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BATTERY DEVELOPMENT AND TESTING AT ESA

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ABSTRACT

The principal activities of the Energy Storage Section of the Space Research & 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 spacecrafts, the enormous diversification in energy storage requirements for future missions such as COLUMBUS (the European contribution to the US 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, brought ESA to start feasability studies on using sodium-sulphur batteries for various types of mission.

Ni-H2 IPV CELL DEVELOPMENT FOR GEOSTATIONARY APPLICATIONS.

ESA is providing support in certain area to 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 figure 1. The cell, which operates at a maximum pressure of 75 bars and covers the capacity range 30-50 Ah 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 reproductibility of which has been improved by greater control of the impregnation bath parameters. Individual electrode capacity is 1.90 Ah at 20°C in flooded KOH which gives a value of 0.146 Ah/g and 0.044 Ah/cm2. The 50 Ah cell has an energy density of 50 Wh/Kg and a volumetric energy density of 70 Wh/l.

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 and indicates that a 5°C maximum temperature gradient between cell stack and inside pressure vessel will exist during 70 % D.O.D 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 Ah cell, due to be completed by December 1987. The final step will be a qualification program to be finished in mid 1988.

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 the volumetric energy density disadvantage compared to 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 figure 2. The cells are bounded 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 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 diameter cells in the 40-50 Ah 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 Ah 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 of 5 Kw to 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 of Ni-H2 CPV (Common Pressure Vessel) cell option.

A contract for the design and validation of a complete 80V, 3.3Kw CPV Ni-H2 battery module including integral active thermal management and with a lifetime requirement of 18000 to 30000 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 Ah dual-stack CPV cell. The cell design in shown in figure 3a. The final choice had been between this concept and a more conventional cylindrical 2-stack CPV design (figure 4a).

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 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 deg.C.

The geometrical difference between the two designs arises from a radical change of the thermal design (figures 3b, 4b). 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 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 to 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 2 contained stacks are independent units which greatly simplifies the cell assembly. The stacks are supported to the central Inconel tube , which also acts as a tie rod, via the positive inner current collector and the series connection is performed by connecting the inner collector of one stack to the outer collector of the other one 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 Wh/Kg (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 mean 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 deg.C, a mounting surface temperature of 5.7 deg.C is required for the spherical CPV which then shows an inside maximal thermal gradient of 6.2 deg.C whereas the figures for the cylindrical gives 7.7 deg.C and 5.3 deg.C.

The volumetric energy density is of course lower for the spherical CPV cell (32 Wh/l against 45 Wh/l) but the overall battery volume is about the same for both battery modules because of the lower foot print 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 a O2-H2 fuel cells to provide energy to the spacecraft during eclipse periods and of 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]).

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 figure 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.

TABLE 1: MAIN ESA ELECTROCHEMICAL POWER SOURCES DEVELOPMENT PROGRAMS

ITEM	TYPE	DEVELOPMENT	APPLICATIONS	PRIME/SUB CONTRACTORS
$Ni-H_2$	GEO	30-50 Ah IPV + ONE PIECE SLEEVE	TELECOM. SATELLITES	SAFT/AEROSPATIALE (F) UNDER CNES MANAGEMENT
		40-50 Ah BATTERY E.M.	TELECOM. SATELLITES	BAe (UK)/SAFT (F) ELECTRONIK CENTRALEN (DK)
$Ni-H_2$	LEO	50 Ah CPV 80 V. 3.3 KW BATTERY MODULE	COLUMBUS IOC	MARCONI/HARWELL (UK)
RFCS	LEO	TRADE-OFF DESIGN STUDIES	20 KW MODULE COLUMBUS AOC	DORNIER SYSTEM (D)
FCS	VEHICLE	KOH (MOBILE-IMMOBILE) SPE	4 KW MODULE HERMES	
Li PRIMARY	DEEP SPACE PROBES	10 Ah D-SIZE CELL 8 YEARS SHELF LIFE C/4 RATE	TITAN PROBE (CASSINI)	BTC VENTURE (UK)
Na/S	LEO GEO	EVALUATION	BASIC DEVELOPMENT	TO BE CHOSEN

TABLE 2 : CNES-SAFT $Ni-H_2$ CELL KEY FEATURES.

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

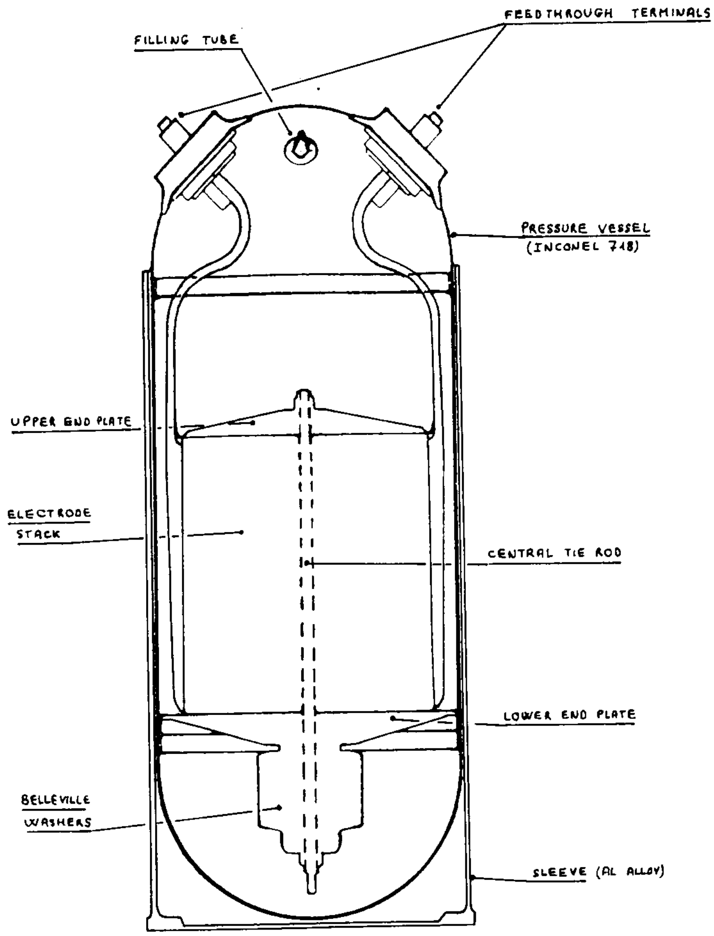

Figure 1. CNES-SAFT 50 Ah Ni-H_2 Cell.

