ENCAPSULATION MATERIALS RESEARCH

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

MATERIALS RELIABILITY

- AGING AND LIFE ASSESSMENT
- ADVANCED STABILIZERS
- ADHESIVE BOND DURABILITY
- FLAMMABILITY
- ELECTRICAL ISOLATION

Phase III

PROCESS SENSITIVITY

- INTERRELATIONSHIPS OF
  - FORMULATION VARIABLES
  - PROCESS VARIABLES
- MANUFACTURING YIELD ANALYSIS

(PROCESS DEVELOPMENT SECTION)
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. REFORMATION)
- SERVICE LIFE PROGNOSIS

PERFORMANCE CRITERIA

- FLAMMABILITY
- ADHESIVE BOND DURABILITY
- ELECTRICAL INTEGRITY
- ENVIRONMENTAL DEGRADATION
- WHAT ARE DOMINANT FAILURE MODES?
- WHERE IS STABILIZATION NEEDED?
Module Flammability

PROBLEM:
- Burning modules can serve as ignition source for other structures
- Most modules constructions not passing UL-790 burning brand test

MECHANISM(?)
- Appears to be rupture of the back cover with the evolution of burning gasses

- Modules with Kapton back covers (high strength) pass test due to ability to retain combustible gasses ("B" brand)
- Kapton is very expensive
- Inexpensive high strength high temperature back cover needed
- Some success with coated fiberglass cloth (proprietary coatings) ("A" brand)
RELIABILITY PHYSICS

GOAL:
- PREVENT SPREAD OF FLAME
- PASS UL-790

APPROACHES:
(1) HIGH STRENGTH HEAT RESISTANT BACK COVERS
   - CERAMIC PAPER
   - POLYMER FILM LAMINATES WITH GLASS CLOTH INTERLAYER
   - METAL FOILS
   - RESIN IMPREGNATED GLASS CLOTH

(2) REDUCTION OF COMBUSTIBLE MATERIALS
   - THINNING OF POTTANT LAYER

(3) FIRE RETARDANT ADDITIVES
   - INERT DILUENTS (TALC, CALCIUM CARBONATE)
   - RELEASE OF WATER WITH HEAT ALUMINA TRIPHYDRATE (35% WATER)
   - FIRE RETARDANTS (FREE RADICAL TRAPS)
     ANTIMONY OXIDE, ZINC BORATE
     BROMINATED ORGANICS
     ORGANIC PHOSPHATES

(4) COMBINATION OF ALL THREE (MOST LIKELY)
EVALUATION OF CANDIDATE MATERIALS

CONVENTIONAL TESTS:

- UL-94 VERTICAL BURN TEST
- ASTM E-262 FLAME SPREAD INDEX
- ASTM D-2863 LIMITING OXYGEN INDEX

SPECIAL TEST METHOD:

- HIGH TEMPERATURE BURST CELL
- DETERMINE BURST STRENGTH AS FUNCTION OF TEMPERATURE AND PRESSURE
- CORRELATE TO ACTUAL EFFECTIVENESS UNDER FIRE CONDITIONS
- DETERMINE ADD-ON COST FOR IMPROVEMENT IN FIRE RATING
- RECOMMEND CANDIDATES FOR UL-790 TESTING

<table>
<thead>
<tr>
<th>DATA:</th>
<th>BURST STRENGTH, PSI</th>
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<tbody>
<tr>
<td></td>
<td>300</td>
</tr>
<tr>
<td>TEDLAR</td>
<td>~ 5</td>
</tr>
<tr>
<td>200BS30WH</td>
<td></td>
</tr>
<tr>
<td>KAPTON</td>
<td>&gt;50</td>
</tr>
<tr>
<td>(4 MIL)</td>
<td></td>
</tr>
</tbody>
</table>
| GLASS CLOTH | - | - | - | POROUS | - | - | - | (PROPRIETARY COATING)

- MOST EFFECTIVE BACK COVER IS POROUS!
- RELEASED GASES DILUTED BELOW LOWER EXPLOSION LIMIT??

