Engineering Laboratory

Service Life Prediction of Sealant Materials

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Building Envelope

- Separating the inside from the outside requires unique properties of polymers.
- Energy, moisture, comfort, security.

IAC building in NY, cold warped curtain wall glass panels

- Modern building techniques constantly challenge the performance envelope of these critical, unique building materials.
- Polymers change during exposure.
- The lifetime or rate of change of these materials dramatically affects the economics of built structures.

- **Two parts:**
  Economics of Material Durability
  State of Art in Service Life Prediction.

Service Life Prediction.

How much does durability really cost?

What are the hidden costs of up-front materials choices?

To investigate this, let us look at an typical example.

Successful small business. Growing to 90 employees. Need new space.

~10% of all firms are in this category, 500k firms.

How much space do you need?

Assume 500 ft^2/employee.

Need a building that is 34 m on a side.
eight stories tall.

So this is 40 km^3 of volume.

Need to build this new building.

Let us just consider the decisions and consequences surrounding the choice of sealant for this building

Call in the consultant.

- How much does it cost to seal this building?

Count the number of windows, other elements. Add up the total linear feet of sealant.

Each module there is 17m of sealant.
Entire building needs 8.2 km of sealant.
Assume a 1.9 cm x 1.6 cm joint

Assume 305 ml cartridge will seal 0.8m. (20% waste)

Need 6,102 cartridges.

Call in the consultant.

- Which sealant to buy?

Sealant ranges from $2 -$7 cartridge.
So initial materials cost decision is spend $12k or spend $43k?

Is there a link between cost and performance?

How long will each of these sealants last?

This is larger problem: There is no effective method to determine the durability of the installed product. We do know from field studies: 50% fails within 10 years, 95% fails in 20 years

Install the Material.

- During the hectic construction process, the someone makes a materials selection decision.

How much does it cost to install?

New installation cost **$4/30.5cm**

retrofit costs **$8/30cm**.

So now we need to spend **$110k** on labor for the first install or **$220k** to retrofit the building.

Take out a loan.

- What is the initial cost to seal the building?
  - Labor $110k, materials $12k for a total of $122k.
- Instead of paying cash, we take out a 10 year loan.
  - Assume a discount rate of 6%.
  - Each year we need to pay $20,727 to pay off the loan.
  - These payments are in years 1-10.

Take out a loan

- What is the initi
  - Labor $110k, m
- Instead of paying ca ar loan.
  - Assume a discount rate of 6%.
  - Each year we need to pay $20,727 to pay off the loan.
  - These payments are in years 1-10.

The Materials Cost is 10% of the total cost!!

Year 3

- In year 3, the building starts leaking, the employees are unhappy.

So you need to reseal the building.

Now it costs $ 12k for materials, and $220k for labor.

To pay for it you take out another 10 year loan

Expenses related to Sealing.

# of years of value	1	0	
Materials replcement			
1	($12,000.00)	($20,726.66)	
2		($20,726.66)	
3		($20,726.66)	
4	($12,000.00)	($20,726.66)	($35,649.85)
5		($20,726.66)	($35,649.85)
6		($20,726.66)	($35,649.85)
7		($20,726.66)	($35,649.85)
8		($20,726.66)	($35,649.85)
9		($20,726.66)	($35,649.85)
10		($20,726.66)	($35,649.85)
11			($35,649.85)
12			($35,649.85)
13			($35,649.85)
14			

Pattern continues:

		Loan 1	Loan 2	Loan 3	Loan 4	Loan 5	Loan 6	Loan 7	Loan 8	Loan 9
1	12,000.00	($20,726.66)								
2		($20,726.66)								
3		($20,726.66)								
4	12,000.00	($20,726.66)	($35,649.85)							
5		($20,726.66)	($35,649.85)							
6		($20,726.66)	($35,649.85)							
7	12,000.00	($20,726.66)	($35,649.85)	($35,649.85)						
8		($20,726.66)	($35,649.85)	($35,649.85)						
9		($20,726.66)	($35,649.85)	($35,649.85)						
10	12,000.00	($20,726.66)	($35,649.85)	($35,649.85)	($35,649.85)					
11			($35,649.85)	($35,649.85)	($35,649.85)					
12			($35,649.85)	($35,649.85)	($35,649.85)					
13	12,000.00		($35,649.85)	($35,649.85)	($35,649.85)	($35,649.85)				
14				($35,649.85)	($35,649.85)	($35,649.85)				
15				($35,649.85)	($35,649.85)	($35,649.85)				
16	12,000.00			($35,649.85)	($35,649.85)	($35,649.85)	($35,649.85)			
17					($35,649.85)	($35,649.85)	($35,649.85)			
18					($35,649.85)	($35,649.85)	($35,649.85)			
19	12,000.00				($35,649.85)	($35,649.85)	($35,649.85)	($35,649.85)		
20						($35,649.85)	($35,649.85)	($35,649.85)		
21						($35,649.85)	($35,649.85)	($35,649.85)		
22	12,000.00					($35,649.85)	($35,649.85)	($35,649.85)	($35,649.85)	
23						($35,649.85)	($35,649.85)	($35,649.85)	($35,649.85)	
24							($35,649.85)	($35,649.85)	($35,649.85)	
25	12,000.00						($35,649.85)	($35,649.85)	($35,649.85)	($35,649.85)
	$81,620.31							($35,649.85)	($35,649.85)	($35,649.85)
								($35,649.85)	($35,649.85)	($35,649.85)
								($35,649.85)	($35,649.85)	($35,649.85)
									($35,649.85)	($35,649.85)
									($35,649.85)	($35,649.85)
									($35,649.85)	($35,649.85)
										($35,649.85)
										($35,649.85)
										($35,649.85)

So how much did it cost?

- 25 year study period
- $81k on materials,
- $964k on Labor
- Payments due of $513k
- But there are still is $179K of value left in the sealing job.
- So it has cost you $1.4M to keep the building sealed for 25 years.

What if the material lasted 10 years?

- 25 year study period
- $32k on materials,
- $252k on Labor
- Payments due of $125k
- But there are still is $125K of value left in the sealing job.
- So it has cost you $283k to keep the building sealed for 25 years.

What if the material lasted 20 years?

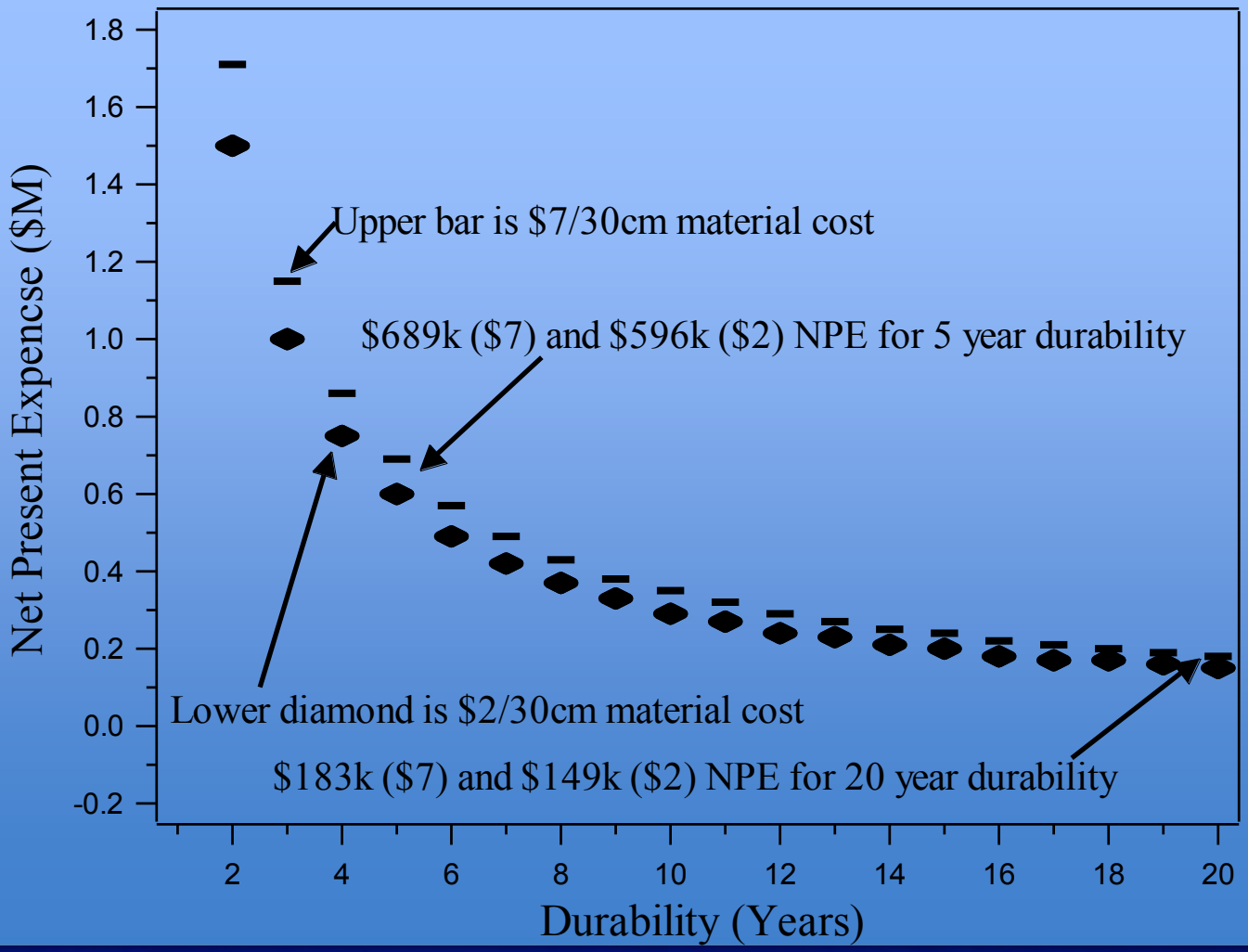
- 25 year study period
- $22k on materials,
- $126k on Labor
- Payments due of $126k
- But there are still is $186K of value left in the sealing job.
- So it has cost you $148k to keep the building sealed for 25 years.

