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

CURRENT EMPHASIS ON MATERIALS AND MODULE PERFORMANCE CHARACTERISTICS

- DETERMINE CURRENT LEVEL OF PERFORMANCE
- ENHANCE PERFORMANCE (E.G. REFORMULATION)
- 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

Modulfs 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)
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 TRIHYDRATE (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

DATA:

<table>
<thead>
<tr>
<th></th>
<th>BURST STRENGTH, PSI</th>
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<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>
<tr>
<td>GLASS CLOTH</td>
<td>-</td>
</tr>
<tr>
<td>(PROPRIETARY COATING)</td>
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</table>
- MOST EFFECTIVE BACK COVER IS POROUS!
- RELEASED GASSES DILUTED BELOW LOWER EXPLOSION LIMIT ??
FIRE RETARDANT ADDITIVES:

- GOAL: FIRE RETARDANT EVA

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<thead>
<tr>
<th>FORMULATION</th>
<th>PARTS</th>
<th>PERCENT</th>
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<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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<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>
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</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
RELIALIBILITY PHYSICS

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 \( \mu \text{m} \), 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\(^\circ\)C, 60\(^\circ\)C, 80\(^\circ\)C
  - TIMES: 100, 250, 500, 1000, 2000 HRS.
- TESTING: MECHANICAL, SPECTROSCOPIC
RELIABILITY PHYSICS

- LARGEST MEASURABLE CHANGE: WEIGHT GAIN
  (WATER ABSORPTION)

**PERCENT WEIGHT GAIN**

<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>2,000 Hr</td>
<td>1,000 Hr</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 DIELECTRIC 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: POLYPROYLENE
  - ARRHENIUS: LOG, $t_i$ vs. $1/K^0$
  - PREDICT SERVICE LIFE BY EXTRAPOLATION TO LOWER TEMPERATURES

TIME, HOURS

TIME, HOURS

200 500 2000

VT (°C), SHOWN AS DEGREES CENTIGRADE

ACTUAL

181
Accelerated Aging (OPTAR)

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

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

- 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

-15%

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%
FORTY SIX MONTHS EXPOSURE
ENFIELD, CONNECTICUT

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

45 MONTHS EXPOSURE

CONTROL, NO TREATMENT
OZONE + E3820

ESTIMATED AVERAGE POWER IMPROVEMENT, 5.5%
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>1.40</td>
<td>85.3</td>
<td>0.096</td>
</tr>
<tr>
<td>FA</td>
<td>1.30</td>
<td>88.4</td>
<td>0.123</td>
</tr>
<tr>
<td>FEP</td>
<td>1.34</td>
<td>93.6</td>
<td>0.109</td>
</tr>
<tr>
<td>FLUOREX</td>
<td>1.46</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 $< 100^\circ$ 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>
</thead>
<tbody>
<tr>
<td>POLYETHYLENE (LDPE)</td>
<td>MANY</td>
<td>.50 - .60</td>
</tr>
<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>1.08 - 1.60</td>
</tr>
<tr>
<td>ALIPHATIC URETHANE</td>
<td>UPJOHN</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, POLYAMIDE,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POLYETHER, ACRYLIC)</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
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 (BOOTH 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