Determining the Acceptable Ranges of Relative Humidity and Temperature in Museums and Galleries

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Smithsonian Museum Conservation Institute

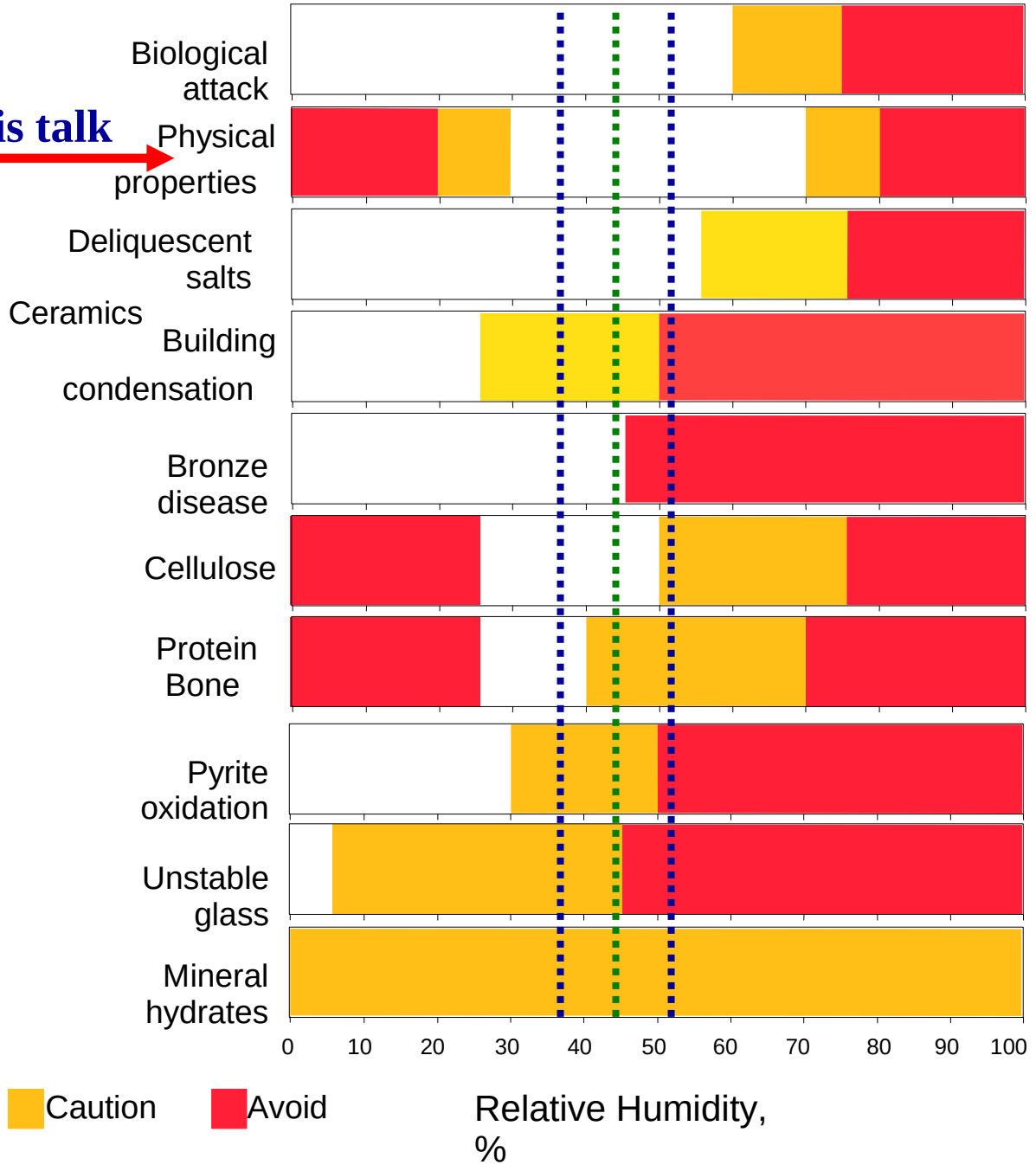
Copenhagen, October 5, 2010

Looking at the Bigger Picture

There is no single environment that works for everything in the collections

RELATIVE HUMIDITY STABILITY ZONES

Focus of this talk



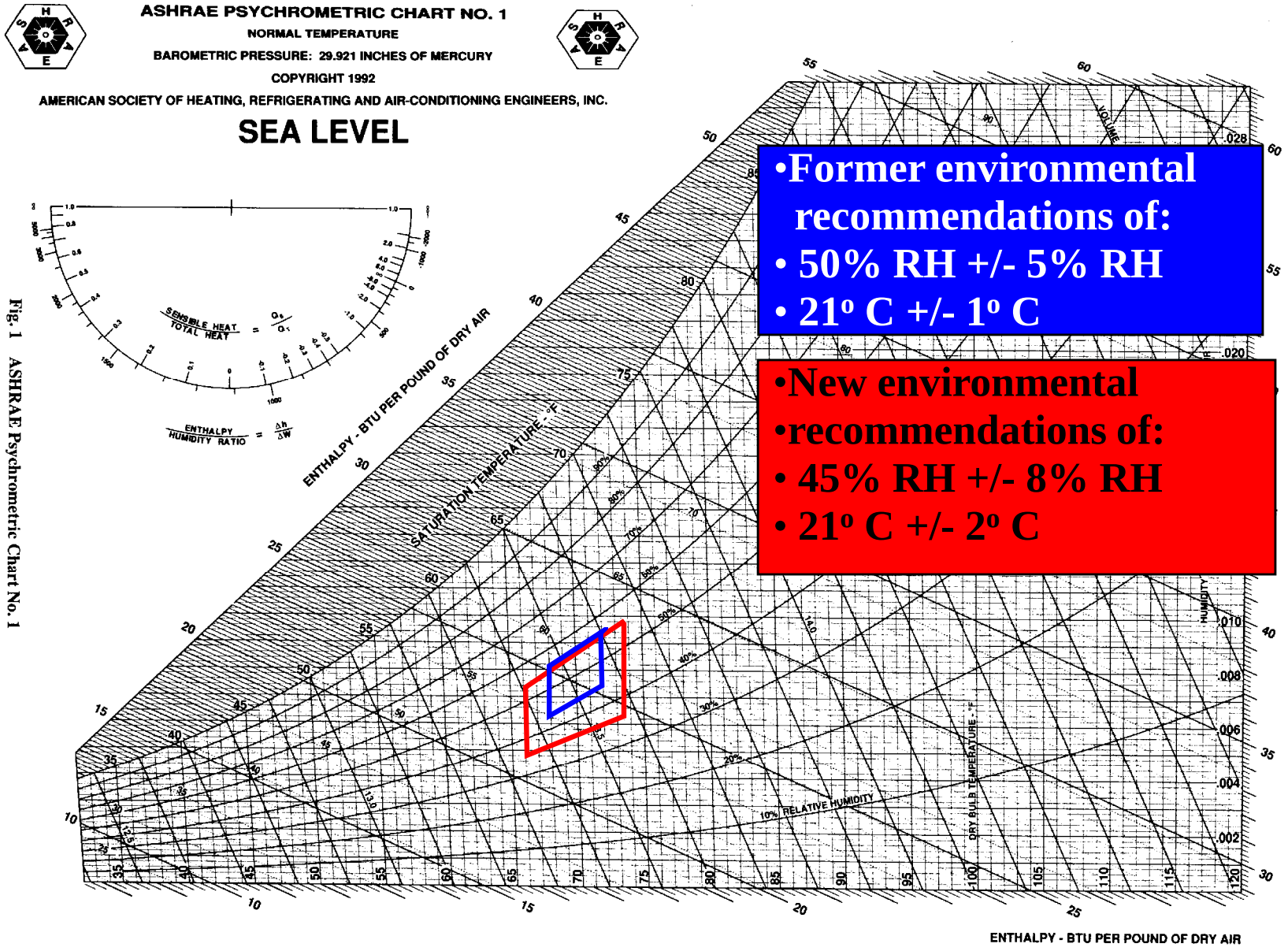


Fig. 1 ASHRAE Psychrometric Chart No. 1

•Former environmental recommendations of:
• 50% RH +/- 5% RH
• 21° C +/- 1° C

•New environmental
•recommendations of:
• 45% RH +/- 8% RH
• 21° C +/- 2° C

Do we ever deviate from the recommended environment?

