considered. The arrows indicate when reconditioning was performed along with the determined capacities. As of October 1986, up to 7000 cycles have been completed. As expected, for a given temperature the end of discharge voltage decreases with time, this being more pronounced at high DOD and high temperature. In the case of the 40% DOD test at 5 °C a voltage stabilisation is apparent which may be due to a second plateau voltage.

The effect of the reconditioning is apparent by comparison of the results from the two batteries at 15 °C and 20% DOD. One can see that the voltage for the reconditioned battery is the same as that for the battery at 5 °C. This reconditioning has also resulted in the cell voltage remaining at a higher value throughout cycling. The capacity remains constant as well. It seems that for 25 °C conditions the voltage decay with cycling is more pronounced than at the three lower temperature levels investigated.

The test on the G.E. cells has just started and the highest values observed remain in the internal resistance difference with the SAFT cells, also coupled with the lowest DOD (18%).



(b)



- (1) 7A for battery at +5 C
15A for battery at +25 C
- (2) 40A for battery at +5 C
20A for battery at +25 C

- (+) Reconditioning and capacity determination every 6 months
- (*) Deep discharge and impedance diagram every 6 months
- within 1.5 %
- ERS-1: Special test profile (SFT V02AS)
- Project battery management support

□	ERS-1
○	6.L 22Ah
▲	SFT V02AS
■	SFT V040S
●	SFT V02AS

(a)

Fig. 7. (a) ESA-CNES ELAN program; (b) typical ELAN cycle profile.

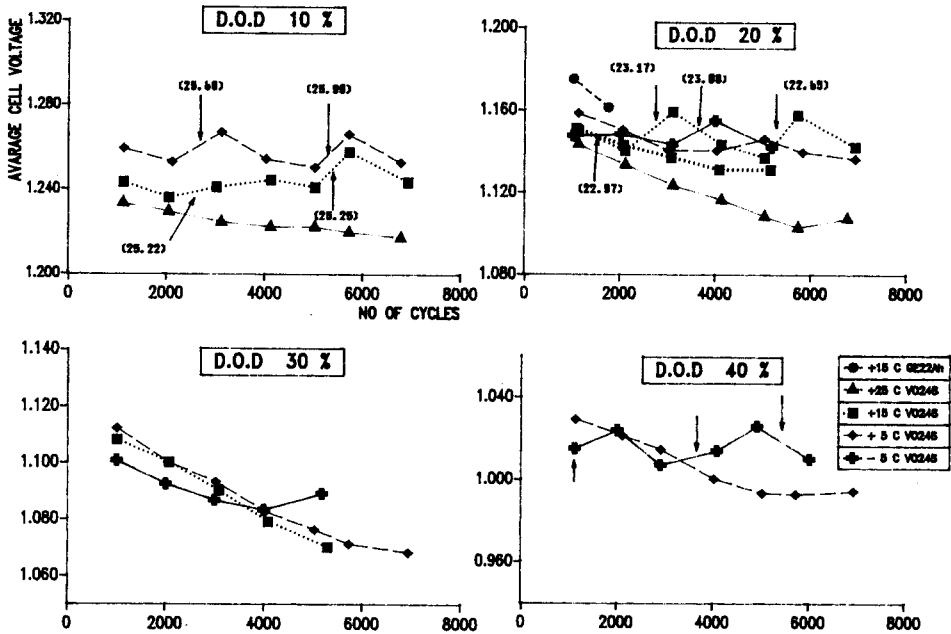


Fig. 8. ELAN: EODC average min. cell voltage/No. of cycles.

Temperature derivative technique evaluation test

Battery lifetime is strongly dependent on the battery management scheme employed. End of charge termination is particularly important in order to minimize overcharge. The comparative study of different charge control methods is of particular interest for LEO applications where high charge rates are necessary, and a new charge control technique developed at ESTEC and recently awarded a patent [3] is under evaluation at the ESBTC.

This method, called Temperature Derivative Technique (TDT) has been described in more detail in previous publications [4, 5]. Briefly, charge is terminated when the temperature of specially positioned thermistors passes through a minimum (which precedes the onset of the thermal dissipation at end of charge). This technique makes use of thermal properties fundamental to the cell reactions and reduces, in general, the amount of overcharge experienced by the cells compared with the more conventional voltage taper charge control method. The avoidance of taper charge decreases significantly the size of the solar array required for battery charging.

