ENCAPSULATION PROCESSING AND MANUFACTURING YIELD ANALYSIS

SPRINGBORN LABORATORIES, INC.

P. Willis

Goals

- Understand the relationships between:
  - Formulation Variables
  - Process Variables

- Define conditions required for optimum performance

- Relate to module reliability

- Predict manufacturing yield

- Provide documentation to industry
PROCESS DEVELOPMENT

Material Variables

LAMINATION POTTANTS
- ETHYLENE/VINYL ACETATE (EVA)
- ETHYLENE/ETHYL ACRYLATE (E/A)

CASTING POTTANTS
- ALIPHATIC POLYURETHANE (PU)

ADHESIVES/PRIMERS
- THREE BASIC PRIMER SYSTEMS

COVER FILMS
- TEDLAR, ACRYLICS, FEP

FORMULATION VARIABLES:
  TYPE AND AMOUNT OF:
- CURING AGENTS (PEROXIDES)
- ANTIOXIDANTS
- ULTRAVIOLET SCREENERS
- ULTRAVIOLET STABILIZERS (HALS)
- SELF PRIMING AGENTS

STORAGE CONDITIONS:
- TIME, TEMPERATURE, HUMIDITY, LIGHT
- AIR EXPOSURE

QUALITY CONTROL:
- DETERMINE ANALYTICAL METHODS TO VERIFY COMPOSITION
- PUBLISH QC SPECIFICATIONS FOR MATERIAL CERTIFICATION
PROCESS DEVELOPMENT

Process Variables

(VACUUM BAG LAMINATION)

- AMBIENT CONDITIONS:
  - TEMPERATURE
  - HUMIDITY
  - BAROMETRIC PRESSURE

- VACUUM PRESSURE (INITIAL) AND TIME OF EVACUATION

- TEMPERATURE - RATE OF RISE

- TEMPERATURE - ULTIMATE

- DWELL TIME, AT TEMPERATURE

- RATE OF COOLING

- TIME/TEMPERATURE/PRESSURE INTERRELATIONSHIP

(CASTING LIQUID SYSTEMS)

ABOVE VARIABLES, PLUS:

- 2 COMPONENT MIX TIME

- DEGASSING PRESSURE

- PUMP AND FILL TIMES

- MIX UNIFORMITY

- GEL TIME
PROCESS DEVELOPMENT

Process Equipment

EXPERIMENTAL LAMINATOR

- VACUUM GAUGE AND REGULATION VALVE LOWER CAVITY
- CLAMP SCREWS
- TOP COVER
- SILICONE RUBBER GASKET
- FLEXIBLE DIAPHRAGM
- ALUMINUM FRAME
- SUPPORT PLATE
- SILICONE RUBBER GASKET

PROCESS PROFILE

- TEMPERATURE °C
- VACUUM IN UPPER CAVITY, in. Hg

1. LOAD ASSEMBLY, PULL VACUUM
2. INITIATE HEATING
3. PRESSURIZE UPPER CAVITY
4. REMOVE FIXTURE FROM HEATED PRESS
5. REMOVE MODULE FROM VACUUM-BAG FIXTURE

- Microprocessor controlled experimental laminator constrained studies started on processing profiles
- Rate of heating (how slow, how fast?)
- Vacuum timing
- Rate of cooling

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Quality and Performance Criteria

**METHOD:**
- Prepare test modules and/or other test specimens with change in significant variable(s)
- Determine the effect

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>CRITERION</th>
<th>TEST</th>
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<tbody>
<tr>
<td>POTTANT</td>
<td>ADEQUATE CURE</td>
<td>PERCENT GEL</td>
</tr>
<tr>
<td></td>
<td>TRAPPED BUBBLES</td>
<td>THERMAL CREEP</td>
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<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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<tr>
<td></td>
<td>INTERCONNECT</td>
<td>RESISTANCE</td>
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<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>

Need to decide on:
- Standard test specimen(s)
- Standard test protocol
- Uniform data sets
Data Analysis

- STATISTICAL ANALYSIS COMPLICATED BY LACK OF UNIFORMITY IN DATA TYPE

- TWO TYPES OF DATA:
  
