THERMAL MODELING OF NIH2 BATTERIES

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THERMAL MODELING OF NIH2 BATTERIES

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SAFT
THERMAL MODELING OF NIH2 BATTERIES

1 - NIH2 BATTERY MISSION AND ENVIRONMENT

IN GENERAL, GEOSTATIONARY AND LOW ORBIT SATELLITES:

- PRELAUNCH OPERATIONS
- LAUNCH AND TRANSFER ORBIT
- ECLIPSES
- PEAK DISCHARGE DURING SUNLIGHT

FOR THERMAL STUDIES, GEO MAXIMUM ECLIPSE PERIOD WITH:

- C/2 TO C/1.5 DISCHARGE CURRENT DURING 1.2 HOUR
- C/20 TO C/10 CHARGE CURRENT WITH RECHARGE FACTOR OF 1.1 TO 1.2
- C/100 TRICKLE CHARGE CURRENT TO COMPLETE THE 24 HOURS CYCLE

THERMAL OPERATING CONDITIONS:

- TEMPERATURE RANGE: -5°C < T < +25°C
- TEMPERATURE DIFFERENCE BETWEEN TWO POINTS OF THE ELECTRODE STACK < 6°C
- TEMPERATURE DIFFERENCE BETWEEN STACK AND CELL WALL < 12°C
- TEMPERATURE DIFFERENCE BETWEEN TWO IDENTICAL POINTS OF TWO CELLS OF THE BATTERY < 9°C
THERMAL MODELING OF NIH2 BATTERIES

2 - NIH2 CELL HEAT DISSIPATION

2.1 - DISCHARGE

HEAT DISSIPATION FORMULATION:

\[ PD = ID \times (U_0 - UD) \]

WITH

\[ PD : HEAT \ DISSIPATION \ IN \ DISCHARGE \ (W) \]

\[ ID : DISCHARGE \ CURRENT \ (A) \]

\[ UD : DELIVERED \ CELL \ VOLTAGE \ (V) \]

\[ U_0 : THERMO-NEUTRAL \ POTENTIAL \ (V) \]

\[ UD = u - R \times ID^2 \]

WITH

\[ u : VOLTAGE \ AT \ COUPLE \ LEVEL \ (V) \]

\[ R : NICKEL \ TABS \ AND \ OUTLET \ RESISTANCE \ (mOHM) \]

\[ PD = \text{PSTACK} + R \times ID^2 \]

WITH

\[ \text{PSTACK} = ID \times (U_0 - u) : HEAT \ DISSIPATION \ IN \ THE \ STACK \ (W) \]

THERMO-NEUTRAL POTENTIAL (U0):

GENERAL ADMITTED VALUE: 1.51 V

SAFT EVALUATION FOR A 96 AH CELL:

EXAMPLES OF HEAT DISSIPATION (AVERAGE):

<table>
<thead>
<tr>
<th></th>
<th>96 AH</th>
<th>84 AH</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>12</td>
<td>10.6</td>
</tr>
<tr>
<td>P STACK</td>
<td>7.7</td>
<td>8.2</td>
</tr>
<tr>
<td>R</td>
<td>1.55</td>
<td>1.7</td>
</tr>
<tr>
<td>ID</td>
<td>52.5</td>
<td>37.7</td>
</tr>
</tbody>
</table>
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2 - NIH2 CELL HEAT DISSIPATION

2.2 - CHARGE & TRICKLE

FORMULATION OF HEAT DISSIPATION IN CHARGE:

HEAT DISSIPATION HAPPENS AT END OF CHARGE AND IS LINKED TO EXOTHERMIC REACTIONS IN THE STACK

FORMULATION RESULTS FROM ANALYSIS OF:

- ENERGETIC BALANCE OVER THE CYCLE
- CELL VOLTAGE PROFILE AT END OF CHARGE

ENERGETIC BALANCE:

\[ QC = Ec - Ed - Qd \]

WITH

- \( QC \): THERMAL ENERGY LOST IN CHARGE (JOULE)
- \( Ec \): ELECTRICAL ENERGY INPUT IN CHARGE (JOULE)
- \( Ed \): ELECTRICAL ENERGY OUTPUT IN DISCHARGE (JOULE)
- \( Qd \): THERMAL ENERGY LOST IN DISCHARGE (JOULE)