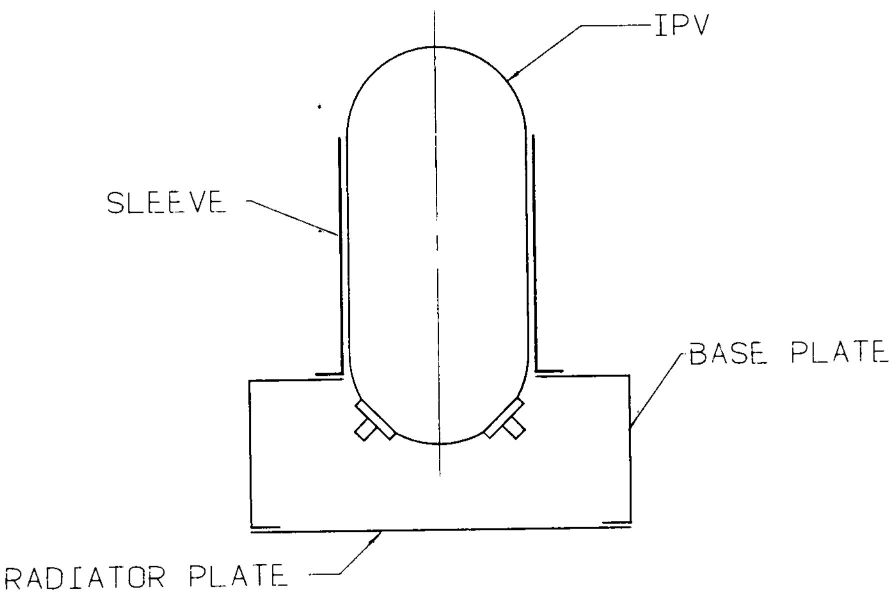

Figure 2. Ni-H_2 Battery Design Concept.

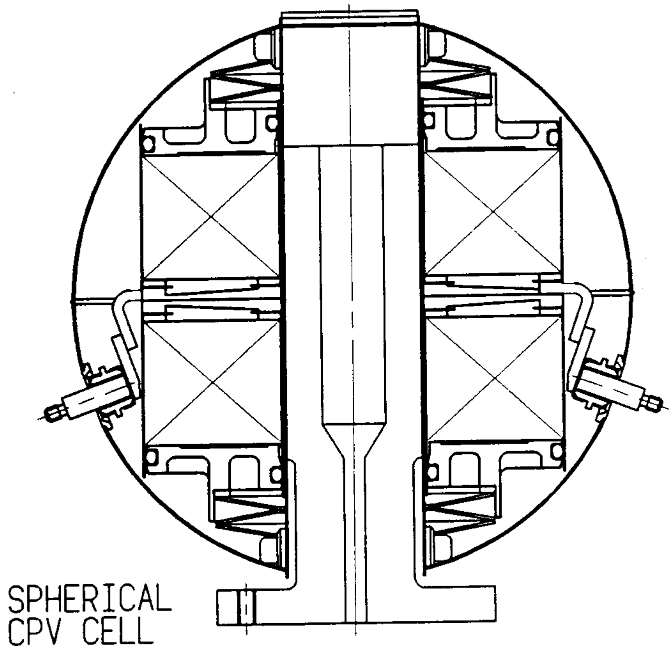

Figure 3a. Spherical CPV Cell Design.

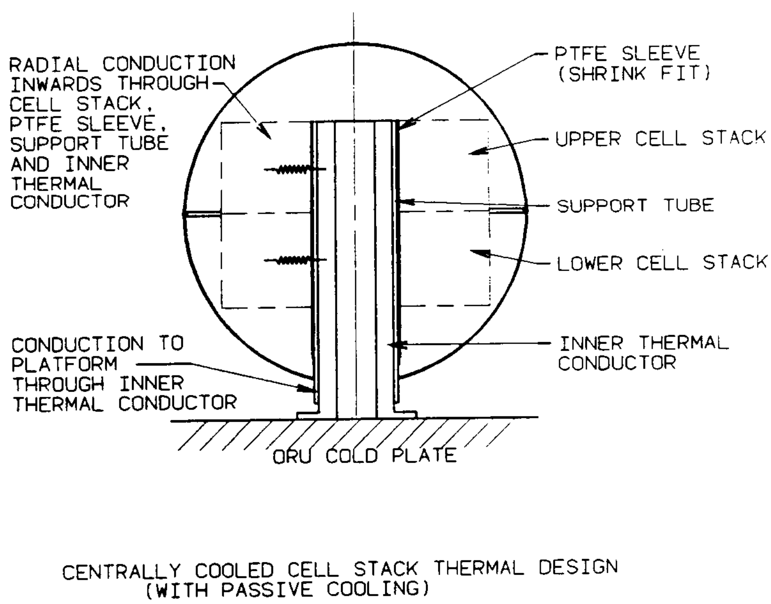

Figure 3b. Spherical Cell Thermal Design Concept.