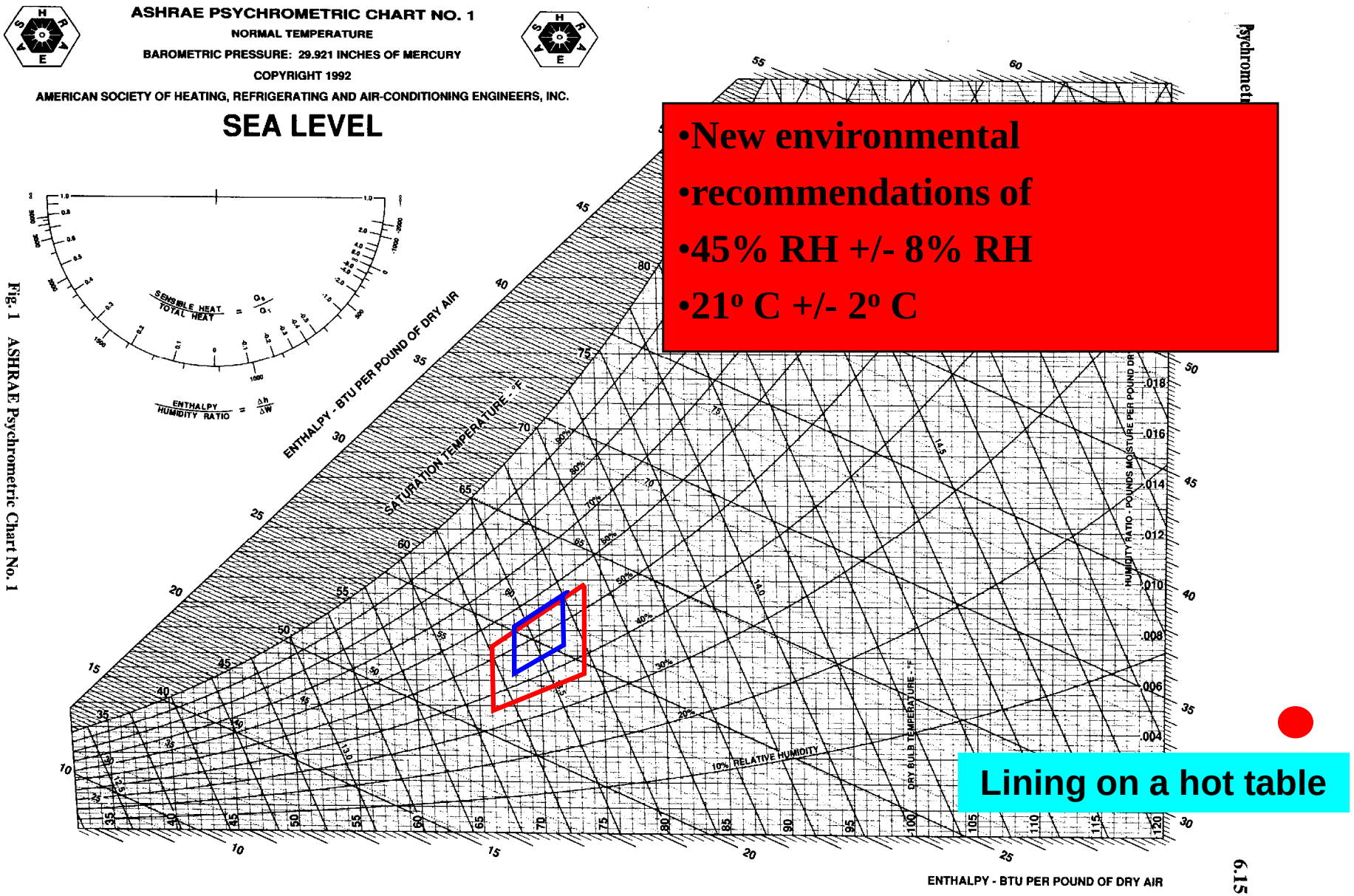


Fig. 1 ASHRAE Psychrometric Chart No. 1

- New environmental
- recommendations of
- 45% RH +/- 8% RH
- 21º C +/- 2º C

Lining on a hot table

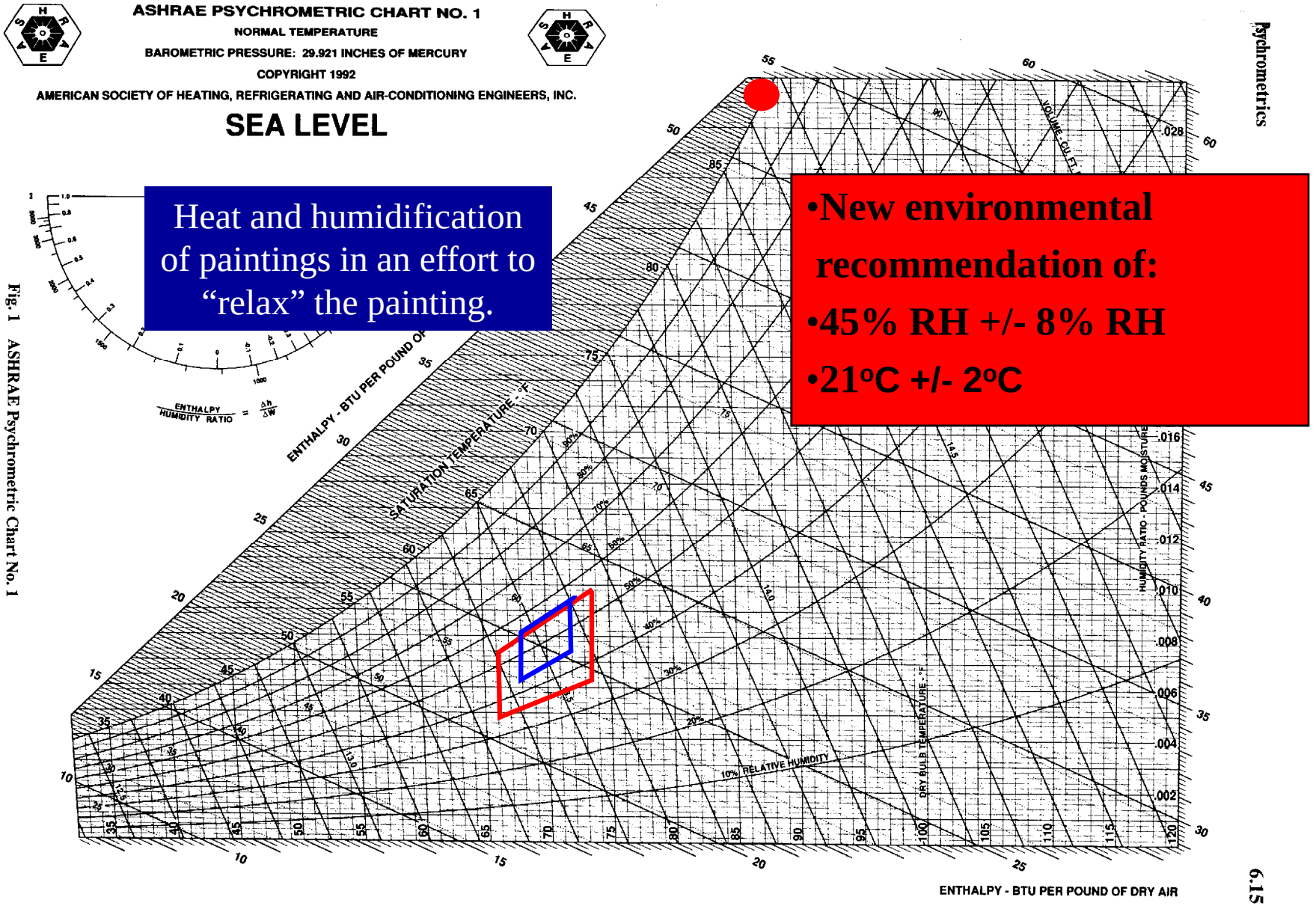


Fig. 1 ASHRAE Psychrometric Chart No. 1

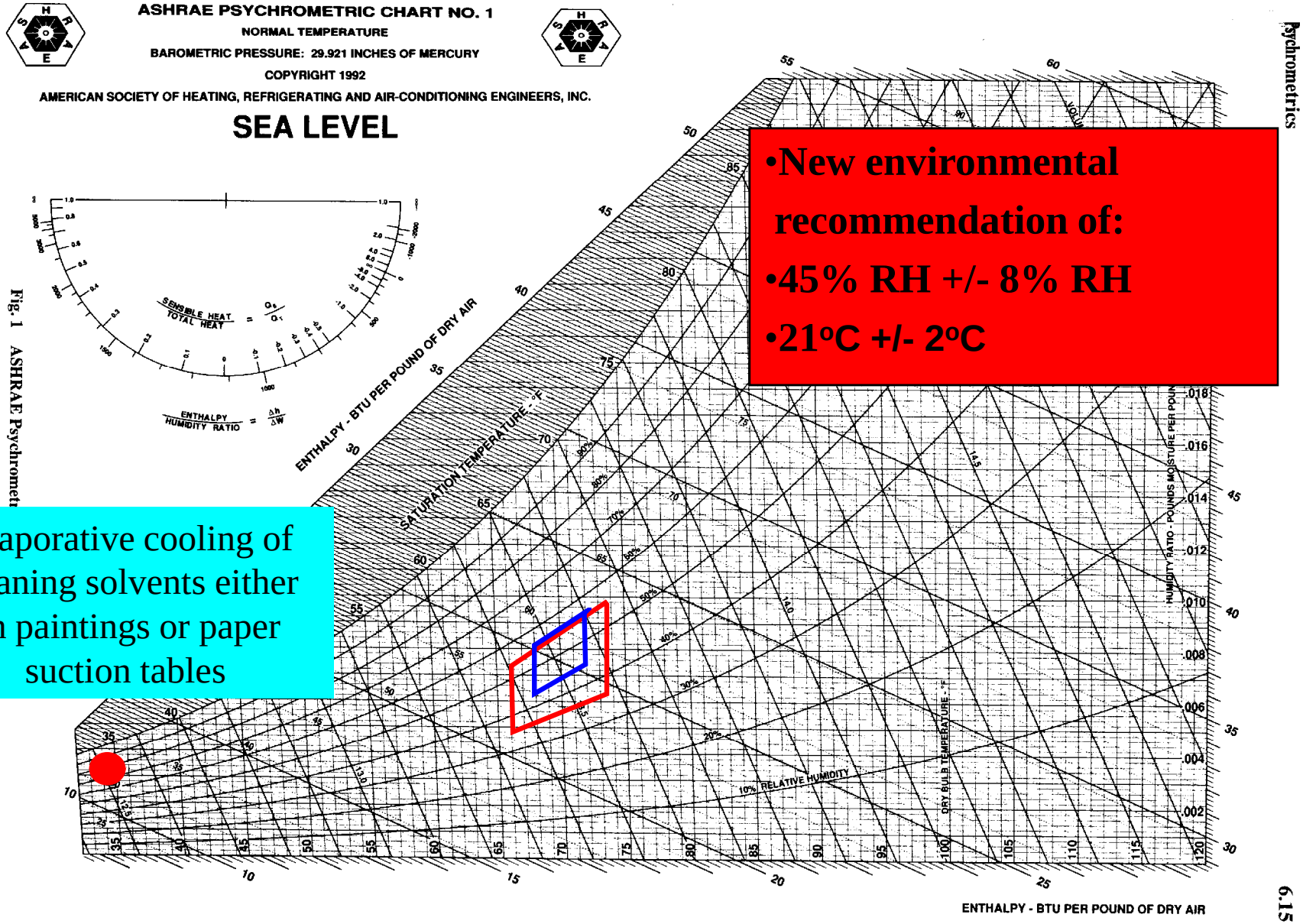


Fig. 1 ASHRAE Psychrometr

- **New environmental recommendation of:**
- **45% RH +/- 8% RH**
- **21°C +/- 2°C**