CORRELATION HAVE BEEN ESTABLISHED FOR SAFT 96AH CELL AND 64 AH BATTERY, FOR C/10 CHARGE AND K FACTOR OF 1.2 AND 1.1 RESPECTIVELY

FORMULATION OF HEAT DISSIPATION IN TRICKLE CHARGE:

\[ P = Ut It \]

ELECTRICAL ENERGY INPUT = HEAT DISSIPATION
64 AH NiH2 CELL VOLTAGE IN CHARGE

POWER DISSIPATED IN CHARGE

electrochemical reactions:

(1) + (2)
(3) + (4)

\[ n_1 = 0.074 \]
\[ n_2 = 0.395 \]

\[ P_c = n_2 U_{clc} \]
\[ P_c = n_1 U_{clc} \]

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3 - NODAL SOFTWARE

2.1 - THERMAL ANALYSER ESACAP

NETWORK ANALYSER FOR THERMAL AND ELECTRONIC PROBLEMS (PRODUCED BY STAN.SIM IN DENMARK)

MAIN ADVANTAGES:

- EASY DESCRIPTION BY BASIC COMPONENTS
- EASY DESCRIPTION OF RADIATIVE COMPONENTS
- MODEL APPROACH
- POSSIBILITY TO INTRODUCE NEW COMPONENTS
- LARGE POSSIBILITIES TO INTRODUCE CONTROL
- TREATMENT OF COUPLED PROBLEMS (ELECTRICAL, FLUID FLOW, MECHANIC, TWO PHASE FLOWS)
- LARGE POSSIBILITY TO INTRODUCE PARAMETERS AND PHYSICAL PROPERTIES
- GEAR INTEGRATING METHOD
- SPECIAL METHODS FOR STEADY-STATE ANALYSIS

<table>
<thead>
<tr>
<th>Thermal parameter</th>
<th>Electrical parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>heat flux</td>
<td>intensity</td>
</tr>
<tr>
<td>temperature</td>
<td>potential</td>
</tr>
<tr>
<td>capacity</td>
<td>capacity</td>
</tr>
<tr>
<td>conductance</td>
<td>conductance</td>
</tr>
<tr>
<td>heat source</td>
<td>current generator</td>
</tr>
<tr>
<td>impressed temperature</td>
<td>voltage generator</td>
</tr>
<tr>
<td>impressed flux</td>
<td>current generator</td>
</tr>
</tbody>
</table>

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3 - NODAL SOFTWARE

2.2 - INTEGRATING GEAR METHOD

- A high stability for orders $k \leq 6$, and at the same time a high precision,

- The automatic control of the time step, control which is performed thanks to the evaluation of the error,

- An optimum modification of the order in such a way that the required precision is obtained,

- Because the control of the time step is automatic, this leads to a gain of time calculation, without instability which is particularly important for stiff problems.

Gear performs the integration in two steps:

- Prediction with an extrapolation by a Newton polynomial

- Correction by solving the implicit equation relative to the energy-balance (successive point iteration method).
THERMAL MODELING OF NIH2 BATTERIES

4 – DEVELOPMENT GENERAL PHILOSOPHY

- TWO FUNDAMENTAL PARTS: CELL AND STRUCTURE, EACH PART CAN BE RUN SEPARATELY

- A CELL HAS TWO FUNDAMENTAL PARTS: ELECTROCHEMICAL HEART AND MECHANICAL STRUCTURE (CELL WALL, NICKEL TABS, OUTLETS)

IT'S WHY THE THERMAL STUDY IS MANAGED HAS FOLLOW:

- DEVELOPMENT OF A MODEL FOR THE ELECTROCHEMICAL COUPLE WITH THERMOPHYSICAL PARAMETERS AND COMBINATION OF CONDUCTIVITIES, HEAT CAPACITIES, TO TAKE INTO ACCOUNT ALL COMPONENTS (MATTER GRID, SEPARATORS, ...) ==> MODEL OF 100 NODES