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FIRE RETARDANT ADDITIVES:

- GOAL: FIRE RETARDANT EVA

<table>
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<tr>
<th>FORMULATION</th>
<th>PARTS</th>
<th>PERCENT</th>
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<tbody>
<tr>
<td>ELVAX 150</td>
<td>100</td>
<td>49</td>
</tr>
<tr>
<td>TBEC PEROXIDE</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>ANTIMONY OXIDE</td>
<td>7.0</td>
<td>3.4</td>
</tr>
<tr>
<td>DECARBROMODIPHENYL OXIDE</td>
<td>20.0</td>
<td>9.8</td>
</tr>
<tr>
<td>ALUMINUM TRIHYDRATE</td>
<td>75.0</td>
<td>35.8</td>
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EVALUATION:

- UL-94 VERTICAL BURN V-0 (SELF EXTINGUISHING)
  - COMPRESSION MOLDED WITH "CRANEGLAS" CLOTH:
- ASTM D-23863 LIMITING OXYGEN INDEX 30% (GOOD)

FOR COMPARISON:

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>OXYGEN INDEX</th>
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<tbody>
<tr>
<td>PARAFFIN</td>
<td>16</td>
</tr>
<tr>
<td>EVA (ELVAX 150)</td>
<td>18</td>
</tr>
<tr>
<td>SILICONE RUBBER</td>
<td>30</td>
</tr>
<tr>
<td>PVC</td>
<td>≈ 50</td>
</tr>
<tr>
<td>TEFLOW (FEP)</td>
<td>≈ 93</td>
</tr>
</tbody>
</table>

CONCLUSIONS:

- FIRE RETARDANCY INCREASES WITH AMOUNT OF ALUMINUM TRIHYDRATE
- 4:1 BROMINE: ANTIMONY RATIO APPEARS TO BE OPTIMUM
- NON-WOVEN GLASS CLOTH PREVENTS DRIPPING - REINFORCES THE COMPOSITION
- EVA CAN BE FORMULATED TO HAVE FLAMMABILITY EQUIVALENT TO SILICONE RUBBER
- HIGHER OXYGEN INDEX VALUES POSSIBLE
Adhesion Experiments

STATUS:
- PRIMER FORMULATIONS IDENTIFIED FOR ALMOST ALL INTERFACES IN MODULES
- SELF-PRIMING FORMULATIONS OF EVA (TO GLASS, CELLS) DEVELOPED; AVAILABLE

CONTINUED PRIMER STUDIES:
- GOAL: REDUCE LIST OF PRIMERS TO "UNIVERSAL" FORMULATION(s)
- EVALUATE THE THREE "BASIC" PRIMERS - DR. PLUEDDEMANN - DOW CORNING
  - POLYMER/METAL
  - POLYMER/INORGANIC
  - POLYMER/ORGANIC
- METAL PRIMER (ALUMINUM) RECOMMENDATIONS
  DR. JIM BOERIO - UNIVERSITY OF CINCINNATI

DURABILITY
ADHESIVE BONDS ARE RESPONSIBLE FOR MECHANICAL INTEGRITY OF ENTIRE MODULE - WHAT IS THEIR LIFETIME?
- HOW DURABLE ARE ADHESIVE BONDS?
- UNDER WHAT CONDITIONS?
- REVERSIBILITY AND RECOVERY?
- MODELLING AND PREDICTION?
- TEST METHODS?

ADHESION DIAGNOSTICS:
- PROGRAM STARTED WITH CASE WESTERN RESERVE UNIVERSITY - JACK KOENIG
Adhesion Diagnostics

TEST SPECIMENS:
- EVA COMPOUNDED WITH HIGH LOADINGS OF SILANE TREATED GLASS BEADS - RESEMBLES GLASS REINFORCED POLYMER
- GLASS: SPHERICAL "A" - GLASS BEADS, MEAN DIAMETER 20 μ, 2% BY WEIGHT SILANE PRIMER
- SPECIMENS AT CASE WESTERN FOR "DRIFT" ANALYSIS (SPECTROSCOPY)
- SPECIMENS AT SPRINGBORN FOR MECHANICAL ANALYSIS

