SAFT NICKEL HYDROGEN CELL CYCLING STATUS

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SAFT ADVANCED BATTERIES
POITIERS FRANCE

1993 NASA AEROSPACE BATTERY WORKSHOP
US SPACE AND ROCKETS CENTER
HUNTSVILLE AL
NOVEMBER 16–18, 1993
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

1 - SAFT NiH2 CELL DEVELOPMENT

1972–1984
Development of NiH2 at SAFT (mass advantage over NiCd) : HRN cell design.

1985–1988
Common CNES—ESA—SAFT—AEROSPATIALE development of VHS BL cell.
Study on reproducibility of electrochemical impregnation and mechanical design.

1989
Qualification of the VHS50BL
Common CNES—ESA—SAFT—AEROSPATIALE development of VHS CM cell : GEO applications.
Focus on pressure vessel fracture mechanical analysis.

1990
Beginning of the battery 27 VHS CM development
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

1 - SAFT NIH2 CELL DEVELOPMENT (Cont'd)

1992

VHS CM range 35–107 Ah : ESA qualified for GEO applications
VHS BL cells reach 33 simulated GEO eclipse seasons
Battery 23 VHS 60 CM selected for ARTEMIS program
Commmon ESA–CNES–SAFT development of VHS DM (LEO applications) for COLOMBUS/MTFF program

1993

Qualification of the VHS CM battery
Battery 27 VHS 50 CM selected for ARABSAT II program
HRN 42 cells reach 6.5 years simulated LEO operation
The NiH2 SAFT system is an electrochemical (single or dual) stack (IPV). The stack is mounted in an hydroformed inconel 718 vessel operating at high pressure (up to 75 bars, 1090 psi with a safety factor of 2.5), equipped with "rabbit ears" ceramic brazed electrical feedthroughs.

Two container diameters used:

- 81 mm (3.2") for HRN and VHS BL designs
- 89 mm (3.5") for VHS CM and VHS DM designs

ENERGY DENSITY (Wh/Kg):

- BETWEEN 50 TO 60 Wh/Kg FOR THE VHS CM CELL (GEO DESIGN)
- BETWEEN 45 TO 55 Wh/Kg FOR THE VHS DM CELL (LEO DESIGN)
### 2-1 POSITIVE ELECTRODE

- Sintered material on steel perforated grid
- Active material deposited by electrochemical process

<table>
<thead>
<tr>
<th></th>
<th>HRN</th>
<th>VHS BL/DM</th>
<th>VHS CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinter manufacturing</td>
<td>Wet slurry</td>
<td>Wet slurry</td>
<td>Wet slurry</td>
</tr>
<tr>
<td>Sintered material thickness (mm)</td>
<td>0.82</td>
<td>0.82</td>
<td>0.87</td>
</tr>
<tr>
<td>Perforated grid thickness (mm)</td>
<td>0.10</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Total sinter material thickness (mm)</td>
<td>0.92</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>86</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>Impregnation</td>
<td>ECI</td>
<td>ECI</td>
<td>ECI</td>
</tr>
<tr>
<td>Loading (g/cm³ of void)</td>
<td>1.65</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Average electrode thickness (mm)</td>
<td>0.98</td>
<td>1.00</td>
<td>1.06</td>
</tr>
<tr>
<td>Capacity Ah/electrode</td>
<td>1.00</td>
<td>1.22/1.52</td>
<td>1.79</td>
</tr>
</tbody>
</table>
### 2-2 NEGATIVE ELECTRODE

- Active charcoal with platinum on expanded nickel collector
- Goretex hydrophobic layer with polypropylene grid

