MODULE AND RELIABILITY TECHNOLOGY

N 8 7 - 1 6 4 3 1

MODULE ENCAPSULATION TECHNOLOGY

SPRINGBORN LABORATORIES

P. Willis

Phase I

IDENTIFY AND DEVELOP LOW COST
MODULE ENCAPSULATION MATERIALS

- POTTANTS
- COVER FILMS
- SUBSTRATES
- ADHESIVES/PRIMERS
- ANTI-SOILING TREATMENTS

Phase II

TASK 1: MATERIALS RELIABILITY
- AGING AND LIFE ASSESSMENT
- ADVANCED STABILIZERS
- ADHESIVE BOND DURABILITY
- HUMIDITY SENSITIVITY
- ELECTRICAL ISOLATION

TASK 2: PROCESS SENSITIVITY
- INTERRELATIONSHIPS OF
  - FORMULATION VARIABLES
  - PROCESS VARIABLES
- IDENTIFY FAILURE MODES
- INDUSTRIAL GUIDEANCE
MODULE AND RELIABILITY TECHNOLOGY

Module Components

[Diagram showing module components: Surface, Outer Cover (or Glass), Pottant, Back Cover (or Substrate), Gasket/Sealant]

CURRENT EMPHASIS ON MATERIALS AND MODULE PERFORMANCE CHARACTERISTICS

- Determine current level of performance
- Enhance performance (e.g., reformulation)
- Service life prognosis

PERFORMANCE CRITERIA

- Environmental degradation
- Maximum service temperature
- Adhesive bond durability
- Electrical insulation durability
- Hydrolytic (water) stability
- What are dominant types of failure?
- Where is stabilization needed?
MODULE AND RELIABILITY TECHNOLOGY

Accelerated Aging Test Program

CONDITIONS USED INITIALLY

<table>
<thead>
<tr>
<th>METHOD</th>
<th>DEFICIENCIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>THERMAL (AIR OVEN)</td>
<td>UNNATURAL LIGHT</td>
</tr>
<tr>
<td>RS/4 50°C</td>
<td>NO &quot; WEATHER &quot;</td>
</tr>
<tr>
<td>RS/4 WET SPRAY</td>
<td>NO PREDICTIVE METHODS</td>
</tr>
<tr>
<td>RS/4 85°C</td>
<td>LONG EXPOSURE TIMES</td>
</tr>
</tbody>
</table>

OUTDOOR PHOTOTHERMAL AGING REACTORS (OPTAR)

- USE NATURAL SUNLIGHT, AVOIDS SPECTRAL DISTRIBUTION PROBLEMS WITH ARTIFICIAL LIGHT SOURCES
- USE TEMPERATURE TO ACCELERATE THE PHOTOTHERMAL REACTION
- INCLUDES DARK CYCLE REACTIONS
- INCLUDES DEW / RAIN EXTRACTION
- INTENDED PRIMARILY FOR MODULE EXPOSURE
- EXTRAPOLATE EFFECTS TO LOWER TEMPERATURES
Accelerated Aging

- **Useful for evaluating candidate formulations - comparison**
- **Whole modules under exposure**
- **Determine upper level service temperatures**
- **Modelling:**
  - Time to onset of degradation
    (induction period, \( t_i \))
    Example: Polypropylene
  - Arrhenius: \( \log t_i \) vs. \( 1/T \)
  - Predict service life by extrapolation to lower temperatures