GOALS:
- CORRELATE SPECTROSCOPIC OBSERVATIONS WITH MECHANICAL PERFORMANCE
- DETERMINE DEGRADATION RATES (KINETICS)
- ASSESS SERVICE LIFE

AGING CONDITIONS:
- HYDROLYSIS CONSIDERED TO BE DOMINANT FAILURE MECHANISM
- WATER IMMERSION:
  - TEMPERATURES: 40°, 60°, 80°
  - TIMES: 100, 250, 500, 1000, 2000 HRS.
- TESTING: MECHANICAL, SPECTROSCOPIC
RELIABILITY PHYSICS

- LARGEST MEASURABLE CHANGE: WEIGHT GAIN
  (WATER ABSORPTION)

<table>
<thead>
<tr>
<th>TEMPERATURE</th>
<th>40°C</th>
<th>60°C</th>
<th>80°C</th>
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<tbody>
<tr>
<td>EVA/GLASS</td>
<td>51%</td>
<td>2015%</td>
<td>500%</td>
</tr>
<tr>
<td>NO PRIMER</td>
<td>2,000 Hr</td>
<td>2,000 Hr</td>
<td>500 Hr</td>
</tr>
<tr>
<td>EVA/GLASS</td>
<td>3.5%</td>
<td>35%</td>
<td>62%</td>
</tr>
<tr>
<td>WITH PRIMER</td>
<td>2,000 Hr</td>
<td>1,000 Hr</td>
<td></td>
</tr>
<tr>
<td>EVA, CONTROL</td>
<td>0.3%</td>
<td>0.4%</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>2,000 Hr</td>
<td>2,000 Hr</td>
<td>2,000 Hr</td>
</tr>
</tbody>
</table>

- NO SPECIMENS SURVIVING THIS POINT

- WEIGHT GAIN ASSUMED TO BE WATER ABSORPTION AT POLYMER/GLASS INTERFACE
  (ALSO OBSERVED BY SPECTROSCOPY)

- PRIMER HAS SIGNIFICANT EFFECT ON ABSORPTION

- MECHANICAL PROPERTIES: LITTLE CHANGE UP TO 50%
  WEIGHT GAIN-ELONGATION BEGINS TO DECREASE

- ALMOST NO CHANGE IN POLYETHYLENE/GLASS BEAD SPECIMENS

REVERSIBILITY:

- DRIED AT 105°C/72 HRS - LIMIT OF REVERSIBILITY
  40°C  60°C  80°C
  NO PRIMER  ALL  500 Hrs  250 Hrs
  WITH PRIMER ALL  ALL  1,000 Hrs
RELIABILITY PHYSICS

- WATER ABSORPTION - LARGEST PROPERTY CHANGE
- PRIMER STABILIZERS GLASS/POLYMER INTERFACE
- HYDROTHERMAL " DAMAGE " TO BONDS AT THE INTERFACE IS REVERSIBLE UP TO A LIMIT
- EQUILIBRIUM WATER ABSORPTION VALUES MAY PROVIDE NEW METHOD OF EVALUATING ADHESIVE BONDS - RECOVERY PROPERTIES

LIFETIME:

- DOES POLYMER GAIN WATER TO POINT OF NON-REVERSIBILITY, OR IS IT " INDUCTION PERIOD " TYPE?
- NEED MORE DATA POINTS FOR MODELING
RELIABILITY PHYSICS

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 DIELCTRIC STRENGTH" (DC)
- MEASUREMENTS TO DATE:
  EVA 9918, $dV/dt = 3.65$ kV/MIL

GOALS:
- REMEASURE $dV/dt$:
  - THERMAL AGING
  - WATER ABSORPTION
  - ENVIRONMENTAL EXPOSURE
  - FIELD STRESS AGING
- RECALCULATE THE REQUIRED INSULATION THICKNESS FOR SERVICE LIFE OF THE MODULE
Accelerated Aging Test Program

OUTDOOR PHOTOTHERMAL AGING REACTORS (OPTAR)