<table>
<thead>
<tr>
<th></th>
<th>HRN</th>
<th>VHS BL/DM</th>
<th>VHS CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active material thickness (mm)</td>
<td>0.35</td>
<td>0.35/0.30</td>
<td>0.22</td>
</tr>
<tr>
<td>Electrode thickness (mm)</td>
<td>0.39</td>
<td>0.39/0.35</td>
<td>0.27</td>
</tr>
<tr>
<td>Pt concentration (%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Binding material</td>
<td>PTFE</td>
<td>PTFE</td>
<td>PTFE</td>
</tr>
<tr>
<td>Expanded grid (collector)</td>
<td>1.45/12/10</td>
<td>1.45/12/10</td>
<td>2.5/12/10</td>
</tr>
<tr>
<td>Hydrophobic layer material</td>
<td>Teflon SAFT</td>
<td>Teflon SAFT/GORE</td>
<td>Teflon GORE</td>
</tr>
<tr>
<td>Support</td>
<td>None</td>
<td>None</td>
<td>None/Polypropylene grid/Polypropylene grid</td>
</tr>
<tr>
<td>Polarization (mV) at 70 mA/cm²</td>
<td>100</td>
<td>100/70</td>
<td>60</td>
</tr>
</tbody>
</table>
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

2–3 STACK CONFIGURATION

- Back to back configuration
- Positive expansion accommodation
- Central tie rod
- Optimised oxygen recirculating

<table>
<thead>
<tr>
<th>HRN</th>
<th>VHS BL/DM</th>
<th>VHS CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of electrodes</td>
<td>24 to 42</td>
<td>24 to 42/20 to 60</td>
</tr>
<tr>
<td>Stack assembly</td>
<td>Single/Single or dual</td>
<td>Single/Single or dual</td>
</tr>
<tr>
<td>Separator</td>
<td>Non Woven polyamide felt</td>
<td>Non Woven polyamide felt</td>
</tr>
<tr>
<td>Gaz screen</td>
<td>Woven nylon</td>
<td>Woven nylon</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>KOH 31%</td>
<td>KOH 31% or 26%</td>
</tr>
<tr>
<td>Stack expansion system</td>
<td>None</td>
<td>Belleville/Spring</td>
</tr>
<tr>
<td>Interelectrode spacing (mm)</td>
<td>0.26</td>
<td>0.26</td>
</tr>
</tbody>
</table>
# SAFT Nickel Hydrogen Cell Cycling Status

## 3 - Cycling Status

<table>
<thead>
<tr>
<th>Year</th>
<th>Design</th>
<th>Qualification</th>
<th>Location</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>HRN</td>
<td>HRN LEO at ESTEC</td>
<td>33,000 cycles</td>
<td></td>
</tr>
<tr>
<td>86</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>VHS BL Design 30-50 AH</td>
<td>Qualification</td>
<td>VHS500BL LEO at SAFT</td>
<td>33 periods</td>
</tr>
<tr>
<td>88</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td></td>
<td></td>
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<tr>
<td>90</td>
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<td>91</td>
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<td>92</td>
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<tr>
<td>93</td>
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<td>94</td>
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<td></td>
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<td></td>
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<tr>
<td>95</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>96</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- VHS CM Design 40-100 AH | Qualification | VHS900CM LEO at ESTEC | 7 periods performed |
- VHS53CM LEO at AEROSPATIALE |
- LEO Components Study |
- VHS DM Design |
- Validation |
- VHS55DM LEO at ESTEC |

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-1 LEO CYCLING

3 LOW EARTH ORBIT CYCLING RUNNING:

- HRN42 CYCLING BEGUN IN 1985: 33,000 CYCLES PERFORMED (T=10°C, DOD=40%)
  Test the suitability of HRN design (electrochemistry) for LEO missions
  Compare taper versus cut-off charge management
  Test in horizontal position

- VHS50BL CYCLING: 10,000 CYCLES PERFORMED (T=10°C, DOD=40%)
  Compare cycle life of different cells (DBAG and SAFT) under Columbus/MTFF conditions
  Compare 26% versus 31% KOH
  Investigate reduction of charge power at EOC
  Test in horizontal position

- VHS50BL CYCLING: 10,000 CYCLES PERFORMED (T=10°C, DOD=40%)
  Verify the cycle life VHS BL versus HRN
  Test in vertical position, in sleeves
### SAFT NICKEL HYDROGEN CELL CYCLING STATUS

