Lifetime prediction—why is this so hard?

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This presentation contains no confidential information.
Why do we do this?

1. To meet a customer’s specification
2. To reduce risk
Why is this so hard?

- We probably are not asking the right questions in the right way
- Applying engineering models to a science problem
  - emphasis on setting and meeting specifications
  - desire for standard tests with correlation factors
  - desire for fast turn-around; pass/fail criteria
- Both physical and chemical changes
- Chemical changes due to “bad” chemistry
  - very slow chemical reactions that are not well understood
  - chemists study reactions that go to high yield in < 24 hours
  - 1% conversion in 10 years is enough to destroy a polymer
  - usually have multiple, competing degradation pathways
- Cannot usually use qualification tests for lifetime prediction
A question of correlation

What is the correlation between Test X and how long this will last in my application?

What is the correlation between tensile strength of steel and how long of a bridge span I can build?

If steel with tensile strength of 250 MPa can make a 20 meter span, I can use steel with 2500 MPa to make a 200 meter span, right?

Test results give one piece of data to be used in a predictive model
What is lifetime?

The properties of the system have changed so that the article no longer meets performance needs.

Some characteristics of change

• Physical and chemical
• Gradual or catastrophic
• Determined by rates of underlying processes
• Caused by environmental stresses
• Multiple routes

There is no such thing as accelerated life tests, only accelerated degradation tests
How mechanisms change

- Complex phenomena often have multiple pathways with different activation energies.
- High $E_a$ processes can dominate at higher (test) temperatures.
- Low $E_a$ processes can dominate at lower (use) temperatures. "bad chemistry"

\[ k = A_1 \exp\left(-\frac{E_{a1}}{RT}\right) + A_2 \exp\left(-\frac{E_{a2}}{RT}\right) + \ldots \]

See papers by Gillen, Celina, Clough e.g. Polymer 46 (2005) 11648–11654
The *status quo*

- Carry out a standard ALT or HALT
  - “severe” conditions
  - pass or fail at some time

- Transfer function to correlate “real world”
  - how to extrapolate from one point?
  - what has worked before?
  - plastic is just like steel, right?

- Predict service life
  - where do you extrapolate to?

But… there may be no unique path connecting test to use in this multi-dimensional space
The three “easy” steps

- Define the use conditions
  - environment: stresses and magnitude
  - duty cycle

- Find material response to conditions
  - degradation kinetics
  - interaction of factors

- Establish valid test conditions
  - high acceleration without changing the mechanism
  - might need multiple tests

Test conditions should be valid for some range of variations of composition and design.
Step #0: Before you start

• How badly do you need to know?
  - what is the risk if the system fails?
  - what type of resources can be committed?
  - are you trying to meet some arbitrary specification?

• What is failure?
  - consequences of failure – design for 95% or 150% of worst case?
  - soft or hard?
  - can you measure changes that occur before failure?

• What has been the experience so far?
  - have there been field failures?
  - what is known about similar systems?
  - are there samples or retains?
Step #1: Define use conditions

- Benchmark to a defined environment, e.g. Miami or Phoenix?

- Determine relevant environmental stresses and their magnitude
  - temperature, moisture, chemical, mechanical, electrical, sunlight, biological, …
  - literature, measure, model

- Must know duty cycle, not just the most extreme conditions
  - must survive the extremes but endure the means
  - measure or model the actual conditions on the part
  - need time-parsed (e.g. hourly) or binned data
  - essential for applying a cumulative damage model using kinetics

- Retrieve and analyze aged and failed parts from the field
  - helps to know what degradation looks like
  - provides validation for test conditions
Step #2: Find material response to stresses

• Apply stresses at several levels alone and in combination, if possible

• This is a science project
  - simple DoE’s may not give enough information
  - really need to understand what is happening physically and chemically
  - must understand where acceleration is coming from

• Look for underlying processes that can be monitored
  - rates of change, not just time to failure
  - rates can predict failure time

• Develop rational model that fits the data
  - beware of “free” acceleration
  - understand the assumptions
Step #3: Establish valid test conditions

