THERMAL MODELING OF NIH2 BATTERIES

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1993 NASA Aerospace Battery Workshop, November 16-18

THERMAL MODELING OF NIH2 BATTERIES

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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

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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)
- \( U_0 \): DELIVERED CELL VOLTAGE (V)
- \( UD \): 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)

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>

SAFT EVALUATION FOR A 96 AH CELL:

GENERAL ADMITTED VALUE: 1.51 V

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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:

\[ P = U l I t \]

ELECTRICAL ENERGY INPUT = HEAT DISSIPATION
90 AH NIH2 CELL VOLTAGE

ELECTROCHEMICAL REACTIONS:

(1) + (2)

(2) + (3) + (4)

POWER DISSIPATED IN CHARGE:
experimental factors:

n1 = 0.074
n2 = 0.64
n3 = 0.4

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64 AH NIH2 CELL VOLTAGE IN CHARGE

\[ U_c (V) \]

\[ k = \frac{C_c}{C_d} \]

\[ U_{clc} \]

\[ \text{power dissipated in charge} \]

\[ \text{experimental factors:} \]

\[ n_1 = 0.074 \]

\[ n_2 = 0.395 \]
THERMAL MODELING OF NIH2 BATTERIES

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>
THERMAL MODELING OF NIH2 BATTERIES

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 – NIH2 BATTERY MODEL DEVELOPMENT

5.1 – AT COUPLE LEVEL

EQUIVALENT THERMAL CAPACITY:

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

EQUIVALENT THERMAL CONDUCTIVITY:

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

\[ \lambda_V = \frac{\sum E_p}{\sum \lambda (1/E_p)} \]

FOR EACH COMPONENT:

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

- POSITIVE ELECTRODE
- SEPARATOR
- NEGATIVE ELECTRODE
- NEGATIVE ELECTRODE SEPARATOR
- ELECTROLYTE
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5.2 - AT CELL LEVEL (1/4 OF A CELL)

H2

36 NODES PER COUPLE

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 + SOLITANE RESIN

STACK

ALUMINIUM BASE PLATE ALVEOLUS + SOLITANE RESIN

RADIATOR

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

CELL MODEL REDUCTION:

BASIC INPUTS:

1/4 CELL
DETAILED MODEL:

1 CELL
ROUGH MODEL:

WITH SAME BATTERY STRUCTURE INTERFACE

250 NODES

3 NODES

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EXPERIMENTAL APPROACH:

--> EVALUATION OF THERMAL CAPACITY  
(SPECIFIC TEST) 

VHS 96 CM  
WITH SLEEVE AND ALVEOLUS  

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

--> EVALUATION OF HEAT GENERATION  
(SPECIFIC TEST) 

VHS 96 CM TOTAL AVERAGE HEAT DISSIPATION IN DISCHARGE:  

\[
\begin{align*}
\text{70% DOD :} & \quad P = 12.2 \text{ W} \\
\text{80% DOD :} & \quad P = 16.5 \text{ W}
\end{align*}
\]

--> 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 PERMITED TO EVALUATE WITH A GOOD CONFIDENCE:

1. HEAT GENERATION WITHIN DISCHARGE AND CHARGE DIODES
2. THERMAL CONDUCTION THROUGH THE DIODE ASSEMBLY SYSTEM
3. PREDICT DIODES TEMPERATURE AT VARIOUS CURRENT LEVEL.

<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)

26 NODES (PER ALVEOLUS)

840 NODES FOR THE WHOLE BASEPLATE

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**5.5—BATTERY COMPLETE MODEL**

**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:

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Nodes</th>
<th>Multiplied Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified Cell Model</td>
<td>5 nodes</td>
<td>135 nodes</td>
</tr>
<tr>
<td>Simplified Diode Model</td>
<td>8 nodes</td>
<td>8 nodes</td>
</tr>
<tr>
<td>Baseplate Model</td>
<td>840 nodes</td>
<td>840 nodes</td>
</tr>
</tbody>
</table>

**COMPLETE SYSTEM**: 983 nodes

A COMPLETE DETAILED MODEL:

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Nodes</th>
<th>Multiplied Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed Cell Model</td>
<td>250 nodes</td>
<td>6750 nodes</td>
</tr>
<tr>
<td>Detailed Diode Model</td>
<td>33 nodes</td>
<td>33 nodes</td>
</tr>
<tr>
<td>Baseplate Model</td>
<td>840 nodes</td>
<td>840 nodes</td>
</tr>
</tbody>
</table>

**COMPLETE SYSTEM**: 7623 nodes

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

### TEST RESULTS COMPARED TO MODEL PREDICTION

<table>
<thead>
<tr>
<th>Node</th>
<th>Max 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</td>
</tr>
<tr>
<td></td>
<td>(model: 10.95)</td>
</tr>
<tr>
<td>upper stack (on sleeve)</td>
<td>1.1 (measured: 26.3)</td>
</tr>
<tr>
<td></td>
<td>end of discharge</td>
</tr>
<tr>
<td></td>
<td>(model: 25.2)</td>
</tr>
<tr>
<td>lower (on sleeve)</td>
<td>1.4 (measured: 17)</td>
</tr>
<tr>
<td></td>
<td>end of discharge</td>
</tr>
<tr>
<td></td>
<td>(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</td>
</tr>
<tr>
<td></td>
<td>(model: 3.1)</td>
</tr>
</tbody>
</table>

---

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6.2 - THERMAL VACUUM TEST ON A VHS90CM CELL

Temperature (deg C)

$t(2204)$

$-2204 \exp$
**THERMAL MODELING OF NIH2 BATTERIES**

### 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>Predicted</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0/°L</td>
<td>27</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>20°/°L</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 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>

**MOUNTING**

- 3.1 -- n1
- 3.2 -- n2
- 3.3 -- n3
- 3.4 -- n4
- 3.5 -- n5

**Insulation Ambient Air**

**Aluminium Plate**

**Peltier Element**

TEMPERATURE PROFILE OF THE PLATE DETERMINED BY THE DETAILED CELL MODEL

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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
## 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>3.6 (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>
80% DOD GEO ECLIPSE CYCLE
SIMULATION OF W FAILED CELL

\[\begin{array}{c}
\text{TIME (h)} \\
\end{array}\]

\[\begin{array}{c}
\text{°C} \\
\end{array}\]

Exp: Model:
NFS  \\
EFS  \\
FFI  \\
FCI  \\
FDI  \\

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Nickel-Hydrogen Technologies Session
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 REALIZED 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