THERMAL MODELING OF NIH2 BATTERIES

Agnes PONTHUS (SAFT) and Alain ALEXANDRE (TSRI)

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1993 NASA Aerospace Battery Workshop
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Nickel-Hydrogen Technologies Session
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 hours
- 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-hour 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:

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

WITH

\[ PD : \text{HEAT DISSIPATION IN DISCHARGE (W)} \]
\[ ID : \text{DISCHARGE CURRENT (A)} \]
\[ UD : \text{DELIVERED CELL VOLTAGE (V)} \]
\[ U_0 : \text{THERMO-NEUTRAL POTENTIAL (V)} \]

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

WITH

\[ u : \text{VOLTAGE AT COUPLE LEVEL (V)} \]
\[ R : \text{NICKEL TABS AND OUTLET RESISTANCE (mOHM)} \]

\[ PD = P\text{STACK} + R \cdot ID^2 \]

WITH

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

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

GENERAL ADMITTED VALUE: 1.51 \text{V}

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:

\[ Q_C = E_c - E_d - Q_d \]

\( Q_c \): 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:

\[ P = U \cdot I \cdot E \]

\( U \): electrical energy input = heat dissipation

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64 Ah NiH2 Cell Voltage in Charge

**Electrochemical Reactions:**

\[ \text{(1)} \quad \text{+} \quad \text{(2)} \]
\[ \text{(2)} \quad \text{+} \quad \text{(3)} \]
\[ \text{(3)} \quad \text{+} \quad \text{(4)} \]

**Power Dissipated in Charge**

**Experimental Factors:**

- \( n_1 = 0.074 \)
- \( n_2 = 0.395 \)

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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 ≤ 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 CAPACITANCE:

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

EQUIVALENT THERMAL CONDUCTIVITY:

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

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

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

FOR EACH COMPONENT:

\[
\rho C, \lambda, \text{THICKNESS (Ep)}
\]
THERMAL MODELING OF NIH2 BATTERIES

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

N COUPLES

36 NODES PER COUPLE

2 EXTREMITY PLATES

22 NODES PER PLATE

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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

ALUMINIUM BASE PLATE ALVEOLUS + SOLITHANE RESIN

CELL CONTAINER

STACK

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

REDUCTION

250 NODES

5 NODES

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EXPERIMENTAL APPROACH:

--> EVALUATION OF THERMAL CAPACITY
(SPECIFIC TEST)

VHS 96 CM WITH SLEEVE AND ALVEOLUS

\( C_{\text{calculated}} = 2333 \, \text{J/°C} \)

\( C_{\text{experimental}} = 2330 \, \text{J/°C} \)

--> EVALUATION OF HEAT GENERATION
(SPECIFIC TEST)

VHS 96 CM TOTAL AVERAGE HEAT DISSIPATION IN DISCHARGE:

70% DOD: \( P = 12.8 \, \text{W} \)
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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COMPLETE SYSTEM: 983 NODES

27 CELLS (5 NODES EACH)

DIODES SYSTEM (8 NODES)

WITH ALL BASIC INPUTS

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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)
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

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6.2 – THERMAL VACUUM TEST ON A VHS90CM CELL

TEST RESULTS COMPARED TO MODEL PREDICTION

<table>
<thead>
<tr>
<th>Model Node</th>
<th>Max Discrepancy (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>upper dome</td>
<td>2204 2.25 (measured: 13.2) end of charge (model: 10.95)</td>
</tr>
<tr>
<td>upper stack (on sleeve)</td>
<td>707 1.1 (measured: 26.3) end of discharge (model: 25.2)</td>
</tr>
<tr>
<td>lower (on sleeve)</td>
<td>107 1.4 (measured: 17) end of discharge (model: 15.6)</td>
</tr>
<tr>
<td>lower dome</td>
<td>1304 0.8 (measured: 2.3) end of trickle (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
- t(1707)
- 1707 exp
- 1.04 e^t

Time (s)
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/Δt level</th>
<th>Upper stack inside (hot)</th>
<th>DT sleeve – dome</th>
<th>DT radial sleeve-stack</th>
<th>DT stack – dome</th>
<th>DT sleeve</th>
<th>DT stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>29</td>
<td>8.1</td>
<td>2</td>
<td>10.1</td>
<td>5.38</td>
<td>5.38</td>
</tr>
<tr>
<td>14.4</td>
<td>-</td>
<td>5.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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
### 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

\[\text{TEMPERATURE (°C)}\]

\[\text{TIME (h)}\]

\[\text{EXP: MODELS:}\]
- NFS
- FES
- FFI
- FCI
- FDI
SIMULATION CYCLE ACCU W DEF.
CAS B

TIME

0  5000  10000  15000  20000  25000  30000  35000  40000

-10  0  10  20  30  40

XF(T(FI))
XF(T(FS))
XF(T(DI))
XF(T(DS))
XF(T(Cl))
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