<table>
<thead>
<tr>
<th>DISCRETE (PASS/FAIL)</th>
<th>CONTINUOUS</th>
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<tbody>
<tr>
<td>CELL FRACTURE</td>
<td>GEL CONTENT</td>
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<tr>
<td>INTERCONNECT BREAKAGE</td>
<td>PEEL STRENGTH</td>
</tr>
<tr>
<td>TRAPPED BUBBLES</td>
<td>STABILIZER LOSS</td>
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<tr>
<td>THERMAL CREEP</td>
<td></td>
</tr>
<tr>
<td>GLASS FRACTURE</td>
<td></td>
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</tbody>
</table>

FOR CONTINUOUS DATA TYPES:
- TWO LEVEL FACTORIAL EXPERIMENTS (MOST INFORMATION, FEWEST EXPERIMENTS)
- NO. EXPERIMENTS = $2^K$, $K =$ NO. VARIABLES
- DETERMINES EFFECT OF SINGLE VARIABLE AT TWO LEVELS
- DETERMINES FACTOR INTERACTIONS (SEVERAL VARIABLES)
- PERMITS RANKING OF VARIABLES ACCORDING TO MAGNITUDE OF EFFECT
- LINEAR ANALYSIS POSSIBLE FOR SUBSEQUENT PREDICTIVE CAPABILITY

FOR DISCRETE DATA TYPES:
- DETERMINE "X SUCCESSES IN N TRIALS" FOR SUITABLY LARGE SAMPLE
- SCATTER PLOT - FOR FIRST ESTIMATE OF ACCEPTABLE PROCESSING RANGE
- BINOMIAL DISTRIBUTION - DETERMINE PROBABILITY OF FAILURE

IN GENERAL:
1. DETERMINE THE DOMINANT FAILURE MODE
2. DETERMINE VARIABLE(s) RESPONSIBLE
3. DETERMINE EXPERIMENTAL CONDITIONS THAT RESULT IN A RANGE OF FAILURES
4. DETERMINE THE MEAN AND STANDARD DEVIATION OF THE DISTRIBUTION
5. USE PROBABILITY DISTRIBUTION FUNCTION TO CALCULATE PROBABLE FAILURE AT OTHER STRESS LEVELS
PROCESS DEVELOPMENT

Manufacturing Practice: Discrete Variables

- Prepare graphical interpretation of data
- Determine "tolerable failure" level
- Define boundary conditions for defect-free manufacturing (first estimate)

Example: Cell breakage

O = Pass
X = Fail

Resin temperature (°C)

Backfill rate (mm Hg/sec)

Vacuum pressure (mm Hg)

Zero failure line
PROCESS DEVELOPMENT

Manufacturing Practice: Continuous Variables

- Graphical presentation also good for continuous variables
- Provides boundaries for process/formulation variables based on criteria of acceptability
- Easily used in manufacturing practice

Example: Percent gel
(Degree of cure)

Diagram showing property lines for percent gel at 70%, 60%, and 50%. The diagram includes temperature (°C) and dwell time (minutes) scales.
**Formulation Sensitivity**

- UV SCREENERS AND OTHER STABILIZERS - SLOW DOWN CURE RATE SLIGHTLY. NO ENORMOUS DIFFERENCE BETWEEN TYPES
- ANTIOXIDANTS CAN HAVE MAJOR EFFECT ON CURE. NOT USED/UNNECESSARY

**CURE VERSUS PEROXIDE CONTENT**
(TIME TO GEL CONTENT >65%, MINUTES)

<table>
<thead>
<tr>
<th></th>
<th>130°</th>
<th>140°</th>
<th>150°</th>
<th>160°</th>
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<tr>
<td>LUPERSOL 101:</td>
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</tr>
<tr>
<td>1.5%</td>
<td>NC</td>
<td>20</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>0.5%</td>
<td>NC</td>
<td>30</td>
<td>20</td>
<td>10</td>
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<table>
<thead>
<tr>
<th></th>
<th>15295</th>
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<tbody>
<tr>
<td>LUPERSOL TBEC:</td>
<td></td>
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<tr>
<td>1.5%</td>
<td>8</td>
</tr>
<tr>
<td>0.5%</td>
<td>NC</td>
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(\(NC = NC\) CURE)