Evaporative cooling of cleaning solvents either on paintings or paper suction tables

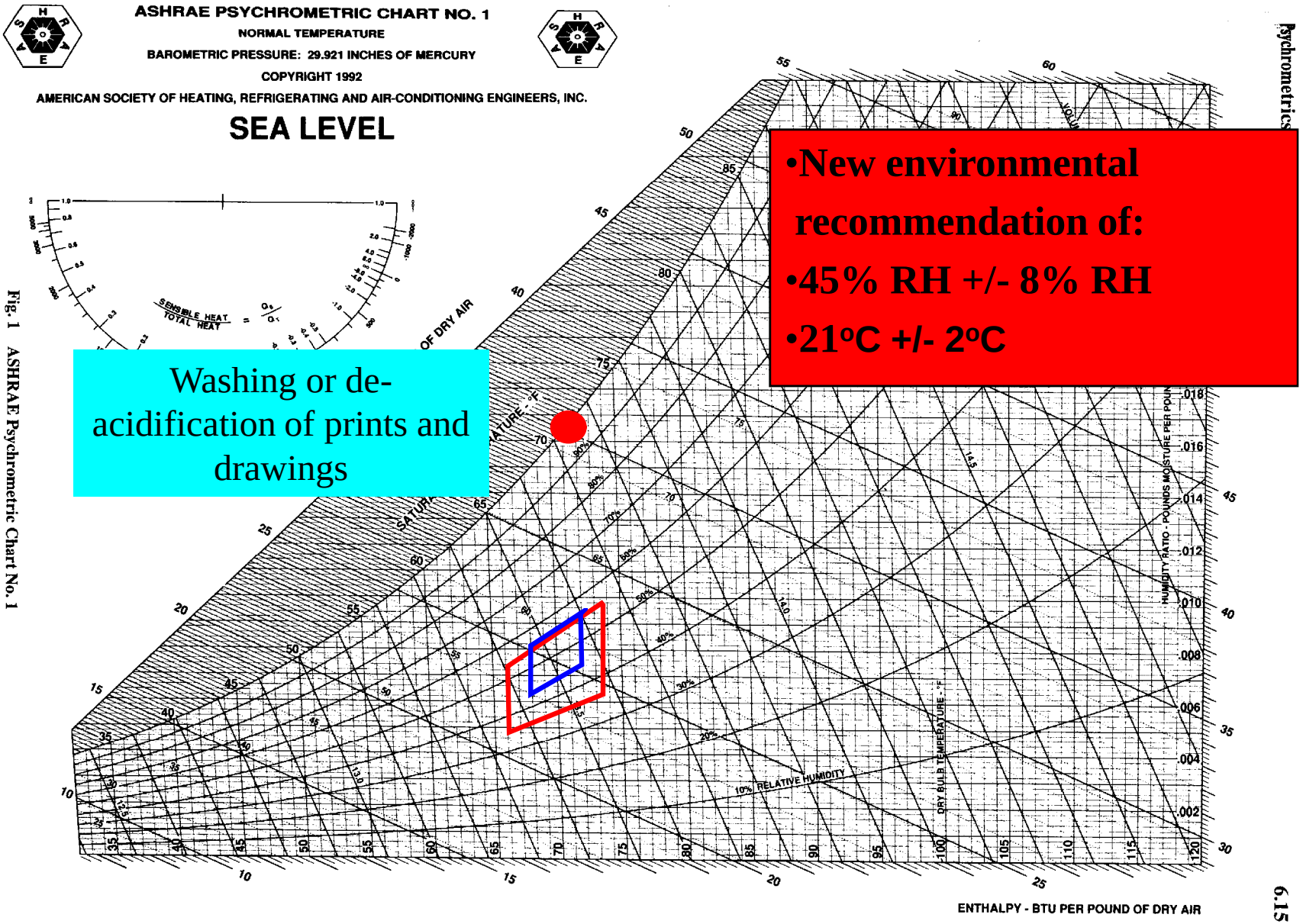


Fig. 1 ASHRAE Psychrometric Chart No. 1

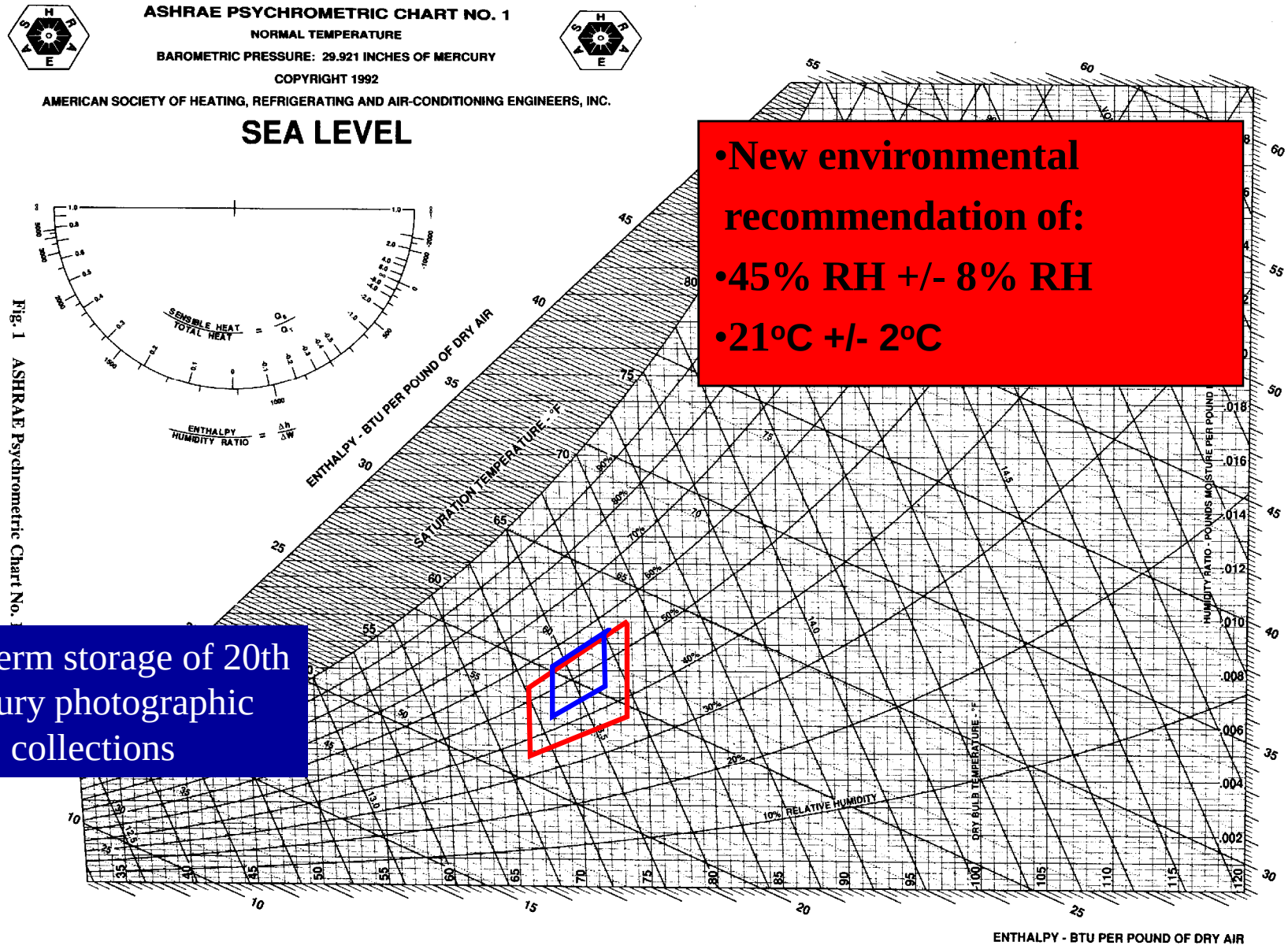


Fig. 1 ASHRAE Psychrometric Chart No.