- REDUCTION OF NODES NUMBER BUT NOT INITIAL PARAMETERS AND EXTENSION TO A COMPLETE CELL (MORE THAN 100 NODES)

- REDUCTION OF A COMPLETE CELL INTO 10 NODES ALWAYS WITH THE INITIAL PARAMETERS

- DEVELOPMENT OF BATTERY STRUCTURE AND INTRODUCTION, AT EACH PLACE, OF A REDUCED CELL MODEL

- SAME APPROACH FOR SUB-COMPONENTS SUCH AS DIODES FOR EXAMPLE

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5.1 - AT COUPLE LEVEL

EQUIVALENT THERMAL CAPACITY:

\[ \rho C_{\text{eq}} = \frac{\sum \rho C_{\text{volume}}}{\text{volume couple}} \]

EQUIVALENT THERMAL CONDUCTIVITY:

\[ \lambda_H = \frac{\sum \lambda E_p}{\sum E_p} \]

\[ \lambda_V = \frac{\sum E_p}{\sum \lambda E_p} \]
5.2 - AT CELL LEVEL (1/4 OF A CELL)

H₂

36 NODES PER COUPLE

N COUPLES

COPPER

CELL CASE

NICKEL TAB

2 EXTREMITY PLATES

22 NODES PER PLATE

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5.2 - AT CELL LEVEL (1/4 OF A CELL)

INTEGRATION OF BATTERY STRUCTURE AT CELL LEVEL:

MODEL APPROACH:

ALUMINIUM SLEEVE + SOLITHANE RESIN

STACK

ALUMINIUM BASE PLATE ALVEOLUS + SOLITHANE RESIN

RADIATOR

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5.2 - AT CELL LEVEL (1/4 OF A CELL)

CELL MODEL REDUCTION:

BASIC INPUTS:

WITH SAME BATTERY STRUCTURE INTERFACE

1/4 CELL
DETAILED MODEL:

1 CELL
ROUGH MODEL:

REDUCTION

250 NODES

5 NODES

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5.1 -

EXPERIMENTAL APPROACH:

-- > EVALUATION OF THERMAL CAPACITY
(SPECIFIC TEST)

VHS 96 CM WITH SLEEVE AND ALVEOLUS

\[ C_{\text{calculated}} = \frac{2333}{\text{J/}^\circ\text{C}} \]
\[ C_{\text{experimental}} = \frac{2330}{\text{J/}^\circ\text{C}} \]

-- > EVALUATION OF HEAT GENERATION
(SPECIFIC TEST)

VHS 96 CM TOTAL AVERAGE HEAT DISSIPATION IN DISCHARGE:

70% DOD : \[ P = 12\,\text{W} \]
80% DOD : \[ P = 16.5\,\text{W} \]

-- > TEMPERATURE DISTRIBUTION ON A VHS 96 CM CELL
CORRELATION WITH MODEL PREDICTIONS
(SEE THERMAL VACCUM TEST ON VHS 96 CM CELL)
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5.3 – AT DIODES LEVEL

EXPERIMENTAL APPROACH:

- Heat generation within discharge and charge diodes
- Thermal conduction through the diode assembly system
- Predict diodes temperature at various current level.

EXPERIMENTAL RESULTS:

<table>
<thead>
<tr>
<th>CURRENT</th>
<th>DISCHARGE P</th>
<th>CHARGE P</th>
<th>DISCHARGE MAX T J</th>
<th>CHARGE MAX T J</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 A</td>
<td>30 W</td>
<td>/</td>
<td>95.5 °C</td>
<td>/</td>
</tr>
<tr>
<td>37 A</td>
<td>20 W</td>
<td>/</td>
<td>66 °C</td>
<td>/</td>
</tr>
<tr>
<td>6 A</td>
<td>/</td>
<td>5.5 W</td>
<td>/</td>
<td>52.5 °C</td>
</tr>
</tbody>
</table>

MODEL APPROACH:

- Detailed model of diodes on their support --- > 33 nodes
- Correlation achieved with tests
- Rough model --- > 8 nodes
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5.4 - AT BATTERY BASEPLATE LEVEL

