



Lifetime prediction— why is this so hard?

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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

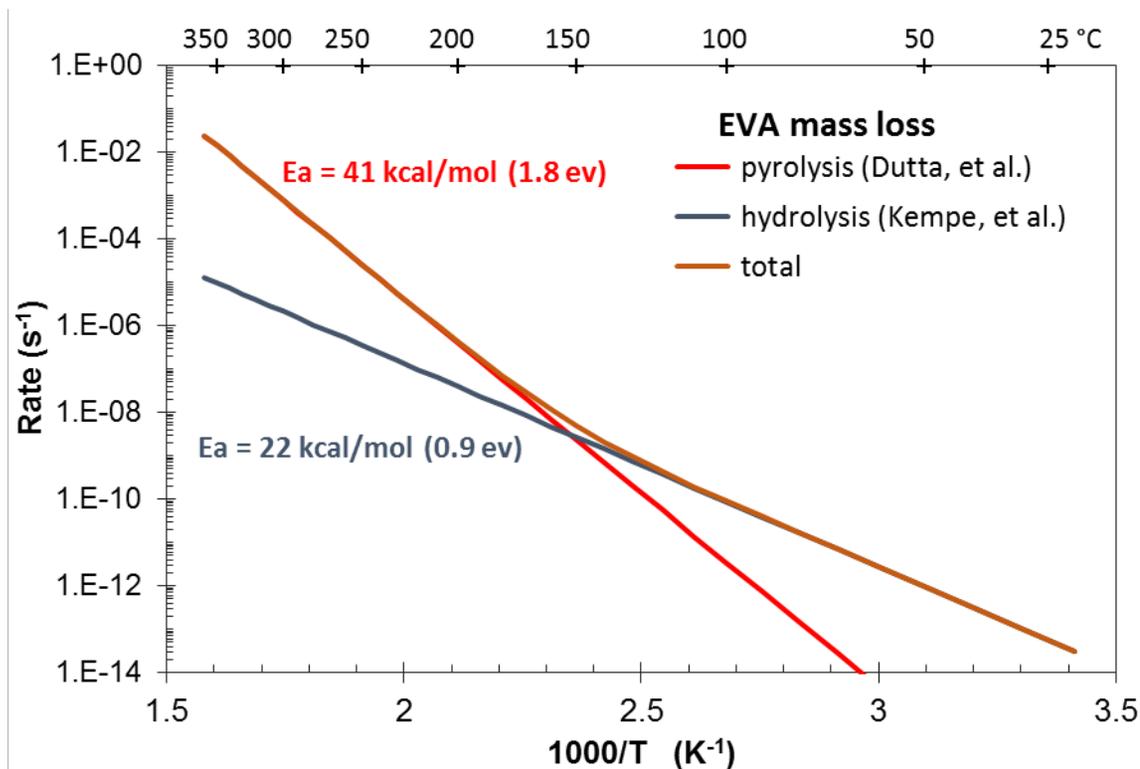
There is no such thing as accelerated **life** tests,
only accelerated **degradation** tests



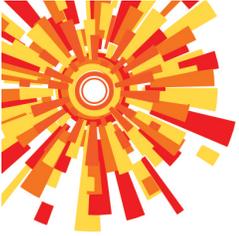
How mechanisms change

- 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*”