The TDT has been tested under LEO conditions on 3 parallel-connected batteries, each of 14 SAFT 35 A h cells and having its own TDT detector. The cycling profile consists of a 3-step discharge giving a DOD of 26.7%, and the charge is terminated when the first of the three detectors is activated. The batteries are mounted on a cold plate set at 15 °C.

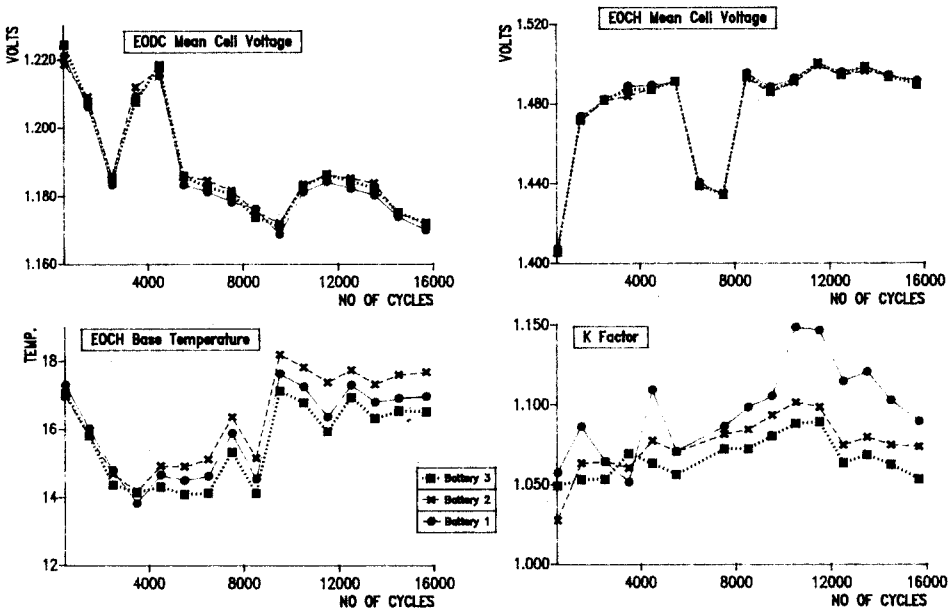


Fig. 9. TDT test results.

Up to now, 16 000 cycles have been achieved and encouraging results obtained. Figure 9 gives some of the battery parameters at 500 cycle intervals. Due to some aged electronic equipment dedicated to this test a number of test hardware failures have occurred. These explain the abnormal values in the upper right plot.

The test results show that the three batteries present the same behaviour during the course of the cycling. Cell EOCX (end of charge) voltages are nearly identical and cell EODC voltages are within 2%. A slight (5%) difference in K factor values is noticeable. The DOD values were within 3%. The battery temperature differences (up to 1.1 °C) are not judged significant. It should be noted that the cells were not matched nor are they of space-grade.

The evolution of the test parameters during the 16 000 cycles is quite remarkable. The average EODC cell voltages after a period of instability showed a slow downward trend interrupted around cycle 9500 by a change in DOD. The overall decrease is very low, EODC cell voltages varying from 1.22 V at cycle 500 to 1.17 V at cycle 15 670. By comparison, the ELAN battery at 30% DOD and 15 °C, for which the discharge rate is less severe, already gives an EODC cell voltage value of 1.07 V at cycle 5500. The EOCX cell voltages show a sharp increase during the first 2000 cycles from 1.41 V to 1.47 V, followed by a gradual stabilisation around 1.49 - 1.5 V. This shows some correlation with the K factor behaviour. The marked rise for

cycle 9500 in the temperature plots results from changes in the set temperature of the cold plate.

These results confirm the interest and advantage of that charge technique which provides battery charging under steady conditions, and consequently may be expected to limit the battery degradation over extended cycling. The battery temperature is reproducible. In this paralleled batteries test, thermal balance is also maintained between the batteries. Balanced electrical performances are then observed, as opposed to previously reported results on a similar test using a tapering method [5].

Metal-hydrogen LEO test

In an initial investigation of nickel-hydrogen cells for future LEO applications, ESTEC has initiated a test to evaluate and compare cells from SAFT and from DAUG (Deutsche Automobil Gesellschaft). Neither design is optimised for this application. In addition, a parallel test is in progress using SAFT Ag-H₂ cells.

The test matrix and preliminary results are presented in Table 5. All cells are cycled at 40% DOD and a comparison of their behaviour with and without charge tapering will be made.