SIDE PLATE (3 NODES)

DIODES PLACE 3 NODES

26 NODES (PER ALVEOLUS)

840 NODES FOR THE WHOLE BASEPLATE

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5.5 - BATTERY COMPLETE MODEL

COMPLETE SYSTEM : 983 NODES

27 CELLS (5 NODES EACH)

WITH ALL BASIC INPUTS

DIODES SYSTEM
(8 NODES)

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WITH THIS APPROACH:

SIMPLIFIED CELL MODEL: 5 NODES $\rightarrow$ 135 NODES
SIMPLIFIED DIODE MODEL: 8 NODES $\rightarrow$ 8 NODES
BASEPLATE MODEL: 840 NODES $\rightarrow$ 840 NODES

COMPLETE SYSTEM: 983 NODES

A COMPLETE DETAILED MODEL:

DETAILED CELL MODEL: 250 NODES $\rightarrow$ 6750 NODES
DETAILED DIODE MODEL: 33 NODES $\rightarrow$ 33 NODES
BASEPLATE MODEL: 840 NODES $\rightarrow$ 840 NODES

COMPLETE SYSTEM: 7623 NODES

FURTHERMORE EXPERIMENTAL STEPS ARE DIRECTLY INCLUDED IN THE DEVELOPMENT OF THE SYSTEM MODEL (AT CELL AND DIODE LEVEL)
6 – NIH2 EXPERIMENTAL DEVELOPMENT

6.1 – CONSIDERATION ON TEST ENVIRONMENT

6.2 – THERMAL VACUUM TEST ON A VHS90CM CELL

6.3 – QUALIFICATION LIFE TEST ON VHS90CM CELLS

6.4 – THERMAL VACUUM QUALIFICATION ON SAFT 27VHS64CM BATTERY
THERMAL MODELING OF NIH2 BATTERIES

6.1 - CONSIDERATION ON TEST ENVIRONMENT

TEST ENVIRONMENT:

AMBIANT SIMULATION:

- AMBIANT AIR
- THERMAL CHAMBER
- THERMAL VACUUM CHAMBER

RADIATOR SIMULATION

- BATTERY SET ON A PLATE AT CONSTANT TEMPERATURE
- BATTERY SET ON PLATE WITH PILOTED TEMPERATURE PROFILE
- BATTERY FIXED ON A PLATE VIEWING A COLD SOURCE
## THERMAL MODELING OF NIH2 BATTERIES

### 6.2 - THERMAL VACUUM TEST ON A VHS90CM CELL

#### MOUNTING

![Diagram of mounting setup]

#### Test Results Compared to Model Prediction

<table>
<thead>
<tr>
<th>Node</th>
<th>Model Node</th>
<th>Max Discrepancy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper dome</td>
<td>2204</td>
<td>2.25 (measured: 13.2), end of charge (model: 10.95)</td>
</tr>
<tr>
<td>Upper stack (on sleeve)</td>
<td>707</td>
<td>1.1 (measured: 26.3), end of discharge (model: 25.2)</td>
</tr>
<tr>
<td>Lower (on sleeve)</td>
<td>107</td>
<td>1.4 (measured: 17), end of discharge (model: 15.6)</td>
</tr>
<tr>
<td>Lower dome</td>
<td>1304</td>
<td>0.8 (measured: 2.3), end of trickle (model: 3.1)</td>
</tr>
</tbody>
</table>
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6.3 - QUALIFICATION LIFE TEST ON VHS90CM CELLS

(ESTEC - NOORDWIJK)

MOUNTING

INSULATION AMBIENT AIR

ALUMINIUM PLATE

PELTIER ELEMENT

TEMPERATURE PROFILE OF THE PLATE DETERMINED BY THE DETAILED CELL MODEL

<table>
<thead>
<tr>
<th>Mode/Δt level</th>
<th>Predicted</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔQ/Δt</td>
<td>27</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>ΔQ/Δt</td>
<td>14.4</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>Upper stack inside (hot)</td>
<td>29</td>
<td>-</td>
<td>31</td>
</tr>
<tr>
<td>ΔT sleeve -dome</td>
<td>8.1</td>
<td>11.6</td>
<td>-</td>
</tr>
<tr>
<td>ΔT radial sleeve-stack</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>ΔT stack-dome</td>
<td>10.1</td>
<td>-</td>
<td>13.6</td>
</tr>
<tr>
<td>ΔT sleeve</td>
<td>5.38</td>
<td>6.2</td>
<td>-</td>
</tr>
<tr>
<td>ΔT stack</td>
<td>5.38</td>
<td>-</td>
<td>6.2</td>
</tr>
</tbody>
</table>