$$k = A_1 \exp(-E_{a1}/RT) + A_2 \exp(-E_{a2}/RT) + \dots$$

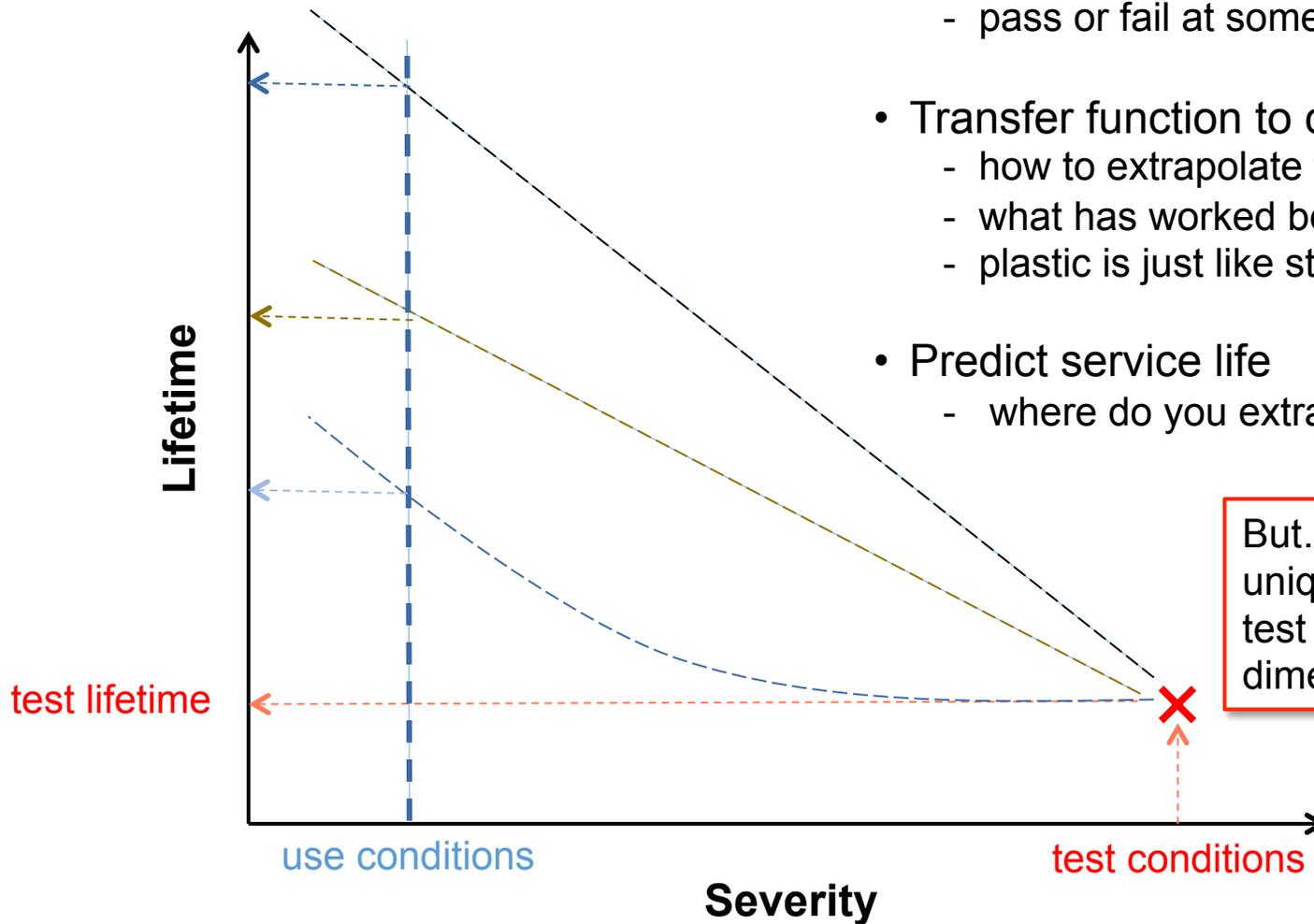


See papers by Gillen, Celina, Clough
e.g. *Polymer* **46** (2005) 11648–11654

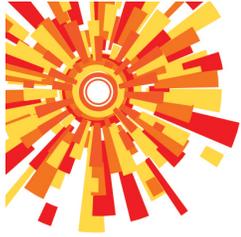


The *status quo*

- 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?