TABLE 5

Metal-hydrogen LEO test matrix

Manufacturer Type	DAUG Ni-H ₂	DAUG Ni-H ₂	SAFT Ni-H ₂	SAFT Ni-H ₂	SAFT Ag-H ₂	SAFT Ag-H ₂
Nom. capacity (A h)	40	40	42	42	26	26
Charge current (A)	(20)	16.6	(21)	17.3	(13)	10.4
Charge technic.	tap.		tap.		tap.	
Disch. current (A)	25.6	25.6	26.8	26.8	16.6	16.6
DOD (%)	40	40	40	40	40	40
Cycles completed	2000	2000	1900	2050	1850	1900
<i>k</i> -fact.	1.04	1.04	1.04	1.03	1.01	1.01
Efficiency (%)	80	80	82	78	72	72
Heat diss.	3.0	3.0	2.8	3.5	2.9	2.9
VB _{eoc} (V)	3.0	3.2	3.0	3.2	3.4	3.5
VB _{eod} (V)	2.3	2.3	2.4	2.3	2.1	2.1
P _{eoc} (bar)	52	57	58	63	60	50
					40	20
P _{eod} (bar)	38	42	43	50	50	40
					30	10
TC _{eoc} (°C)	11.5	10.5	11	11	11.5	11.5
TC _{eod} (°C)	14	14	12	12	13.5	13.5

Test parameters: charge period: 60 min
disch. period: 37 min 30 s
mean base plate temp.: 10 - 11 °C
each test with two cells in series

