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

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?

526
### 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

![Graph showing time in hours on the x-axis and temperature in degrees centigrade on the y-axis with data points and lines indicating the relationship between the two.](attachment:accelerated_aging_graph.png)
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 UV2048 T770  TBEC UV2048 T770  LUR-101 UV3090 T770

70°C  20,000 Hr

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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>Standard</td>
<td>Standard</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td>Control</td>
<td>Control</td>
</tr>
<tr>
<td>TBEC UV2098 T770</td>
<td>TBEC UV2098 T770</td>
<td>LUP-101 UV2098 T770</td>
<td>LUP-101 UV2098 T770</td>
</tr>
</tbody>
</table>

20,000 Hr

90°C

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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
STANDARD fast cur. 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 ???
MODULE AND RELIABILITY TECHNOLOGY

Adhesion Experiments

STATUS:

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

DR. PLUDEDEMMANN - 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

- 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, Vₐ VS THICKNESS
- STRAIGHT LINE RELATIONSHIP: SLOPE EQUALS "INTRINSIC DIELECTRIC STRENGTH " DC"
- MEASUREMENTS TO DATE:
  - EVA 9918, \(\frac{dv}{dt} = 3.48 \text{ kv/MIL}\)

RESULTS TO DATE: EVA 9918

<table>
<thead>
<tr>
<th>Sample</th>
<th>Duration</th>
<th>Voltage</th>
<th>Result</th>
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<tbody>
<tr>
<td>RS/4 (50°C)</td>
<td>4,000 HR</td>
<td>3.24 kv/MIL</td>
<td>93%</td>
</tr>
<tr>
<td>RS/4 (85°C)</td>
<td>4,000 HR</td>
<td>1.98 kv/MIL</td>
<td>57%</td>
</tr>
<tr>
<td>RS/4 WET</td>
<td>4,000 HR</td>
<td>4.12 kv/MIL</td>
<td>118%</td>
</tr>
<tr>
<td>OPTAR 70°C</td>
<td>2,000 HR</td>
<td>2.85 kv/MIL</td>
<td>82%</td>
</tr>
<tr>
<td>OPTAR 90°C</td>
<td>2,000 HR</td>
<td>3.14 kv/MIL</td>
<td>90%</td>
</tr>
<tr>
<td>OPTAR 105°C</td>
<td>2,000 HR</td>
<td>- - UNTESTABLE - -</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\(^\circ\)C, 60\(^\circ\)C, 70\(^\circ\)C, 80\(^\circ\)C AND 90\(^\circ\)C
- MEASURE CHANGE IN WEIGHT VERSUS TIME

![Graph showing hydrolytic stability over time and temperature](image)

### Time to Onset of Change, Hours

<table>
<thead>
<tr>
<th>Material</th>
<th>70(^\circ)C</th>
<th>80(^\circ)C</th>
<th>90(^\circ)C</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>CONTINUAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- EVA VERY HYDROLYTICALLY STABLE
- DATA WILL BE USED FOR KINETICS
MODULE AND RELIABILITY TECHNOLOGY

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

1 LOSS IN \( I_{sc} \) WITH STANDARD CELL TREATED
TEDLAR 100BG300UT
(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 + E3620

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
# 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>POT TANT</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>
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</table>
Module and Reliability Technology

Process Equipment

Experimental Laminator

Vacuum gauge and regulation valve

Lower cavity

Clamp screws

Top cover

Silicone rubber gasket

Support plate

Silicone rubber gasket

Flexible diaphragm

Aluminum frame

Process Profile

Temperature

Vacuum upper cavity

Vacuum lower cavity

0 10 20 30 40 50 60

Time (in min)

1. Initiate heating
2. Pressure
3. Remove fixture from heated press
4. Remove module from vacuum bag fixture
5. Cool

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>$/Ft2/Mil</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>.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>
</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°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, 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
HYDROLYTIC STABILITY:
- EVA APPEARS EXCELLENT

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

SOILING:
- TREATMENTS STILL EFFECTIVE AFTER 56 MONTHS

THIN-FILM PV:
- CANDIDATES BEING SELECTED / DEVELOPED