TEST RESULTS COMPARED TO MODEL PREDICTIONS

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6.4 - THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

MOUNTING:
- THERMAL VACUUM CHAMBER
- FIXED ON A RADIATIVE PANEL
- SUSPENDED OVER A COLD PLATE AT -170°C

CYCLE:
- 80% DOD DISCHARGE OF 1.2 HOUR
- C/10 CHARGE, K FACTOR OF 1.1
- C/100 TRICKLE CHARGE
- 1.8 W HEATING PER CELL, SWITCH ON WHEN CELL TEMP. IS BETWEEN 2 AND 4 °C

ONE FAILED CELL SIMULATION:
- W CELL IS PUT IN OPEN CIRCUIT AND RELAYED BY DIODES
- DISCHARGE DIODE IS PLACED ON SUPPORT N°32
- CHARGE DIODES ARE PLACED ON SUPPORT N°32, 29, 30.

THERMOCOUPLES:
- 81 THERMOCOUPLES WHERE INSTALLED
- 17 ON THE BASEPLATE
- 4 ON THE RADIATIVE PANEL
- 3 CELLS COMPLETELY EQUIPPED (5 thermocouples at least)
- ABOUT 20 CELLS EQUIPPED WITH ONE THERMOCOUPLES PLACED ON THE HOT POINT
- 3 DIODES SUPPORTS COMPLETELY EQUIPPED
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## 6.4 - THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

### RESULTS:

<table>
<thead>
<tr>
<th></th>
<th>SPECIFICATION</th>
<th>MODEL</th>
<th>TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX CELL STACK TEMP.</td>
<td>+35°C</td>
<td>33.7 (X)</td>
<td>34.6 (X)</td>
</tr>
<tr>
<td>MIN CELL STACK TEMP.</td>
<td>-5°C</td>
<td>-4 (F)</td>
<td>-3.75 (F)</td>
</tr>
<tr>
<td>% HEATING USED</td>
<td>&lt; 80%</td>
<td>70%</td>
<td>73%</td>
</tr>
<tr>
<td>MAX STACK GRADIENT</td>
<td>6°C</td>
<td>3.6 (F)</td>
<td>3.8 (F)</td>
</tr>
<tr>
<td>MAX STACK TO CELL GRADIENT</td>
<td>12°C</td>
<td>9.7 (F)</td>
<td>9.95 (F)</td>
</tr>
<tr>
<td>CELL TO CELL GRADIENT</td>
<td>8°C</td>
<td>7°C (N-F)</td>
<td>8°C (N-F)</td>
</tr>
<tr>
<td>MAX DIODE JUNCTION TEMP.</td>
<td>110°C</td>
<td>105</td>
<td>105.6</td>
</tr>
</tbody>
</table>
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6.4 - THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

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7 - CONCLUSION

NIH2 BATTERIES ARE CAREFULLY STUDIED FROM A THERMAL POINT OF VIEW

MODEL AT COUPLE LEVEL, CELL LEVEL AND BATTERY LEVEL ARE PERFORMED WITH THE SAME PARAMETERS

THERMAL MODELING IS REALISED WITH AN EASY AND POWERFUL NODAL SOFTWARE: ESACAP

TESTS IN VACUUM CHAMBER OR WITH PELTIER ELEMENTS ARE DEFINED IN ASSOCIATION WITH MODEL

GENERAL THERMAL DEVELOPMENT PROGRAM DELIVER NOW A TOOL ABLE TO ANSWER QUICKLY TO NEW REQUIREMENTS OF FUTURE BATTERIES