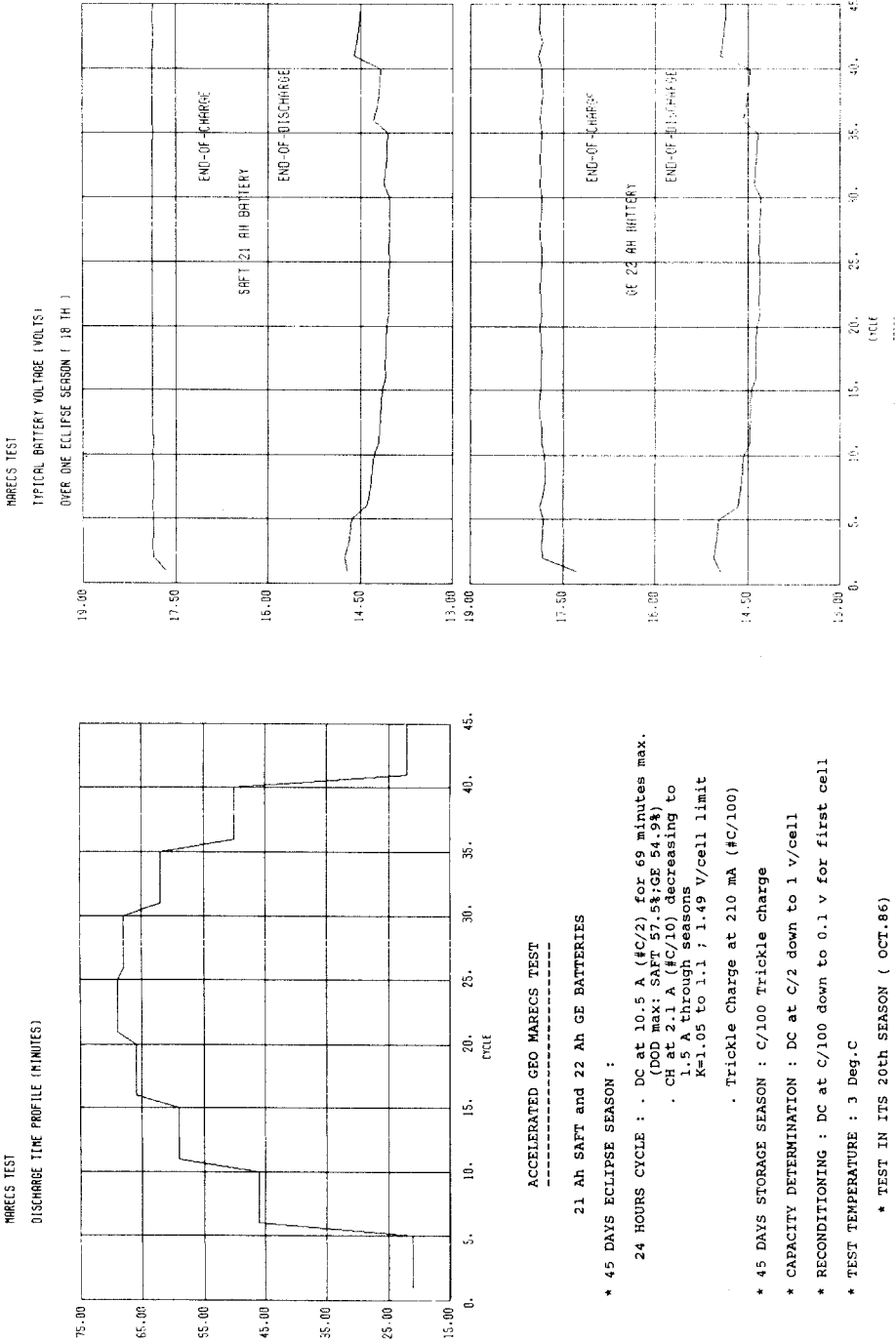


Fig. 10. MARECS test profile.

MARECS accelerated GEO test

This test was initiated in 1981 in support of the ESA MARECS (Maritime European Communication Satellite) program, which requires a battery lifetime of 10 years at 57% (max) DOD. It is an accelerated GEO cycling test using 12-cell batteries, one of SAFT VO 21 S3 cells (coming from the MARECS B1 flight production batch) and the other using General Electric 22 A h cells.

The test program is presented in Fig. 10 along with a typical EODC and EOCB battery voltage evolution through one eclipse season. For the first 8 eclipses, battery charging was terminated when a pre-set charge time was reached, to achieve a recharge factor of 1.05, or when a voltage limit of 1.49 V per cell was reached. Later it was noticed that the tendency of the batteries was to accept more charge during the second half of the eclipse period. The K factor was then set to 1.10 in order to favor charge termination due to the voltage setting and to allow the natural tendency of an increase in the K factor. In orbit solar array degradation was simulated from the 4th season by a gradual decrease of the charge current. The solstice simulation period is reduced to 45 days so as to simulate the 10 years of operation in half the time. Battery capacity determination and battery reconditioning are performed prior to the eclipse period. The initial capacities were 26.1 A h (average) for SAFT cells and 23.36 A h for the G.E. cells.

Both batteries are now in their 20th season, and maintain good performance. Figure 11 shows some battery parameters through the 19

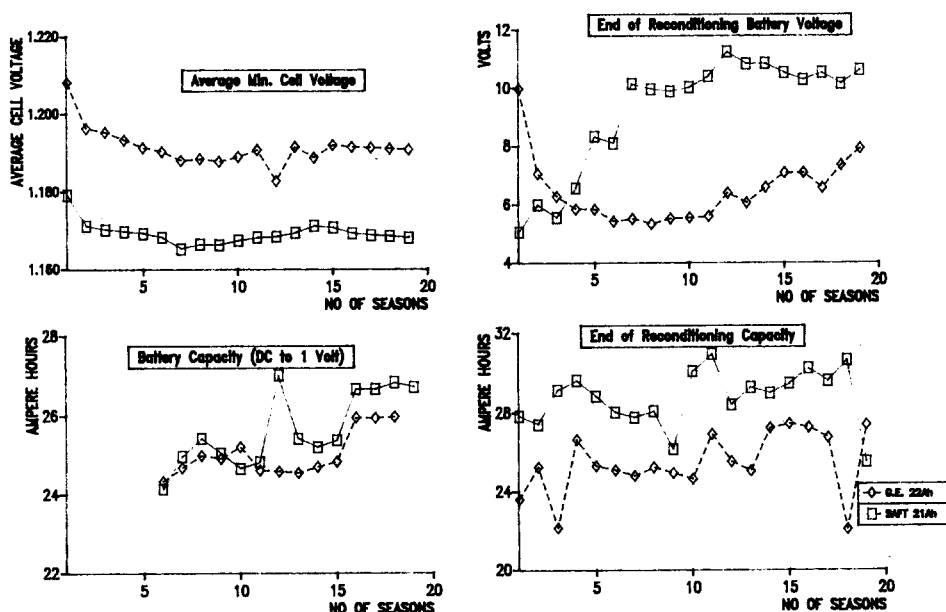


Fig. 11. MARECS test: parameters evolution through 19 seasons.

completed seasons. Except for the battery voltages at the end of the reconditioning, the trend in the parameters is the same for both batteries. The plot showing the minimum EODC cell voltages (which occur during period 5 or 6) indicates a marked degradation up to season 6 followed by stabilisation, with a tendency towards improvement noticeable from season 10 where the K factor setting was modified from 1.05 to 1.10. A reproducible voltage difference exists between the two batteries arising from an internal resistance difference of about $2 \text{ m}\Omega$. At season 19 the minimum cell voltages are 1.168 for SAFT cells and 1.19 for G.E. cells. No battery capacity data are available for seasons 1 - 5. Nevertheless, the plot shows no sign of capacity degradation.