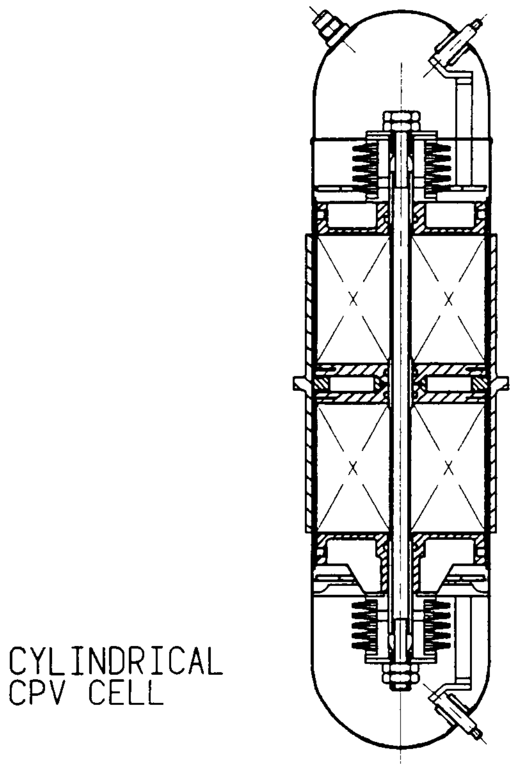

Figure 4a. Cylindrical CPV Cell Design.

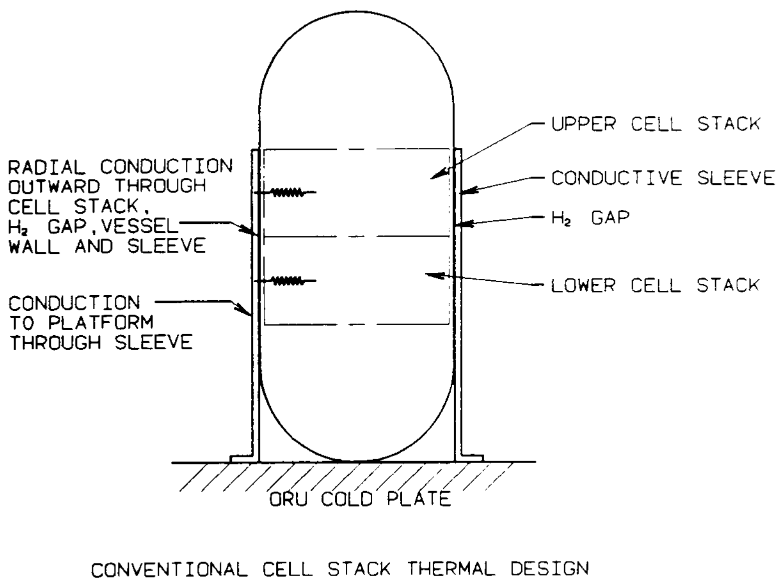

Figure 4b. Cylindrical Cell Thermal Design Concept.

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TABLE 3: COMPARISON OF MAIN DESIGN REQUIREMENTS

	HERMES	COLUMBUS AOC
AVERAGE POWER LEVEL	4 kW	20 kW
VOLTAGE LEVEL	85-135 VDC	150 VDC
MISSION DURATION	11 (28) DAYS	5 YEARS
OPERATING TIME BETWEEN MAINTENANCE	30 DAYS max.	90 DAYS min.
ORBITAL REPLACEMENT UNIT	NO	YES
OPERATION DURING LAUNCH	YES	NO
REACTANT STORAGE	CRYOGENIC	PRESSURE TANK
GAS/LIQUID SEPARATOR	YES	YES

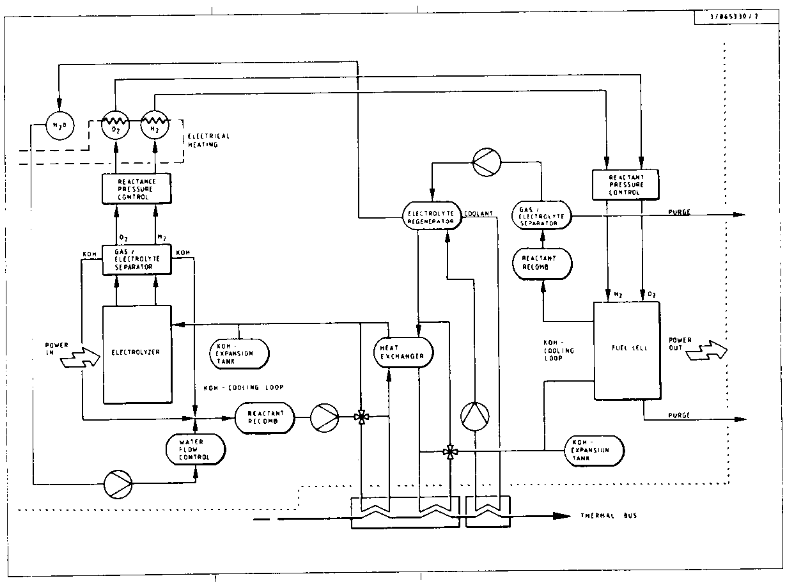

Figure 5. Mobile KOH RFCS.

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 figure 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.

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 figure 6, each test station will be under direct control of a dedicated microcomputer 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 to enable removal of individual cells in case of failure.

The matrix of the cycling program, including the test conditions are presented in figure 7a. Figure 7b shows a typical battery cycling profile which derives from the French SPOT earth observation program. A 35 mn discharge is performed in two different constant current steps and a 65 mn charge starting at a constant current is terminated at a temperature-compensated constant voltage (tapering technique) which is selectable among 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 Ah cells has just begun and therefore is not mentioned. 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 deg.C a voltage stabilisation is apparent which may due to reaching a second plateau voltage.

The effect of the reconditioning is visible by comparison of the results from the 2 batteries at 15 deg.C and 20 % DOD. One can see that the voltage for the reconditioned battery is the same as that for the battery at 5 deg. C. This reconditioning has also resulted in the cell voltage remaining at a higher value throughout the cycling. The capacity remains constant as well. It seems that for 25 deg. C. conditions the voltage decay with cycling is more pronounced than at the 3 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, coupled as well with a lowest DOD (18 %).