#### 3-1 LEO CYCLING (Cont'd)

<table>
<thead>
<tr>
<th>CELL TYPE</th>
<th>ESA</th>
<th>CNES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HRN 42 S2</td>
<td>HRN 42 S2</td>
</tr>
<tr>
<td>SAFT TEST REFERENCE</td>
<td>504</td>
<td>503</td>
</tr>
<tr>
<td>BATTERY REFERENCE</td>
<td>35</td>
<td>33</td>
</tr>
<tr>
<td>DOD (%)</td>
<td>40*</td>
<td>40*</td>
</tr>
<tr>
<td>TEMPERATURE (°C)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>DISCHARGE (A)</td>
<td>26.88</td>
<td>26.88</td>
</tr>
<tr>
<td>CHARGE (A)</td>
<td>17.35</td>
<td>21</td>
</tr>
<tr>
<td>VOLTAGE LIMIT (V)</td>
<td>1.67</td>
<td>1.54</td>
</tr>
<tr>
<td>RECHARGE RATIO</td>
<td>1.04</td>
<td>1.04</td>
</tr>
<tr>
<td>CYCLES</td>
<td>33954</td>
<td>35264</td>
</tr>
<tr>
<td>END OF DISCHARGE VOLTAGE (V)</td>
<td>1.04</td>
<td>1.19</td>
</tr>
</tbody>
</table>

*BASED ON 42 Ah

1 CELL REMOVED FOR DPA AFTER 15694 Cycles

1 FAILED CELL AFTER 31629 Cycles

26% KOH

1 CELL REMOVED at beginning of life after 5500 cycles

2 FAILED CELLS at beginning of life

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3–1 LEO CYCLING (Cont'd)

2 HRN 42 S2 Cells; 10°C; 40 % DOD

SAFT TEST N°504

DISCHARGE:
37.5 mn
at 26.88 Amps

CHARGE:
60 mn at 17.35A
Non tapering

No reconditioning

As per june 93

1 cell removed
for DPA
(CYCLE 15694)
Cycling still running
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-1 LEO CYCLING (Cont'd)

2 HRN 42 S2 Cells; 10 °C; 40 DOD

SAFT TEST N°503

DISCHARGE:
37.5 mn at 26.88 Amps

CHARGE:
21 A max
Voltage tapering

No reconditioning

As per June 93

1 failed cell removed
(cycle 31629)
Cycling still running
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-1 LEO CYCLING (cont'd)

BATTERY 1

4 VHS 50 BL Cells; 10°C; 40 % DOD

VOLTAGE (V)

0 2 4 6 8 10 12 14

0 2 4 6 8 10 12 14

Cycles

EODV, EOCV

SAFT TEST N°511

COLUMBUS Program

Discharge:
58 mn at 130 W

Charge:
54 mn at 130 W
26 mn at 70 W

As per June 1993

No Cell removed
Cycling still running

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3–1 LEO CYCLING (cont’d)

BATTERY 2
4 VHS 50 BL Cells; 10°C; 40 % DOD

VOLTAGE (V)

CYCLES

- EODV - EOCV -

SAFT TEST N°512

COLUMBUS Program

Discharge: 34.29 A

Charge: 22.69 A

As per June 1993

1 Cell removed at beginning of life

Cycling still running

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-1 LEO CYCLING (cont’d)

BATTERY 5
4 VHS 50 BL Cells; 10°C; 40% DOD

SAFT TEST N°513
COLUMBUS Program
Discharge: 34.29 A
Charge: 22.69 A
As per June 1993
No Cell removed
Cycling still running

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

EFFECT OF REDUCED ELECTROLYTE CONCENTRATION

26% Electrolyte (Battery 2)

Standard Electrolyte (Battery 5)

LEO cycle number (40% DoD)
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-1 LEO CYCLING (Cont'd)

10 VHS 50 BL Cells; 10°C; 40% DOD

SAFT TEST N°509

DISCHARGE:
35 mn at 34.3 A

Charge:
55 mn at 30 A
Voltage Tapering

As per April 1993

2 cells removed
(cycles 448, 3691)