**Time, Hours**

```
<table>
<thead>
<tr>
<th>200</th>
<th>500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```
Outdoor Photothermal Aging Reactors (OPTAR), Enfield, Connecticut (70, 90, and 105°C)
MODULE AND RELIABILITY TECHNOLOGY

OPTAR/70°C, 20,000 Hours

- SOME COPPER REACTION W/ EVA 9918
- NO OTHER EFFECTS NOTICEABLE

EVA 9918  EVA 16718  EMA 16717  EVA 14747

STANDARD
FAST CURE
CONTROL

TBEC UV2018 T770  TBEC UV2018 T770  LURAN UV3000 T770

70°C
20,000 Hr

ORIGINAL PAGE IS OF POOR QUALITY.
MODULE AND RELIABILITY TECHNOLOGY

OPTAR/90°C, 20,000 Hours

- COPPER REACTION IN LUPERSOL-101 RESINS
- OVERALL CONDITION: VERY GOOD

<table>
<thead>
<tr>
<th>EVA 9918</th>
<th>EVA 16718</th>
<th>EMA 16717</th>
<th>EVA 14747</th>
</tr>
</thead>
<tbody>
<tr>
<td>STANDARD</td>
<td>FAST CURE</td>
<td>LUP-101</td>
<td>UV2018 T770</td>
</tr>
<tr>
<td>TBEC</td>
<td>TBEC UV2018 T770</td>
<td>LUP-101 UV2018 T770</td>
<td></td>
</tr>
</tbody>
</table>

20,000 Hr

90°C
Module and Reliability Technology

OPTAR/105°C, 20,000 Hours

- All show severe copper reaction
- Best performance: EVA-ADVANCED STABILIZER TBEC, UV-2098, TINUVIN 770

EVA 9918    EVA 16718    EMA 16717    EVA 14747

Original page is of poor quality
MODULE AND RELIABILITY TECHNOLOGY

Accelerated Aging: Summary of Investigations

- OPTARS MOST EFFICIENT AGING TECHNIQUE
- MODULES HAVE VERY HIGH ENDURANCE
  NO EFFECT: 20,000 HRS - 70°C / SUNLIGHT
- DEGRADED MODULES SHOW NO POWER LOSS
- EVA 9918 (STANDARD FORMULA) PERFORMS VERY WELL
- OPTIMIZED EVA FORMULATION:
  LUPERSOL TBEC CURING AGENT
  CYASORB UV-2098 UV SCREENER
  TINUVIN 770 STABILIZER
- RADIOMETER INSTALLED ON OPTAR DEVICES - POSSIBILITY
  FOR MODELING BASED ON HEAT PLUS LIGHT ??
MODULE AND RELIABILITY TECHNOLOGY

Adhesion Experiments

STATUS:

- PRIMER FORMULATIONS IDENTIFIED FOR ALMOST ALL INTERFACES IN MODULES
- POLYMER / METAL
- POLYMER / INORGANIC
- POLYMER / ORGANIC

DR. PLUEDDEMMANN - DOW CORNING
DR. JIM BOERIO - UNIVERSITY OF CINCINNATI

- SELF-PRIMING FORMULATIONS OF EVA (TO GLASS, CELLS) DEVELOPED: AVAILABLE - SPRINGDORN
- NEW PRIMER AVAILABLE - DOW CORNING WITH IMPROVED PROPERTIES - UNDER TEST

Adhesion Diagnostics

- NEW METHOD DEVELOPED
- EVA COMPOUNDED WITH HIGH LOADINGS OF SILANE TREATED GLASS BEADS - RESEMBLES GLASS REINFORCED POLYMER
- EQUILIBRIUM WATER ABSORPTION VALUES MAY PROVIDE NEW METHOD OF EVALUATING ADHESIVE BONDS - INDICATES "DAMAGE" TO BONDS AT THE INTERFACE IS REVERSIBLE UP TO A LIMIT
- DETERMINE DEGRADATION RATES (KINETICS)
- ASSESS SERVICE LIFE
- GENERAL CONCLUSION - BOND DURABILITY - EXCELLENT
MODULE AND RELIABILITY TECHNOLOGY

Electrical Isolation

- POTENTIALS AND COVER FILMS SERVE AS ELECTRICAL INSULATION
- NEED TO KNOW THICKNESS REQUIRED FOR VOLTAGE STANDOFF
- VARIATION WITH TEMPERATURE, ABSORBED WATER?
- NEED TO KNOW VARIATION DIELECTRIC STRENGTH WITH AGING: LIGHT, HEAT, HUMIDITY, FIELD STRESS

METHOD:
- HV-DC POWER SUPPLY, SYMMETRIC ELECTRODES
- SPECIFIED RATE OF RISE (500 V/SEC)
- PLOT AVERAGE BREAKDOWN VOLTAGE, Vₐ VS THICKNESS
