Evaluation of Adhesive Materials for High-Reliability Flip-Chip Assembly

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Presentation Outline

- Objectives & Technology Overview
- Flip-Chip Adhesives Evaluation Programme
  - Materials Selection & Property Evaluation
  - Flip-Chip Test Chip
  - VFL Substrate
  - Test Vehicle Assembly / Assembly Verification
  - Reliability Evaluation
- Conclusions & Acknowledgements
Introduction - Aims & Objectives

- Evaluate reliability of commercially-available flip-chip adhesives for use in space applications.
- Study a representative range of materials.
- Determine thermomechanical properties & behaviour.
- Assess quality of assembly achievable.
- Measure thermal performance.
- Investigate ability to withstand harsh environmental stresses.

Work Undertaken by:
- Tyndall National Institute, Cork, Ireland (Prime Contractor)
- ASTRIUM, Velizy, France (VFL substrates)
Micropackaging Technology

Traditional Packaging Technologies:

- **Advantages:**
  - Well proven technologies
  - Robust & Reliable (especially ceramic & metal-can)
  - Good thermal performance (ceramic / metal)
  - Cost-effective (plastic)

- **Drawbacks:**
  - More complex than necessary
  - Electrical performance
  - Limited density
  - Size & weight
Micropackaging Technology

Comparison of Alternative Packaging Options:

<table>
<thead>
<tr>
<th>Type</th>
<th>Footprint Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>QFP:</td>
<td>900 mm² - 100%</td>
</tr>
<tr>
<td>TAB:</td>
<td>400 mm² - 44%</td>
</tr>
<tr>
<td>COB:</td>
<td>225 mm² - 25%</td>
</tr>
<tr>
<td>CSP:</td>
<td>115 mm² - 13%</td>
</tr>
<tr>
<td>Flip-Chip:</td>
<td>100 mm² - 11%</td>
</tr>
</tbody>
</table>

(Source: Hewlett Packard)
Flip-Chip Technology

Flip-Chip Packaging:

- **What?**
  - Direct attachment of the IC to a substrate

- **Why?**
  - Almost zero interconnection parasitics between chip and package
  - Possible to put chips almost edge to edge
  - High packing density of ICs
    - Standard PCB: 10% of area occupied by silicon (“packing density”)
    - Flip-chip PCB: 75% packing density
  - Very short interconnect – high speed

IC edge to edge distance using plastic packages

IC edge to edge distance using flip-chip
Flip-Chip Technology

Solder-based Flip-Chip Assembly:

- Controlled Collapse Chip Connection (C4)
- Originally developed by IBM in 1960’s.
  - Form solder bumps on chip pads
    - *Mask & deposit*
    - *Plated bumps*
  - Place chip on substrate & align accurately
  - Reflow (high temp.)
  - Underfill (increases bond area – reduces stress)

Adhesive-based Assembly:

- Chip bumps not always required
- Typical bump metalisation Ni/Au (Electroless deposition)
  - Adhesive applied to substrate (blanket or selective deposition)
  - Place & align chip
  - Cure adhesive (usually low temp. process).
Flip-Chip Assembly Technologies

Solder Flip-Chip:

- **Advantages:**
  - Very robust joints.
  - Solder wetting forces aid alignment.
  - Good thermal performance
    - heat transfer through joints.
  - Good electrical performance.
  - High density, small size & weight.

- **Disadvantages:**
  - Thermo-mechanical stresses high
    - joints unyielding.
  - Requires very well controlled process.
  - High temperature process.
  - Cost – need high density to justify.

Adhesive Flip-Chip:

- **Advantages:**
  - Compliant nature - low stresses.
  - Fine pitch capability.
  - Easy assembly process
    - low temp & no fluxes.
  - Reasonable cost.