So what is an additional year of durability worth?

- Depends on the current durability.

Yeas of Durability	25 year NPV	Savings
7	($404,857)	
8	($354,136)	$50,721
9	($314,957)	$89,900
10	($283,905)	$120,952
11	($262,346)	$142,511
12	($237,363)	$167,494
13	($219,885)	$184,972
14	($205,315)	$199,542

Increased Durability yields significant savings.



Why not increased durability?

- There is no test method to effectively measure durability.
- That materials decision impacts durability, but there is no accurate method to determine durability.
- If you cannot measure it, you cannot control it.

State of Art in Service Life Prediction.

How is it done now?

I. Product Approval
   - ASTM, RILEM, ISO,
   - Threshold Methods

II. Product Development
   - Outdoor Weathering
   - “Acceleration Factors”

Threshold Test:

ASTM- C 719 Hockman Cycle

- Developed 40 years ago.
- **Static Cure of sealant joint 21 days.**
- Immersion in water, for 7 days,
- Oven(7 Days)
- Cyclic movement @ room temp
- Movement at Elevated Temp
- Evaluate with Visual Inspection.

In Service:

Typical House movement

- 7.5% of joint width/day
- 25% seasonally.

So a installation would
See 7.5% within 24h
And 25% over months.

Commercial buildings
Depends on design,
Up to 400% movement

Conventional SLP Metrology

Outdoor Timed exposure

Just comparing outdoor with indoor- no model of behavior

Make **Visual** Comparison
Outdoor exposure
Vs.
"Accelerated" exposure

Indoor timed exposure

No Correlation; No Mechanism
Adjust Accelerated
Again Factors.

There has got to be a better way…

- Has any other field of science looked at service life prediction?
- **Reliability-Based Metrology**
  - **1800's Actuarial Science, Insurance**
  - **1960's Aeronautics, Space, Nuclear**
  - **1970's Electronics**
  - **1990's Automotive**

Reliability-Based SLP Methodology

Instrumented Outdoor Exposure

Cumulative Dosage Model

$$D_{total}(t) = \int_0^{\lambda} \int_{\lambda_{min}}^{\lambda_{max}} E_0(\lambda,t)\left(1-10^{-A(\lambda)}\right)\phi(\lambda)\,d\lambda\,dt$$

Damage Mechanism

Databases

SLP Estimate

Laboratory

Moisture

Material Response

Temperature

Characterize the Service Environment

What are the Factors that Most Affect Sealant Durability?

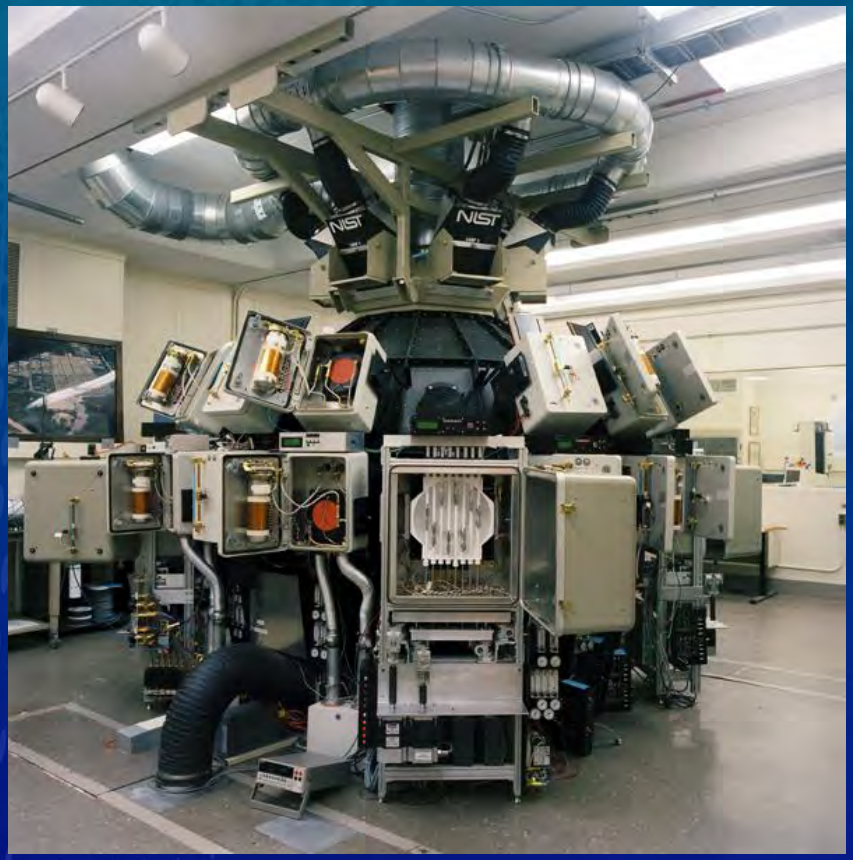
From 1999 State of the Art Report: (Rilem/ASTM)

- Moisture/Relative Humidity.
- Temperature
- Ultra Violet Radiation
- Mechanical Loading

} DOSE

How does mechanical loading, especially for an elastomer affect durability?

Creating Controlled Dosage



SPHERE: Simulated Photodegradation by High Energy Radiant Exposure

Lots of Light
- Stabile to limit of detection
- Uniformity >95 %

Temperature ± 0.1 C

Humidity ± 0.2%

32 Chambers, 17 samples/chamber

>500 samples at a time.

Use DOE to look at all correlations of **Temp, Humidity, UV, & Load**

How do Biologists think about skin exposure?

- Dose versus Damage.
  - 1 hour x 1 “sun” = 8 hours with SPF 8.

So why not:

  - 1 hour x 8 “suns” = 8 hours x 1 “sun”

Two issues:
Reciprocity- Medical Literature and Photography
Action Spectra – Well Defined in the Literature.

Biological Cumulative Dosage Models

$$D_{total}(t) = \int_0^t \int_{\lambda_{min}}^{\lambda_{max}} E_o(\lambda, t)(1 - 10^{-A(\lambda)})\phi(\lambda) d\lambda \, dt$$

- D_{total} (t) = Dosage to material.
- λ_{min} and λ_{max} = minimum and maximum photolytically effective wavelengths
- $E_o(\lambda,t)$ = spectral UV irradiance from light source
- $(1-10^{-A(\lambda)})$ = spectral adsorption of specimen
- $\phi(\lambda)$ = spectral quantum yield of specimen
- $A(\lambda)$ = adsorption at wavelength λ

What does that mean?

- Total dose is important, not time or rate of exposure.

Not time based

Outdoor Aging (26 months)

?

=

Laboratory (2 weeks)

- New methods are not limited to one "Sun" of intensity.
- Much faster than real time.