- ONE THIRD THE STANDARD PEROXIDE CONCENTRATION DOUBLES THE REQUIRED TIME
- EVA FORMULATIONS NOT SENSITIVE TO MINOR VARIATIONS ON PEROXIDE CONTENT
PROCESS DEVELOPMENT

Process Sensitivity

EVA STORAGE / AIR EXPOSURE

<table>
<thead>
<tr>
<th>EVA NUMBER</th>
<th>0918</th>
<th>15295</th>
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<tbody>
<tr>
<td>PEROXIDE:</td>
<td>LUPERSOL 101</td>
<td>LUPERSOL TBEC</td>
</tr>
<tr>
<td>CURE:</td>
<td>150° / 20 MIN</td>
<td>150° / 5 MIN</td>
</tr>
<tr>
<td>CONDITIONS:</td>
<td>140° / 20 MIN</td>
<td>140° / 5 MIN</td>
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<table>
<thead>
<tr>
<th>AIR EXPOSURE</th>
<th>GEL CONTENTS:</th>
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<tbody>
<tr>
<td>CONTROL, 0</td>
<td>80 % 95 %</td>
</tr>
<tr>
<td></td>
<td>64 % 91 %</td>
</tr>
<tr>
<td>24 HOURS</td>
<td>82 % 85 %</td>
</tr>
<tr>
<td></td>
<td>71 % 78 %</td>
</tr>
<tr>
<td>48 HOURS</td>
<td>78 % 81 %</td>
</tr>
<tr>
<td></td>
<td>0 % 72 %</td>
</tr>
<tr>
<td>72 HOURS</td>
<td>70 % 83 %</td>
</tr>
<tr>
<td></td>
<td>0 % 82 %</td>
</tr>
<tr>
<td>168 HOURS (ONE WEEK)</td>
<td>0 % 70 %</td>
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<tr>
<td></td>
<td>0 % 0 %</td>
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- EVA FORMULATIONS STRONGLY AFFECTED BY AIR EXPOSURE.
- FORMULATION WITH TBEC PEROXIDE MUCH LESS AIR SENSITIVE
- EVA STORED IN ROLL FORM - APPEARS TO HAVE LONG STORAGE LIFE
- CUT EVA SHEET ONLY BEFORE USE, DISCARD FIRST WRAP OF ROLL
JPL Process Sensitivity Analysis

PROCESS DEVELOPMENT

DEFINE VARIABLES

PROCEED DEVELOPMENT

DETERMINE CRITERIA OF PERFORMANCE

UNIFORM TEST SPECIMEN(S)

UNIFORM TEST PROTOCOL

UNIFORM DATA SET

DISCRETE DATA

CONTINUOUS DATA

PLOT DATA

FACTORIAL EXPERIMENTATION

RANK VARIABLES AND COFACTORS

RANK VARIABLE(S) AND COFACTORS

BRACKETS AND BOUNDARIES

BRACKETS AND BOUNDARIES

BERNOULLI PROBABILITY DISTRIBUTION

MULTIVARIATE ANALYSIS

GRAPHICAL PRESENTATION

ASSIGN PROBABILITY VALUES-REQUIRED CRITERIA

DETERMINE MANUFACTURING YIELDS

GRAPHICAL PRESENTATION

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PROCESS DEVELOPMENT

Conclusions

- EVA FORMULATIONS RELATIVELY INSENSITIVE TO QUANTITY OF PEROXIDE BUT VERY SENSITIVE TO AIR EXPOSURE
- UNWRAP/CUT EVA JUST BEFORE MODULE MANUFACTURING - LIMIT AIR EXPOSURE

Accomplishments

- ANALYTICAL METHODS DEVELOPED FOR PEROXIDE CONTENT
- MICROPROCESSOR CONTROLLED EXPERIMENTAL LAMINATOR CONSTRUCTED
- EXPERIMENTAL TEST METHODOLOGY DEVELOPED (FIRST CUT)
- REVISED EVA PRODUCT BROCHURE AVAILABLE INCLUDES "TROUBLE SHOOTING" SECTION

Future Work

- DETERMINE DOMINANT FAILURE MODES
- CONVERT DATA TO PRACTICAL ENGINEERING FORMAT
- RELATE DATA TO MANUFACTURING YIELD
  - ASSIGN PROBABILITY OF FAILURE
  - NORMAL DISTRIBUTION (?)
  - WEIBUL (?)