- **Disadvantages:**
  - Poorer electrical performance
  - Reduced thermal performance
  - Long term reliability questionable
    - harsh environments ??
  - Best suited to small-area die.
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## Adhesive Flip-Chip Technology

<table>
<thead>
<tr>
<th>ACA:</th>
<th>Filler types:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need not be selectively deposited</td>
<td>- Au-coated polymer spheres</td>
</tr>
<tr>
<td>Low filler particle loading</td>
<td>- Solid metal spheres (plated)</td>
</tr>
<tr>
<td>Particles form connections when adhesive is compressed</td>
<td>- LMP Solders (Sn-Bi)</td>
</tr>
<tr>
<td>Z-axis conduction only</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICA:</th>
<th>Must be selectively deposited:</th>
</tr>
</thead>
<tbody>
<tr>
<td>High filler particle loading (typically Ag flake)</td>
<td>- Screen / stencil printing with very accurate alignment</td>
</tr>
<tr>
<td>Conductive in all directions</td>
<td>- Transfer by contact with thin film</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NCA:</th>
<th>Connection quality enhanced by surface asperities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposited on entire placement area</td>
<td></td>
</tr>
<tr>
<td>Non-conductive – no filler particles</td>
<td></td>
</tr>
<tr>
<td>Connection formed by pressure</td>
<td></td>
</tr>
<tr>
<td>Connection maintained by high shrinkage forces after cure</td>
<td></td>
</tr>
<tr>
<td>Can be used with fusible solder coatings on contact surfaces</td>
<td>- Reflow after high-temp cure</td>
</tr>
<tr>
<td></td>
<td>- Robust connection.</td>
</tr>
</tbody>
</table>
Evaluation Programme

**Phase 1:**
Materials & Technology Selection

**WP1:** - Selection of Adhesives.
- Physics-of-Failure Investigation.

**WP2:** - Test Chips Design & Fabrication.

**WP3:** - VFL Substrate Design & Manufacture.

**Phase 2:**
Manufacturing & Reliability Evaluation

**WP4:** - Assembly of Test Structures.
- Non-Destructive Evaluation.

**WP5:** - Reliability Performance Testing.
Summary of Selected Materials

Anisotropic Conductive Adhesives (ACA)

ACA 1: Loctite 3441 - Anisotropic Conductive Adhesive, Gold-coated polymer filler.
ACA 2: Loctite 3446 - Anisotropic Conductive Adhesive, Fusible Bismuth Spheres filler.
ACA 3: Bondline 2909 - Anisotropic Conductive Adhesive, Gold-coated polymer filler.
ACA 4: Creative Materials Inc. - CMI 121-23, Anisotropic Conductive Adhesive, Silver flake filler.
ACA 5: Dexter TG 9001 R1 - Anisotropic Conductive Adhesive, Gold particle filler.

Isotropic Conductive Adhesives (ICA)

ICA 1: Loctite 3880 - Isotropic Conductive Adhesive - Silver flake filler.
ICA 2: Delo ICABOND IC182 - Isotropic Conductive Adhesive - Silver flake filler (75% wt.)
ICA 3: Bondline 2920 - Isotropic Conductive Adhesive - Silver Flake filler.
ICA 4: Creative Materials Inc. - CMI 118-06-SD - Isotropic Conductive Adhesive - Silver (74% wt.).

Non-Conductive Adhesives (NCA)

NCA 1: Loctite 3565 - Non-Conductive Underfill Adhesive
NCA 2: Hysol QMI 536 Non-Conductive Adhesive, PTFE-filled.
NCA 4: Bondline 6900 - Low Viscosity Non-Conductive Underfill Adhesive
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WP1: Materials Property Evaluation

Material Properties Studied:

- Coefficient of Thermal expansion (CTE) – Thermo-mechanical Analyser (TMA)
- Glass Transition temperature \((T_g)\) – Differential Scanning Calorimeter
- Young’s Modulus \((\epsilon)\) – DMTA / Instron Tester
- Lap Shear Strength – Instron Tensile Tester