TEMPERATURE DERIVATIVE TECHNIQUE EVALUATION TEST

Battery lifetime is strongly dependant 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 pulications (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 to 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 Ah 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.

Up to now 16000 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 failure have occured. These explain the abnormal values in the upper right plot.

The test results show that the 3 batteries present the same behaviour during the course of the cycling. Cell EOCH (end of charge) voltages are nearly indendical 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 deg.C) are not judged significant. It should be noted that the cells were not matched nor are of space-grade.

The evolution of the test parameters during the 16000 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 volts at cycle 500 to 1.17 at cycle 15670. In comparison the ELAN battery at 30% DOD and 15 deg.C, for which the discharge rate is less severe already gives at cycle 5500 an EODC cell voltage value of 1.07 volts. The EOCH cell voltages show a sharp increase during the first 2000 cycles from 1.41 volts to 1.47 volts, followed by a gradual stabilisation around 1.49-1.5 volts. 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.

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-cells batteries, one of SAFT VO 21 S3 cells (coming from the MARECS B1 flight production batch) and the other one using General Electric 22 Ah cells.

The test program is presented in figure 10 along with a typical EODC and EOCH 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 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 4 th 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 Ah (average) for SAFT cells and 23.36 for the G.E cells

Both batteries are now in their 20 th season, and maintain good performance. Figure 11 shows some battery parameters through the 19 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 occurs 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. There exists a reproducible voltage difference between the two batteries arising from a internal resistance difference of about 2 milliohms. At season 19 the minimum cell voltages are 1.168 for SAFT cells and 1.19 for G.E cells. No battery capacity data is available for seasons 1 to 5. Nevertheless the plot indicates no sign of capacity degradation.

Since reconditioning is stopped as soon as the first cell reaches 0.1 volts, 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 within 3% in capacity. 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 density for GEO spacecrafts are usually about 20 Wh/Kg. 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 Ah cells) on a cold at 3 deg.C . The test sequence is identical to that of the MARECS test, except that the maximum DOD's are respectively 100%, 90% and 70% of nameplate capacity.

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

THERMAL CHARACTERISATION OF SPACE BATTERY CELLS

The thermal design of batteries becomes particularly important in LEO spacecrafts because of the strong negative impact of increased temperature on lifetime. In order that the necessary cell-level thermal data is available for use in battery design a flow calorimeter has been developed under ESA contract by ElektronikCentralen (DK). Figure 13 shows the 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. This data has been used to establish a dynamic thermal model of the cells.

As an example figure 14 shows the instantaneous heat transfer across the surface of a SAFT 40 Ah Ni-Cd cell during a LEO cycle at 40% 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 (figures 15 and 16).

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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 22500 CYCLES COMPLETED AT 23% D.O.D EODC CELL VOLTAGE STILL ABOVE 1 VOLT
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 ASSESSMENT 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 TEMPERATURE CONTROLLED CHAMBER	LIFETIME ASSESSMENT PRODUCT COMPARISON
MARECS	ACC.GEO	Ni-Cd (SAFT) Ni-Cd (G.E.)	2 BATTERIES 12 CELL ASSEMBLY IN TEMPERATURE CONTROLLED CHAMBER	SUPPORT TO SPACECRAFT LIFETIME ASSESSMENT PRODUCT COMPARISON
ECS	ACC.GEO	Ni-Cd (SAFT)	3 EX-FLIGHT MODELS 28 CELL ASSEMBLY ON COLD PLATE	HIGH D.O.D LIFETIME ASSESSMENT
OTS	REAL TIME GEO	Ni-Cd (SAFT)	1 BATTERY 2-14 CELLS MODULES IN SERIE IN TWO DIFFERENT CHAMBERS	REAL LIFETIME FLIGHT SIMULATION

TABLE 5: METAL-HYDROGEN LEO TEST MATRIX

manufact.	DAUG	DAUG	SAFT	SAFT	SAFT	SAFT
type	Ni-H_2	Ni-H_2	Ni-H_2	Ni-H_2	Ag-H_2	Ag-H_2
nom. capacity (Ah)	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
k-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
VBeoc (V)	3.0	3.2	3.0	3.2	3.4	3.5
VBeod (V)	2.3	2.3	2.4	2.3	2.1	2.1
Peoc (bar)	52	57	58	63	60 40	50 20
Peod (bar)	38	42	43	50	50 30	40 10
TCeoc (deg C)	11.5	10.5	11	11	11.5	11.5
TCeod (deg C)	14	14	12	12	13.5	13.5

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

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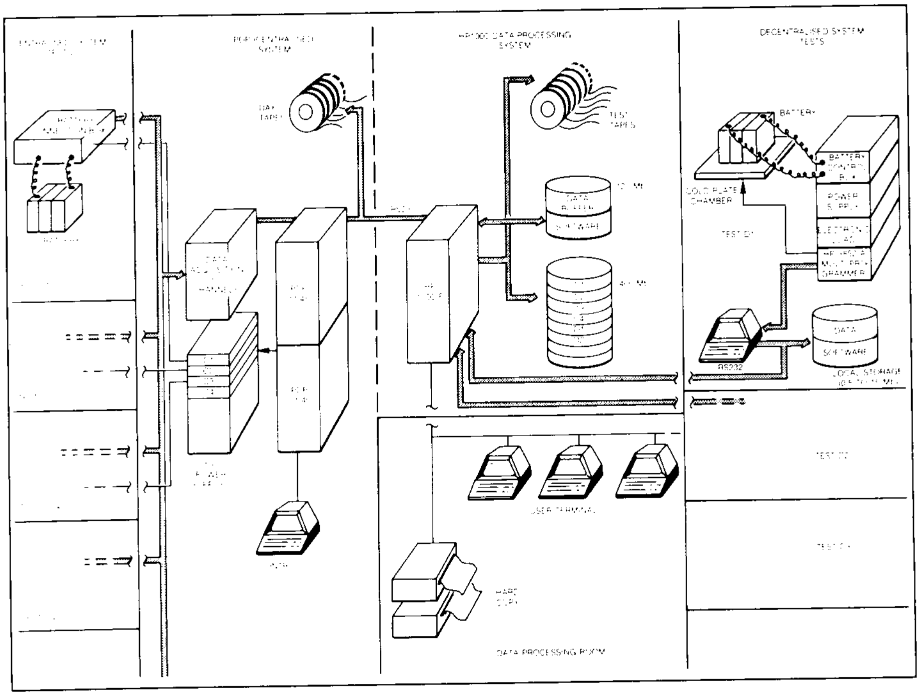