- STRAIGHT LINE RELATIONSHIP: SLOPE EQUALS "INTRINSIC DIELECTRIC STRENGTH" / DC
- MEASUREMENTS TO DATE:
  EVA 9918, dv/dt = 3.48 kv/MIL

RESULTS TO DATE: EVA 9918

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RS/4 (50°C)</td>
<td>4,000 HR</td>
<td>3.24 kv/MIL</td>
<td>93%</td>
<td></td>
</tr>
<tr>
<td>RS/4 (85°C)</td>
<td>4,000 HR</td>
<td>1.98 kv/MIL</td>
<td>57%</td>
<td></td>
</tr>
<tr>
<td>RS/4 WET</td>
<td>4,000 HR</td>
<td>4.12 kv/MIL</td>
<td>118%</td>
<td></td>
</tr>
<tr>
<td>OPTAR 70°C</td>
<td>2,000 HR</td>
<td>2.85 kv/MIL</td>
<td>82%</td>
<td></td>
</tr>
<tr>
<td>OPTAR 90°C</td>
<td>2,000 HR</td>
<td>3.14 kv/MIL</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>OPTAR 105°C</td>
<td>2,000 HR</td>
<td>- - UNTESTABLE - -</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- NEW SPECIMEN GEOMETRY NEEDED - NOW UNDER TEST
- SOME EVIDENCE FOR DECREASE IN DIELECTRIC STRENGTH WITH ACCELERATED AGING
- INCREASE IN STRENGTH WITH WATER EXPOSURE

535
Hydrolytic Stability

- CANDIDATE POTENTIAL - WATER IMMERSION AT 40°, 60°, 70°, 80° A & 90°
- MEASURE CHANGE IN WEIGHT VERSUS TIME

<table>
<thead>
<tr>
<th></th>
<th>70°</th>
<th>80°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA</td>
<td>?</td>
<td>21,000</td>
<td>14,000</td>
</tr>
<tr>
<td>EMA</td>
<td>?</td>
<td>15,000</td>
<td>9,800</td>
</tr>
<tr>
<td>PU</td>
<td></td>
<td>CONTINUAL</td>
<td></td>
</tr>
</tbody>
</table>

- EVA VERY HYDROLYTICALLY STABLE
- DATA WILL BE USED FOR KINETICS
Anti-Soiling Treatments

SURFACE CHEMISTRY:
- HARD
- SMOOTH
- HYDROPHOBIC
- OLEOPHOBIC
- ION FREE
- LOW SURFACE ENERGY

SURFACE INVESTIGATED:
- SUNADEX GLASS
- TEDLAR (100 BG 30 UT)
- ACRYLAR (ACRYLIC FLIM)

MOST EFFECTIVE TREATMENT:
- E-3820 PERFLUORODECANOIC ACID/
  SILANE (DOW CORNING)
- STILL EFFECTIVE AT 56 MONTHS
  OUTDOOR EXPOSURE
- RESULTS IN IMPROVED POWER OUTPUT
  OF 1% TO 4% - DEPENDING ON SURFACE
- FLUOROALKYL SILANE CHEMISTRY
  APPEARS TO BE MOST EFFECTIVE

NEW TREATMENTS:
- TWO NEW CANDIDATES FROM DOW CORNING
  STARTED
Soiling Experiments

FIFTY-SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

% LOSS IN $I_{sc}$ WITH STANDARD CELL TREATED
SUNDEX GLASS

56 MONTHS EXPOSURE

CONTROL, NO TREATMENT
- - - - - E3820
- ESTIMATED AVERAGE POWER IMPROVEMENT, 1%
Soiling Experiments (Cont'd)

FIFTY-SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

LOSS IN $I_{sc}$ WITH STANDARD CELL TREATED
TEDLAR 100BG500UT
(SUPPORT ON GLASS)

56 MONTHS EXPOSURE

---

CONTROL, NO TREATMENT
--- E3820

ESTIMATED AVERAGE POWER IMPROVEMENT, 3.8%
Soiling Experiments (Cont’d)

FIFTY-SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

% LOSS IN $I_{sc}$ WITH STANDARD CELL TREATED ACRYLAR
(SUPPORTED ON GLASS)

56 MONTHS EXPOSURE

---

CONTROL, NO TREATMENT
--- OZONE + E3820

ESTIMATED AVERAGE POWER IMPROVEMENT, 3.9%
MODULE AND RELIABILITY TECHNOLOGY

Process Sensitivity

GOALS:
- Understand relationships between all manufacturing variables
- Define failure / acceptability criteria