Reliability-Based SLP Methodology

Instrumented Outdoor Exposure

Cumulative Dosage Model

$$D_{total}(t) = \int_0^{\lambda} \int_{\lambda_{min}}^{\lambda_{max}} E_0(\lambda,t)\left(1-10^{-A(\lambda)}\right)\phi(\lambda)\,d\lambda\,dt$$

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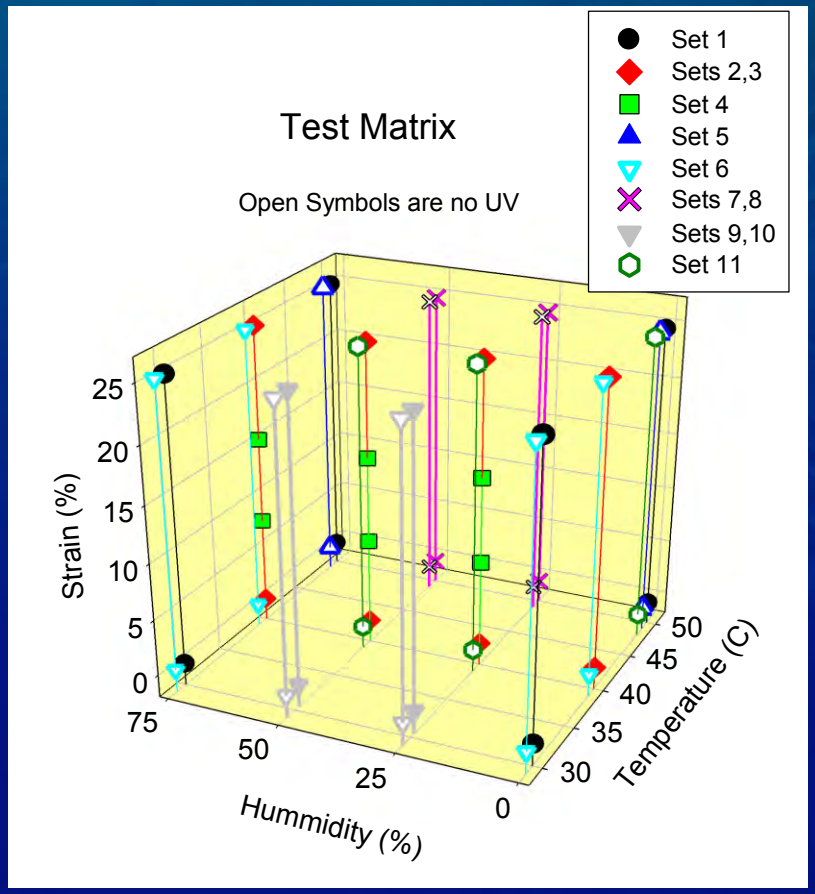
Data Sets for Analysis

- Data set given to Statistical Group.



56 data points
(4 samples/point)

224 samples points.

Data is >30C

Reliability-Based SLP Methodology

Instrumented Outdoor Exposure

Cumulative Dosage Model

$$D_{total}(t) = \int_0^{\lambda} \int_{\lambda_{min}}^{\lambda_{max}} E_b(\lambda,t)\left(1-10^{-A(\lambda)}\right) f(\lambda)\, d\lambda\, dt$$

