THERMAL MODELING OF NIH2 BATTERIES

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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°C
- TEMPERATURE DIFFERENCE BETWEEN STACK AND CELL WALL < 12°C
- TEMPERATURE DIFFERENCE BETWEEN TWO IDENTICAL POINTS OF TWO CELLS OF THE BATTERY < 9°C

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2 - NIH2 CELL HEAT DISSIPATION

2.1 - DISCHARGE

HEAT DISSIPATION FORMULATION:

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

WITH

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

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

WITH

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

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

WITH

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

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>
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:

\[ P = U t I t : ELECTRICAL ENERGY INPUT = HEAT DISSIPATION \]
90 AH NII2 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

**Electrochemical reactions:**

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

**Power Dissipated in Charge**

Experimental factors:

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

**SAFT**

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U: CELL VOLTAGE

JOULE EFFECT
CONTACT RESISTANCE
TERMINAL 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

Thermal parameter | Electrical parameter
--- | ---
heat flux | intensity
temperature | potential
capacity | capacity
conductance | conductance
heat source | current generator
impressed temperature | voltage generator
impressed flux | current generator

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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).

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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:

\[ \rho C_{\text{eq}}, \lambda_V \rightarrow \lambda_H \rightarrow \]

EQUATION OF EACH THERMAL CAPACITY OF THE COMPONENTS:

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

EQUATION OF THERMAL CONDUCTIVITY:

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

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

- 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)

H2

36 NODES PER COUPLE
22 NODES PER PLATE

NIKEL TAB - CELL CASE - COUPLE

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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 + SOLUTHANE RESIN

STACK

ALUMINIUM BASE PLATE ALVEOLUS + SOLUTHANE RESIN

RADIATOR

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THERMAL MODELING OF NiH2 BATTERIES

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

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  

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

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

--> 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 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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5.5 - BATTERY COMPLETE MODEL

COMPLETE SYSTEM: 983 NODES

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</th>
<th>Nodes Initially</th>
<th>Nodes Modelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified Cell Model</td>
<td>5</td>
<td>135</td>
</tr>
<tr>
<td>Simplified Diode Model</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Baseplate Model</td>
<td>840</td>
<td>840</td>
</tr>
<tr>
<td><strong>Complete System</strong></td>
<td>983</td>
<td></td>
</tr>
</tbody>
</table>

A COMPLETE DETAILED MODEL:

<table>
<thead>
<tr>
<th>Model</th>
<th>Nodes Initially</th>
<th>Nodes Modelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed Cell Model</td>
<td>250</td>
<td>6750</td>
</tr>
<tr>
<td>Detailed Diode Model</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>Baseplate Model</td>
<td>840</td>
<td>840</td>
</tr>
<tr>
<td><strong>Complete System</strong></td>
<td>7623</td>
<td></td>
</tr>
</tbody>
</table>

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:

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

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</td>
</tr>
<tr>
<td>2.25 (measured: 13.2) end of charge (model: 10.95)</td>
<td></td>
</tr>
<tr>
<td>upper stack</td>
<td>707</td>
</tr>
<tr>
<td>1.1 (measured: 26.3) end of discharge (model: 25.2)</td>
<td></td>
</tr>
<tr>
<td>lower stack</td>
<td>107</td>
</tr>
<tr>
<td>1.4 (measured: 17) end of discharge (model: 15.6)</td>
<td></td>
</tr>
<tr>
<td>lower dome</td>
<td>1304</td>
</tr>
<tr>
<td>0.8 (measured: 2.3) end of trickle (model: 3.1)</td>
<td></td>
</tr>
</tbody>
</table>
THERMAL MODELING OF NIH2 BATTERIES

6.2 - THERMAL VACUUM TEST ON A VHS90CM CELL

Temperature (deg C)

Time

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6.3 - QUALIFICATION LIFE TEST ON VHS90CM CELLS

(ESTEC – NOORDWIJK)

**TEMPERATURE PROFILE OF THE PLATE DETERMINED BY THE DETAILED CELL MODEL**

**MOUNTING**

<table>
<thead>
<tr>
<th>Mode/En level</th>
<th>Predicted</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 &lt;θO%</td>
<td>27</td>
<td>29</td>
<td>-</td>
</tr>
<tr>
<td>&lt;θO%</td>
<td>14.4</td>
<td>16.1</td>
<td>-</td>
</tr>
<tr>
<td>Upper stack</td>
<td>29</td>
<td>-</td>
<td>31</td>
</tr>
<tr>
<td>inside (hot)</td>
<td>-</td>
<td>-</td>
<td>10.3</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>-</td>
<td>2</td>
</tr>
<tr>
<td>sleeve-stack</td>
<td>2.7</td>
<td>-</td>
<td>1.2</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>3.5</td>
<td>-</td>
</tr>
<tr>
<td>DT stack</td>
<td>5.38</td>
<td>-</td>
<td>6.2</td>
</tr>
</tbody>
</table>

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6.3 – QUALIFICATION LIFE TEST ON VHS90CM CELLS

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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>Specification</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 27VHS84CM BATTERY**

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6.4 - THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

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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