- USE NATURAL SUNLIGHT, AVOIDS SPECTRAL DISTRIBUTION PROBLEMS WITH ARTIFICIAL LIGHT SOURCES
- USE TEMPERATURE TO ACCELERATE THE PHOTO- THERMAL 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
- Evaluated whole modules
- Determine upper level service temperatures
- Modelling:
  - Time to onset of degradation (induction period, $t_i$)
    Example: Polypropylene
  - Arrhenius: $\log t_i$ vs. $1/K^0$
  - Predict service life by extrapolation to lower temperatures

![Graph showing temperature vs. time for accelerated aging](chart.png)
RELIABILITY PHYSICS

Accelerated Aging (OPTAR)

- INDUCTION PERIOD MEASUREMENT - USEFUL FOR STABILIZER SELECTION
- EXAMPLE: HALS TYPE STABILIZERS

![Graph showing percent elongation over time for different samples.]

- ADVANCE EVA FORMULATION (NO. 18170)
  LUPERSOL TBEC, UV-2098 (CYANAMIDE, UV-SCREEN) UV-3346 (CYANAMIDE, HALS)
- MASSIVE TEST PROGRAM STARTED: MODULES, OUTER COVERS, ADHESION TEST SPECIMENS, POTTANT FORMULATIONS, ETC.
- RADIOMETER INSTALLED ON OPTAR DEVICES - POSSIBILITY FOR MODELING BASED ON HEAT PLUS LIGHT ???
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 FILM)

TREATMENTS REMAINING:
- L-1668 FLUOROSILANE (3M)
- E-3820 PERFLUORODECANOIC ACID/SILANE (DOW CORNING)
- STILL EFFECTIVE AT 46 MONTHS OUTDOOR EXPOSURE
- RESULTS IN IMPROVED POWER OUTPUT
- FLUOROALKYL SILANE CHEMISTRY APPEARS TO BE MOST EFFECTIVE

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

FORTY SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

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

46 MONTHS EXPOSURE

--- CONTROL, NO TREATMENT

--- L1668 (3M)

ESTIMATED AVERAGE POWER IMPROVEMENT, 1%
RELIABILITY PHYSICS

FORTY SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

% LOSS IN $I_{sc}$ WITH STANDARD CELL TREATED
TEDLAR 106BG500UT

(SUPPORT ON GLASS)
MONTHS EXPOSURE

---

CONTROL, NO TREATMENT

---
E3820

* ESTIMATED AVERAGE POWER IMPROVEMENT, 3.8%
% LOSS IN $I_{sc}$ WITH STANDARD CELL TREATED ACRYLAR (SUPPORTED ON GLASS)

CONTROL, NO TREATMENT
--- OZONE + E3820

ESTIMATED AVERAGE POWER IMPROVEMENT, 3.5%
RELIABILITY PHYSICS

Outer Covers

(SUBSTRATE DESIGN)

- RECENT INDUSTRIAL INTEREST - BOTH CRYSTAL AND THIN FILM AMORPHOUS APPLICATIONS
- NEW CONCEPT: POTTANTS ARE VERY STABLE - NO FURTHER NEED FOR UV SCREENING IN OUTER COVER (?)
- NON-SCREENING FILM REQUIREMENTS:
  TRANSPARENT, LOW SHRINKAGE, WEATHERABLE, BONDABLE
- BEST CANDIDATES: FLUOROPOLYMERS

<table>
<thead>
<tr>
<th>FILM</th>
<th>REF. INDEX</th>
<th>% T</th>
<th>COST $/FT²/MIL</th>
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<tbody>
<tr>
<td>TEFZEL</td>
<td>1.403</td>
<td>85.6</td>
<td>0.128</td>
</tr>
<tr>
<td>KAYNAR</td>
<td>1.420</td>
<td>88.8</td>
<td>0.055</td>
</tr>
<tr>
<td>HALAR</td>
<td>1.400</td>
<td>85.3</td>
<td>0.096</td>
</tr>
<tr>
<td>.FA</td>
<td>1.300</td>
<td>88.4</td>
<td>0.123</td>
</tr>
<tr>
<td>FEP</td>
<td>1.340</td>
<td>93.6</td>
<td>0.109</td>
</tr>
<tr>
<td>FLUOREX</td>
<td>1.460</td>
<td>90.0</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- FEP MAY BE GOOD CHOICE:
  - HIGH TRANSPARENCY
  - OUTSTANDING WEATHERABILITY
  - MAY IMPROVE OPTICAL THROUGHPUT BY 2% DUE TO OPTICAL COUPLING
  - REQUIRES BONDING TECHNOLOGY:
    SURFACE TREATMENT NOT UV STABLE (DU PONT)
  - UNDER EVALUATION IN MODULE FABRICATION AND OUTDOOR EXPOSURE EXPERIMENTS
RELIABILITY PHYSICS