Damage Mechanism

Databases

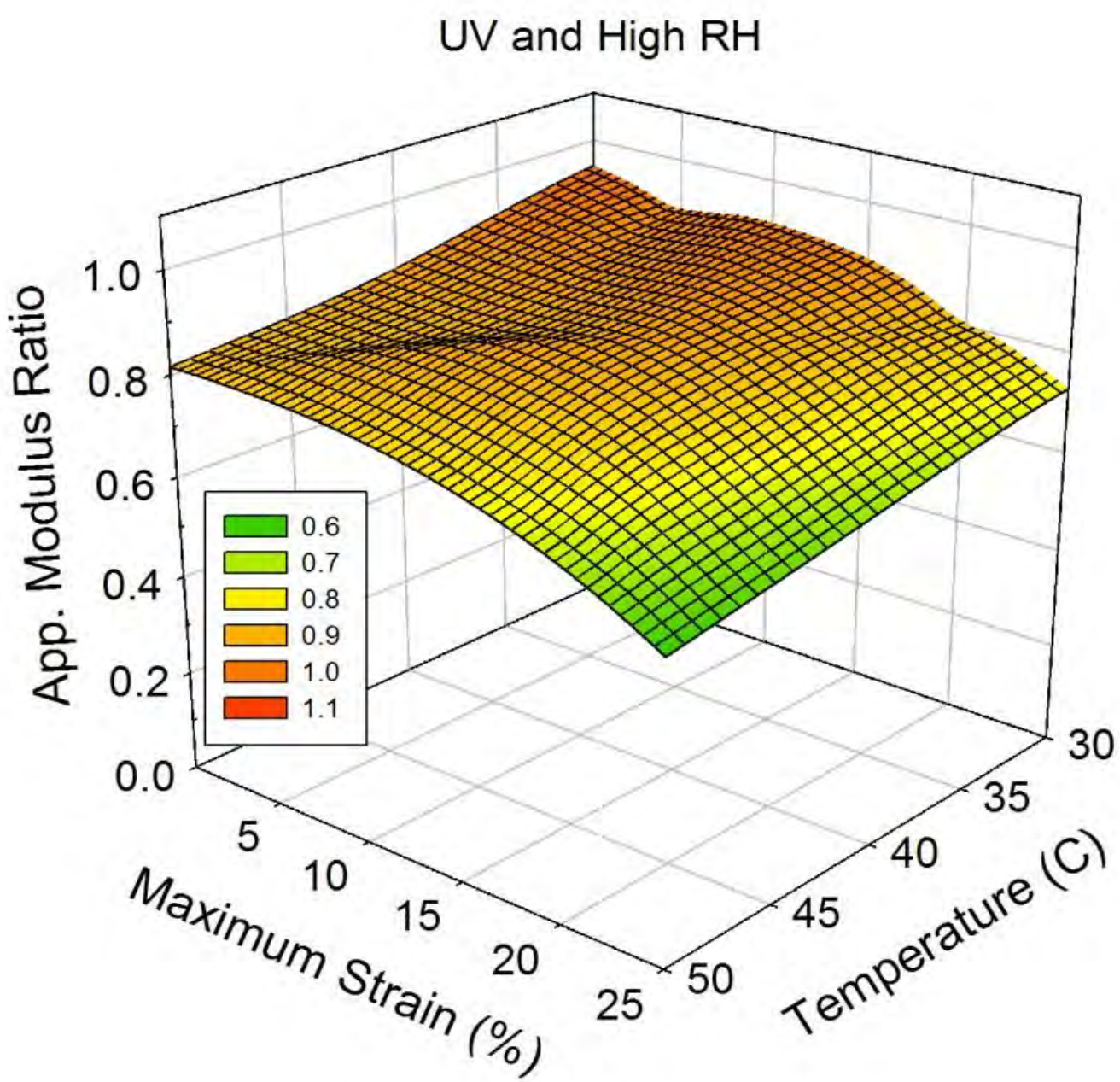
SLP Estimate

Laboratory

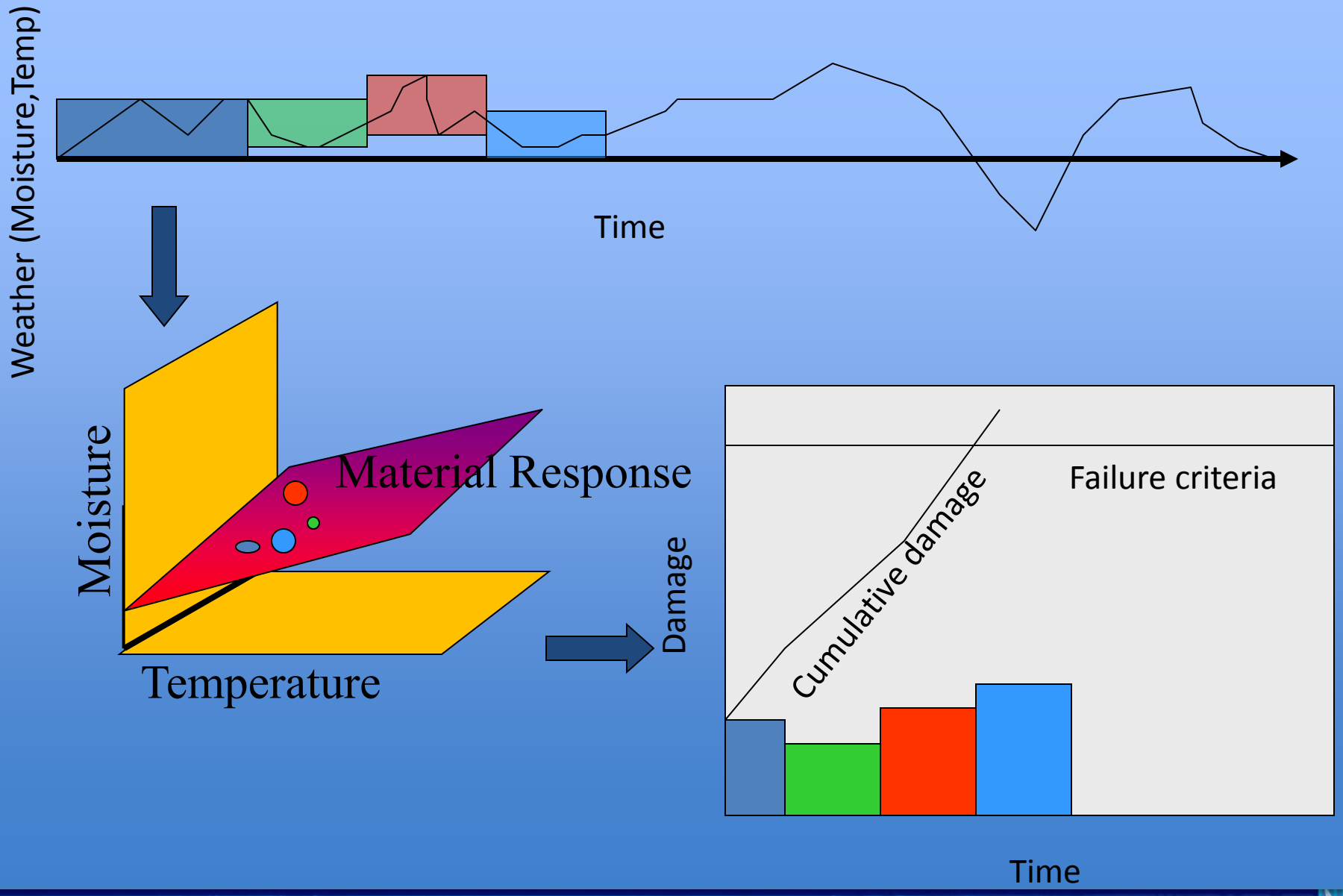
Moisture

Material Response

Temperature


UV and High RH
App. Modulus Ratio
1.0
0.8
0.6
0.4
0.2
0.0
0.6
0.7
0.8
0.9
1.0
1.1
5
10
15
20
25
Maximum Strain (%)
30
35
40
45
50
Temperature (C)

