IMPROVED HIGH INSOLATION AND TEMPERATURE SOLAR CELLS AND CELL ASSEMBLY TECHNOLOGY

ESTEC Noordwijk, The Netherlands
23-02-2005
Agenda

- Objective of TDA
- Technology requirements
- Scope of TDA
  - Estimate of achieved TRL
- Deliverables
- Critical technology requirements not met
- Critical technology items not covered
- Lessons learnt
- Planning to flight model
Objective of TDA

• Purpose of this work was the selection and testing of materials and manufacturing processes able to withstand the high solar intensity and temperature conditions (HIT) typical of interplanetary missions towards the Sun and Mercury

• The development approach was aimed to use as much as possible already existing technologies and materials
## Technology requirement

<table>
<thead>
<tr>
<th>HIT overall requirements</th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Solar Radiation</strong></td>
<td></td>
</tr>
<tr>
<td>1. SEPM, 10.7 SC close to Mercury (SAA 70°)</td>
<td></td>
</tr>
<tr>
<td>2. MPO, 4.6 SC close to Mercury (90° SAA)</td>
<td></td>
</tr>
<tr>
<td>3. SOLO, 25 SC</td>
<td></td>
</tr>
<tr>
<td><strong>PVA Maximum Temperature</strong></td>
<td></td>
</tr>
<tr>
<td>1. SEPM &lt;200°C</td>
<td></td>
</tr>
<tr>
<td>2. MPO &lt;300°C</td>
<td></td>
</tr>
<tr>
<td>3. SOLO &lt;250°C (TBC)</td>
<td></td>
</tr>
<tr>
<td><strong>Solar Aspect Angle</strong></td>
<td>From 0° to 75°</td>
</tr>
<tr>
<td><strong>Radiation Damage</strong></td>
<td>3.0E+15 e/cm²</td>
</tr>
<tr>
<td><strong>Power Needs</strong></td>
<td></td>
</tr>
<tr>
<td>1. SEPM &gt; 15 kW AM0</td>
<td></td>
</tr>
<tr>
<td>2. SOLO &gt; 500 W at 0.89 AU</td>
<td></td>
</tr>
<tr>
<td>3. MPO covered by SOLO module</td>
<td></td>
</tr>
<tr>
<td><strong>Sun Sensor Requirements</strong></td>
<td>Develop a solar cell based low precision SS</td>
</tr>
</tbody>
</table>
Scope of TDA

- Definition and preliminary testing of solar cells and PVA related parts and materials (including substrate)
- Development of a PVA 3D mathematical model
- Testing and calibration to measurements of the models
- Final assessment on the HIT technology readiness level
Scope of TDA

- A finite element analysis (p-method), using PRO-MECHANICA software, was performed with the aim to:
  - generate 3-D and 2-D models for behavioural simulations
  - provide indications / recommendations
  - identify critical areas

Example of mathematical model concept (courtesy of Pretech)
Scope of TDA

After the identification of a representative PVA geometry, all the enveloping mission cases have been analysed.

- Temperature distributions
- Displacements of PVA parts
- Eq. von Mises stresses

Example of analysis output (courtesy of PreTech)
Scope of TDA

SCA level

- BOL and EOL EP
- TC BOL and EOL
- SAA influence at different T
- Influence of HT baking
- INTC adherence after ageing test (4000 CY)

Coupon level

- Thermal gradient High Temperature
- Temperature baking
- Thermal cycling (4000 CY)
- Destructive investigation on pre-aged hardware
Scope of TDA

• Test house identification and HIT set up modifications
  – SCA level
    • sample stage for HT measurement under different SAA (INTA Spasolab)
  – Coupon level
    • thermal chamber for temperature gradient monitoring (DLR)
    • thermal chamber capable to reproduce, under controlled atmosphere, HIT worst case cycling profile (QinetiQ)
Scope of TDA

- Solar cell high temperature bake out
  - Cell performance after more than 1000 hours at +300°C