Figure 6. ESBTC Configuration.

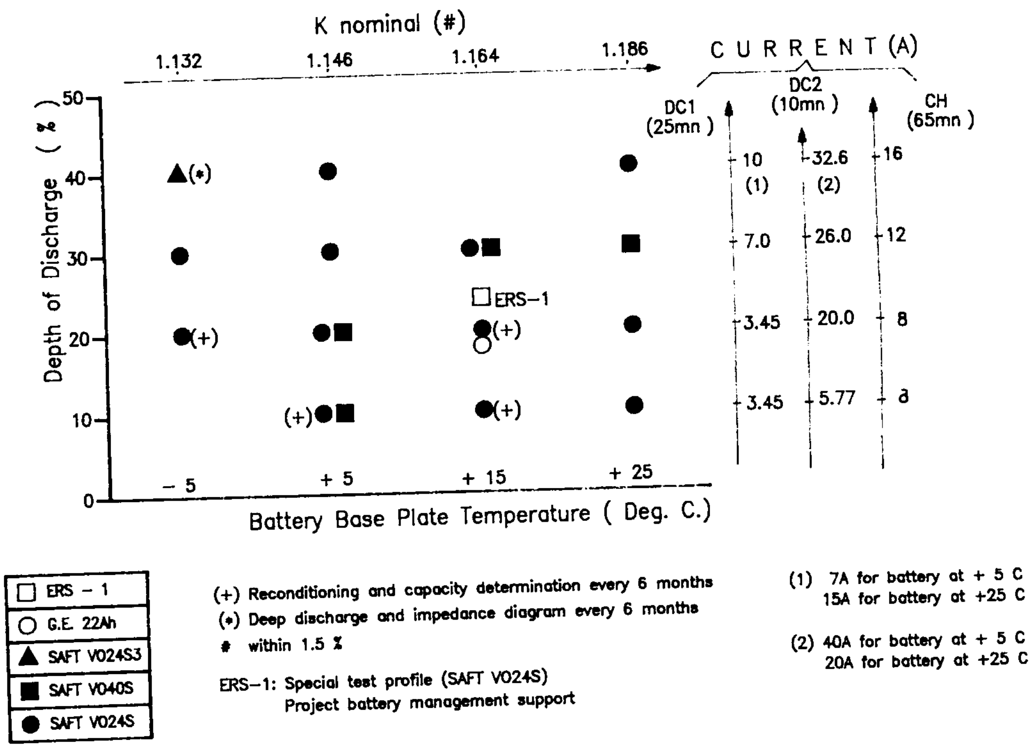


Figure 7a. ESA-CNES Elan Program.

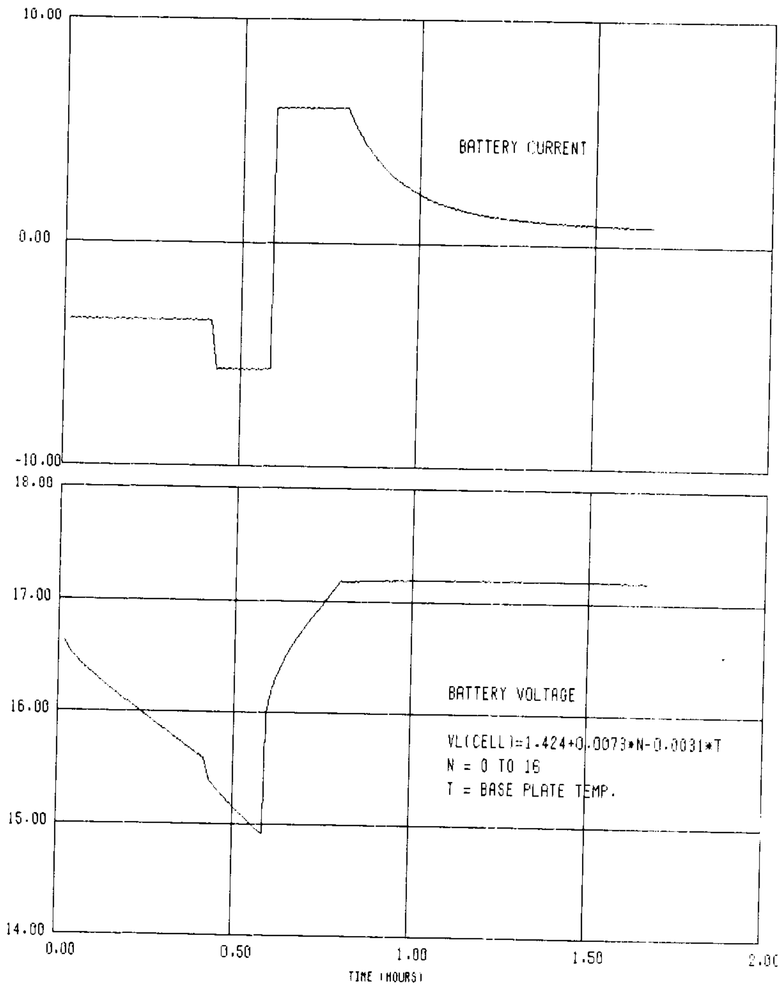


Figure 7b. Typical Elan Cycle Profile.