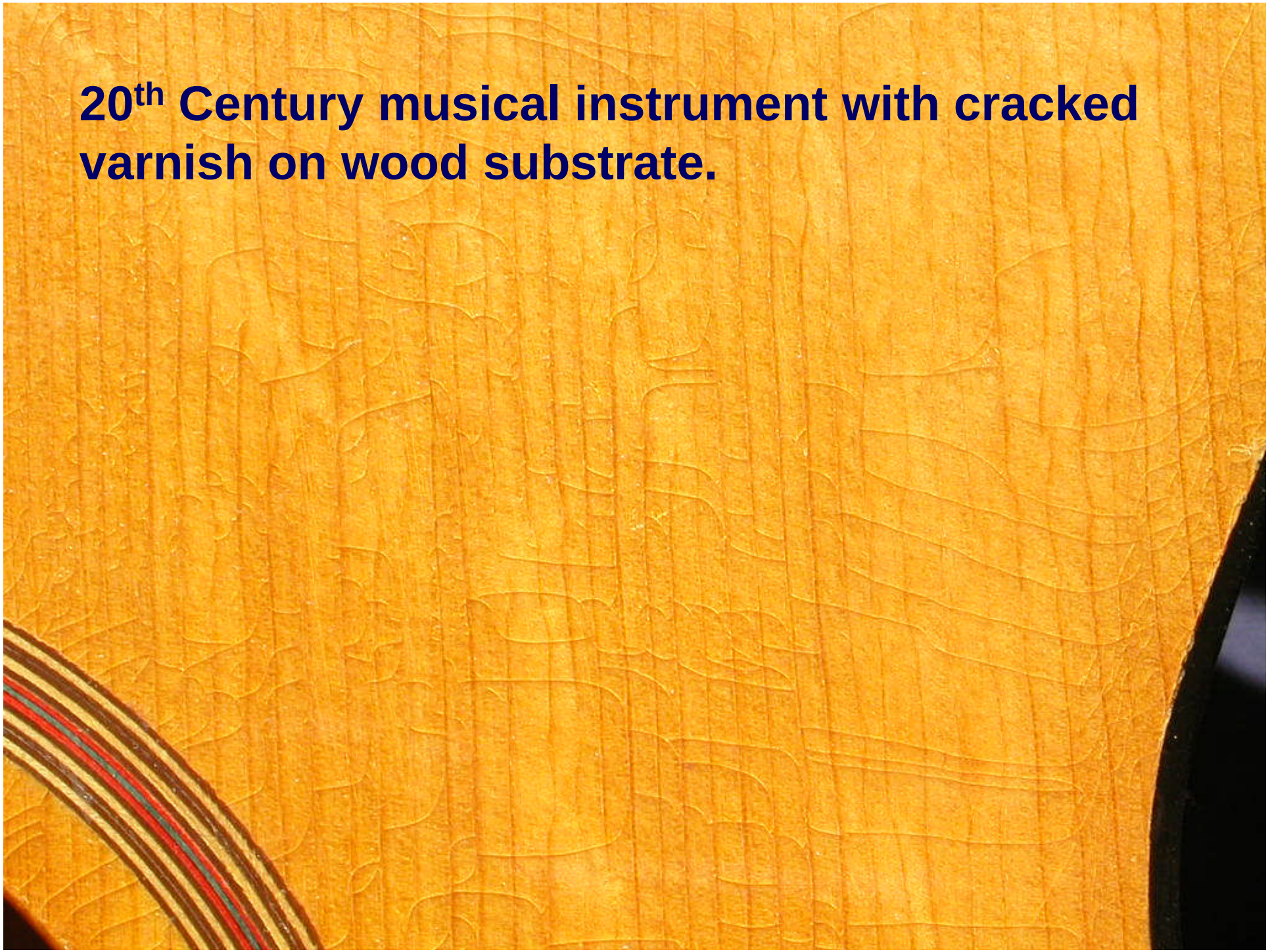
- **New environmental recommendation of:**
- **45% RH +/- 8% RH**
- **21°C +/- 2°C**

Long term storage of 20th century photographic collections

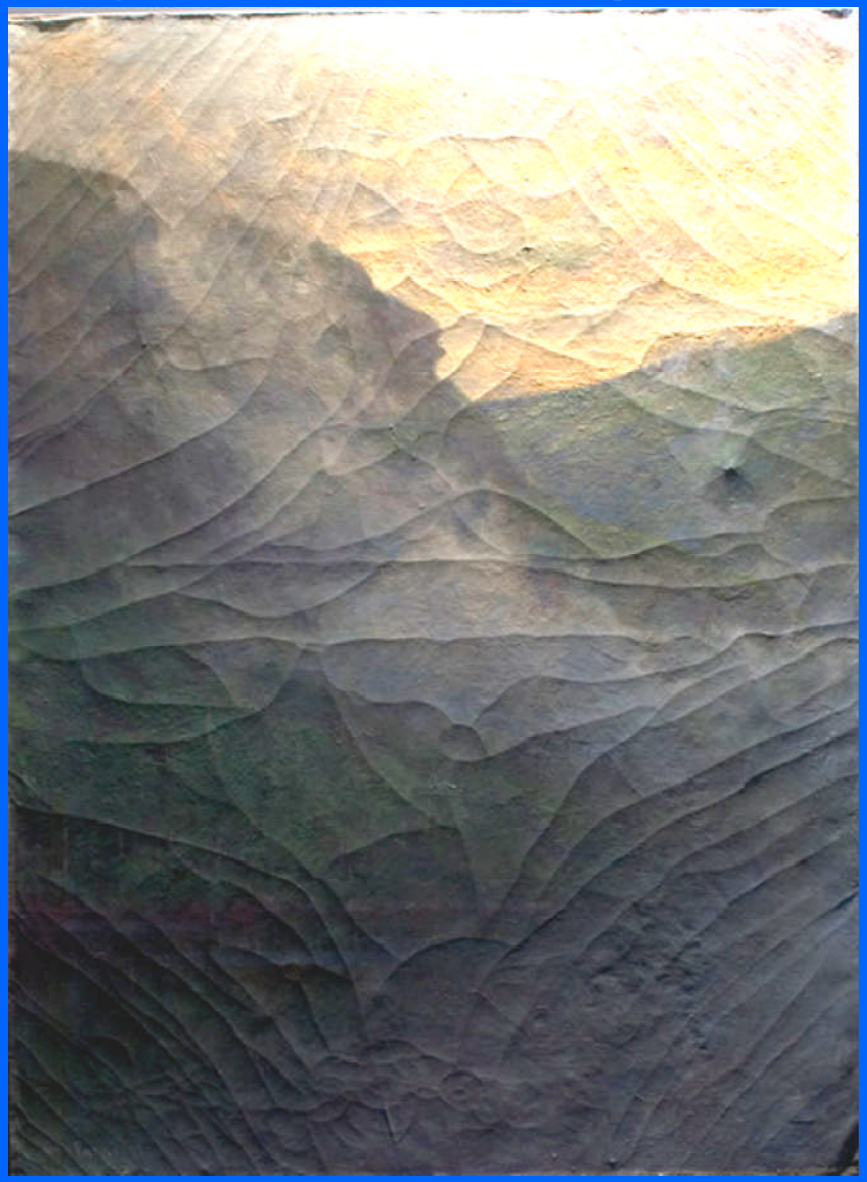
Historically there has been considerable confusion and controversy with regards to determining the correct temperature and relative humidity settings for museums and galleries.

Few were able to say with any certainty what caused damages in any specific object. There has certainly been anecdotal reports but rarely were specific details available.

For example, let's look at a few damaged objects.


20th Century musical instrument with cracked varnish on wood substrate.

20th century American landscape, oil on canvas.



George Parker, Untitled, (Lower Ausable Lake at Indian Head), American, 1911, 48in. x 35.5in. . (Photo by James Hamm and courtesy of the Adirondack Museum in Blue Mountain Lake, N.Y.)


19th century American landscape, oil on canvas.

20th century American abstract, oil and acrylic on canvas.

20th century American abstract, oil and acrylic on canvas.
(Photo by James Hamm and courtesy of the owner)

All of the objects just seen were damaged by exposure to low temperatures and RH played no role at all.

The reason these object were damaged by low temperature is because all oil, alkyd and acrylic paints have low glass transition temperatures. If the ambient temperature falls enough below the glass transition temperature, the paint layers will crack.

Detail, 20th century English Abstract, oil on canvas.

(Photograph courtesy of Richard Saltoun and taken by Steve Gayler)

The prior painting was damaged by rolling and neither temperature or relative humidity played any role in the damage.

The reason the damage was so extensive with interlayer cleavage was that zinc oxide was mixed with the lead carbonate in the oil. Zinc is notorious for cracking and delaminating.