Since reconditioning is stopped as soon as the first cell reaches 0.1 V, the battery voltage at the end of the reconditioning gives information about the matching of the cells in the battery assembly. Both types of cells were initially matched in capacity within 3%. A high battery voltage indicates a larger deviation in voltage amongst the 12 cells at the end of the $C/100$ discharge. For the SAFT cells one can observe a rapid increase in the deviation followed by a stabilization. For the G.E. cells this deviation was reduced at the beginning but has increased somewhat since.

Ni-Cd high DOD GEO lifetime assessment

Useful Ni-Cd battery energy densities for GEO spacecraft are usually about 20 W h kg^{-1} . This results from a limitation of the battery DOD to a maximum value of 60%, chosen conservatively to meet lifetime requirements.

From MARECS test and in flight data it appears that higher DOD values may be used. ESTEC has initiated an accelerated test program on three spare ECS-1 (European Communication Satellite) battery models (28 SAFT 18 A h cells) on a cold plate at 3°C . The test sequence is identical with that of the MARECS test, except that the maximum DODs are, respectively, 100%, 90%, and 70% of nameplate capacity.

Results for the first 5 seasons are presented in Fig. 12. The degradation of the minimum end-of-discharge cell voltage is low and if the trend remains linear, one would expect to achieve 20 seasons above a minimum cell voltage of 1 V.

Thermal characterisation of space battery cells

The thermal design of batteries becomes particularly important in LEO spacecraft because of the strong negative impact of increased temperature on lifetime. In order that the necessary cell-level thermal data are available for use in battery design a flow calorimeter has been developed under ESA contract by Elektronik Centralen (DK). Figure 13 shows the calorimeter

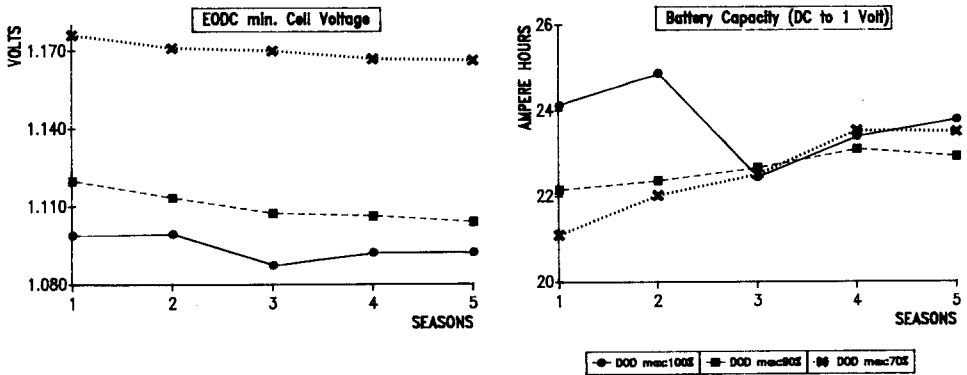


Fig. 12. Ni-Cd high DOD test results.

