THERMAL MODELING OF NIH2 BATTERIES

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HUNTSVILLE AL
NOVEMBER 16–18, 1993
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°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

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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>

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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

\[ QC : \text{THERMAL ENERGY LOST IN CHARGE (JOULE)} \]
\[ Ec : \text{ELECTRICAL ENERGY INPUT IN CHARGE (JOULE)} \]
\[ Ed : \text{ELECTRICAL ENERGY OUTPUT IN DISCHARGE (JOULE)} \]
\[ Qd : \text{THERMAL ENERGY LOST IN DISCHARGE (JOULE)} \]

CORRELATION HAVE BEEN ESTABLISHED FOR SAFT 95AH 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:

\[ P = Ut It : \text{ELECTRICAL ENERGY INPUT} = \text{HEAT DISSIPATION} \]
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64 AH NIH2 CELL VOLTAGE IN CHARGE

Electrochemical reactions:

1. \( + \)  
2. \( + \)  
3. \( + \)  
4. \( + \)

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>
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

\[ \rho \mathcal{C}_{\text{eq}}, \lambda_N \rightarrow \lambda_H \rightarrow \]

EQUIVALENT THERMAL CAPACITY:

\[ \rho \mathcal{C}_{\text{equivalent}} = \frac{\sum \mathcal{C} \cdot \text{Volume}}{\text{Volume couple}} \]

EQUIVALENT THERMAL CONDUCTIVITY:

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

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

FOR EACH COMPONENT:

\[ \rho \mathcal{C}, \lambda, \text{THICKNESS (E)} \]
5.2 - AT CELL LEVEL (1/4 OF A CELL)

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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:

[Diagram showing battery structure with components labeled: Aluminum sleeve, Solithane resin, Aluminum base plate, Alveolus, Solithane resin, Stack, Cell container, Radiator.]

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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:

1 Cell Rough Model:

5 Nodes

250 Nodes

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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 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:

- 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
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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THERMAL MODELING OF NIH2 BATTERIES

5.5 - BATTERY COMPLETE MODEL

COMPLETE SYSTEM: 983 NODES

27 CELLS (5 NODES EACH)

WITH ALL BASIC INPUTS

DIODES SYSTEM
(8 NODES)

840 NODES
BASE PLATE

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5.1 -

WITH THIS APPROACH:

<table>
<thead>
<tr>
<th>Model</th>
<th>Node Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified Cell Model</td>
<td>5 nodes → 135 nodes</td>
</tr>
<tr>
<td>Simplified Diode Model</td>
<td>8 nodes → 8 nodes</td>
</tr>
<tr>
<td>Baseplate Model</td>
<td>840 nodes → 840 nodes</td>
</tr>
</tbody>
</table>

COMPLETE SYSTEM: 983 nodes

A COMPLETE DETAILED MODEL:

<table>
<thead>
<tr>
<th>Model</th>
<th>Node Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detailed Cell Model</td>
<td>250 nodes → 6750 nodes</td>
</tr>
<tr>
<td>Detailed Diode Model</td>
<td>33 nodes → 33 nodes</td>
</tr>
<tr>
<td>Baseplate Model</td>
<td>840 nodes → 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)
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 (measured: 13.2) end of discharge (model: 10.95)</td>
<td></td>
</tr>
<tr>
<td>upper stack (on sleeve)</td>
<td>707</td>
</tr>
<tr>
<td>end of discharge (measured: 26.3) end of discharge (model: 25.2)</td>
<td></td>
</tr>
<tr>
<td>lower (on sleeve)</td>
<td>107</td>
</tr>
<tr>
<td>end of discharge (measured: 17) end of discharge (model: 15.6)</td>
<td></td>
</tr>
<tr>
<td>lower dome</td>
<td>1304</td>
</tr>
<tr>
<td>end of trickle (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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THERMAL MODELING OF NIH2 BATTERIES

6.3 - QUALIFICATION LIFE TEST ON VHS90CM CELLS

(ESTEC - NOORDWIJK)

MOUNTING

INSULATION AMBIENT AIR

ALUMINIUM PLATE

PELTERIER 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>ΔQ/Δt</td>
<td>27</td>
<td>29</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>2.2</td>
<td>-</td>
<td>2.2</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>

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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
### THERMAL MODELING OF NIH2 BATTERIES

#### 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 (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 Grad.</td>
<td>12°C</td>
<td>9.7 (F)</td>
<td>9.95 (F)</td>
</tr>
<tr>
<td>Cell to Cell Grad.</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>
THERMAL MODELING OF NIH2 BATTERIES

6.4— THERMAL VACUUM QUALIF. ON SAFT 27VHS64CM BATTERY

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1993 NASA Aerospace Battery Workshop

Nickel-Hydrogen Technologies Session
80% DOD GEO ECLIPSE CYCLE

SIMULATION OF W FAILED CELL

TIME (h)
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