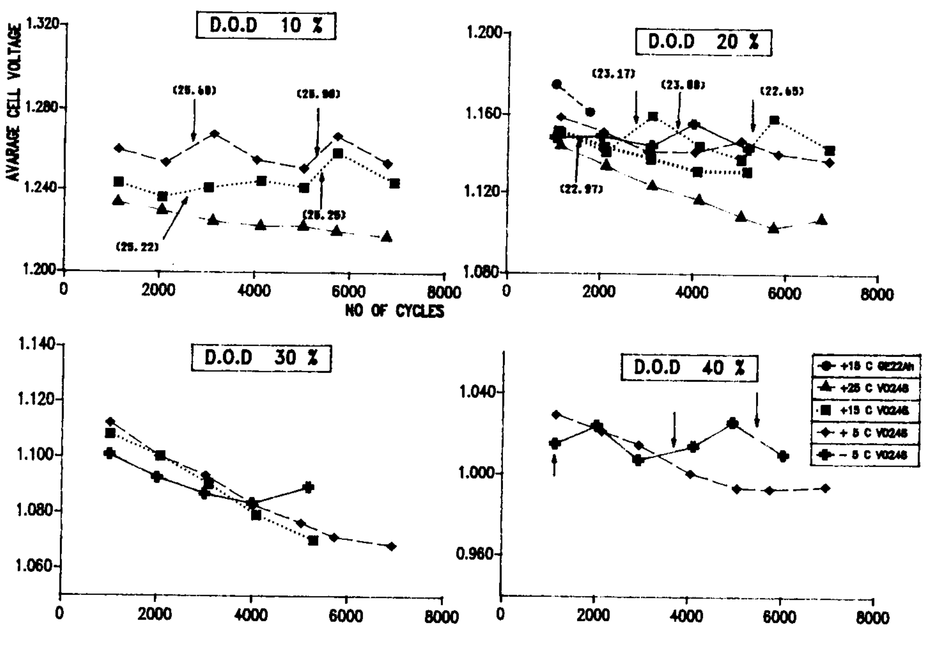


Figure 8. Elan: EODC Average Min. Cell Voltage/No. of Cycles.

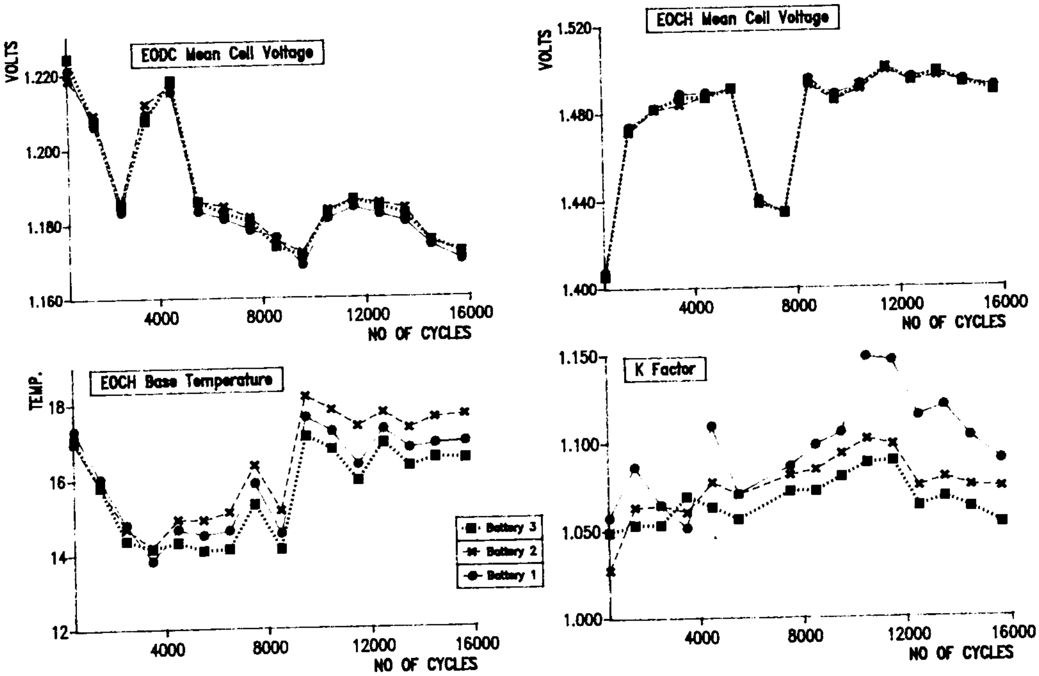
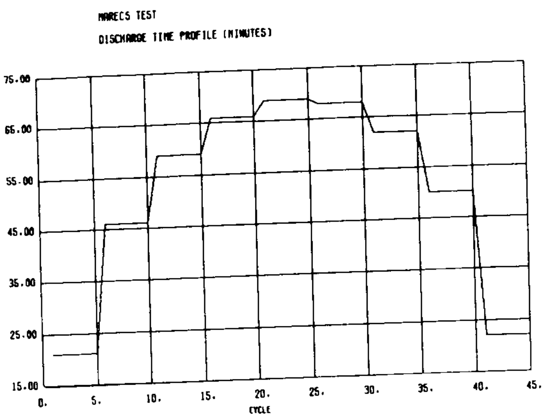


Figure 9. TDT Test Results.