Cycling still running

Test performed at SAFT

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-2 GEO CYCLING

3 GEOSTATIONNARY EARTH ORBIT CYCLING:

- VHS50BL CYCLING: 33 PERIODS DEMONSTRATED
  Test the suitability of VHS BL for GEO applications
  Test completed
  Accelerated shadow period

- VHS50BL CYCLING: 20 PERIODS PERFORMED
  Demonstrate the GEO life cycle with a constant DOD profile (70 %)
  Reconditionning after each season

- VHS96CM CYCLING: 7 PERIODS PERFORMED
  Compare GEO cycle life of VHS BL and VHS CM
  Test in semi accelerated conditions at 80 %
  Reconditionning before each season

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## SAFT Nickel Hydrogen Cell Cycling Status

### 3-2 GEO Cycling (Cont'd)

<table>
<thead>
<tr>
<th></th>
<th>ESA</th>
<th>CNES</th>
<th>AEROSPATIALE SPACEBUS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cell Type</strong></td>
<td>VHS 96 CM</td>
<td>VHS 50 BL</td>
<td>VHS 50 BL</td>
</tr>
<tr>
<td><strong>SAFT Test Reference</strong></td>
<td>514</td>
<td>507</td>
<td>510</td>
</tr>
<tr>
<td><strong>DOD Max (%)</strong></td>
<td>80</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td><strong>Temperature (°C)</strong></td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Discharge (A)</strong></td>
<td>64</td>
<td>29.2</td>
<td>29</td>
</tr>
<tr>
<td><strong>Charge (A)</strong></td>
<td>9.6</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Voltage Limit (V)</strong></td>
<td>1.53</td>
<td>1.5</td>
<td>1.49</td>
</tr>
<tr>
<td><strong>Recharge Ratio</strong></td>
<td>1.18</td>
<td>1.15</td>
<td>1.15</td>
</tr>
<tr>
<td><strong>Shadow Number</strong></td>
<td>7</td>
<td>33</td>
<td>20</td>
</tr>
<tr>
<td><strong>End of Discharge Voltage (V)</strong></td>
<td>1.09</td>
<td>1.16</td>
<td>1.09</td>
</tr>
</tbody>
</table>

- **Reconditioning Before Each Shadow Period**
- 1 Failed Cell at Period 28 Test Completed
- Reconditioning After Each Shadow Period
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-2 GEO CYCLING (Cont'd)

9 VHS 50 BL Cells: 70% DOD max; 10°C

VOLTAGE (V)

<table>
<thead>
<tr>
<th>EODV</th>
<th>EOCV</th>
<th>AVERAGE DV</th>
</tr>
</thead>
</table>

SAFT test N°507
Real DOD profile
Discharge: 29.2 A
Charge: 3.7 A
Accelerated shadow period
1 Cell removed after shadow period 28
Test completed
End of life characterization:
Int. resistance: +6%
Capacity: −10%
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-2 GEO CYCLING (Cont'd)

9 VHS 50 BL Cells; 70% DOD max; 10°C

SAFT test N°507

Capacity check between each shadow period

Charge:
7 H 42 mn at 10 A

Discharge:
25 A first Cell to 1 V
10 A first Cell to 0.5V

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3-2 GEO CYCLING (Cont'd)

9 VHS 50 BL; 10 °C; 70 %DOD

SAFT test N°510
SPACEBUS program
AEROSPATIALE

Shadow periods
1 to 18 at constant
DOD profile and
19 to 20 at real
DOD profile

Discharge:
1 H 12 at 29 A

Charge:
10 H 48 at 3.7 A

No cell removed
Cycling stopped

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

3–2 GEO CYCLING (Cont'd)

9 VHS 50 BL; 10 °C; 70 %DOD

SAFT test N°510
SPACEBUS program
AEROSPATIALE
Capacity check

Charge:
7 H 42 mn at 10 A

Discharge:
25 A first cell
to 0.5V

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## SAFT Nickel Hydrogen Cell Cycling Status

