THERMAL MODELING OF NIH2 BATTERIES

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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: $-5^\circ C < T < +25^\circ C$
- TEMPERATURE DIFFERENCE BETWEEN TWO POINTS OF THE ELECTRODE STACK < 6$^\circ C$
- TEMPERATURE DIFFERENCE BETWEEN STACK AND CELL WALL < 12$^\circ C$
- TEMPERATURE DIFFERENCE BETWEEN TWO IDENTICAL POINTS OF TWO CELLS OF THE BATTERY < 9$^\circ C$
THERMAL MODELING OF NiH$_2$ BATTERIES

2 - NiH$_2$ CELL HEAT DISSIPATION

2.1 - DISCHARGE

HEAT DISSIPATION FORMULATION:

PD = ID (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 ID$^2$  
WITH  
u : VOLTAGE AT COUPLE LEVEL (V)  
R : NICKEL TABS AND OUTLET RESISTANCE (mOHM)

PD = PSTACK + R ID$^2$  
WITH  
PSTACK = ID (U$_0$ - u) : HEAT DISSIPATION IN THE STACK (W)

THERMO-NEUTRAL POTENTIAL (U$_0$):

GENERAL ADMITTED VALUE : 1.51 V

EXAMPLES OF HEAT DISSIPATION (AVERAGE):

<table>
<thead>
<tr>
<th></th>
<th>98 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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THERMAL MODELING OF NIH2 BATTERIES

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

- \( Q_c \): THERMAL ENERGY LOST IN CHARGE (JOULE)
- \( E_c \): ELECTRICAL ENERGY INPUT IN CHARGE (JOULE)
- \( E_d \): ELECTRICAL ENERGY OUTPUT, IN DISCHARGE (JOULE)
- \( Q_d \): 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:

\[ P = U t \ t \]: ELECTRICAL ENERGY INPUT = HEAT DISSIPATION

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90 Ah NiH2 Cell Voltage

Electrochemical Reactions:

\[ (1) + (2) \]
\[ (2) + (3) \]
\[ (4) \]

Power Dissipated in Charge:

Experimental factors:

- \( n_1 = 0.074 \)
- \( n_2 = 0.64 \)
- \( n_3 = 0.4 \)

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1.65
1.6
155
15
_L45
L4
1.35
1.3
3.5
1.5
-
1
64 AH NIH2 CELL VOLTAGE IN CHARGE

[Graph showing voltage vs. charge, with labels and equations]

Power Dissipated in Charge

Experimental factors:
n1 = 0.074
n2 = 0.395

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THERMAL MODELING OF NIH2 BATTERIES

3 - NODAL SOFTWARE

2.1 - THERMAL ANALYSE E S A C A P

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

Thermal parameter | Electrical parameter
---|---
heat flux | intensity
temperature | potential
capacity | capacity
conductance | conductance
current generator | current generator
impressed temperature | voltage generator
impressed flux | current generator
THERMAL MODELING OF NIH2 BATTERIES

2.2 - INTEGRATING GEAR METHOD

- A HIGH STABILITY FOR ORDERS K ≤ 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
THERMAL MODELING OF NIH2 BATTERIES

5 - NIH2 BATTERY MODEL DEVELOPMENT

5.1 - AT COUPLE LEVEL

EQUIVALENT THERMAL CAPACITY:

\[ \rho c_{\text{eq}} = \sum \rho c \frac{\text{Volume}}{\text{Volume couple}} \]

EQUIVALENT THERMAL CONDUCTIVITY:

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

FOR EACH COMPONENT:

\( \rho c, \lambda, \text{THICKNESS (Ep)} \)

- POSITIVE ELECTRODE
- SEPARATOR
- NEGATIVE ELECTRODE
- NEGATIVE ELECTRODE SEPARATOR
- ELECTROLYTE

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THERMAL MODELING OF NIH2 BATTERIES

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
THERMAL MODELING OF NiH2 BATTERIES

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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THERMAL MODELING OF NiH₂ BATTERIES

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

CELL MODEL REDUCTION:

1/4 CELL
DETAILED MODEL:

WITH SAME BATTERY STRUCTURE INTERFACE

1 CELL
ROUGH MODEL:

BASIC INPUTS:

250 NODES

REDUCTION

5 NODES

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EXPERIMENTAL APPROACH:

--> EVALUATION OF THERMAL CAPACITY (SPECIFIC TEST)

VHS 96 CM WITH SLEEVE AND ALVEOLUS:

\[ \rho C_{\text{calculated}} = 2333 \text{ J/°C} \]
\[ \rho C_{\text{experimental}} = 2330 \text{ J/°C} \]

--> EVALUATION OF HEAT GENERATION (SPECIFIC TEST)

VHS 96 CM TOTAL AVERAGE HEAT DISSIPATION IN DISCHARGE:

70% DOD: \[ P = 12.0 \text{ W} \]
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
THERMAL MODELING OF NIH2 BATTERIES

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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COMPLETE SYSTEM: 983 NODES

840 nodes
BASE PLATE

27 CELLS (5 NODES EACH)

DIODES SYSTEM (8 NODES)

WITH ALL BASIC INPUTS

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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)
THERMAL MODELING OF NIH2 BATTERIES

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:
- AMBIENT SIMULATION:
  - AMBIENT 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

<table>
<thead>
<tr>
<th>Test 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) (model: 10.95)</td>
</tr>
<tr>
<td>Upper Stack (on sleeve)</td>
<td>707</td>
<td>1.1 (measured: 26.3) (model: 25.2)</td>
</tr>
<tr>
<td>Lower (on sleeve)</td>
<td>107</td>
<td>1.4 (measured: 17) (model: 15.6)</td>
</tr>
<tr>
<td>Lower Dome</td>
<td>1304</td>
<td>0.8 (measured: 2.3) (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

(ESTEC - NOORDWIJK)

TEST RESULTS COMPARED TO MODEL PREDICTION

<table>
<thead>
<tr>
<th>Mode/Dt level</th>
<th>3.2</th>
<th>Predicted</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta T )</td>
<td>27</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta T )</td>
<td>14.4</td>
<td>16.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper stack inside (hot)</td>
<td>29</td>
<td>-</td>
<td>31</td>
<td>10.3</td>
</tr>
<tr>
<td>DT sleeve -dome</td>
<td>8.1</td>
<td>11.6</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DT radial sleeve-stack</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>DT stack-dome</td>
<td>10.1</td>
<td>-</td>
<td>13.6</td>
<td>8.2</td>
</tr>
<tr>
<td>DT sleeve</td>
<td>-</td>
<td>5.38</td>
<td>6.2</td>
<td>-</td>
</tr>
<tr>
<td>DT stack</td>
<td>-</td>
<td>5.38</td>
<td>-</td>
<td>6.2</td>
</tr>
</tbody>
</table>

TEMPERATURE PROFILE OF THE PLATE DETERMINED BY THE DETAILED CELL MODEL
THERMAL MODELING OF NIH2 BATTERIES

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
### 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>
THERMAL MODELING OF NIH2 BATTERIES

6.4 - THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

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THERMAL MODELING OF NIH2 BATTERIES

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