ACCELERATED GEO MARECS TEST

21 Ah SAFT and 22 Ah GE BATTERIES

* 45 DAYS ECLIPSE SEASON :

  24 HOURS CYCLE : . DC at 10.5 A (#C/2) for 69 minutes max.
  (DOD max: SAFT 57.5%;GE 54.9%)
  . CH at 2.1 A (#C/10) decreasing to
  1.5 A through seasons
  K=1.05 to 1.1 ; 1.49 V/cell limit

  . Trickle Charge at 210 mA (#C/100)

* 45 DAYS STORAGE SEASON : C/100 Trickle charge
* CAPACITY DETERMINATION : DC at C/2 down to 1 v/cell
* RECONDITIONING : DC at C/100 down to 0.1 v for first cell
* TEST TEMPERATURE : 3 Deg.C
* TEST IN ITS 20th SEASON (OCT.86)

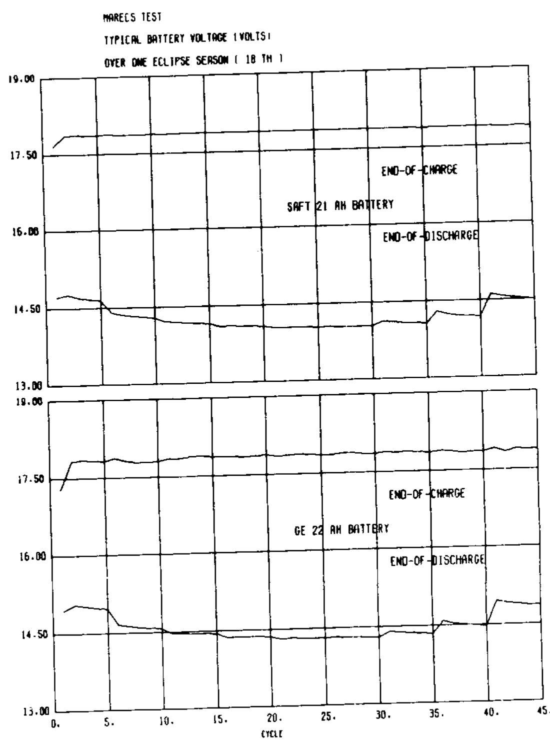


Figure 10. Marecs Test Profile.

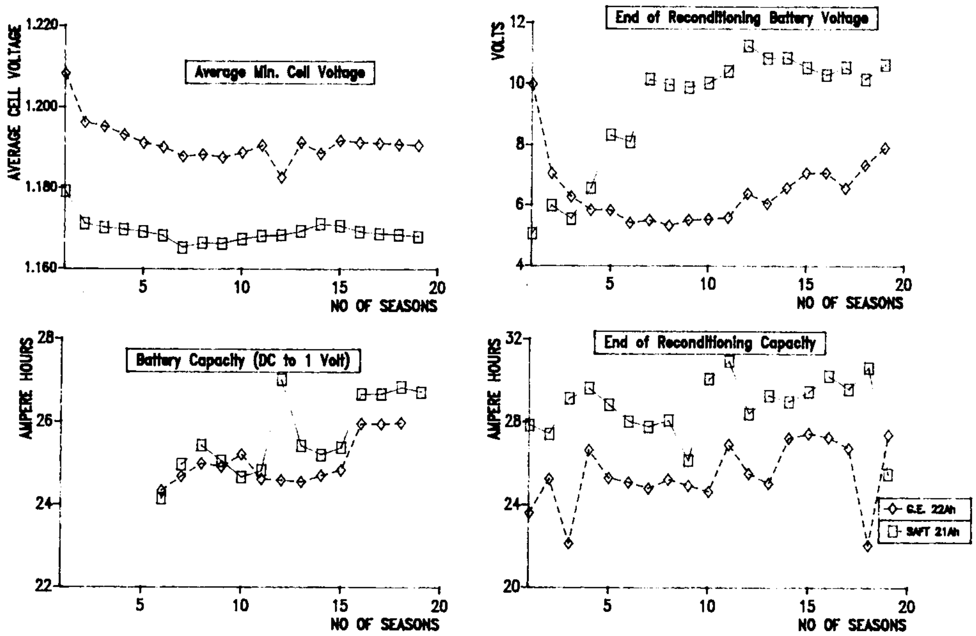


Figure 11. Marecs Test: Parameters Evolution Through 19 Seasons.

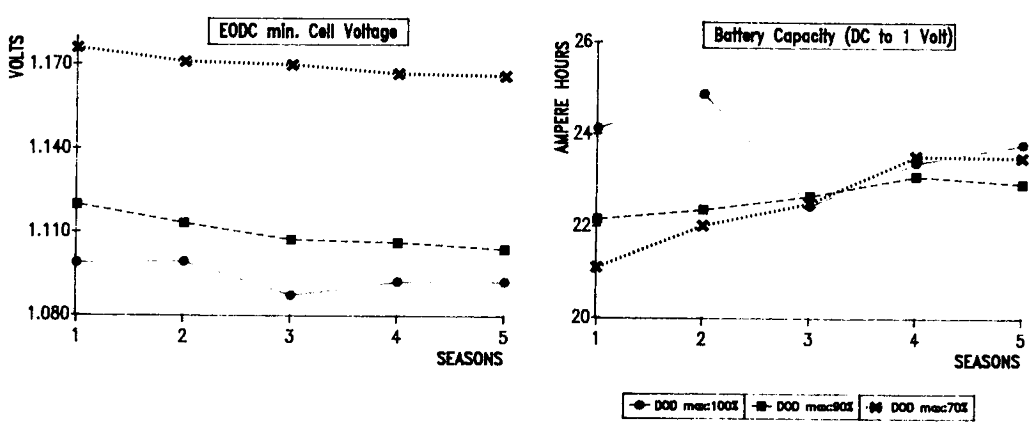


Figure 12. Ni-Cd High DOD Test Results.