(Research on the mechanical properties of artists paints at the SI, MCI)

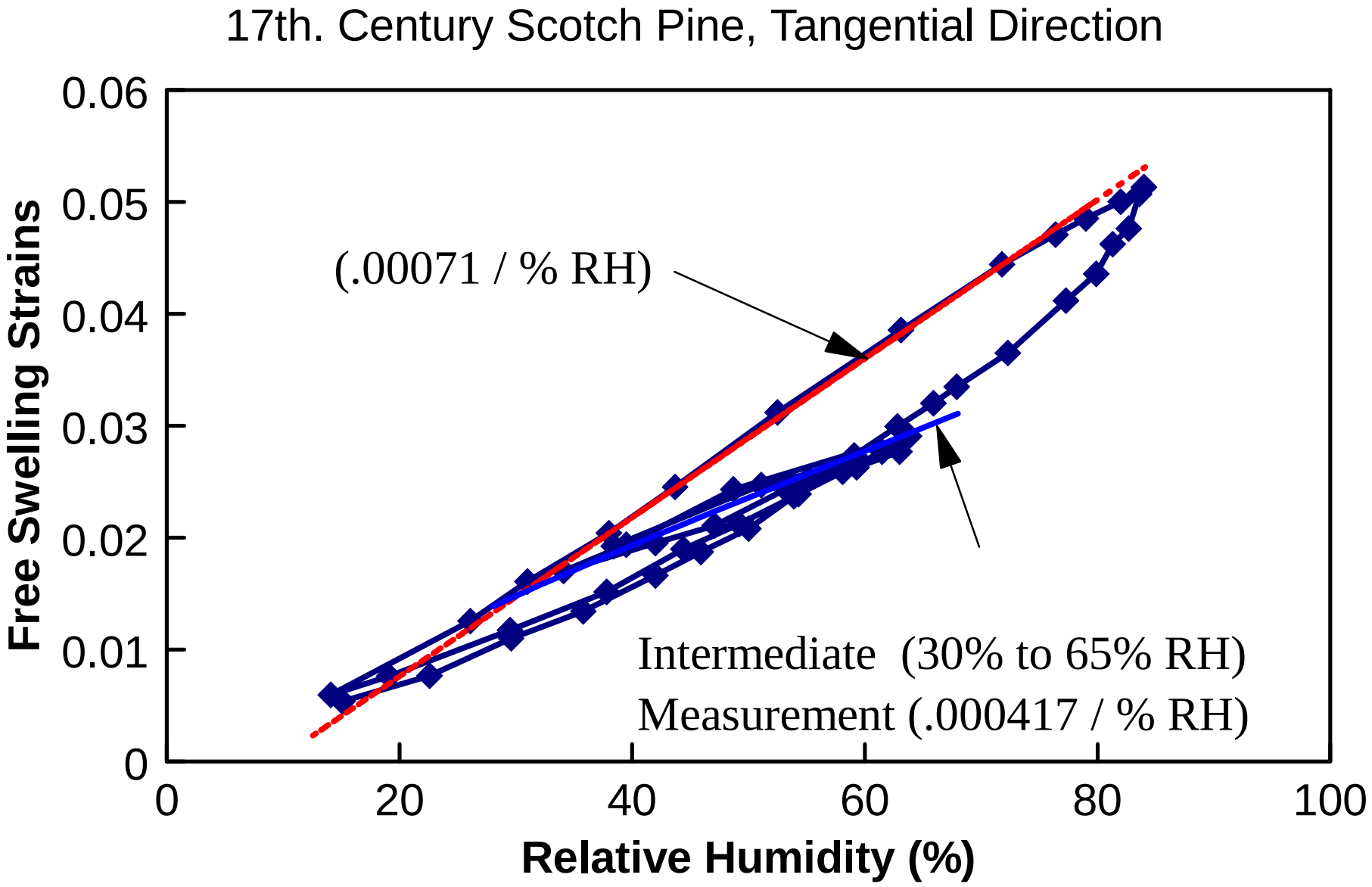
In order to show exactly how objects respond mechanically to different environmental changes, it is necessary to first look at the individual materials used in their construction.

There are three types of tests needed to define The materials:

1. **The dimensional response to changes in RH and temperature.**
2. **The stress-strain test.**
3. **The restrain and desiccate (or cool) test.**

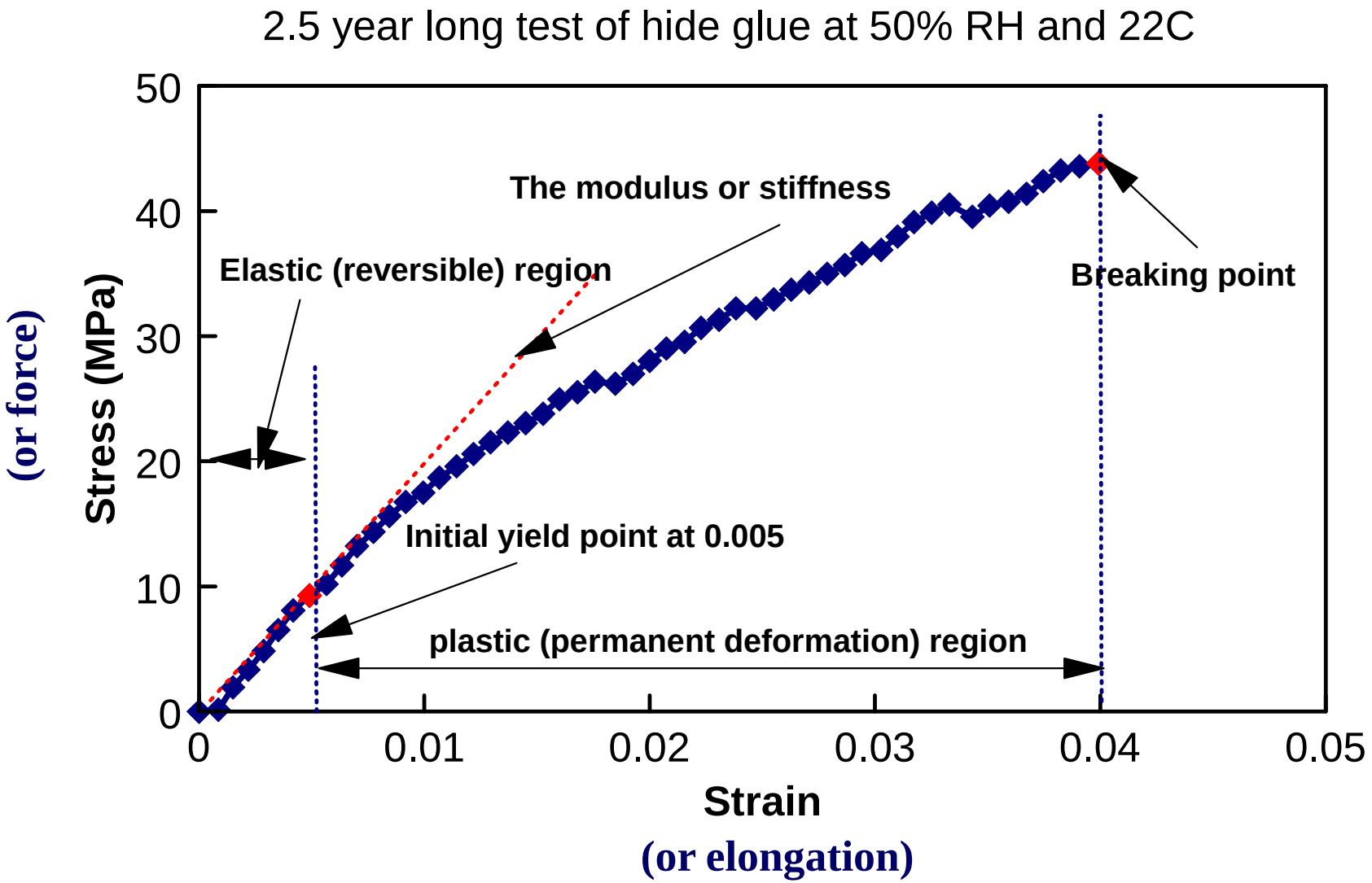
Testing the dimensional response of materials to changes in RH.

Wood's dimensional response to moisture.

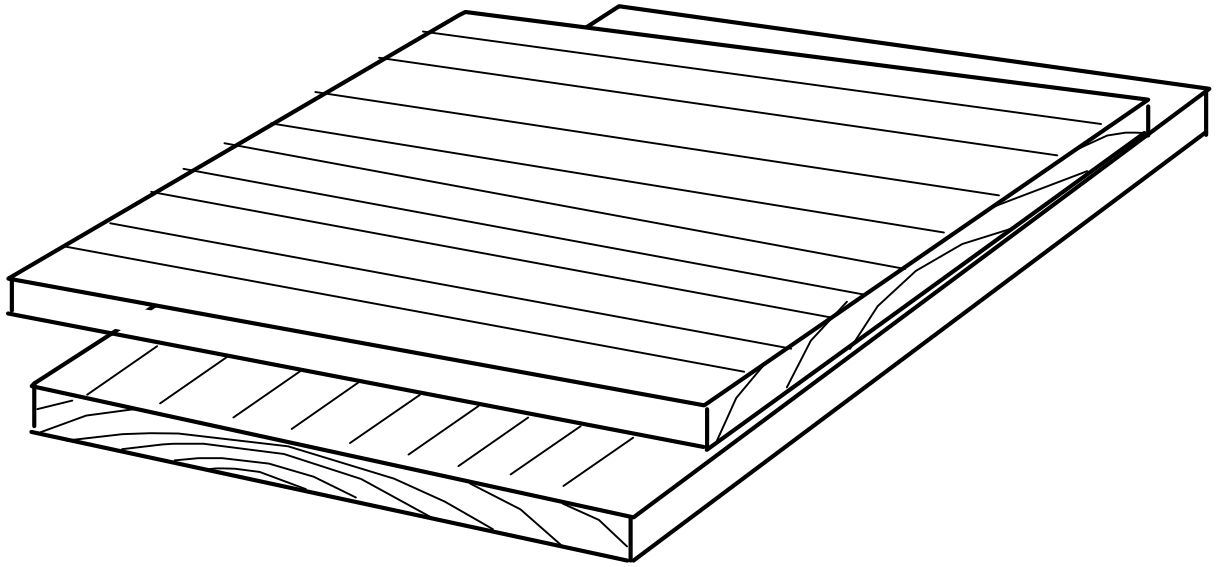


Measuring the mechanical properties of materials; the stress strain test.

The stress strain test: Stress is force divided by the cross-sectional area of the sample and Strain is the change in the sample length divided by it original length.