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Type</th>
<th>Measured (T_g) (°C)</th>
<th>Datasheet (T_g) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loctite 3441</td>
<td>ACA</td>
<td>146.3</td>
<td>150</td>
</tr>
<tr>
<td>Loctite 3446</td>
<td>ACA</td>
<td>151.7</td>
<td>156</td>
</tr>
<tr>
<td>Bondline 2909</td>
<td>ACA</td>
<td>117.8</td>
<td>121</td>
</tr>
<tr>
<td>CMI-121-23</td>
<td>ACA</td>
<td>107.3</td>
<td>105</td>
</tr>
<tr>
<td>Dex TG9001-R1</td>
<td>ACA</td>
<td>109.3</td>
<td>110</td>
</tr>
<tr>
<td>Loctite 3880</td>
<td>ICA</td>
<td>95.3</td>
<td>64</td>
</tr>
<tr>
<td>Delo AC-182</td>
<td>ICA</td>
<td>86.7</td>
<td>90</td>
</tr>
<tr>
<td>Bondline 2920</td>
<td>ICA</td>
<td>110.6</td>
<td>113</td>
</tr>
<tr>
<td>CMI-118-06</td>
<td>ICA</td>
<td>98.1</td>
<td>100</td>
</tr>
<tr>
<td>Loctite 3565</td>
<td>NCA</td>
<td>145.3</td>
<td>155</td>
</tr>
<tr>
<td>Hysol QMI 536</td>
<td>NCA</td>
<td>N/a</td>
<td>-31</td>
</tr>
<tr>
<td>CMI 122-24</td>
<td>NCA</td>
<td>95.3</td>
<td>127</td>
</tr>
<tr>
<td>Bondline 6900</td>
<td>NCA</td>
<td>125.4</td>
<td>Not Quoted</td>
</tr>
</tbody>
</table>

Measured Glass Transition Temp. \((T_g)\) v Datasheet Values.
WP1: Materials Property Evaluation

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Measured CTE below $T_g$ (ppm)</th>
<th>CTE above $T_g$ (ppm)</th>
<th>Datasheet Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loctite 3441</td>
<td>57.3</td>
<td>151.2</td>
<td>55</td>
</tr>
<tr>
<td>Loctite 3446</td>
<td>54.0</td>
<td>147.8</td>
<td>55</td>
</tr>
<tr>
<td>Bondline 2909</td>
<td>36.3</td>
<td>104.1</td>
<td>35</td>
</tr>
<tr>
<td>CMI-121-23</td>
<td>58.7</td>
<td>160.2</td>
<td>Not Quoted</td>
</tr>
<tr>
<td>Dex TG9001-R1</td>
<td>70.1</td>
<td>154.2</td>
<td>67</td>
</tr>
<tr>
<td>Loctite 3880</td>
<td>68.7</td>
<td>191.2</td>
<td>110</td>
</tr>
<tr>
<td>Delo AC-182</td>
<td>88.3</td>
<td>197.2</td>
<td>Not Quoted</td>
</tr>
<tr>
<td>Bondline 2920</td>
<td>76.7</td>
<td>173.2</td>
<td>79</td>
</tr>
<tr>
<td>CMI-118-06</td>
<td>28.7</td>
<td>148.2</td>
<td>17</td>
</tr>
<tr>
<td>Loctite 3565</td>
<td>28.7</td>
<td>92.4</td>
<td>25</td>
</tr>
<tr>
<td>Hysol QMI 536</td>
<td>N/a</td>
<td>190.9</td>
<td>93</td>
</tr>
<tr>
<td>CMI 122-24</td>
<td>38.2</td>
<td>160.2</td>
<td>55</td>
</tr>
<tr>
<td>Bondline 6900</td>
<td>60.5</td>
<td>120.1</td>
<td>31</td>
</tr>
</tbody>
</table>

Measured CTE Values v Datasheet Values.

**Results:**

- CTE, $T_g$ & Bond Strength show reasonable agreement with manufacturer’s values (where quoted).
- For CMI-122-24, Measured $T_g = 95.3^\circ$ (Manufacturer’s $T_g = 127^\circ$C).
- In many cases $T_g < 125^\circ$C
- Modulus values not quoted in many cases.
- Bond strengths generally high, but Loctite 3565 has quoted bond strength of 4.9 MPa.
CTB Programme

WP1: Materials Property Evaluation

ACA:

ICA:

NCA:

Blanket deposited ACA with thickness = 8.0 μm

Selectively-deposited ICA with thickness = 8.0 μm

Blanket-deposited NCA
No adhesive assumed in joints
WP1: Materials Property Evaluation

**ACA Results:**
- Acts as own underfill – large bond.
- Compliant & relieves stress.
- Stress negligible at each temp (-55°C and +125°C).
- Unlikely to fail due to stress
- Conduction may be disrupted by movement – 3 μm possible.