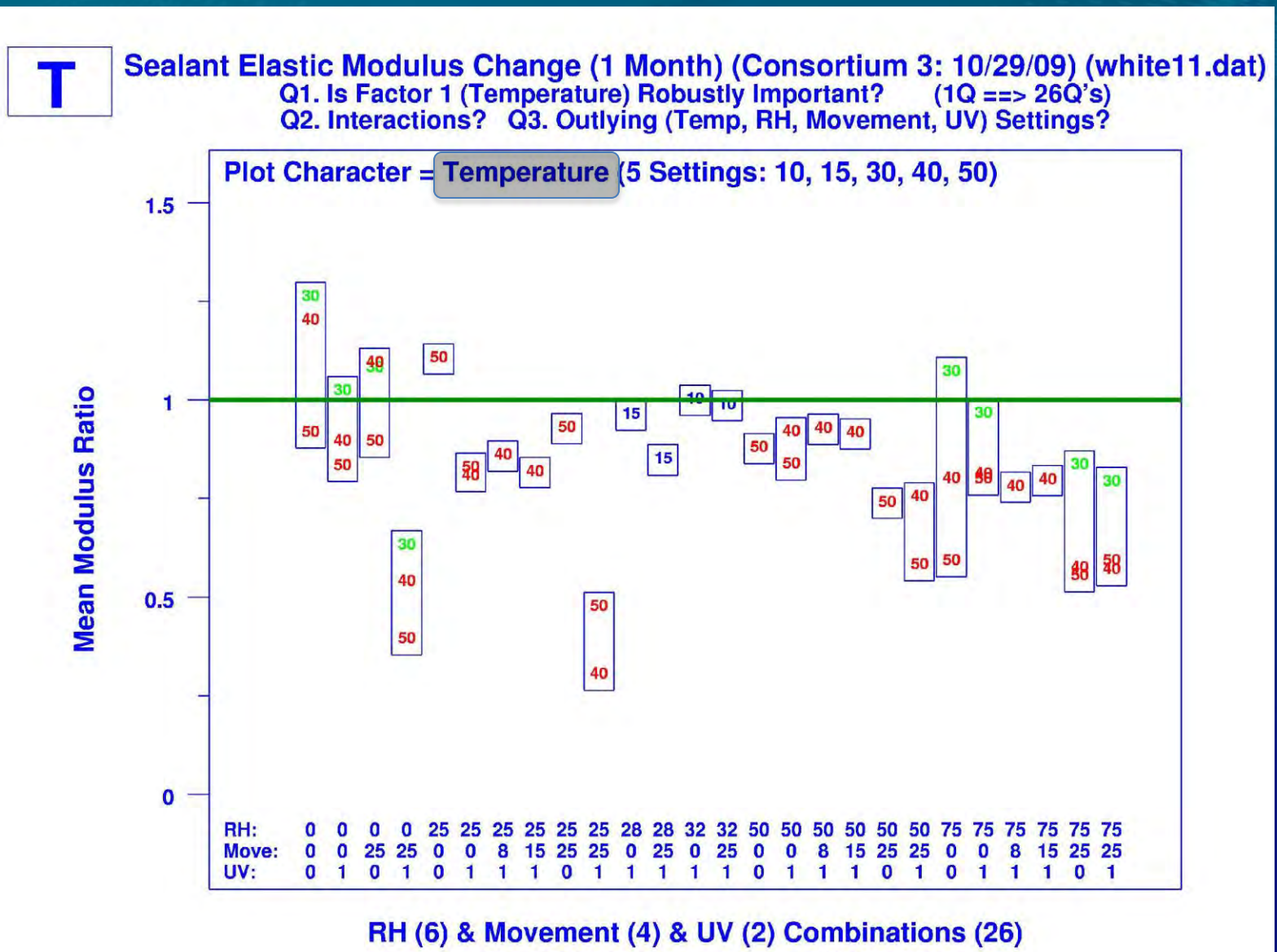
How this would work

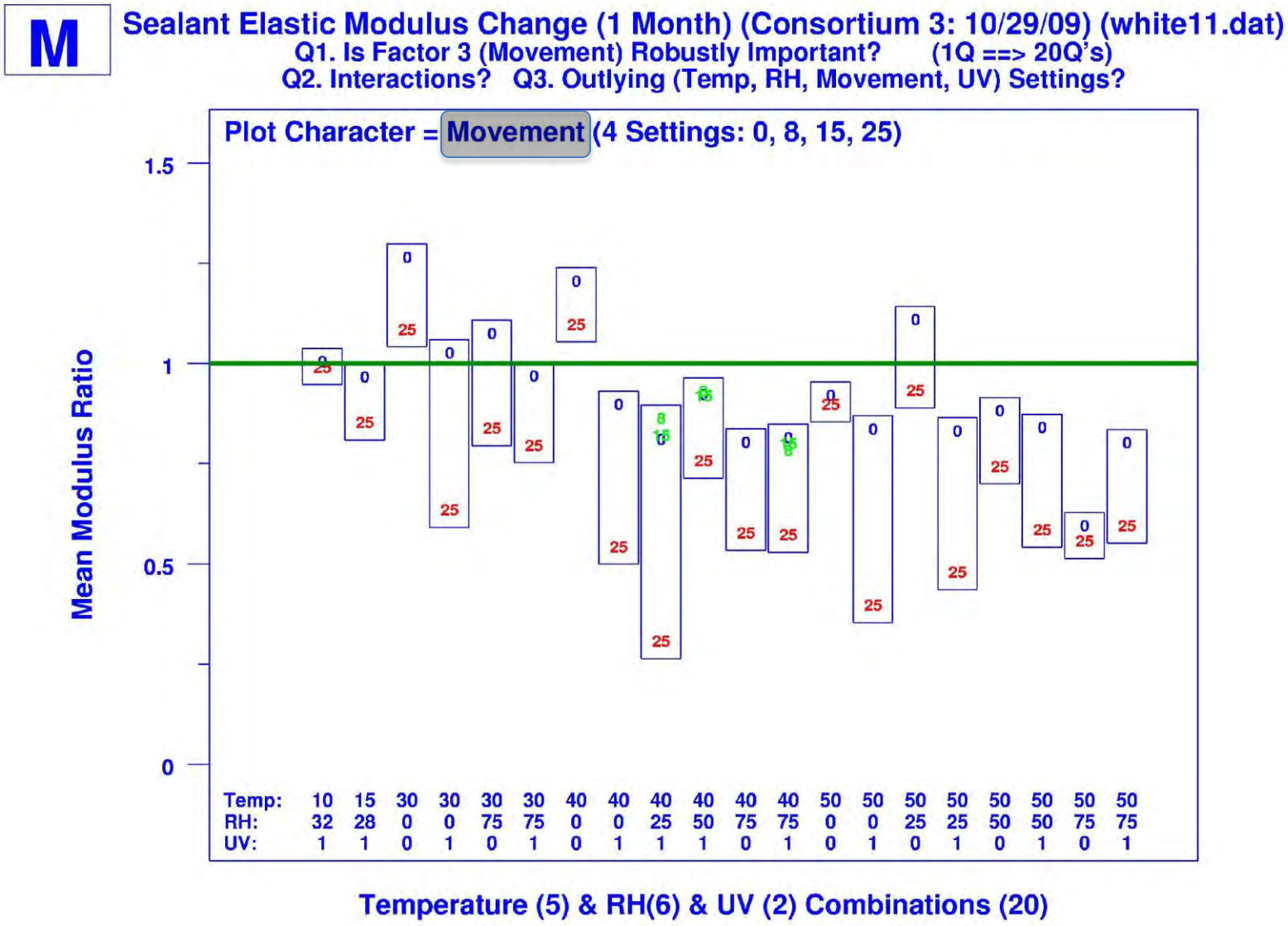


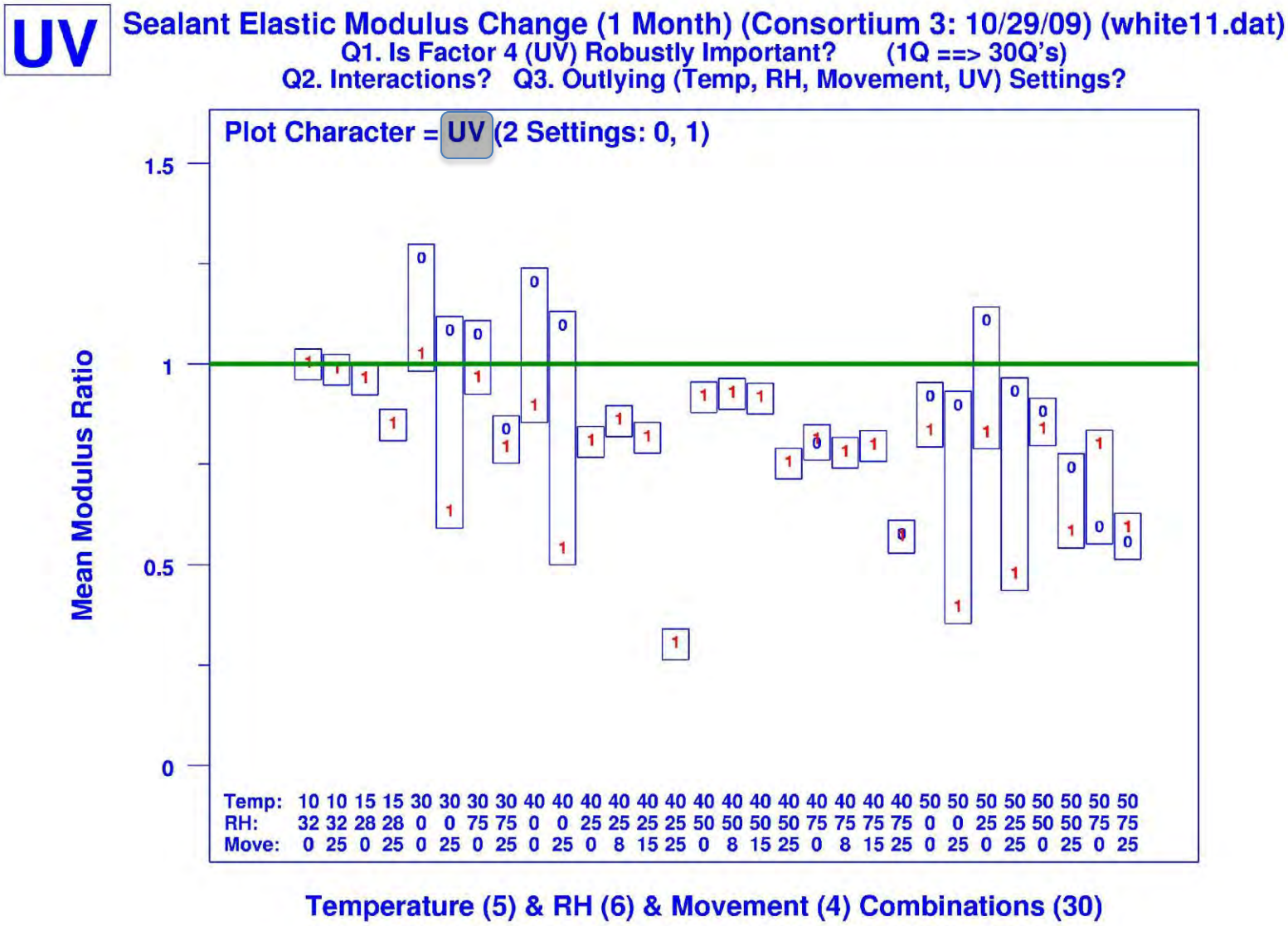
Real Statisticians model:

Some Analysis Techniques/Tools …

1. *ANOVA & t tests*
2. *Tukey test of non-additivity*
3. *Main effects plot*
4. *Multi-trace plots*
5. *Block plots*
6. *Best settings plots*
7. *Ordered settings plots*
8. *Tabular highlighting*


T
Sealant Elastic Modulus Change (1 Month) (Consortium 3: 10/29/09) (white11.dat)
Q1. Is Factor 1 (Temperature) Robustly Important? (1Q ==> 26Q's)
Q2. Interactions? Q3. Outlying (Temp, RH, Movement, UV) Settings?
Plot Character = Temperature (5 Settings: 10, 15, 30, 40, 50)
Mean Modulus Ratio
1.5
1
0.5
0
RH: 0 0 0 0 25 25 25 25 25 25 28 28 32 32 50 50 50 50 50 50 75 75 75 75 75 75
Move: 0 0 25 25 0 0 8 15 25 25 0 25 0 25 0 0 8 15 25 25 0 0 8 15 25 25
UV: 0 1 0 1 0 1 1 1 0 1 1 1 1 1 0 1 1 1 0 1 0 1 1 1 0 1
RH (6) & Movement (4) & UV (2) Combinations (26)


M
Sealant Elastic Modulus Change (1 Month) (Consortium 3: 10/29/09) (white11.dat)
Q1. Is Factor 3 (Movement) Robustly Important? (1Q ==> 20Q's)
Q2. Interactions? Q3. Outlying (Temp, RH, Movement, UV) Settings?
Plot Character = Movement (4 Settings: 0, 8, 15, 25)
Mean Modulus Ratio
1.5
1
0.5
0
Temp: 10 15 30 30 30 30 40 40 40 40 40 40 50 50 50 50 50 50 50 50
RH: 32 28 0 0 75 75 0 0 25 50 75 75 0 0 25 25 50 50 75 75
UV: 1 1 0 1 0 1 0 1 1 1 0 1 0 1 0 1 0 1 0 1
Temperature (5) & RH(6) & UV (2) Combinations (20)