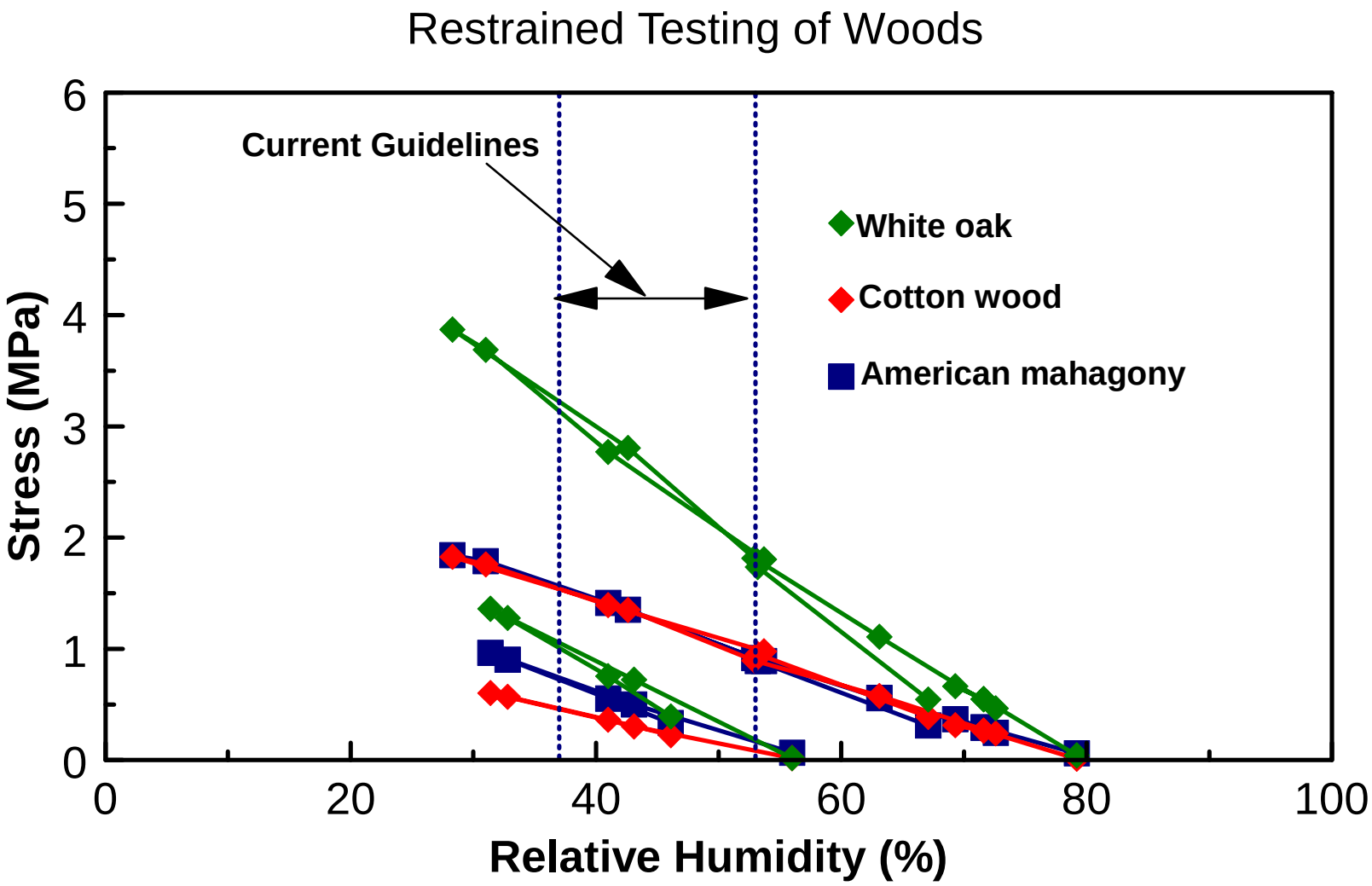


Measuring the stresses (or forces) when materials are under restraint and the environment is changing

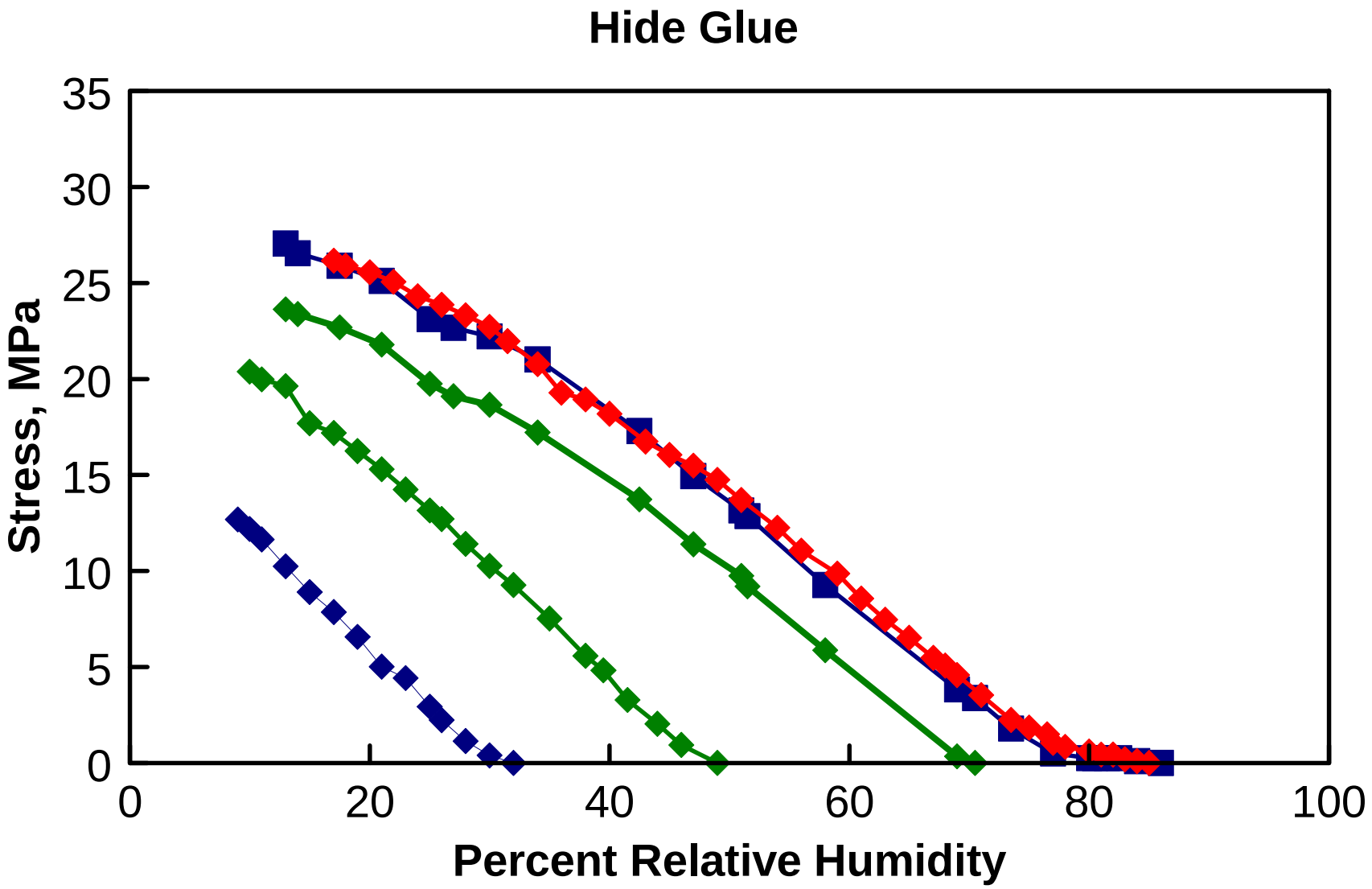


Woods glued cross-grained develop mutual restraint to dimensional response with changes in either temperature or RH.

Wood samples restrained in a changing environment.



Samples of hide glue restrained and desiccated.



Connecting the Three Tests

Relating the tests is required. For example: How are the strains in the stress strain test related to the strains in the dimensional response test?

From an environmental perspective The magnitude of the strains in the stress strain test are identical to the magnitude of the strains in the dimensional response test.*

*1996, Mecklenburg, M. F. and C. S. Tumosa, "The Relationship of Externally Applied Stresses to Environmentally Induced Stresses", in Fiber Composites in Infrastructure, H. Saadatmanesh and M. R. Ehsani Eds., Proceedings of the First International Conference on Composites in Infrastructure, NSF and University of Arizona, 956-971.