Thin-Film/Amorphous Photovoltaics

CANDIDATE POLYMERS:

- PROCESSABLE <100° C
- OPTICALLY TRANSPARENT (BEFORE OR AFTER CURING)
- CURABLE: NO THERMAL CREEP
- EXTRUSION: THIN FILMS DESIRABLE
- WEATHERABLE OR UNGRADABLE
- FLEXIBLE

<table>
<thead>
<tr>
<th>MATERIAL CLASS</th>
<th>MANUFACTURER</th>
<th>$/LB</th>
</tr>
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<tbody>
<tr>
<td>Polyethylene (LDPE)</td>
<td>MANY</td>
<td>0.50 - 0.60</td>
</tr>
<tr>
<td>Ethylene/Vinyl Acetate</td>
<td>DU PONT, USI</td>
<td>0.60 - 0.80</td>
</tr>
<tr>
<td>Ethylene/Acrylic</td>
<td>DOW, GULF</td>
<td>0.80 - 1.00</td>
</tr>
<tr>
<td>Ionomer</td>
<td>DU PONT</td>
<td>1.08 - 1.60</td>
</tr>
<tr>
<td>Aliphatic Urethane</td>
<td>UPGUHN</td>
<td>1.70 - 2.50</td>
</tr>
<tr>
<td>Hot Melt Adhesives</td>
<td>MANY</td>
<td>80 - 2.50</td>
</tr>
<tr>
<td>(Hydrocarbon, PolyamidePolyether, Arylic)</td>
<td></td>
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</table>

ENCAPSULATION METHOD:

- EXTRUSION COATING
- FILM LAMINATION: EXTRUDE THE POTTANT ON AN OUTER COVER FILM AS A CARRIER, USE COMBINATION FOR LAMINATION.

CURE METHOD:

- MOISTURE CURE (MODIFIED CHEMISTRY)
- PEROXIDE DECOMPOSITION (HEAT)
- UV CURE (PHOTOINITIATION)
- ELECTRON BEAM (?)
  MAY BE POSSIBLE WITH AMORPHOUS SILICON
RELIABILITY PHYSICS

Conclusions

FLAMMABILITY:
- BACK COVERS - FUNCTION?
- SELF EXTINGUISHING FIRE RETARDANT EVA DEVELOPED

ADHESION:
- NEW TEST METHOD FOR PRIMER EVALUATION AND BOND DURABILITY
- CAN DEMONSTRATE BOND RECOVERY & LIMIT OF REVERSIBILITY

ELECTRICAL ISOLATION:
- INTRINSIC DIELECTRIC TEST METHOD DEVELOPED

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
- LUPERSOL - TBEC CURED FORMULATIONS APPEAR MORE STABLE
- BEST STABILIZERS: UV-2098 SCREENER, UV-3346 HALS TYPE (BOTH CYANAMIDE)

SOILING:
- TREATMENTS STILL EFFECTIVE AFTER 46 MONTHS
- MOST EFFECTIVE ON ORGANIC FILMS

THIN-FILM PV:
- ENCAPSULANT INVESTIGATIONS BEGUN
Future Work

- **FLAMMABILITY:**
  - Enhanced fire retardant formulations
  - Small scale module "burns"

- **ADHESION:**
  - More work on "universal" primers
  - More development of diagnostic test method
  - Aging of adhesion test specimens

- **ELECTRICAL INTEGRITY:** Dielectric strength versus aging of encapsulation materials:
  - Accelerated aging
    - Massive number of test specimens being developed - modules, outer covers
    - Advanced stabilizer systems
  - Non-screening weatherable outer covers
    - Emphasis on bonding
  - Thin-film PV: Development work and materials recommendations