UV
Sealant Elastic Modulus Change (1 Month) (Consortium 3: 10/29/09) (white11.dat)
Q1. Is Factor 4 (UV) Robustly Important? (1Q ==> 30Q's)
Q2. Interactions? Q3. Outlying (Temp, RH, Movement, UV) Settings?
Plot Character = UV (2 Settings: 0, 1)
Mean Modulus Ratio
1.5
1
0.5
0
Temp: 10 10 15 15 30 30 30 30 40 40 40 40 40 40 40 40 40 40 40 40 40 50 50 50 50 50 50 50 50
RH: 32 32 28 28 0 0 75 75 0 0 25 25 25 25 50 50 50 50 75 75 75 75 0 0 25 25 50 50 75 75
Move: 0 25 0 25 0 25 0 25 0 25 0 8 15 25 0 8 15 25 0 8 15 25 0 25 0 25 0 25 0 25
Temperature (5) & RH (6) & Movement (4) Combinations (30)

ANOVA

```
*** Analysis of Variance Model ***

aov(formula = Y ~ X1 + X2 + X3 + X5, data = Book2, na.action = na.exclude)


Terms:
                       X1       X2       X3       X5     Residuals

 Sum of Squares    0.69060  1.31257  1.92587  1.10464      26.83499
Deg. of Freedom          4        3        3        1           228


Residual standard error: 0.3430705

2 out of 14 effects not estimable
Estimated effects may be unbalanced

            Df Sum of Sq  Mean Sq  F Value       Pr(F)
      X1    4   0.69060 0.172651 1.466906   0.2131036
      X2    3   1.31257 0.437524 3.717369   0.0122131
      X3    3   1.92587 0.641956 5.454293   0.0012248
      X5    1   1.10464 1.104640 9.385429   0.0024503

Residuals 228  26.83499 0.117697
```

➔ **Ranked List**

1. **Move**
2. **UV**
3. **RH**
4. **Temp**

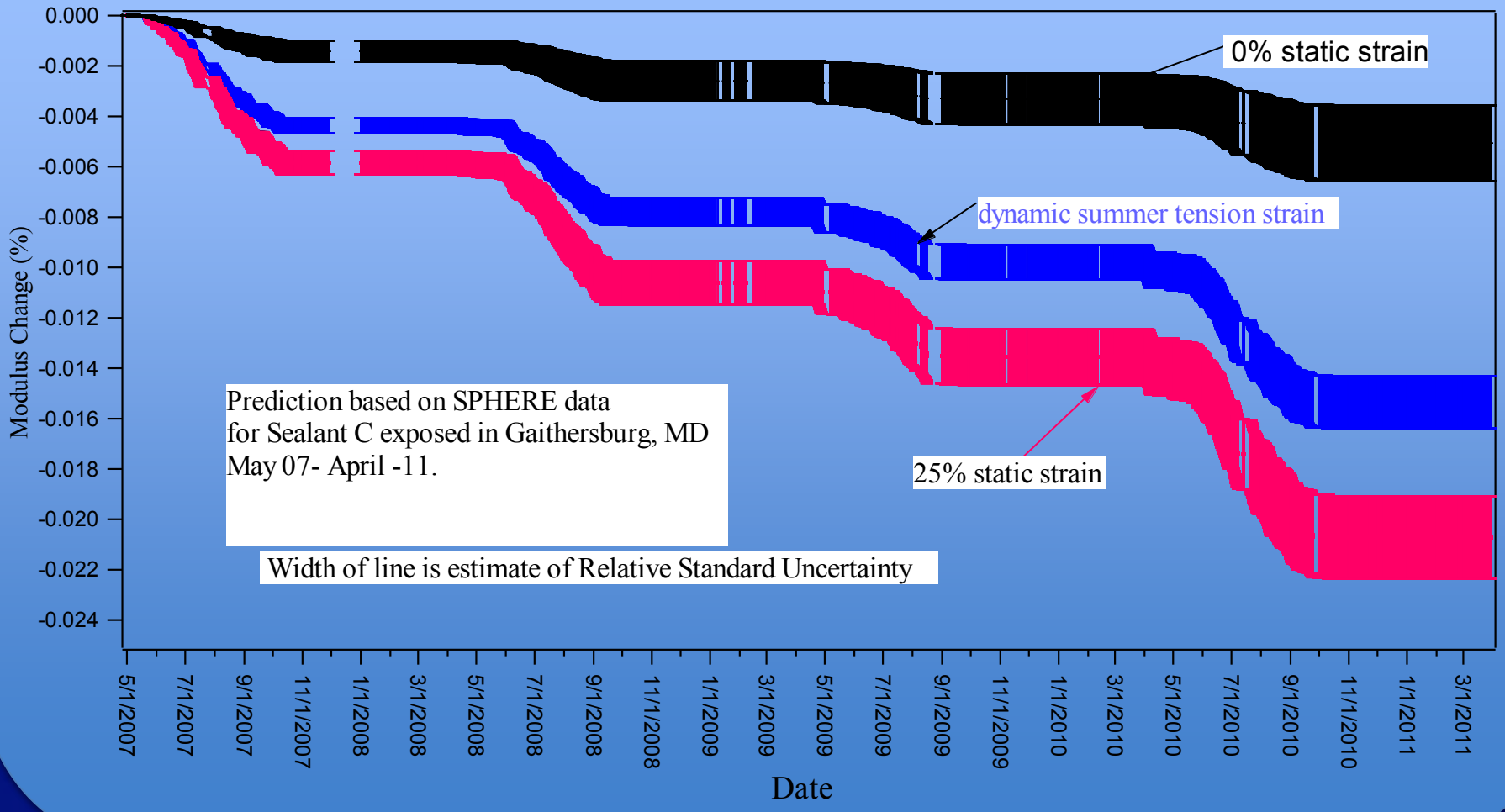
Temp
RH
Move
UV

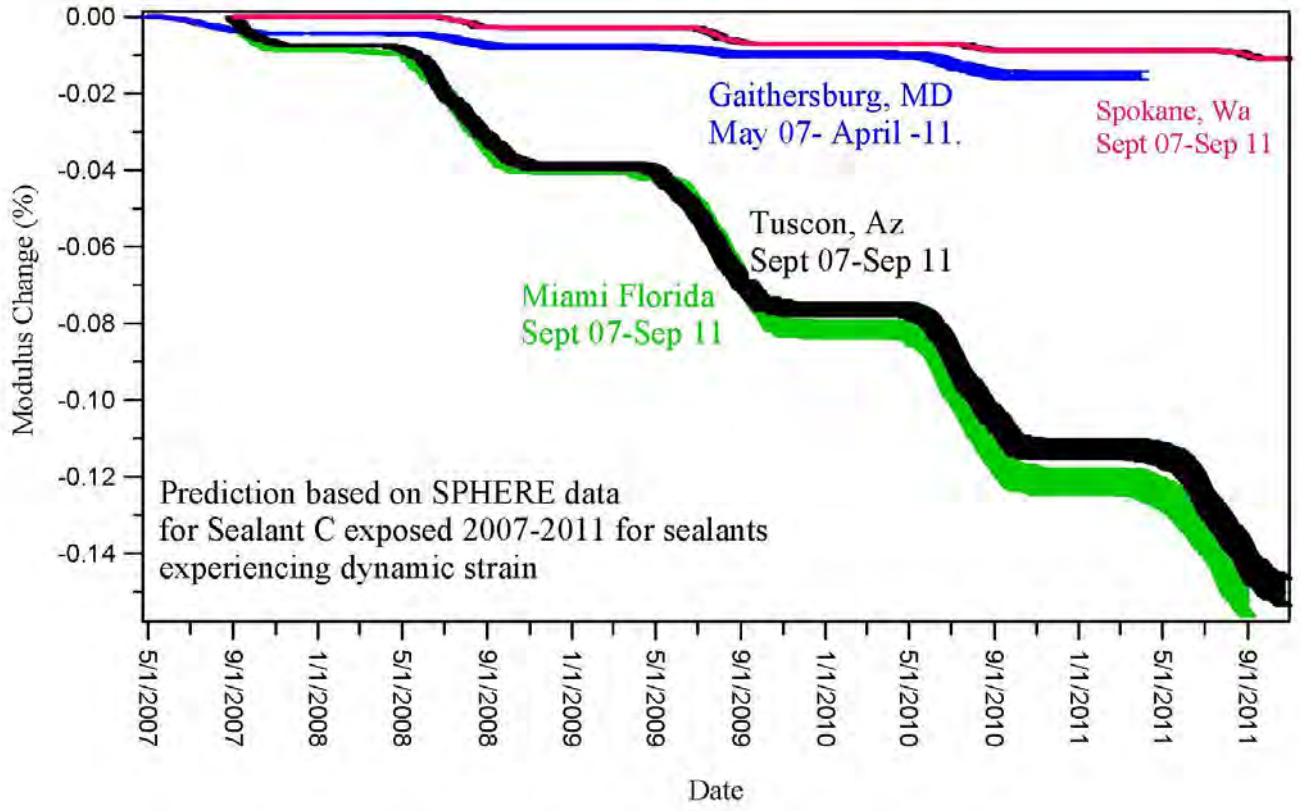
What about Service Life Prediction?