### 4 - DPA Results

#### LEO Cycling

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>CYCLING</th>
<th>Saft test reference</th>
<th>Number of Cycles completed</th>
<th>Reason of Removal</th>
<th>DPA Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRN42 n°4</td>
<td>ESA</td>
<td>504</td>
<td>15694</td>
<td>Study of the ageing of electrochemical components</td>
<td>9.5 % positive thickness increase, KOH distribution evolution due to the positive expansion</td>
</tr>
<tr>
<td>HRN42 n°5</td>
<td>ESA</td>
<td>503</td>
<td>31629</td>
<td>Short circuit</td>
<td>Short due to too small insulator part compared to the positive swelling: Old design limitation: no positive expansion accommodation system, 15.2 % positive thickness increasing, Small loss of positive capacity (9%), No critical ageing of the separator: only 10 % hydrolysis of polyamid</td>
</tr>
</tbody>
</table>

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## 4—DPA RESULTS (Cont’d)

### LEO CYCLING

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>CYCLING</th>
<th>Saft test reference</th>
<th>Number of Cycles completed</th>
<th>Reason of Removal</th>
<th>DPA Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHS50BL n°7</td>
<td>ESA</td>
<td>512</td>
<td>5500</td>
<td>EOD Voltage below 1 V Low EODV since the beginning of cycling</td>
<td>Ageing of electrochemical components:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- high internal resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- high positive swelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- totally modified KOH repartition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>due to acceptance test deviation</td>
</tr>
<tr>
<td>VHS50BL n°1</td>
<td>CNES at SAFT</td>
<td>509</td>
<td>448</td>
<td>EOD Voltage below 1 V Low EODV since the beginning of cycling as cell n°7</td>
<td>H2 leakage on test equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- high internal resistance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- FET positive capacity stable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- flooding of negative plates and gaz screen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>due to acceptance test deviation</td>
</tr>
</tbody>
</table>

### FAILURE LIMITED TO REWORKED CELLS

564,000 HOURS OF LOW EARTH ORBIT CYCLING SIMULATED
SAFT NICKEL HYDROGEN CELL CYCLING STATUS

4 - DPA RESULTS (Cont'd)

GEO CYCLING

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>CYCLING</th>
<th>Saft test reference</th>
<th>Shadow Number</th>
<th>Reason of Removal</th>
<th>DPA Observations</th>
</tr>
</thead>
</table>
| VHS50BL n°11 | SAFT   | 507                | 28            | Short circuit     | Degradation of the nilsan sleeve around the tie rod inducing the short:
|            |         |                     |               |                   | Problem of test battery insulation (at season 27) leading to oxygen evolution by electrolyte electrolysis along the tie rod |
|            |         |                     |               |                   | Very small ageing of electrochemical components:
|            |         |                     |               |                   | - 2.1 % positive thickness increasing                                           |
|            |         |                     |               |                   | - FET positive capacity stable                                                  |
|            |         |                     |               |                   | - no modification of KOH repartition                                            |

NO FAILURE BY POPPING, ELECTRODE SHORTS OR HYDROGEN LEAKAGE

15 YEARS GEO CYCLING:
- 6% INCREASING OF INTERNAL RESISTANCE
- 10% MAXIMUM LOSS OF THE CELL CAPACITY

4.3 MILLION HOURS OF GEOSTATIONNARY ORBIT CYCLING SIMULATED

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SAFT NICKEL HYDROGEN CELL CYCLING STATUS

4—CONCLUSION

GEOSTATIONNARY EARTH ORBIT SIMULATED CYCLING PERFORMED ON VHS50BL:
- REACHES 33 SHADOW PERIODS WITH SMALL PERFORMANCES EVOLUTIONS
- VALIDATES THE SUITABILITY OF THE VHS CM FOR GEO MISSIONS

LOW EARTH ORBIT SIMULATED CYCLING:
- REACHES 35,000 CYCLES FOR HRN42
- DEMONSTRATES 10,000 CYCLES ON VHS50BL
- GIVES CONFIDENCE ON THE CYCLE LIFE OF THE DM DESIGN

THE CYCLING AND DPA RESULTS
DEMONSTRATE THAT SAFT NH2 IS CHARACTERISED BY:
- HIGH RELIABILITY
- VERY STABLE PERFORMANCES