Under true equilibrium conditions, all three tests:

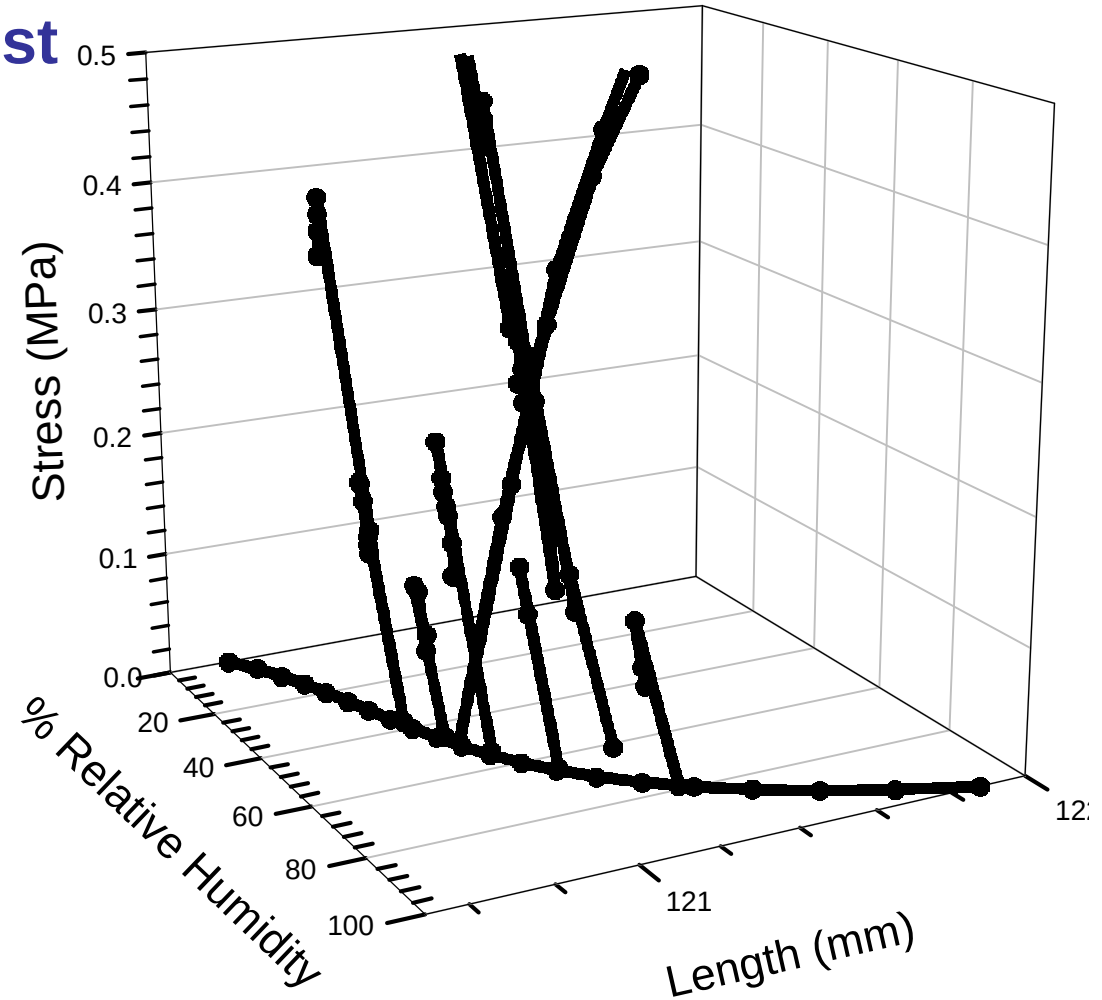
1. The stress-strain test

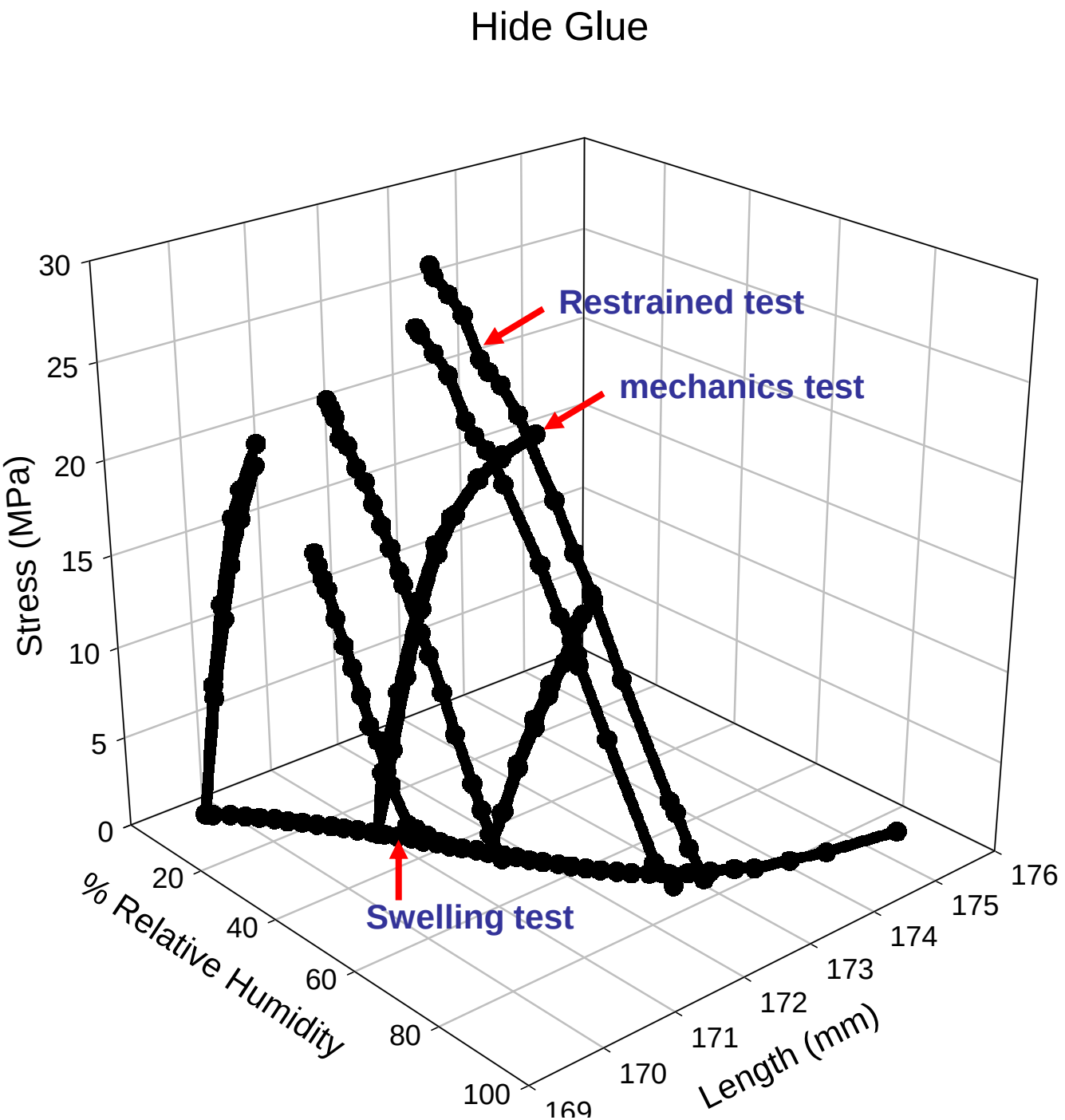
2. The swelling test

3. And the restrained test

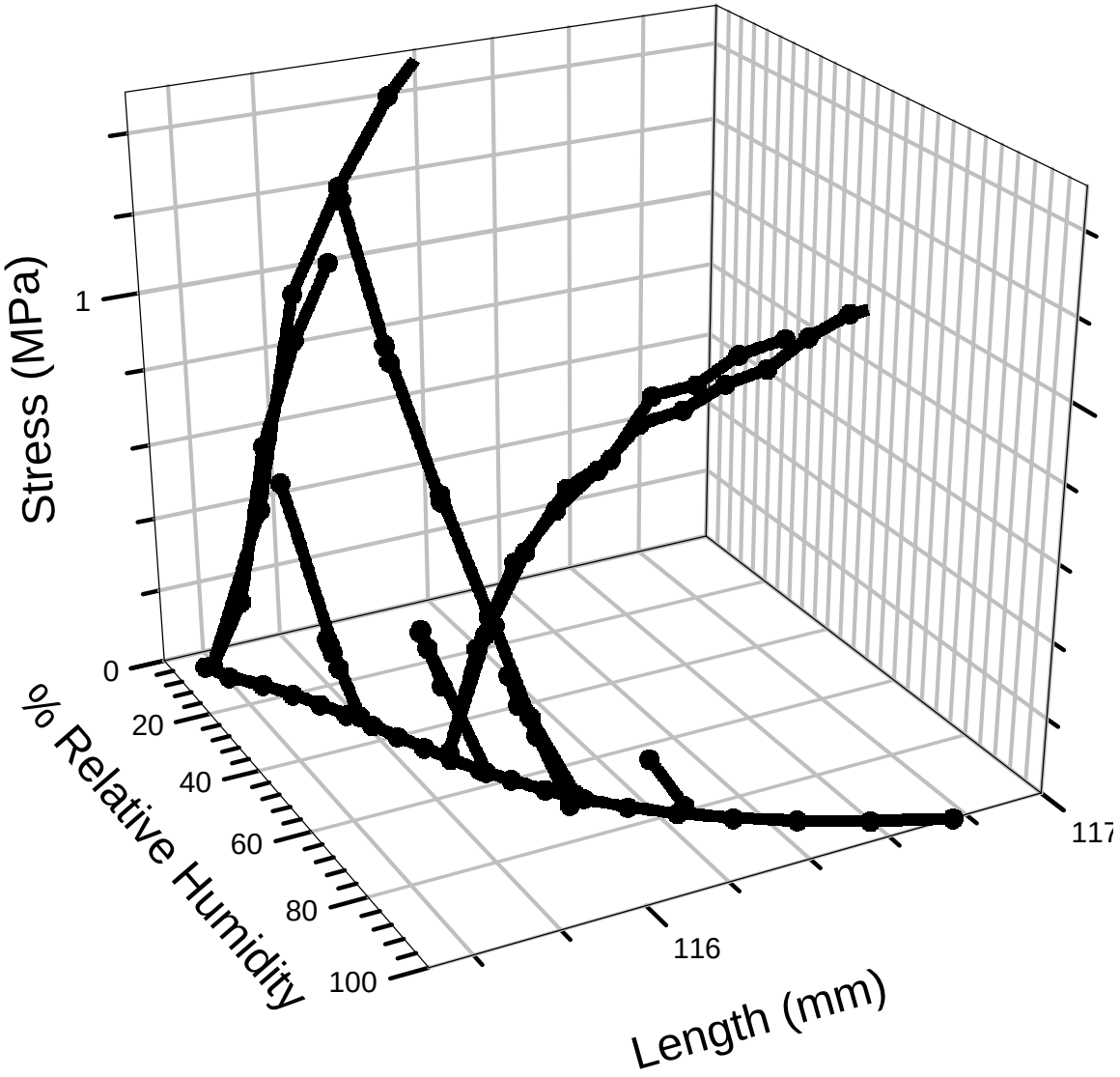
can be related.

