THERMAL MODELING OF NIH2 BATTERIES

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THERMAL MODELING OF NIH2 BATTERIES

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THERMAL MODELING OF NIH2 BATTERIES

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 NH2 BATTERIES

2 - NH2 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)

\[ PD = P_{STACK} + R \times ID^2 \]

WITH

- \( P_{STACK} \): HEAT DISSIPATION IN THE STACK (W)

THERMO-NEUTRAL POTENTIAL (\( U_0 \)):

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:

\[ Q_C = E_C - E_d - Q_d \]

WITH

\[ Q_C : \text{THERMAL ENERGY LOST IN CHARGE (JOULE)} \]
\[ E_C : \text{ELECTRICAL ENERGY INPUT IN CHARGE (JOULE)} \]
\[ E_d : \text{ELECTRICAL ENERGY OUTPUT IN DISCHARGE (JOULE)} \]
\[ Q_d : \text{THERMAL ENERGY LOST IN DISCHARGE (JOULE)} \]

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:

\[ P = U \cdot i \cdot t : \text{ELECTRICAL ENERGY INPUT = HEAT DISSIPATION} \]

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90 Ah NiH2 Cell Voltage

ELECTROCHEMICAL REACTIONS:

\[
\begin{align*}
1 & \quad + \\
2 & \quad + \\
3 & \quad + \\
4 & \quad + 
\end{align*}
\]

POWER DISSIPATED IN CHARGE:

Experimental factors:

\[
\begin{align*}
n_1 &= 0.074 \\
n_2 &= 0.64 \\
n_3 &= 0.4
\end{align*}
\]

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64 AH NiH2 CELL VOLTAGE IN CHARGE

**POWER DISSIPATED IN CHARGE**

experimental factors:

n1 = 0.074
n2 = 0.395

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3 - NODAL SOFTWARE

2.1 - THERMAL ANALYSER ESACAP

NETWORK ANALYSER FOR THERMAL AND ELECTRONIC PROBLEMS
(PRODUCED BY STANSIM 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).
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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
THERMAL MODELING OF NIH2 BATTERIES

5 – NIH2 BATTERY MODEL DEVELOPMENT

5.1 – AT COUPLE LEVEL

EQUIVALENT THERMAL CAPACITY:

\[ \rho C_{eq}, \lambda_v \rightarrow \lambda_H \rightarrow \]

ADDITION OF EACH THERMAL CAPACITY OF THE COMPONENTS:

\[ \rho C_{equivalent} = \frac{\sum \rho c \text{ Volume}}{\text{Volume couple}} \]

EQUIVALENT THERMAL CONDUCTIVITY:

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

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

36 NODES PER COUPLE

22 NODES PER PLATE

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Nickel-Hydrogen Technologies Session
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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

CELL CONTAINER

RADIATOR

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

CELL MODEL REDUCTION:

WITH SAME BATTERY STRUCTURE INTERFACE

BASIC INPUTS:

1/4 CELL
DETAILED MODEL:

1 CELL
ROUGH MODEL:

REDUCTION

5 NODES

250 NODES

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5.1 -

EXPERIMENTAL APPROACH:

--> EVALUATION OF THERMAL CAPACITY (SPECIFIC TEST)

VHS 96 CM WITH SLEEVE AND ALVEOLUS

\[
\begin{align*}
\phi C_{\text{calculated}} &= 2333 \text{ J/°C} \\
\phi C_{\text{experimental}} &= 2330 \text{ J/°C}
\end{align*}
\]

--> 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 VACUUM TEST ON VHS 96 CM CELL)
THERMAL MODELING OF NIH2 BATTERIES

5.3 - AT DIODES LEVEL

EXPERIMENTAL APPROACH:

TWO TESTS HAVE PERMITTED TO EVALUATE WITH A GOOD CONFIDENCE:

. 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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5.1 - WITH THIS APPROACH:

SIMPLIFIED CELL MODEL: 5 NODES -> 135 NODES
SIMPLIFIED DIODE MODEL: 8 NODES -> 8 NODES
BASEPLATE MODEL: 840 NODES -> 840 NODES

COMPLETE SYSTEM: 983 NODES

A COMPLETE DETAILED MODEL:

DETAILED CELL MODEL: 250 NODES -> 6750 NODES
DETAILED DIODE MODEL: 33 NODES -> 33 NODES
BASEPLATE MODEL: 840 NODES -> 840 NODES

COMPLETE SYSTEM: 7623 NODES

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

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6.2 - THERMAL VACUUM TEST ON A VHS90CM CELL

Test Results Compared to Model Prediction

<table>
<thead>
<tr>
<th>Node</th>
<th>Model discrepancy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper dome</td>
<td>2.25 (measured : 13.2)</td>
</tr>
<tr>
<td></td>
<td>end of charge (model : 10.95)</td>
</tr>
<tr>
<td>Upper stack</td>
<td>1.1 (measured : 26.3)</td>
</tr>
<tr>
<td>(on sleeve)</td>
<td>end of discharge (model : 25.2)</td>
</tr>
<tr>
<td>Lower</td>
<td>1.4 (measured : 17)</td>
</tr>
<tr>
<td>(on sleeve)</td>
<td>end of discharge (model : 15.6)</td>
</tr>
<tr>
<td>Lower dome</td>
<td>0.8 (measured : 2.3)</td>
</tr>
<tr>
<td></td>
<td>end of trickle (model : 3.1)</td>
</tr>
</tbody>
</table>
THERMAL MODELING OF NiH2 BATTERIES

6.2 - THERMAL VACUUM TEST ON A VHS90CM CELL

Temperature (deg C)

- t(2204)
- -2204 exp

- t(107)
- -107 exp
- t(707)
- 707 exp

Time

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6.3 - QUALIFICATION LIFE TEST ON VHS90CM CELLS

THERMAL MODELING OF NIH2 BATTERIES

MOUNTING

INSULATION AMBIENT AIR
ALUMINIUM PLATE
PELTIER ELEMENT

TEMPERATURE PROFILE OF THE PLATE DETERMINED BY THE DETAILED CELL MODEL

TEST RESULTS COMPARED TO MODEL PREDICTION

<table>
<thead>
<tr>
<th>Mode/Dt level</th>
<th>Predicted</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>β0/θ</td>
<td>27</td>
<td>29</td>
<td>-</td>
</tr>
<tr>
<td>Δθ/θ</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>DT sleeve-dome</td>
<td>8.1</td>
<td>11.6</td>
<td>-</td>
</tr>
<tr>
<td>DT sleeve</td>
<td>5.0</td>
<td>7.0</td>
<td>-</td>
</tr>
<tr>
<td>DT radial sleeve-stack</td>
<td>2</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>DT stack-dome</td>
<td>10.1</td>
<td>-</td>
<td>13.6</td>
</tr>
<tr>
<td>DT sleeve</td>
<td>5.38</td>
<td>6.2</td>
<td>-</td>
</tr>
<tr>
<td>DT stack</td>
<td>5.38</td>
<td>-</td>
<td>6.2</td>
</tr>
</tbody>
</table>

Nickel-Hydrogen Technologies Section

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6.3 – QUALIFICATION LIFE TEST ON VHS90CM CELLS

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THERMAL MODELING OF NIH2 BATTERIES

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
## THERMAL MODELING OF NIH2 BATTERIES

### 6.4 - THERMAL VACUUM QUALIF. ON SAFT 27VHS84CM 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>3.6 (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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80% DOD GEO ECLIPSE CYCLE
SIMULATION OF W FAILED CELL
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