**ICA Results:**
- Smaller bond area.
- Also compliant.
- Stresses higher than ACA, but still low overall.
- Unlikely to fail due to stress
- High filler density – less affected by movement.

**NCA Results:**
- No adhesive in joint area.
- Compliant.
- Slightly higher stresses than ACA.
- One material could fail due to stress > bond strength (Loctite 3565).
WP1: Materials Property Evaluation

Conclusions – Materials Property Evaluation:

- Greatest choice of adhesives for flip-chip assembly were in the ACA category.
- Measurement of CTE for all of the selected materials showed good agreement with manufacturers values (where quoted).
- Measurements of $T_g$ for the adhesives also agreed closely with the manufacturers figures (except one NCA - CMI-122-24 where $T_g = 95.3^\circ$C (CMI $T_g = 127^\circ$C).
- $T_g$ in many cases is lower than the target $125^\circ$C upper operating temperature.
- Modulus information not quoted for many adhesives.
- Expected stresses in all materials are low due to their compliant / soft nature.
- ACA may be prone to movement of up to 3.0 $\mu$m leading to a risk of open circuits.
- ICA also prone to risk of movement, but open circuits less likely due to filler density.
- Highest risk of stress failure is with NCA material (L 3565) at $125^\circ$C where model predicts Von Mises stress of 3.9 MPa. Loctite 3565 has quoted bond strength of 4.9 MPa.
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WP2: Flip-Chip Test Chip

Test Chip Details:

- 1 Polysilicon Heater Resistor.
- 6 Temp-Sensing Diodes.
- 1 Triple-track Corrosion Monitor.
- 14 Peripheral Daisy Chains.
- 1 Pad Array (23 X 23).
- Basic unit size = 5 mm X 5mm.
- Designed to allowed multi-unit die.
  - 10 mm X 10 mm.
  - 15 mm X 15 mm.
WP3: VFL Substrate

Substrate Details:

- Very Fine Line (VFL).
- High-reliability substrate.
- Ceramic material.
- Thick film technology.
- Single interconnect layer.
- 3 chip sizes per substrate.
  - 5 mm X 5 mm.
  - 10 mm X 10 mm.
  - 15 mm X 15 mm.
- 50.0 mm X 50.0 mm.
- 50 μm track & gap.
- Edge connector.
- 180 i/o pads.
WP3: VFL Substrate

Substrate Verification:

- **Electrical continuity**
  - *Flying probe tester* (Astrium)
- **Optical & SEM Inspection** (NMRC)
  - *Dimensions & pitch etc. correct*
  - *Metalisation quality / composition*
- **Metal tape adhesion test**
- **80 manufactured / 60 required**

**Single Chip Site**
- 2 daisy chains per chip
- Continuity & isolation measurements.
- 2 inputs, 2 outputs & 2 intermediate.
- 1 set of heater & diode connections

**3 X 3 Chip Site (15 mm X 15 mm)**
- 2 daisy chains per single chip.
- Continuity & isolation measurements across full area of 15 mm X 15 mm chip.
- 2 inputs, 2 outputs & 11 intermediate connections in total.
- Only 2 intermediate connections for dice 4,5,6.
- 6 sets of heater & diode connections
WP4: Test Vehicle Assembly

Process Flow:

1. Dispense Adhesive on Substrate
   - Dispense pressure
   - Volume / thickness

2. Align Chip and Substrate
   - X, Y, θ

3. Place in Contact
   - Light Pressure

4. Apply Pressure
   - Load per bond

5. Cure at elevated Temperature
   - Temperature
   - Curing time / profile

Finetech Aligner / Bonder Diagram (FINETECH Electronic GmbH)
WP4: Test Vehicle Assembly

- Tyndall Fineplacer 145 PICO Flip-Chip Bonder.
- Manual Alignment.
- Small Volume Lab System.
- Semi-automatic.
- Prototyping Quantities.