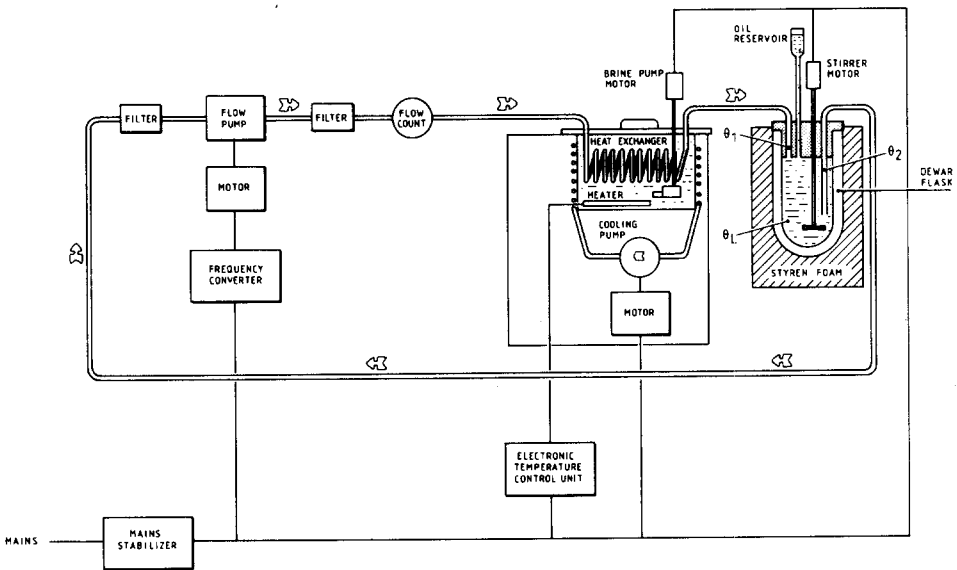


Fig. 13. Schema of the flow calorimeter.

version adapted to high capacity cells. Complete cells are cycled totally immersed in the calorimeter and the results deconvoluted to remove effects due to non-ideality of the calorimeter. In the case of nickel-cadmium cells, measurements have also been made of the thermal conductivity along the X and Y cell directions and of the thermal capacity at various states of charge. These data have been used to establish a dynamic thermal model of the cells.

As an example, Fig 14 shows the instantaneous heat transfer across the surface of a SAFT 40 A h Ni-Cd cell during a LEO cycle at 40% DOD.

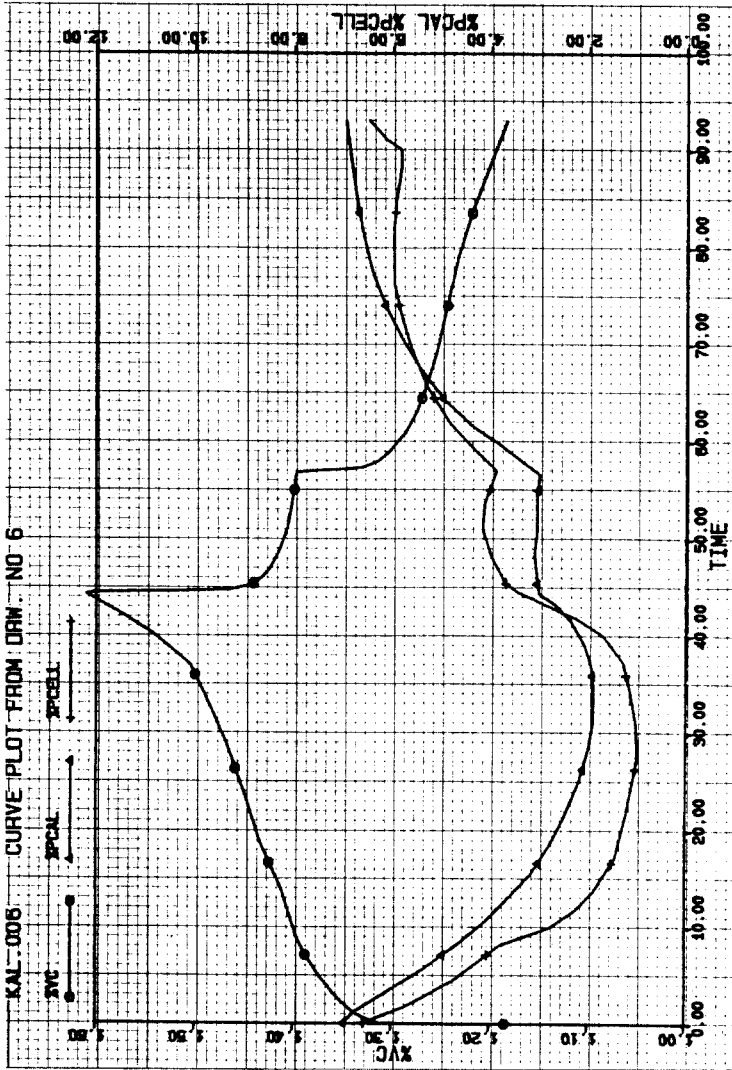


Fig. 14. 40 A h Ni-Cd cell heat dissipation during a LEO cycle at 40% DOD.

