THERMAL MODELING OF NIH2 BATTERIES

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NOVEMBER 16–18, 1993
THERMAL MODELING OF NIH2 BATTERIES

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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:

\[ \text{PD} = \text{ID} (U_0 - UD) \]

WITH

\[ \text{PD} : \text{HEAT DISSIPATION IN DISCHARGE (W)} \]
\[ \text{ID} : \text{DISCHARGE CURRENT (A)} \]
\[ \text{UD} : \text{DELIVERED CELL VOLTAGE (V)} \]
\[ \text{U}_0 : \text{THERMO-NEUTRAL POTENTIAL (V)} \]

\[ \text{UD} = u - R \text{ID}^2 \]

WITH

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

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

WITH

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

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:

\[ P = Ut I_t \]

ELECTRICAL ENERGY INPUT = HEAT DISSIPATION
90 Ah NiH2 Cell Voltage

Electrochemical Reactions:

1. \( n_1 = \frac{U_{c1}}{i} \)
2. \( n_2 = \frac{U_{c2}}{i} \)
3. \( n_3 = \frac{U_{c3}}{i} \)

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
1.55
1.5
1.35
1.3
1.2

64 AH NIH2 CELL VOLTAGE IN CHARGE

$U_c (V)$

1.63
1.6
1.53
1.5
1.43
1.4
1.33
1.3
1.23

$1.51 \rightarrow 1.546 \rightarrow 1.552 \rightarrow 1.491$

electrochemical reactions:

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

$0 < k = C_c/C_d < 0.94$

$0.94 < k < 1.06$

$1.06 < k < 1.28$

$1.28 < k$

$P_c (W)$

3.5
3
2.5
2
1.5
1
0.5

$1.5$ 1993 NASA Aerospace Battery Workshop, November 16–18
U: CELL VOLTAGE

JOULE EFFECT

CONTACT RESISTANCE
TERMİNAL RESISTANCE
CONTACT RESISTANCE

ELECTROCHEMICAL
HEATING

STACK

NICKEL TABS RESISTANCE

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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, temperature</td>
<td>intensity, potential</td>
</tr>
<tr>
<td>capacity, conductance</td>
<td>capacity, power</td>
</tr>
<tr>
<td>heat source, impressed</td>
<td>current generator, voltage generator</td>
</tr>
<tr>
<td>temperature, impressed</td>
<td>flux</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 NH2 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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Thermal Modeling of NiH2 Batteries

5 - NiH2 Battery Model Development

5.1 - At Couple Level

Equivalent Thermal Capacity:

Addition of each thermal capacity of the components:

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

Equivalent Thermal Conductivity:

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

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

CELL CONTAINER

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THERMAL MODELING OF NiH2 BATTERIES

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

CELL MODEL REDUCTION:

BASIC INPUTS:

1/4 CELL
DETAILED MODEL:

WITH SAME BATTERY STRUCTURE INTERFACE

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

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

-- > 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)
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

RADIATOR

ALVEOLUS

26 NODES (PER ALVEOLUS)

840 NODES FOR THE WHOLE BASEPLATE

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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)
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

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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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THermal Modeling of NiH2 Batteries

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 2204</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 707</td>
<td>1.1 (measured: 26.3)</td>
</tr>
<tr>
<td>(on sleeve)</td>
<td>end of discharge</td>
</tr>
<tr>
<td></td>
<td>(model: 25.2)</td>
</tr>
<tr>
<td>lower stack 107</td>
<td>1.4 (measured: 17)</td>
</tr>
<tr>
<td>(on sleeve)</td>
<td>end of discharge</td>
</tr>
<tr>
<td></td>
<td>(model: 15.6)</td>
</tr>
<tr>
<td>lower dome 1304</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>
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(104)
- 104 exp

time

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THERMAL MODELING OF NIH2 BATTERIES

6.3 - QUALIFICATION LIFE TEST ON VHS90CM CELLS

(ESTEC - NOORDWIJK)

MOUNTING

INSULATION AMBIENT AIR

ALUMINUM 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>3.2</td>
<td>29</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>29%</td>
<td>29</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>Upper stack</td>
<td>29</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td>inside (hot)</td>
<td></td>
<td>-</td>
<td>19.3</td>
</tr>
<tr>
<td>DT sleeve</td>
<td>8.1</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>-dome</td>
<td>5.0</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>DT radial</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>sleeve-stack</td>
<td>1.2</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>DT stack-dome</td>
<td>10.3</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>-</td>
<td>2.7</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>DT stack</td>
<td>5.38</td>
<td>-</td>
<td>6.2</td>
</tr>
<tr>
<td>-</td>
<td>3.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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THERMAL MODELING OF NIH2 BATTERIES

6.3 - QUALIFICATION LIFE TEST ON VHS90CM CELLS

![Graph showing thermal modeling results for VHS90CM cells.](image-url)
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

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### 6.4 - THERMAL VACUUM QUALIF. ON SAFT 27V-1840M BATTERY

<table>
<thead>
<tr>
<th>SPECIFICATION</th>
<th>TEST</th>
<th>MODEL</th>
<th>MAX CELL STACK TEMP.</th>
<th>MIN CELL STACK TEMP.</th>
<th>% HEATING USED</th>
<th>MAX STACK TO CELL GRADIENT</th>
<th>CELL TO CELL GRADIENT</th>
<th>MAX DIODE JUNCTION TEMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>34.6 (X)</td>
<td>+35°C</td>
<td>-5°C</td>
<td>73%</td>
<td>3.6 (F)</td>
<td>9.95 (F)</td>
<td>105.6</td>
</tr>
</tbody>
</table>

**RESULTS:**
THERMAL MODELING OF NIH2 BATTERIES

6.4—THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

Image of a thermal model diagram of NIH2 batteries, showing a grid layout with labels and connections. Additional annotations include "DISCHARGE DIODE CASE," "DIODE SUPPORT UPPER PART," and "DIODE SUPPORT BASE." Text at the bottom reads: "Nasa Aerospace Battery Workshop, November 16-18."
80% DOD GEO ECLIPSE CYCLE

SIMULATION OF W FAILED CELL

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

\[ \text{oC} \]

Exp: Model:
NFS EES EWI FCI FDI
THERMAL MODELING OF NIH2 BATTERIES

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