- What we really need is a **model** to predict in service performance in less than real time.
- Two goals:
  - Verify the assumption about the weather elements
  - Predict property change resulting from exposure.
    - Need high resolution, precise data for basis of model.
    - Use Statistical Smoothing to interpolate between data.

Model Prediction!!

Prediction of Modulus Change 2007-2011

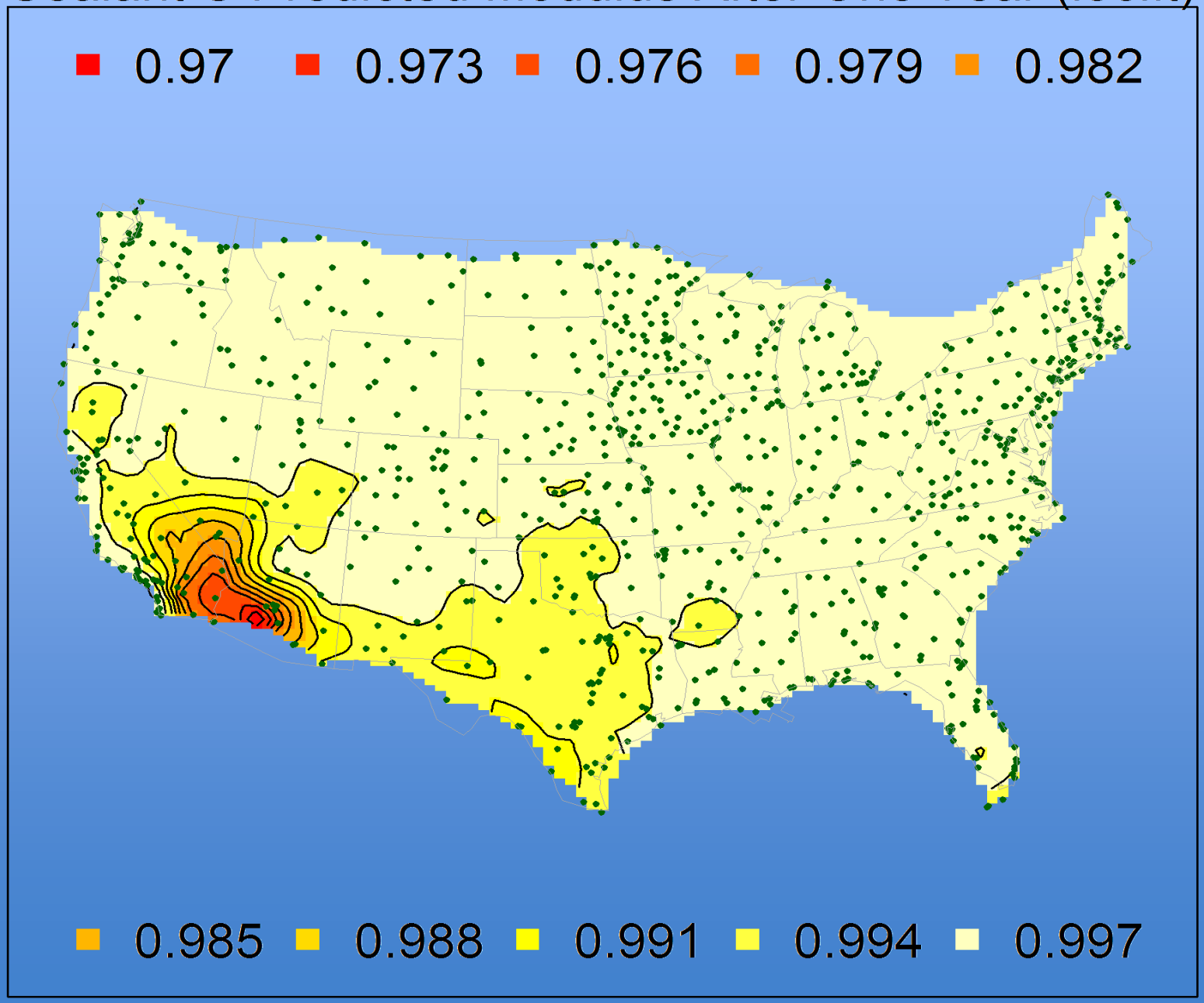



0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
Modulus Change (%)
Gaithersburg, MD
May 07- April -11.
Spokane, Wa
Sept 07-Sep 11
Tuscon, Az
Sept 07-Sep 11
Miami Florida
Sept 07-Sep 11
Prediction based on SPHERE data
for Sealant C exposed 2007-2011 for sealants
experiencing dynamic strain
5/1/2007
9/1/2007
1/1/2008
5/1/2008
9/1/2008
1/1/2009
5/1/2009
9/1/2009
1/1/2010
5/1/2010
9/1/2010
1/1/2011
5/1/2011
9/1/2011
Date

Energy Plus Simulation Software.

- **EnergyPlus Key Capabilities**
- The following is a representative list of EnergyPlus capabilities:
- **Integrated, simultaneous solution** where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- **ASCII text based weather, input, and output files** that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively
- Lots (1000's) of weather stations across the US….

Sealant C Predicted Modulus After One Year (locfit)



Summary.

Significant downstream economic costs for the lack of knowledge of durability.

- Most of those costs are labor
- Lack the ability to make accurate economic efficient materials decisions.
- Even a small change in durability from 7 yrs to 10 years. Yields 30% gain in economic efficiency ($129k out of $404k NPE).

New research should produce a test method to establish durability estimates in the near future.

Building Envelope

- Separating the inside from the outside requires unique properties of polymers.
- Energy, moisture, comfort, security.

IAC building in NY, cold warped curtain wall glass panels

- Modern building techniques constantly challenge the performance envelope of these critical, unique building materials.
- Polymers change during exposure.
- The lifetime or rate of change of these materials dramatically affects the economics of built structures.

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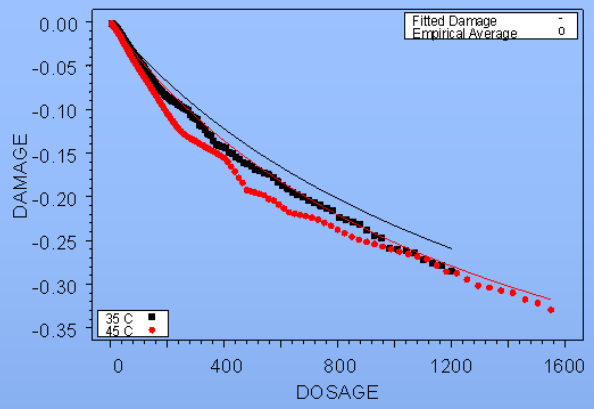
Need to Validate these predictions.

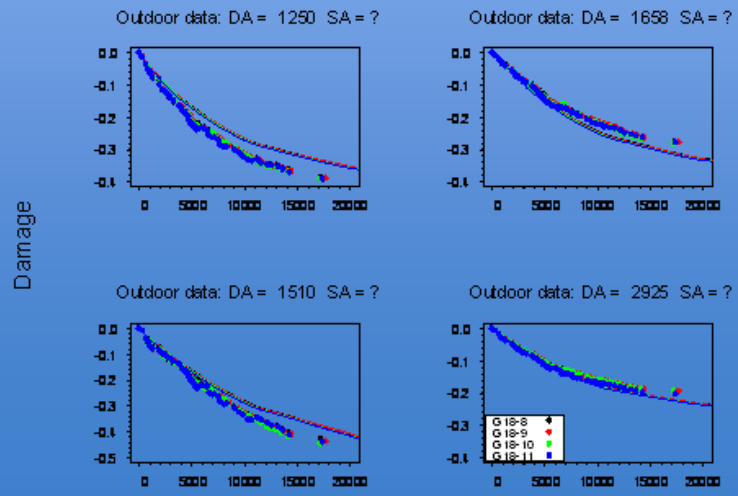
- Has it been done elsewhere?
- Coatings.

Other Systems?