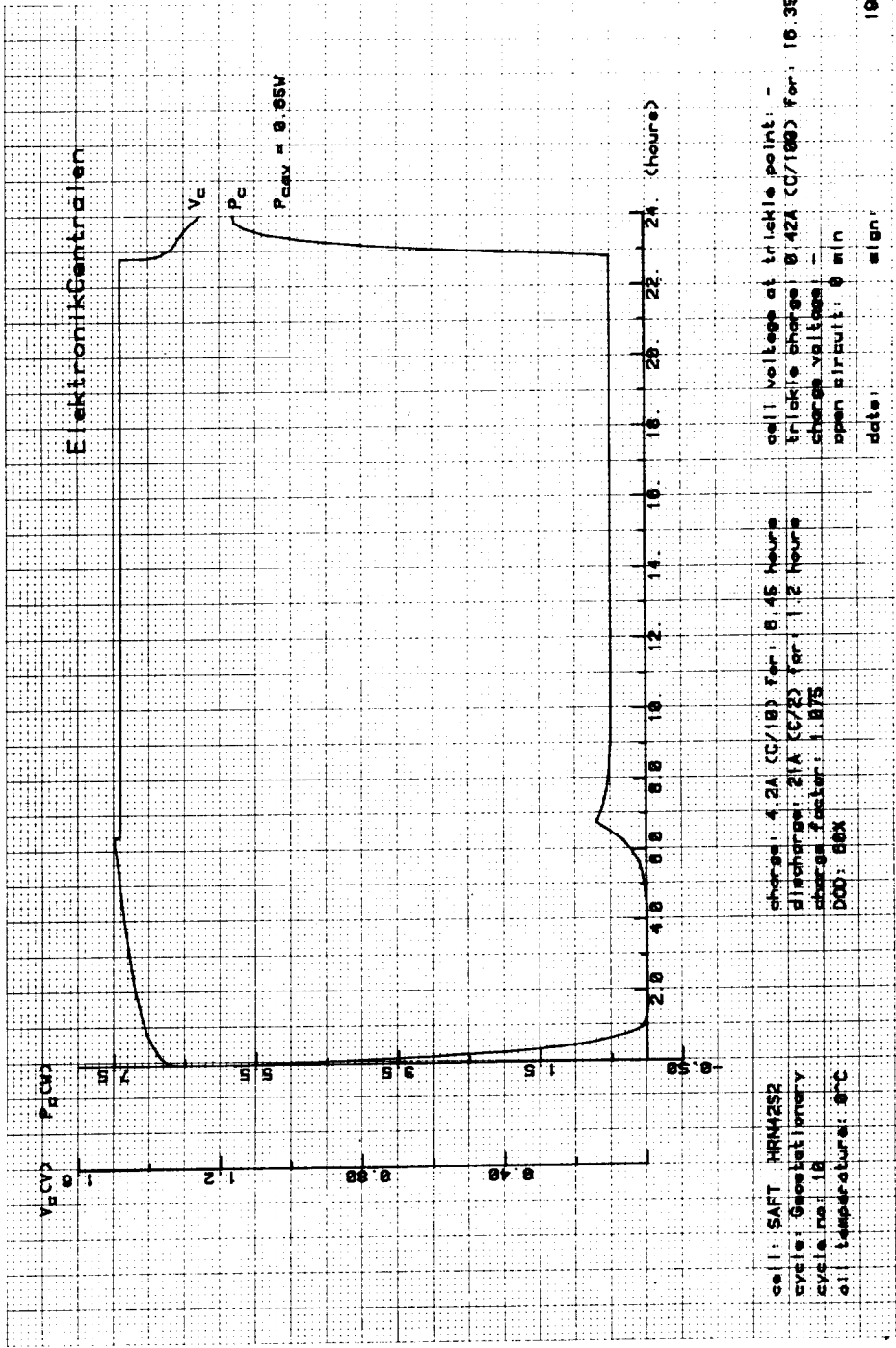


Fig. 15. 42 A h Ni-H₂ cell heat dissipation during a GEO cycle at 60% DOD.