- Statistical analysis of results
- Define optimum conditions
- Predict manufacturing yield
- Provide documentation to industry

VARIABLES

FORMULATION:
- Potting composition
- Curing agents
- Primers
- Storage conditions

PROCESSING:
- Vacuum pressure
- Temperature, ultimate, °C
- Temperature, rate of rise, °C/min.
- Dwell times
- Rate of cooling
## Testing and Performance Criteria

**METHOD:**
- Prepare test modules and/or other test specimens with change in significant variable(s)
- Developed standard test specimen
- Developed standard test protocol
- Collected uniform data sets
- Quantitate the effects

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CRITERION</th>
<th>TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>POTTANT</td>
<td>Adequate Cure</td>
<td>Percent Gel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Thermal Creep</td>
</tr>
<tr>
<td></td>
<td>Trapped Bubbles</td>
<td>Visual</td>
</tr>
<tr>
<td></td>
<td>Discoloration</td>
<td>Visual</td>
</tr>
<tr>
<td>CELLS</td>
<td>Breakage</td>
<td>Visual, Resistance</td>
</tr>
<tr>
<td></td>
<td>Interconnect</td>
<td>Resistance</td>
</tr>
<tr>
<td></td>
<td>Registration</td>
<td>Visual</td>
</tr>
<tr>
<td>COVER FILMS</td>
<td>Tears/Punctures</td>
<td>Visual</td>
</tr>
<tr>
<td></td>
<td>Warping/Shrinkage</td>
<td>Visual</td>
</tr>
<tr>
<td>GLASS (SUPERSTRATE)</td>
<td>Fracture</td>
<td>Visual</td>
</tr>
<tr>
<td>ADHESION</td>
<td>Bond Strength</td>
<td>Peel Test</td>
</tr>
<tr>
<td></td>
<td>Endurance</td>
<td>Water Soak (50°C)</td>
</tr>
</tbody>
</table>
PROCESS PROFILE

- MICROPROCESSOR CONTROLLED EXPERIMENTAL LAMINATOR CONSTRUCTED
- STUDIES STARTED ON PROCESSING PROFILES
  - RATE OF HEATING (HOW SLOW, HOW FAST?)
  - VACUUM TIMING
  - RATE OF COOLING
Process Sensitivity: Observations and Recommendations

FORMULATION VARIABLES

- EVA FORMULATIONS RELATIVELY INSENSITIVE TO QUANTITY OF PEROXIDE BUT VERY SENSITIVE TO AIR EXPOSURE - EVAPORATION
- EVA WITH LUPERSOL - TBEC MUCH LESS SENSITIVE
- UNWRAP / CUT EVA JUST BEFORE MODULE MANUFACTURING - LIMIT AIR EXPOSURE
- SELF-PRIMING GRADE WORKS WELL

PROCESS VARIABLES

- UPPER AND LOWER LIMITS DETERMINED:
  - ULTIMATE TEMPERATURE
  - RATE OF RISE - TEMPERATURE
  - BACKPRESSURE TIMING
- DOMINANT FAILURE : ADHESION (POTTANT / GLASS)
  - BOUNDS THE NARROWEST PROCESSING " WINDOW "
- EVA WITH LUPERSOL-TBEC HAS WIDER WINDOW THAN EVA 9918
  - STORAGE : MORE STABLE TO EXPOSURE
  - PROCESSING : WIDER RANGE OF CONDITIONS
- INDUSTRIAL * TROUBLE SHOOTING GUIDE * PREPARED
MODULE AND RELIABILITY TECHNOLOGY

Thin-Film Encapsulation

(AMORPHOUS PHOTOVOLTAICS)

TYPES:
- SUPERSTRATE - ON GLASS
- SUBSTRATE - ON STAINLESS STEEL

FAILURE MECHANISMS:
- CORROSION, BREAKAGE (GLASS), ABRASION,
- ELECTRICAL SHORTING, OTHERS ???

Encapsulation Requirements (Anticipated)

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>PROPERTY</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTER COVER</td>
<td>• INHERENTLY WEATHERABLE</td>
</tr>
<tr>
<td></td>
<td>• ABRASION / CUT RESISTANT</td>