<table>
<thead>
<tr>
<th>Type</th>
<th>Time (hours)</th>
<th>$\Delta I_{sc}$ %</th>
<th>$\Delta V_{oc}$ %</th>
<th>$\Delta F_{FF}$ %</th>
<th>$\Delta P_{m}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs/Ge single junction</td>
<td>1199</td>
<td>-0.3</td>
<td>-1.5</td>
<td>-9.2</td>
<td>-11.2</td>
</tr>
<tr>
<td>InGaP/GaAs/Ge single junction</td>
<td>1199</td>
<td>-5.7</td>
<td>2.9</td>
<td>-4.6</td>
<td>-7.4</td>
</tr>
<tr>
<td>GaAs/Ge SJ with InGaP filter</td>
<td>1199</td>
<td>0.2</td>
<td>1.8</td>
<td>-2.9</td>
<td>-0.9</td>
</tr>
<tr>
<td>InGaP/GaAs/Ge DJ-plus</td>
<td>1123</td>
<td>-1.9</td>
<td>0.9</td>
<td>-6.3</td>
<td>-3.7</td>
</tr>
<tr>
<td>TJ using TECSTAR wafer</td>
<td>1274</td>
<td>-6.3</td>
<td>-0.4</td>
<td>-5.2</td>
<td>-11.5</td>
</tr>
<tr>
<td>SCA with RWE cell</td>
<td>962</td>
<td>-1.8</td>
<td>0</td>
<td>-0.2</td>
<td>-2.0</td>
</tr>
</tbody>
</table>
Scope of TDA

- Coverglasses sandwich temperature bake out
  - Transmission and reflectivity after about 1000 hours at +300°C
Scope of TDA

- SCA temperature coefficients
  - test conditions: $T= 25^\circ C, 150^\circ C$ and $200^\circ C$
  - results:

Demonstration of TJ GaAs/Ge solar cell suitability for HIT missions
• Extrapolation of temperature coefficient results up to +300°C
Scope of TDA

- SCA Solar Aspect Angle Test
  - test conditions: SAA = 0°, 60°, 70° and 85°
    T= 25°C, 150°C and 200°C
    BOL & EOL
  - results:
Scope of TDA

- Concentration
  - test conditions: \( SC = \) from 1 to 10.7
    \( T = \) from 25°C to 200°C
  - results:

TJ cells are suitable for medium concentration applications with a dedicated grid design
Scope of TDA

• Coupons photos:

  - Al orbiter
  - Carbon cruise
  - C-C orbiter
Scope of TDA

- Thermal Gradient test @ coupon level (DLR test facility)
  - Test conditions
    - Simulation of mission environment through solar irradiation of samples in a vacuum chamber with increasing temperatures and different angles
    - Backside temperature: below -100°C - Front side temperature: from 50°C to 300°C
    - 3 different inclinations: 0°, 45°, 70°
## Scope of TDA

<table>
<thead>
<tr>
<th>Candidates</th>
<th>Cells</th>
<th>Adhesives</th>
<th>Cover glasses</th>
<th>Substrates</th>
<th>interconnector</th>
<th>Wiring</th>
</tr>
</thead>
<tbody>
<tr>
<td>SJ GaAs/Ge with integrated by pass diode (CESI)</td>
<td>CVG adh.</td>
<td>CMO (Thales Space Technology)</td>
<td>Aluminium plate (thickness: 2.0 mm) with insulating layer (0.05 mm thick – Upilex-S / Kapton).</td>
<td>Silver plated Invar 0.03 mm (Parallel Gap Resistance Welding)</td>
<td>Gore type SCC 3901/019 (*) locally shielded with protection tape (Dunmore)</td>
<td></td>
</tr>
<tr>
<td>Lay down adh.</td>
<td>CMO adh. DC-93 500</td>
<td></td>
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<tr>
<td>Lay down adh.</td>
<td>Lay down adh. RTV-S691</td>
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<tr>
<td>Lay down adh.</td>
<td>Lay down adh. RTV 566</td>
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<tr>
<td>Lay down adh.</td>
<td>Lay down adh. CV 2568</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Candidates</th>
<th>Miscellaneous Adhesives</th>
<th>Bleed Resistor</th>
<th>Blocking and external by-pass diodes</th>
<th>Thermistor</th>
<th>Insulation plates</th>
<th>Feed thru wiring protection inserts</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV 2-1142-2 (Nuval Technology)</td>
<td>CVG adh. RTV-S691 (Wacker Chemie)</td>
<td>RWR (Dale) Crimped</td>
<td>Planar GaAs diode (CESI) Crimped</td>
<td>118 MF (manufactured by Rosemount) Crimped</td>
<td>Kapton (Du Pont)</td>
<td>Teflon inserts (Du Pont)</td>
</tr>
<tr>
<td>RTV 566 (GE Silicones)</td>
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</tbody>
</table>