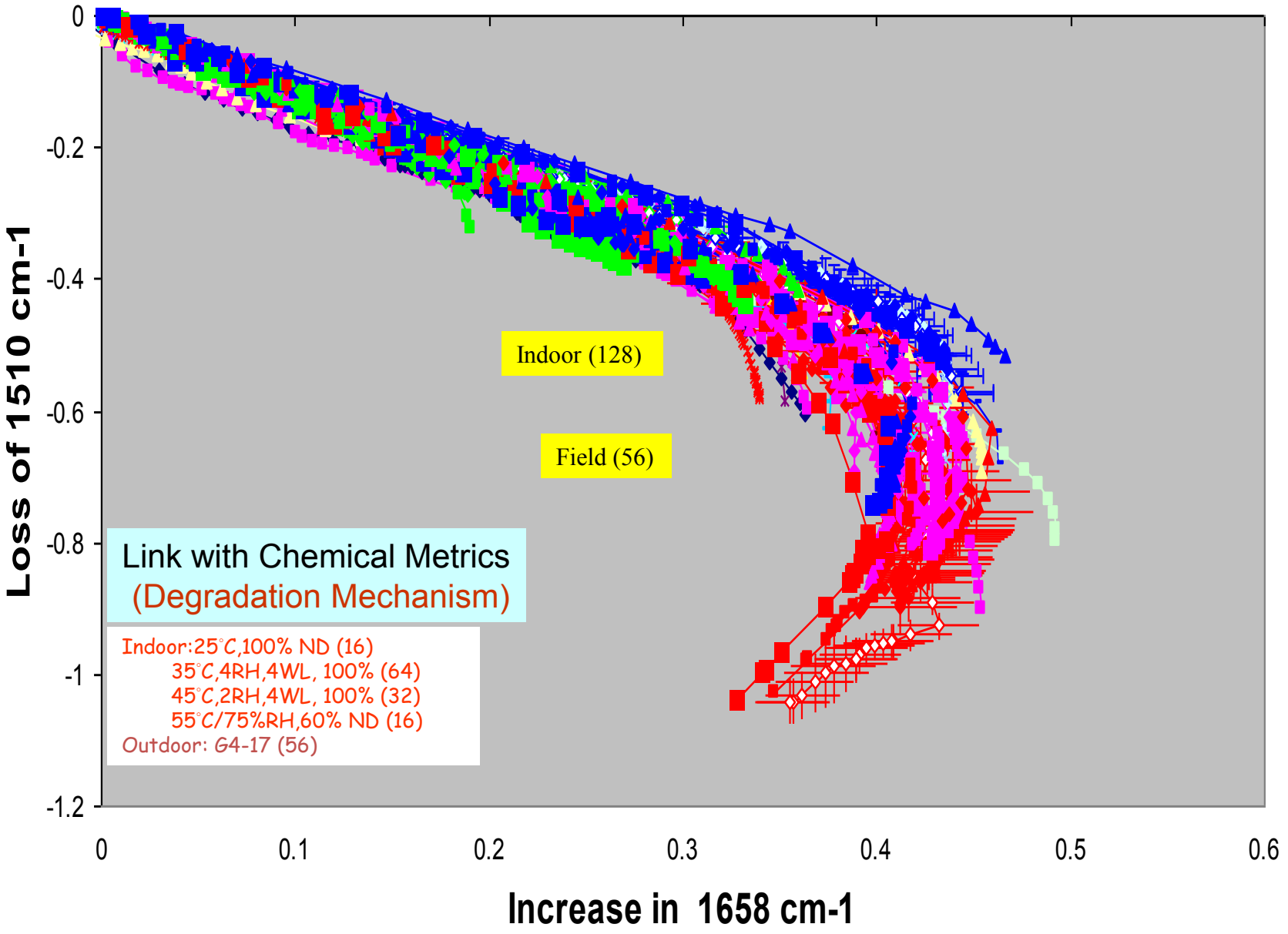
Model linking SPHERE to Outdoor- Coatings.



$$g'(t) = \frac{d\text{Đ}[\tau, \xi(\tau)]}{d(t)} = \frac{1}{d(t) \times \sigma}\left[\text{Đ}(\infty) - \text{Đ}(0)\right]\left[\frac{\exp(z)}{(1+\exp(z))^2}\right]$$

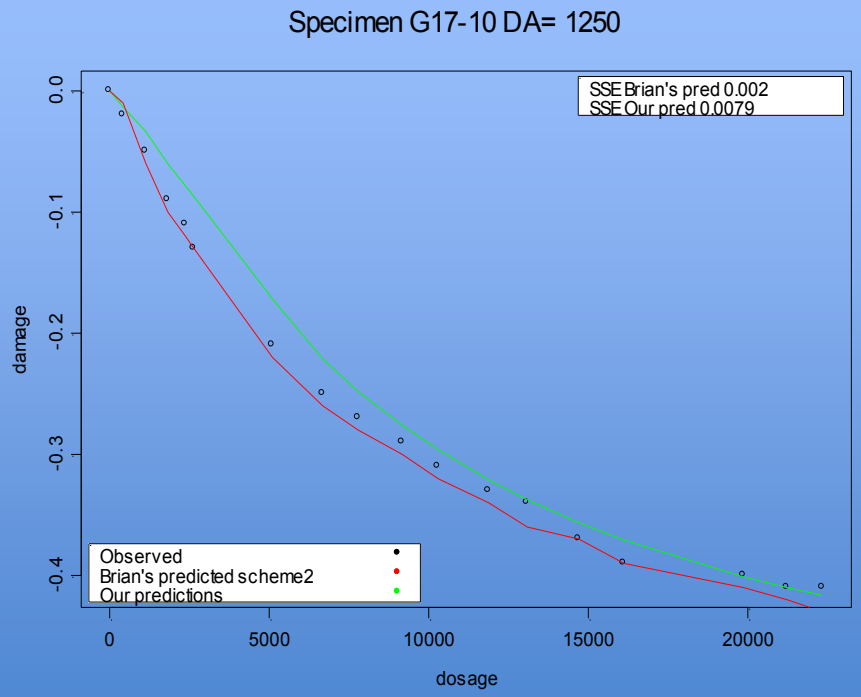


Degradation Mechanism is the same.

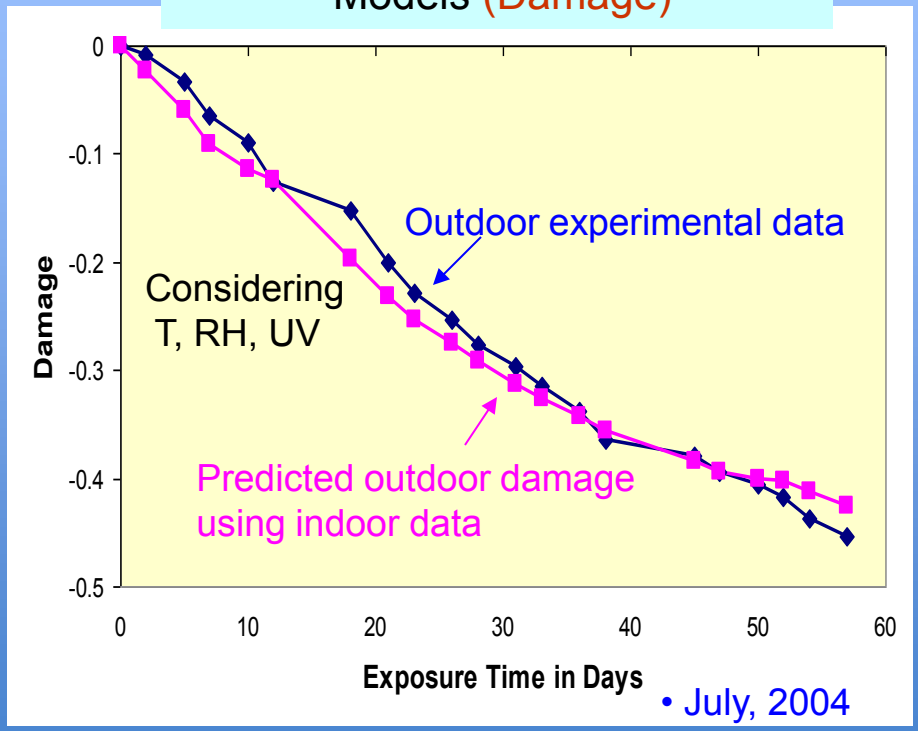


Linkage of Field and Laboratory Results

a) Successfully Link Field and Laboratory Exposure for An Unfilled Polymer



Link with Dosage and Cumulative Models (Damage)



- July, 2004
- 1250 cm^{-1}