ElektronikControlen

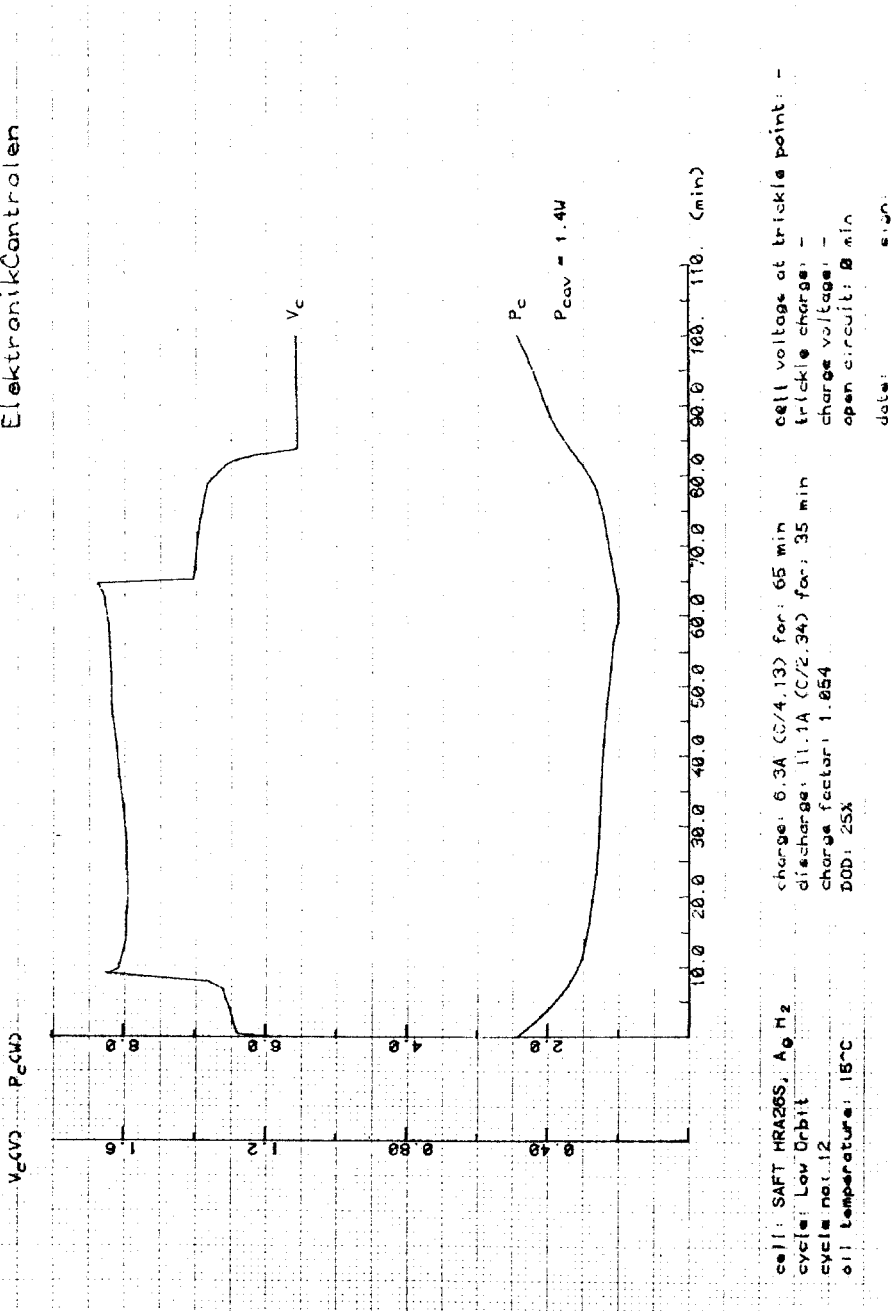


Fig. 16. 26 A h Ag-H₂ cell heat dissipation during a LeO cycle at 25% DOD.

Similar heat transfer characterisations have also been performed on SAFT Ni-H₂ cells during GEO cycles and on SAFT Ag-H₂ cells during LEO cycles (Figs. 15 and 16).

Acknowledgements

My acknowledgements are addressed to G. Dudley and all the other ESTEC members who helped in the preparation of this presentation.

References

- 1 *ESA Rep.-CR(P)-2106-vol-2.*
- 2 G. J. Dudley and F. Baron, Space Battery Testing in ESTEC, *ESA Bull. No. 48*, November, 1986.
- 3 *ESA Pat./1.2/MM/6838* (H. J. Spruijt).
- 4 H. J. Spruijt, Temperature derivative technique, *Proc. 16th Power Electronic Specialists Conf., Toulouse (France), June 24 - 28, 1985*, ESA SP-300, pp. 107 - 121.
- 5 F. Baron, LEO life testing with different charge control, *The 1984 Goddard Space Flight Center Battery Workshop*, NASA CP-2385, pp. 343 - 367.