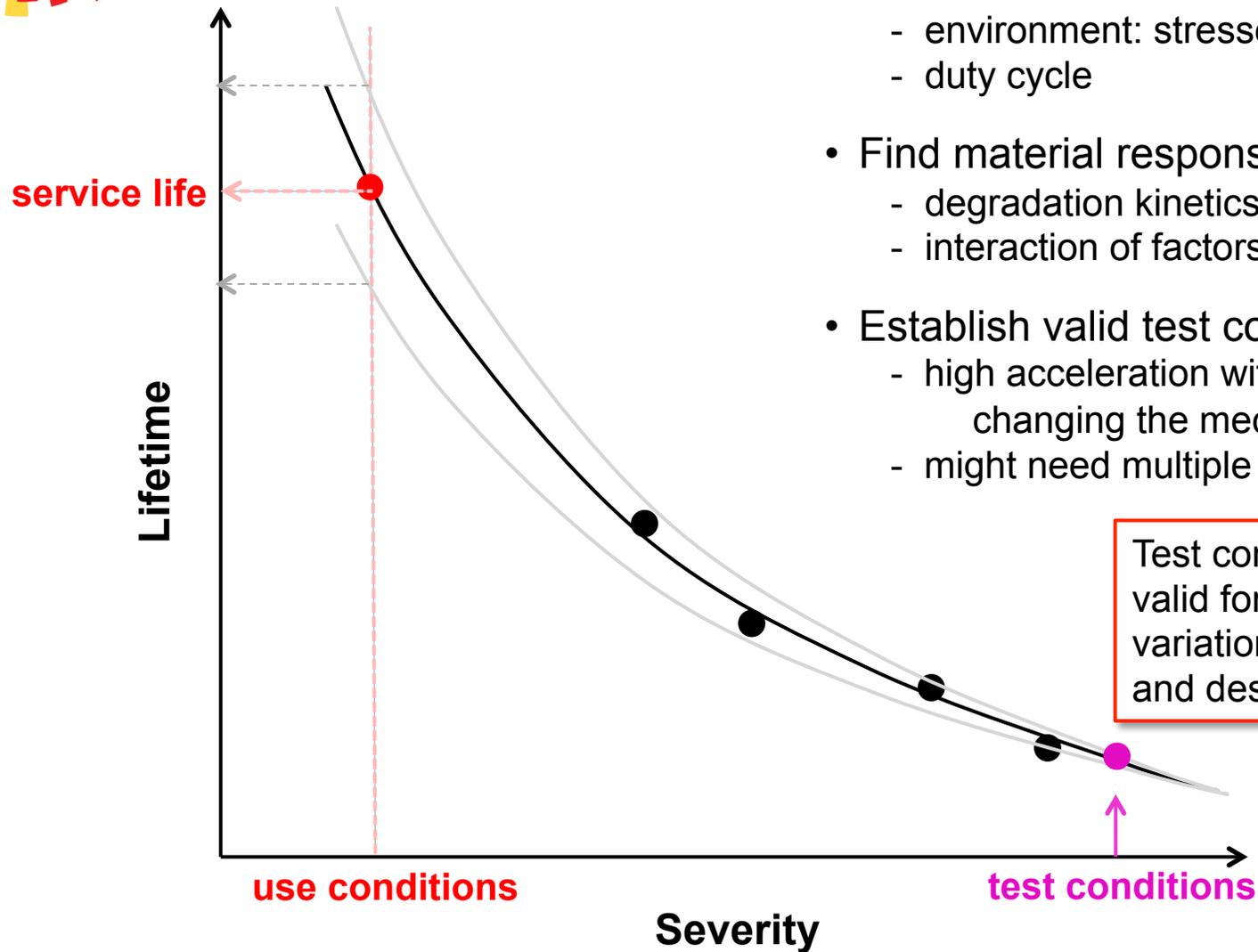


But... there may be no unique path connecting test to use in this multi-dimensional space



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





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

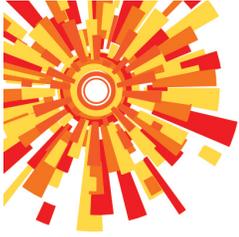
- Plastic PV front sheet application
- 7-10 mil films of polycarbonate, Melinex PET, and resorcinol polyarylate
- Test by bend around ¼” diameter rod
- Constant humidity jars at 95, 83, 75, 50, (23) %RH
- In ovens at 95, 85, and 75 °C

temp (°C)	RH (%)	PC (days)	PET-A (days)	PET-B (days)	PET-C (days)	PET-D (days)	RPA-A (days)	RPA-B (days)	RPA-C (days)
95	95	182	21	25	21	19	11	21	32
	83	206	25	28	25	25	14	28	35
	75	245	32	28	32	28	19	35	42
	65	357	56	49	49	49	25	63	70
	50	560	70	63	63	63	28	77	88
	23	-	119	112	112	102	102	140	168
85	95	399	84	84	84	77	28	63	-
	85	483	98	98	98	70	42	77	-
	83	469	98	105	98	98	42	98	-
	75	591	126	133	126	105	49	112	-
	65	907	207	207	207	175	84	178	-
	50	1301	266	266	266	231	105	259	-
75	95	907	231	221	231	207	84	154	-
	83	-	294	287	294	252	112	210	-
	75	-	357	343	357	280	112	-	-
65	95	-	-	-	-	-	189	-	-

Polymer Degradation and Stability, **98**, 1311-1320 (2013);

Service Life Prediction of Exterior Plastics. Vision for the Future, C.C. White et al., Eds., Springer (2015)

Kempe and Wohlgemuth, NREL PV Module Reliability Workshop, Golden Colorado, February 26-27, 2013.



