MODULE AND RELIABILITY TECHNOLOGY

MODULE ENCAPSULATION TECHNOLOGY

SPRINGBORNE 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 A

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>
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</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. $1/\theta$
  - PREDICT SERVICE LIFE BY EXTRAPOLATION TO LOWER TEMPERATURES

TIME, HOURS

<table>
<thead>
<tr>
<th>TIME, HOURS</th>
<th>200</th>
<th>500</th>
<th>2000</th>
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<tbody>
<tr>
<td>VI (%) SHOWN AS DEGREES CELSIUS</td>
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<tr>
<td>110</td>
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<td>90</td>
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<td>50</td>
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<tr>
<td>20</td>
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</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 16716  EMA 16717  EVA 14747
STANDARD  FAST CURE
CONTROL    TBE C UV2098 T770  TBE C UV2098 T770  LORAM UV3000 T770

Original page is of poor quality.
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></td>
<td></td>
</tr>
<tr>
<td>TBEC UV2018 T770</td>
<td>TBEC UV2018 T770</td>
<td>LUP-101 UV2018 T770</td>
<td></td>
</tr>
</tbody>
</table>

- 90°C 20,000 Hr

ORIGINAL PAGE IS OF POOR QUALITY
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

Standard Control  TBEC UV2098 T770  TBEC UV2098 T770  LUR-101 UV2098 T770

Original page is of poor quality
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???
Adhesion Experiments

STATUS:

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

DR. PLUEDDEMMAN - 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
Electrical Isolation

- POTTANTS 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, V_A 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 A9918

<table>
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<tr>
<th>Specimen</th>
<th>HR</th>
<th>kV/MIL</th>
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<tr>
<td>RS/4 (50°C)</td>
<td>4,000</td>
<td>3.24</td>
</tr>
<tr>
<td>RS/4 (85°C)</td>
<td>4,000</td>
<td>1.98</td>
</tr>
<tr>
<td>RS/4 WET</td>
<td>4,000</td>
<td>4.12</td>
</tr>
<tr>
<td>OPTAR 70°C</td>
<td>2,000</td>
<td>2.85</td>
</tr>
<tr>
<td>OPTAR 90°C</td>
<td>2,000</td>
<td>3.14</td>
</tr>
<tr>
<td>OPTAR 105°C</td>
<td>2,000</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
Hydrolytic Stability

- CANDIDATE POTTANTS - WATER IMMERSION AT 40°, 60°, 70°, 80°, AND 90°
- MEASURE CHANGE IN WEIGHT VERSUS TIME

**Graph:**
- **Temperature, 80°C**
- **Immersion Hours**
- **Time to Onset of Change, Hours**

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

- EVA VERY HYDROLYTICALLY STABLE
- DATA WILL BE USED FOR KINETICS
ANTI-SOILING TREATMENTS

SURFACE CHEMISTRY:
- HARD
- SMOOTH
- HYDROPHOBIC
- OLEPHOBIC
- 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

ESTIMATED AVERAGE POWER IMPROVEMENT,

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Soiling Experiments (Cont’d)

FIFTY-SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

LOSS IN $I_{SC}$ WITH STANDARD CELL TREATED
TEDLAR 100B6300UT
(SUPPORT ON GLASS)

56 MONTHS EXPOSURE

---

CONTROL, NO TREATMENT
--- E3820

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

FIFTY-SIX MONTHS EXPOSURE
ENNFIELD, CONNECTICUT

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

56 MONTHS EXPOSURE

---

CONTROL, NO TREATMENT

OZONE + E3020

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:
- Potant composition
- Curing agents
- Primers
- Storage conditions

PROCESSING:
- Vacuum pressure
- Temperature, ultimate, °C
- Temperature, rate of rise, °C / min.
- Dwell times
- Rate of cooling
MODULE AND RELIABILITY TECHNOLOGY

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>
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<tbody>
<tr>
<td>POTENT</td>
<td>ADEQUATE CURE</td>
<td>PERCENT GEL, 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>
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</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
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>
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<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>
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Manufacture/Process

- FAST
- AUTOMATABLE
- INEXPENSIVE
MODULE AND RELIABILITY TECHNOLOGY

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>$/FT2/MIL</th>
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</thead>
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<tr>
<td>FEP</td>
<td>1.34</td>
<td>93.6</td>
<td>0.10</td>
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</tbody>
</table>

POTTANTS: CONDUCTING INVESTIGATIONS

<table>
<thead>
<tr>
<th>MATERIAL CLASS</th>
<th>MANUFACTURER</th>
<th>$/LB</th>
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<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>.08 - 1.60</td>
</tr>
<tr>
<td>ALIPHATIC URETHANE</td>
<td>UPJOHN</td>
<td>.3 - 2.50</td>
</tr>
<tr>
<td>HOT MELT ADHESIVES (HYDROCARBON, POLYAMIDE, POLYETHER, ACRYLIC)</td>
<td>MANY</td>
<td>.80 - 2.50</td>
</tr>
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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.

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Conclusions

ACCELERATED AGING:

- OPTAR® METHOD BEST AGING TECHNIQUE DISCOVERED SO ARE
- MODELING / LIFE PREDICTION ENCOURAGING
- 70°C & 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, TINOVIN 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