ACA Flip-Chip Bonds
**WP4: Test Vehicle Assembly**

**Optimised Process Conditions:**

<table>
<thead>
<tr>
<th>Bondline 2909 ACA:</th>
<th>Loctite 3565 NCA:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recommended cure:</strong></td>
<td><strong>Recommended cure:</strong></td>
</tr>
<tr>
<td>175°C, 30 sec, 35 MPa.</td>
<td>150°C, &gt; 60 min</td>
</tr>
<tr>
<td><strong>Optimised cure:</strong></td>
<td><strong>Optimised cure:</strong></td>
</tr>
<tr>
<td>140°C, 30 sec, 160°C, 5 sec</td>
<td>150°C, 60 min</td>
</tr>
<tr>
<td>Load = 40 Mpa.</td>
<td>Load = 50 MPa</td>
</tr>
<tr>
<td>→ Thickness = 7.0 μm.</td>
<td>→ Thickness ~ 28.0 μm (between joint</td>
</tr>
<tr>
<td>(approx)</td>
<td>areas)</td>
</tr>
<tr>
<td><strong>Bond Strength:</strong></td>
<td><strong>Bond Strength:</strong></td>
</tr>
<tr>
<td>&gt; 5 Kg shear for 5x5 die</td>
<td>&gt; 5 Kg shear for 5X5 die</td>
</tr>
<tr>
<td>(non destructive test)</td>
<td>(non destructive test)</td>
</tr>
<tr>
<td><strong>Joint Resistance:</strong></td>
<td><strong>Joint Resistance:</strong></td>
</tr>
<tr>
<td>4.0 to 9.0 Ω (mean).</td>
<td>10.0 Ω</td>
</tr>
</tbody>
</table>
WP4: Test Vehicle Assembly

Verification Procedure:

- High Mag. Inspection.
- X-Ray Inspection.
- SAM Inspection.
- Electrical Check.
- Bond Test (5Kg Shear).
- Thermal Resistance.
- Bond Shear Test (Destructive).
- Microsection (Destructive).

Main Problems / Issues:

- Misalignment.
- Excess Adhesive.
- Inadequate Pressure.
- Substrate Flatness.

Open Circuits

Hybrids, MCM, Interconnection & Micropackaging WG – 27th Apr. ‘05
CTB Programme

WP4: Test Vehicle Assembly

Assembly Verification:

- Good Edge Fillet - ACA
- Good ACA Joint
- Good ACA Joint
- NCA – Well Aligned
- Good NCA Joint
- Good NCA Joint
## WP4: Test Vehicle Assembly

### Summary of Thermal Evaluation:

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Quoted Conductivity (W/m°C)</th>
<th>Measured Conductivity (W/m°C)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICA Materials</td>
<td>2.00 – 3.20</td>
<td>2.57</td>
<td>High Ag content but selective deposition</td>
</tr>
<tr>
<td>ACA Materials</td>
<td>0.70 - 1.20</td>
<td>1.05</td>
<td>Blanket deposition helps conductivity result</td>
</tr>
<tr>
<td>NCA Materials</td>
<td>0.02 - 0.03</td>
<td>0.92 (good)</td>
<td>Good bump-to-substrate contact helps result</td>
</tr>
</tbody>
</table>

![Diagram of Dual Cold Plate System]

Water Cooled Cold Plate

Insulator

Recirculating Water

Water Cooled Cold Plate

Baseplate

Topplate

Dual Cold Plate System
WP4: Test Vehicle Assembly

Electrical Evaluation:

ACA – Loctite 3446:
- Mean Chain Resistance = 127.58 Ω
- Standard Deviation = 51.54 Ω
- No of Opens Chains = 2 / 22
- Smallest no. of opens.
- High resistance chains.

ICA – CMI-118-06:
- Mean Chain Resistance = 22.92 Ω
- Standard Deviation = 13.66 Ω
- No of Opens Chains = 3 / 22
- Best overall results.
- Small no. of opens.
- Low resistance joints.

