THERMAL MODELING OF NIH2 BATTERIES

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NOVEMBER 16-18, 1993
THERMAL MODELING OF NIH2 BATTERIES

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THERMAL MODELING OF NIIH2 BATTERIES

1 - NIIH2 BATTERY MISSION AND ENVIRONMENT

IN GENERAL, GEOSTATIONARY AND LOW ORBIT SATELLITES:
- PRELUNCH 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:

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

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

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:

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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:

\[ P = I t \]

\( P \): ELECTRICAL ENERGY INPUT = HEAT DISSIPATION
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SAFT

90 AH NiH2 CELL VOLTAGE

ELECTROCHEMICAL REACTIONS:

\[ \begin{array}{c}
(1) \\
+ \\
(2)
\end{array} \]

\[ \begin{array}{c}
(2) \\
+ \\
(3)
\end{array} \]

\[ \begin{array}{c}
(3) \\
+ \\
(4)
\end{array} \]

\[ \begin{array}{c}
\text{charge} \\
\text{trickle}
\end{array} \]

POWER DISSIPATED IN CHARGE:

experimental factors:

\[ n_1 = 0.074 \]
\[ n_2 = 0.64 \]
\[ n_3 = 0.4 \]

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64 AH NiH2 CELL VOLTAGE IN CHARGE

 electrochemical reactions:

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

\[ n_1 U_{clc} \]

\[ n_2 U_{clc} \]

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

\[ \text{charge} \]

1.546 1.552

1.51

1.491

\[ \text{trickle} \]

1.5

0.5

\[ 0 \]

1.65

1.6

1.45

1.4

1.35

1.3

1.25

\[ U_c (V) \]

POWER DISSIPATED IN CHARGE

experimental factors:

\[ n_1 = 0.074 \]

\[ n_2 = 0.395 \]

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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

<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 $k \leq 6$, 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).
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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, ...) \Rightarrow 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:

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

ADDITION OF EACH THERMAL CAPACITY OF THE COMPONENTS:

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

EQUIVALENT THERMAL CONDUCTIVITY:

\[ \begin{align*}
\lambda_H &= \frac{\Sigma \lambda E_p}{\Sigma E_p} \\
\lambda_V &= \frac{\Sigma E_p}{\Sigma \lambda / E_p}
\end{align*} \]

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)

--- Diagram Image ---

36 NODES PER COUPLE

22 NODES PER PLATE

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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:

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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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EXPERIMENTAL APPROACH:

---> EVALUATION OF THERMAL CAPACITY
(SPECIFIC TEST)

VHS 96 CM WITH SLEEVE AND ALVEOLUS

\[
\begin{align*}
\rho C_{\text{calculated}} &= 2333 \text{ J/}^\circ\text{C} \\
\rho C_{\text{experimental}} &= 2330 \text{ J/}^\circ\text{C}
\end{align*}
\]

---> EVALUATION OF HEAT GENERATION
(SPECIFIC TEST)

VHS 96 CM TOTAL AVERAGE HEAT DISSIPATION IN DISCHARGE:

\[
\begin{align*}
70\% \text{ DOD} & : & P &= 12.0 \text{ W} \\
80\% \text{ DOD} & : & P &= 16.5 \text{ W}
\end{align*}
\]

---> TEMPERATURE DISTRIBUTION ON A VHS 96 CM CELL
CORRELATION WITH MODEL PREDICTIONS
(SEE THERMAL VACUUM TEST ON VHS 96 CM CELL)
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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</th>
<th>CHARGE</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)

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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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

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>end of charge</td>
<td>2.25 (measured: 13.2)</td>
</tr>
<tr>
<td>end of charge</td>
<td>1.1 (model: 10.95)</td>
</tr>
<tr>
<td>upper stack</td>
<td>707</td>
</tr>
<tr>
<td>(on sleeve)</td>
<td>1.4 (measured: 26.3)</td>
</tr>
<tr>
<td>lower dome</td>
<td>1304</td>
</tr>
<tr>
<td>(on sleeve)</td>
<td>0.8 (measured: 2.3)</td>
</tr>
<tr>
<td>lower dome</td>
<td>107</td>
</tr>
<tr>
<td>end of discharge</td>
<td>1.4 (model: 15.6)</td>
</tr>
<tr>
<td>end of discharge</td>
<td>0.8 (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(107)
- -107 exp

Time (s)

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6.3 – QUALIFICATION LIFE TEST ON VHS90CM CELLS

(ESTEC – NOORDWIJK)

MOUNTING

INSULATION AMBIANT AIR

ALUMINIUM PLATE

PELTIER ELEMENT

TEMPERATURE PROFILE OF THE PLATE DETERMINED BY THE DETAILED CELL MODEL

TEST RESULTS COMPARED TO MODEL PREDICTIC

<table>
<thead>
<tr>
<th>Mode/Dt level</th>
<th>Predicted</th>
<th>Measured</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>80°C</td>
<td>27</td>
<td>29</td>
</tr>
<tr>
<td>20°C</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>18.3</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>1.2</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>6.2</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td>3.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>DT stack</td>
<td>5.38</td>
<td>-</td>
<td>6.2</td>
</tr>
<tr>
<td>-</td>
<td></td>
<td>-</td>
<td>3.5</td>
</tr>
</tbody>
</table>

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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
### 6.4 – THERMAL VACUUM QUALIF. ON SAFT 27VHS84CM 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</td>
<td>34.6</td>
</tr>
<tr>
<td>MIN CELL STACK TEMP.</td>
<td>-5°C</td>
<td>-4</td>
<td>-3.75</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</td>
<td>3.6</td>
</tr>
<tr>
<td>MAX STACK TO CELL GRADIENT</td>
<td>12°C</td>
<td>9.7</td>
<td>9.95</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>
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