Hydrolytic stability

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

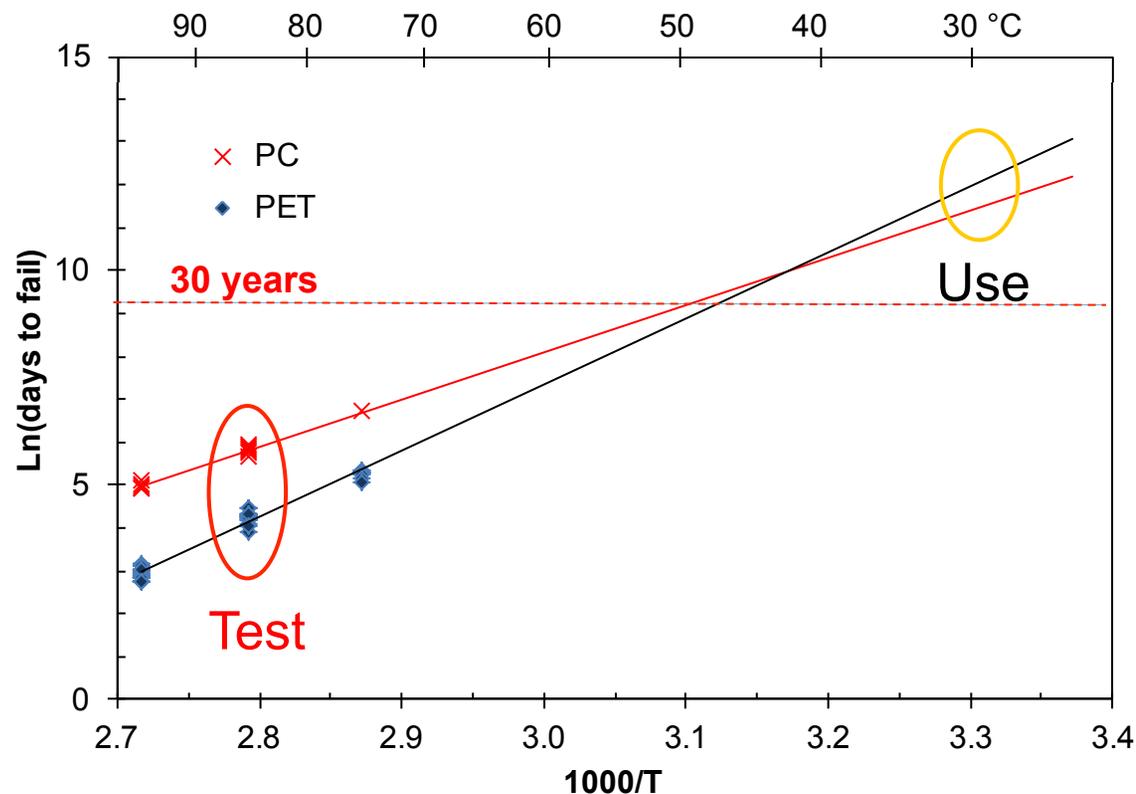
- Found 1-hour parsed climatic data (Typical Meteorological Year)
- Used models for to calculate PV module temperature & RH for each hour
- Calculate progress toward failure for each hour of year
- Add it up to find progress toward failure for each year
- Calculate # of years to get to failure

	PC	PET
E_a (kcal/mol)	22.1	30.5
$\ln(A)$	25.2	38.7
n	2	2
predicted life (years)	837	1023



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

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

k is UVA loss rate
 T_0 is initial transmission
 D_{fail} is transmitted UV dose to cause failure

- *Journal of Testing and Evaluation*, **32**, 240-245 (2004).

- 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
 - in **Service Life Prediction: Challenging the Status Quo**,
Federation of Societies for Coatings Technology (2005) pp. 93-10



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