Phase I

IDENTIFY AND DEVELOP LOW COST MODULE ENCAPSULATION MATERIALS

- POTENTIALS
- 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 GUIDANCE
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>
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<tbody>
<tr>
<td>THERMAL (AIR OVEN)</td>
<td>• UNNATURAL LIGHT</td>
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</tbody>
</table>
| RS/4 50°C           | • NO "WEATHER"
| RS/4 WET SPRAY     | • NO PREDICTIVE METHODS |
| RS/4 85°C           | • LONG EXPOSURE TIMES |

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, ti)
    EXAMPLE: POLYPROPYLENE
  - ARRHENIUS: LOG ti vs. 1/Θ
  - PREDICT SERVICE LIFE BY EXTRAPOLATION TO LOWER TEMPERATURES

TIME, HOURS

<table>
<thead>
<tr>
<th>200</th>
<th>500</th>
<th>2000</th>
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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 16718  EMA 16717  EVA 14747

STANDARD  FAST CURE  CONTROL

TBEC UV2018 T770  TBEC UV2018 T770  LUR311 UV3008 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>
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<tbody>
<tr>
<td>STANDARD</td>
<td>FAST CURE</td>
<td></td>
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</tr>
<tr>
<td>TBEC UV2098 T770</td>
<td>TBEC UV2098 T770</td>
<td>LUP-101 UV2098 T770</td>
<td></td>
</tr>
</tbody>
</table>

90°C 20,000 Hr
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 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 TEEC 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. PLOEDDEMMANN - 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 (50V/SEC)
- PLOT AVERAGE BREAKDOWN VOLTAGE, V_a 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

\[
\begin{array}{cccc}
\text{RS/4 (50°C)} & 4,000 \text{ HR} & 3.24 \text{ kV/MIL} & \triangle 93% \\
\text{RS/4 (85°C)} & 4,000 \text{ HR} & 1.98 \text{ kV/MIL} & 57% \\
\text{RS/4 WET} & 4,000 \text{ HR} & 4.12 \text{ kV/MIL} & 118% \\
\text{OPTAR 70°C} & 2,000 \text{ HR} & 2.85 \text{ kV/MIL} & 82% \\
\text{OPTAR 90°C} & 2,000 \text{ HR} & 3.14 \text{ kV/MIL} & 90% \\
\text{OPTAR 105°C} & 2,000 \text{ HR} & - - \text{UNTESTABLE} - - \\
\end{array}
\]

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

<table>
<thead>
<tr>
<th>TIME TO ONSET OF CHANGE, HOURS</th>
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<tbody>
<tr>
<td>70°</td>
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<tr>
<td>------</td>
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<tr>
<td>EVA</td>
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<tr>
<td>EMA</td>
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<td>PU</td>
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</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 100BG300UT
(SUPPORT ON GLASS)

56 MONTHS EXPOSURE

-10% -5% 0 8 24 40 56

--- 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

\[ \begin{array}{c}
\text{CONTROL, NO TREATMENT} \\
\text{OZONE + E3020} \\
\text{ESTIMATED AVERAGE POWER IMPROVEMENT, 3.9%}
\end{array} \]
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:
- POTTANT 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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</thead>
<tbody>
<tr>
<td>POTTANT</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>
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<td>INTERCONNECT</td>
<td>RESISTANCE</td>
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<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>
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<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>
EXPERIMENTAL LAMINATOR

- 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 - TBECS 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>
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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>POTNTANT</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>
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<td></td>
<td>• HIGH OPTICAL TRANSMISSION</td>
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<tr>
<td>DURABLE BONDING</td>
<td>• ALL INTERFACES</td>
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<td>• LONG SERVICE LIFE</td>
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<td>• LOW COST</td>
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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>
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<tbody>
<tr>
<td>FEP</td>
<td>1.34</td>
<td>93.6</td>
<td>0.10</td>
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</table>

POTTANTS: CONDUCTING INVESTIGATIONS

**MATERIAL CLASS** | **MANUFACTURER** | **$/LB**
--- | --- | ---
ETHYLENE/VINYL ACETATE | DU PONT, USI | .60 - .80
ETHYLENE/ACRYLIC | DOW, GULF | .80 - 1.00
IONOMER | DU PONT | .08 - 1.60
ALIPHATIC URETHANE | UPJOHN | .3 - 2.50
HOT MELT ADHESIVES | MANY | .80 - 2.50
(HYDROCARBON, POLYAMIDE, POLYETHER, ACRYLIC)

**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

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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