- Step 2 actually will lead to a prediction, but a test is useful for material variations and modifications assuming validity of underlying assumptions
  - never lose sight of the assumptions
  - once the original designer is gone, tests become sacred

- Acceleration requires taking at least one factor outside of its natural range
  - e.g. reducing down time decreases effects of diffusion
  - use lessons from Step 2 to understand risk
  - avoid going through a phase transition
  - verify that the failure mechanism is the same as field samples

- Acceleration must be rational
  - it should follow from lessons from Step 2
  - avoid or understand sources of “free” acceleration
  - don’t be too greedy: ADT is very hard HADT can be just silly

- May not be able to get the full story from one set of conditions
Hydrolytic stability

- Plastic PV front sheet application
- 7-10 mil films of polycarbonate, Melinex PET, and resorcinol polyarylate
- Test by bend around ¼” diameter rod
- Constant humidity jars at 95, 83, 75, 50, (23) %RH
- In ovens at 95, 85, and 75 °C

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<th>RH (%)</th>
<th>PC (days)</th>
<th>PET-A (days)</th>
<th>PET-B (days)</th>
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Hydrolytic stability

\[
\frac{1}{t_{\text{fail}}} = A \exp\left(-\frac{E_a}{RT}\right)[RH]^n
\]

- Found 1-hour parsed climatic data (Typical Meteorological Year)
- Used models for to calculate PV module temperature & RH for each hour
- Calculate progress toward failure for each hour of year
- Add it up to find progress toward failure for each year
- Calculate # of years to get to failure

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<th>PET</th>
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<td>(E_a) (kcal/mol)</td>
<td>22.1</td>
<td>30.5</td>
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<td>(\ln(A))</td>
<td>25.2</td>
<td>38.7</td>
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<td>(n)</td>
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<td>predicted life (years)</td>
<td>837</td>
<td>1023</td>
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Folly of the qualification test

- 85 °C and 85% RH (1000 hours) carved into stone
- But… need two more pieces of information to be useful
  - slope ($E_a$, assuming Arrhenius extrapolation is valid)
  - effective use temperature and other conditions
- PC hydrolysis slower than PET at 85 °C, but faster < 43 °C
Other examples

- **Coatings on polycarbonate**
  - lifetime limited by UV absorber stability
  - find loss rate in 1-2 months testing, predict max. lifetime

\[
t_{\text{fail}} = \frac{1}{k} \log_{10} \left[ \frac{10^{kD_{\text{fail}}} + T_0 - 1}{T_0} \right]
\]

- \( k \) is UVA loss rate
- \( T_0 \) is initial transmission
- \( D_{\text{fail}} \) is transmitted UV dose to cause failure


- **Predictive accelerated weathering of engineering thermoplastics**
  - examined effects of UV source, temperature, moisture
  - critical to get lamp spectrum right
  - critical to get “rain” right
  - found conditions that will predict Miami weathering \( \pm 20\% \) at 95% confidence for certain classes of engineering thermoplastics
  - no guarantee it works outside of these classes of materials
Technical needs and challenges

- **Characterization of use environments**
  - measurements, sensors, and modeling of harsh environments
  - characterization of actual duty cycles
  - data sets useful for cumulative damage models (like meteorological data sets)

- **Methods for multi-variable testing**
  - “combinatorial” testing
  - apply multiple stresses simultaneously at several levels with high throughput

- **Define useful mechanical data that can be obtained non-destructively or on very small samples**

- **Define measurable changes that underlie failure mechanisms**
  - enables kinetic models for predicting failure
  - e.g. what are the measurable chemical and physical changes that lead to adhesion failure?
  - can sensors be developed to measure these changes early and easily?

- **Characterization of changes observed in field-aged or failed samples**
Conclusions

• **We should abandon quest for the holy grail of tests**
  - has not worked for > 50 years
  - *cannot* work across multiple materials
  - must separate *qualification* testing from *lifetime* testing

• **Recognize lifetime prediction as a science problem**
  - multiple variables under multiple levels
  - develop models that make chemical and physical sense
  - know where acceleration is coming from
  - never lose sight of the assumptions