</tr>
<tr>
<td>BACK COVER</td>
<td>• WHITE (EMISSIVE)</td>
</tr>
<tr>
<td></td>
<td>• WEATHER RESISTANT</td>
</tr>
<tr>
<td>POTTANT</td>
<td>• PROCESSABLE &lt;100°C</td>
</tr>
<tr>
<td></td>
<td>• CURABLE - CREEP RESISTANT</td>
</tr>
<tr>
<td></td>
<td>• LOW WATER ABSORPTION</td>
</tr>
<tr>
<td></td>
<td>• HIGH OPTICAL TRANSMISSION</td>
</tr>
<tr>
<td>DURABLE BONDING</td>
<td>• ALL INTERFACES</td>
</tr>
<tr>
<td></td>
<td>• LONG SERVICE LIFE</td>
</tr>
<tr>
<td></td>
<td>• LOW COST</td>
</tr>
</tbody>
</table>

Manufacture/Process

- FAST
- AUTOMATABLE
- INEXPENSIVE
Thin-Film Encapsulation: Candidate Materials and Processes

BACK COVERS
- WHITE TEDLAR

OUTER COVERS
- FLUOROPOLYMERS BEST CHOICE
- FEP CURRENTLY FAVORED DUE TO HIGH TRANSPARENCY AND OUTSTANDING WEATHERABILITY

<table>
<thead>
<tr>
<th>FILM</th>
<th>REF. INDEX</th>
<th>% T</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEP</td>
<td>1.34</td>
<td>93.6</td>
<td>0.10</td>
</tr>
</tbody>
</table>

POTTANTS:
CONDUCTING INVESTIGATIONS

<table>
<thead>
<tr>
<th>MATERIAL CLASS</th>
<th>MANUFACTURER</th>
<th>$/LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETHYLENE/VINYL ACETATE</td>
<td>DU PONT, USI</td>
<td>.60 - .80</td>
</tr>
<tr>
<td>ETHYLENE/ACRYLIC</td>
<td>DOW, GULF</td>
<td>.80 - 1.00</td>
</tr>
<tr>
<td>IONOMER</td>
<td>DU PONT</td>
<td>.05 - 1.60</td>
</tr>
<tr>
<td>ALIPHATIC URETHANE</td>
<td>UPJOHN</td>
<td>.9 - 2.50</td>
</tr>
<tr>
<td>HOT MELT ADHESIVES</td>
<td>MANY</td>
<td>.80 - 2.50</td>
</tr>
<tr>
<td>HYDROCARBON, POLYAMIDE, POLYETHER, ACRYLIC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CURE METHOD:
- MOISTURE CURE (MODIFIED CHEMISTRY)
- PEROXIDE DECOMPOSITION (HEAT)
- UV CURE (PHOTOINITIATION)

- MOISTURE CURABLE SELF-PRIMING POTTANT UNDER DEVELOPMENT. SILANE / ACRYLIC CHEMISTRY

ENCAPSULATION METHOD:
- FILM LAMINATION: EXTRUDE THE POTTANT ON AN OUTER COVER FILM AS A CARRIER, USE COMBINATION FOR LAMINATION.
Conclusions

ACCELERATED AGING:
- OPTAR® METHOD BEST AGING TECHNIQUE DISCOVERED SO ARE
- MODELING / LIFE PREDICTION ENCOURAGING
- 70° & 90°C VERY GOOD CONDITION
- COPPER REACTIONS NOT AS SEVERE AS ANTICIPATED - EXCEPT AT 105°C
- LUPEPSOL - TBEC CURED FORMULATIONS APPEAR MORE STABLE
- BEST STABILIZERS: UV-2098 SCREENER, TINUVIN 770 ( BOTH CYANAMIDE )
- MODULE PERFORMANCE - EXCELLENT ( OPTAR 90°C - 20,000 HR - NO CHANGE )

ADHESION:
- NEW TEST METHOD FOR PRIMER EVALUATION AND BOND DURABILITY
- CAN DEMONSTRATE BOND RECOVERY & LIMIT OF REVERSIBILITY
- SELF-PRIMING EVA WORKS WELL

ELECTRICAL ISOLATION:
- INTRINSIC DIELECTRIC TEST METHOD DEVELOPED
- SOME EVIDENCE OF DECREASE IN DIELECTRIC STRENGTH WITH ACCELERATED AGING
Conclusions (Cont’d)

HYDROLYTIC STABILITY:
- EVA APPEARS EXCELLENT

PROCESS SENSITIVITY:
- DOMINANT PROCESS FAILURE MODE: ADHESION
- EVA STORAGE ESSENTIAL
- LUPERSOL TBEC FORMULATIONS - WIDER PROCESS LATITUDE, BETTER STORAGE STABILITY

SOILING:
- TREATMENTS STILL EFFECTIVE AFTER 56 MONTHS

THIN-FILM PV:
- CANDIDATES BEING SELECTED / DEVELOPED