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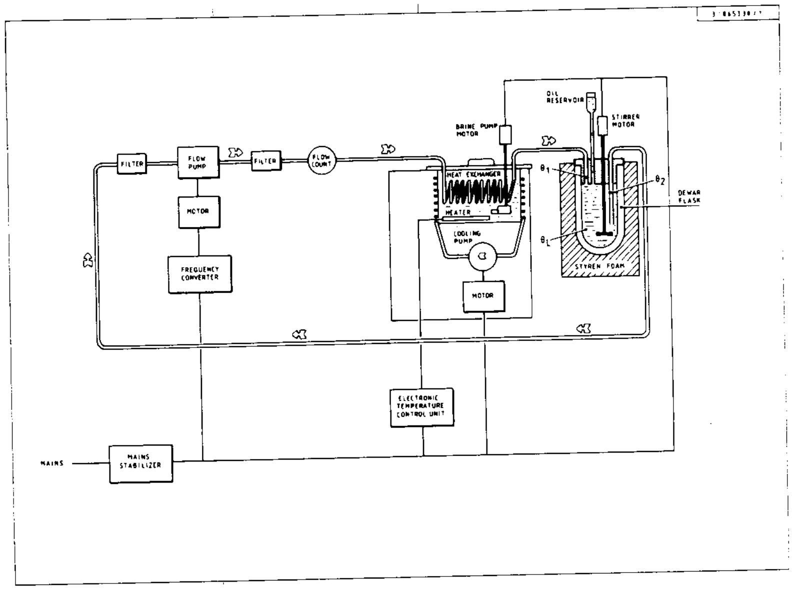

Figure 13. Schema of the Flow Calorimeter.

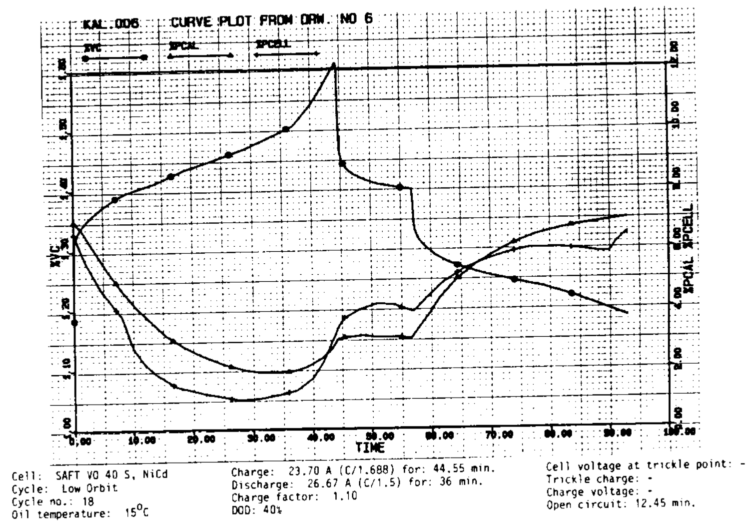

Figure 14. 40 Ah Ni-Cd Cell Heat Dissipation During a LEO Cycle at 40% DOD.

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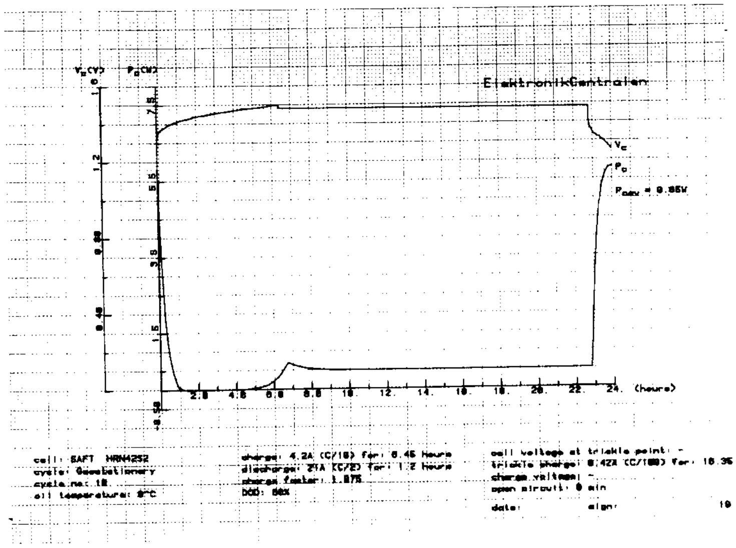

Figure 15. 42 Ah Ni–H_2 Cell Heat Dissipation During a GEO Cycle at 60% DOD.

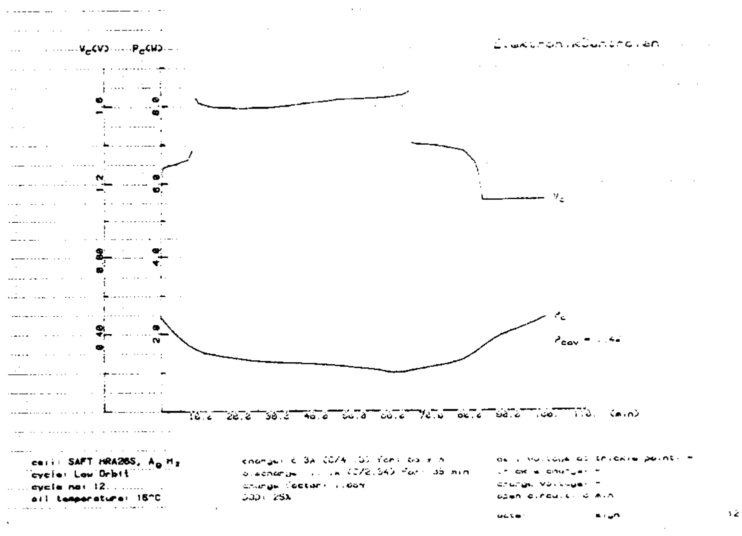

Figure 16. 26 Ah Ag–H_2 Cell Heat Dissipation During a LEO Cycle at 25% DOD.