NCA – Bondline 6900:
- Mean Chain Resistance = 31.04 Ω
- Standard Deviation = 42.13 Ω
- No of Opens Chains = 13 / 22
- Worst overall results.
- Large no. of opens.
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WP5: Reliability Evaluation

**Test Sample Assembly**
(5 Samples - Each Material)

**Initial Characterisation**
- Visual Inspection
- Electrical test
- Thermal Resistance
- Radiographic Inspection
- SAM Inspection

**Control Samples**
1 per material

**Monitored Thermal Cycling**
(5 X 100 cycles – 55°C/+125°C)

**Assessment Tests**
- External Visual (each 100c)
- Thermal Res. (200 & 500)
- X-ray (200 & 500 cycles)
- SAM (200 & 500 cycles)

**THB Test**
(1,000 hrs / 85°C / 85% RH)

**Assessment (168, 500, 1,000 h)**
- Electrical Test
- External Visual
- Thermal Resistance
- X-ray & SAM

**Analysis of Failures (WP5)**
DPA of 1 sample of each
DPA of any failures

Hybrids, MCM, Interconnection & Micropackaging WG – 27th Apr. ‘05
WP5: Reliability Evaluation

Monitored Thermal Cycling Test:
- Mil-Std-883E, Method 1010.7
- Upper Temp: +125°C
- Lower Temp: -55°C
- Dwell: 15 Min
- No. of Cycles: 500
- Tests at 100, 200 & 500 cycles.

Temp / Humidity / Bias Test:
- JESD A-101 B
- Temperature: +85°C
- Humidity: 85% RH
- Bias: -10V / Gnd /+10V
- Duration: 1,000 hours
- Interim Tests at 168, 500 & 1,000 hrs.

Interim Test Sequence:
- Electrical Check
- Visual Inspection
- X-ray Inspection
- SAM Inspection
- Thermal Resistance
WP5: Reliability Evaluation

Monitored Thermal Cycling Test (Daisy Chain Resistance):

Start 100 Cycles 200 Cycles 500 Cycles

A C A

I C A

N C A

Hybrids, MCM, Interconnection & Micropackaging WG – 27th Apr. ‘05
Monitored Thermal Cycling Test:

- Significant Electrical Failure Rate from all three adhesive families.
- Significant early failure trend with ACAs.
- More gradual trend with ICA materials.
- Dramatic early failure rate with NCAs.
- Thermal performance also deteriorates.
- Failures due mainly to thermo-mechanical expansion, movement, delamination & softening (Tg).
WP5: Reliability Evaluation

Temperature / Humidity / Bias Test (Corrosion Track Resistance):

Start 168 hours 500 hours 1,000 hours

![Histograms showing corrosion monitor track resistance over time](image)
**WP5: Reliability Evaluation**

**Temperature / Humidity / Bias Test:**

- Significant Electrical Failure Rate from all three adhesive families.
- Least no. open circuits from ICAs.
- Worst open circuit performance from NCAs.
- Highest leakage current in ICA case (Ag).
- Lowest leakage current in NCA case (no filler).
- Open circuit failures due mainly to corrosion.
- High leakage currents due to dendrites, & ionic content of materials.
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Conclusions 1

- Adhesive do not meet demands of harsh-environment stress tests.

- Tg is much lower than +125°C in many cases:
  - Poor thermomechanical behaviour.
  - Materials soften at elevated temperatures.
  - Movements & open circuits occur.

- Adhesive flip-chip best suited to small-area dice:
  - More difficult to control deposition quality over a large area
  - Substrate roughness an issue

- Selectively-Deposited ICA materials probably best overall:
  - Best electrical & thermal properties.
  - Selective deposition – lower risk of shorts
  - Did show higher leakage currents in THB tests (migration / dendrite growth).
Conclusions 2

- Performance in Temperature Cycling Test Poor
  - *Large no. of open circuits caused.*
  - *Thermomechanical movement.*

- Corrosion failures occurred in THB test:
  - *Adhesives absorb moisture.*
  - *Non-hermetic protection.*
  - *Adhesives contain ionic elements.*
  - *High leakage currents, especially with ICAs.*

- Adhesives best suited to small area die used in benign environments.

- Not suited to the demands of the space environment!!
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