* Candidate lists: SJ GaAs/Ge with integrated by pass diode (CESI), Planar GaAs diode (CESI) Crimped, Planar GaAs diode (CESI) Crimped, Planar GaAs diode (CESI) Crimped.
Estimate of achieved TRL

- TRL 9: Actual system “flight proven” through successful mission operations
- TRL 8: Actual system completed and “flight qualified” through test and demonstration (ground or space)
- TRL 7: System prototype demonstration in a space environment
- TRL 6: System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL 5: Component and/or elegant breadboard validation in relevant environment
- TRL 4: Component and/or breadboard validation in laboratory environment
- TRL 3: Analytical and experimental critical function and/or characteristic proof of concept
- TRL 2: Technology concept and/or application formulated
- TRL 1: Basic principles observed and reported
Deliverables

- Solar cell assemblies dedicated to environmental and destructive testing

- Adhesive samples dedicated to characterization at HT and destructive testing

- PVA coupons dedicated to thermal gradient / shock test and rapid cycling
  - Substrate materials were Al and C-C
**Critical technology requirements not met**

- To test all the hardware @ +300°C was impossible in combination with illumination and electrical biasing
  - Extrapolation by analysis and superposition of effects for deriving the 300°C data
- Combination of HT and sun concentration was not possible at component level
  - Performed only at coupon level but … Set up interference to be solved
- To find TC test facilities 100% compliant to the HIT test levels
  - Reduction of the temperature extreme leaving unchanged the maximum delta T
- Implicit requirement to achieve TRL 4
Critical technology items not covered

• **Component level**
  – UV on SCA
    • Test rate, acceleration factor for qual purposes, lifetime prediction
  – Mercury environment induced degradation
    • Protons and non ionising particles in general
    • Component ageing
  – Solar Cell Electrical biasing
    • Illumination and HT effects, acceleration factors for qual purposes, lifetime behaviour
  – Diode (by-pass and blocking)
    • Technology definition
    • Acceleration factors for qual purposes, lifetime behaviour

• **Coupon level**
  – Shunt Diode Integration
    • External diode solution not explored
  – Development of OSR’s suitable for high temperature applications
Lessons learnt

• Bare Solar Cells and SCA’s
  – Existing TJ solar cell structure may be adequate for the HIT environment but the influence of electrical biasing (with or without illumination) and high temperature should be further investigated
  – Testing of bare cell is extremely difficult as far as the set up is concerned especially at high temperature
  – Whenever possible comparison of bare cell and SCA test results is extremely meaningful (understanding of degradation mechanisms, if any)
  – Integral diode behaviour at high temperature is doubtful and so external solutions should be considered as mandatory alternatives
Lessons learnt

• **Photovoltaic Assembly**
  – Standard integration processes and methods could be compatible with the HIT environment
  – There are few EEE parts to be further developed in terms of technology, housing and integration process
    • Si-C diode, “flat case”
    • Thermistor bonding process
    • Reflective tape selection and bonding process
  – Test set up correct tuning
    • Dry run on representative hardware is mandatory
    • Interference with the test environment should be avoided
    – EMC issues
    – Good control of imposed test levels
Planning to flight model

past

High Insolation and Temperature TDA

future

BepiColombo TDA 18 months

Characterization of critical items:
• Diodes (shunt plus blocking)
• Solar cells
• OSR’s
• Other PVA components

BepiColombo Formal PVA Qualification 20 months

Flight