Cadmium Yellow in Alkyd




Hide Glue
Restrained test
mechanics test
Swelling test
Stress (MPa)
30
25
20
15
10
5
0
% Relative Humidity
20
40
60
80
100
Length (mm)
169
170
171
172
173
174
175
176

Titanium Dioxide in Oil



Establishing Criteria for Determining RH Boundaries

Setting initial assumptions and criteria for determining the allowable RH for rigid objects, this includes furniture, ivory, panel paintings, painted wood, etc.

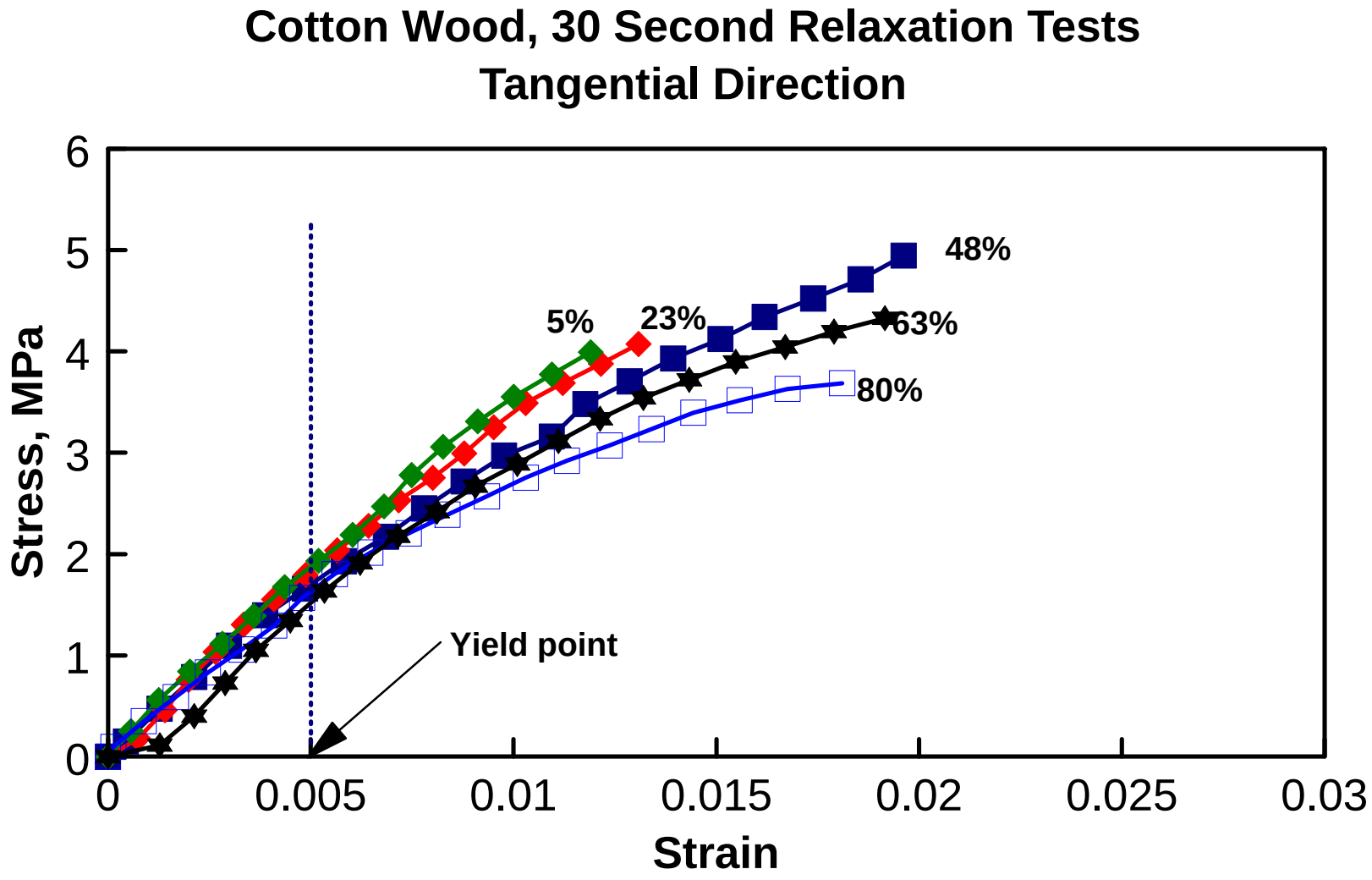
1. **All materials in the objects in the collections are assumed to be fully restrained from any movement.**

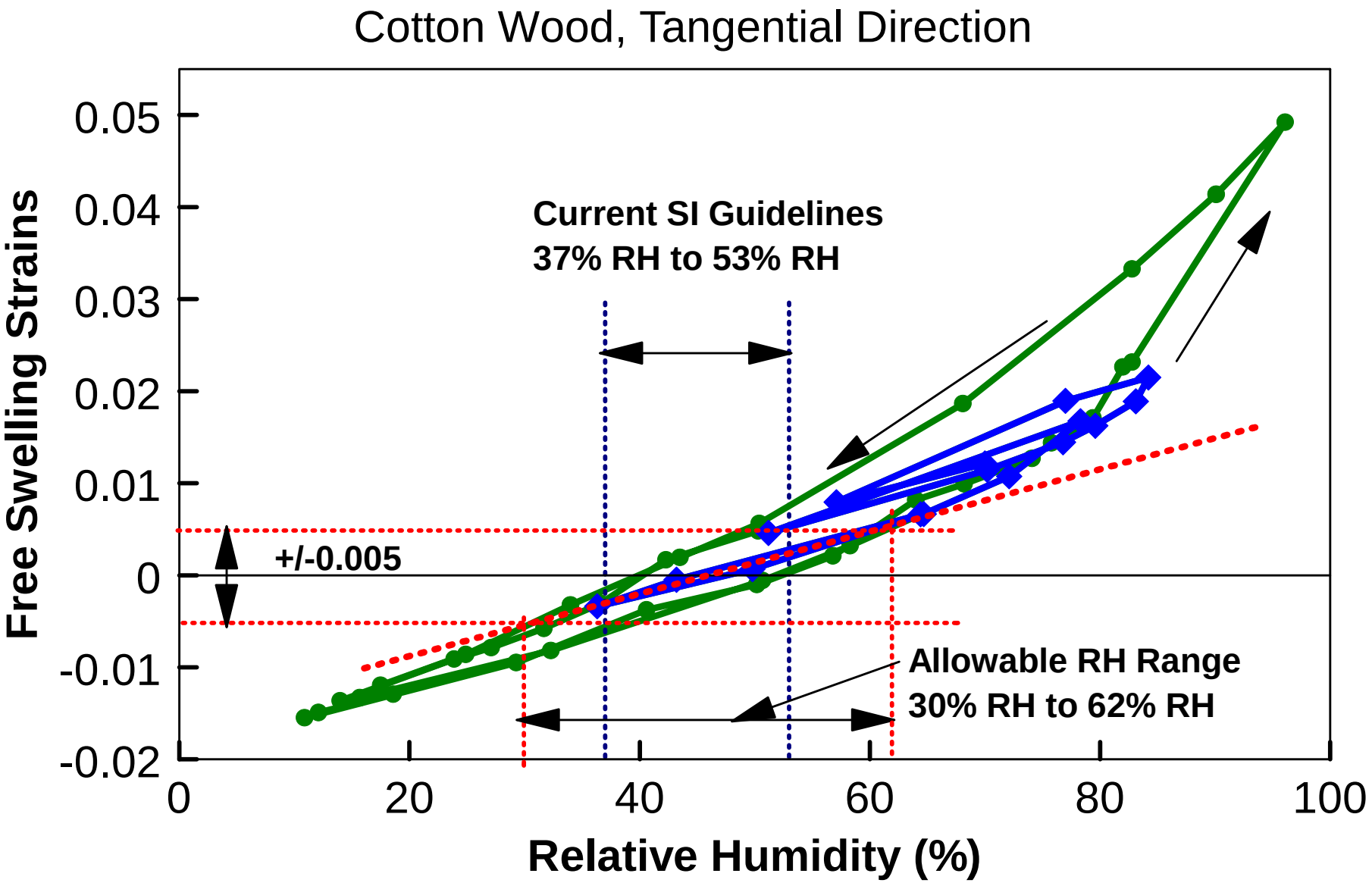
2. **The strain in any material in any object is not to exceed the yield strain in either tension or compression.**

3. **There can be initial stresses in the materials in the object.**

4. **There are no cracks in the objects**

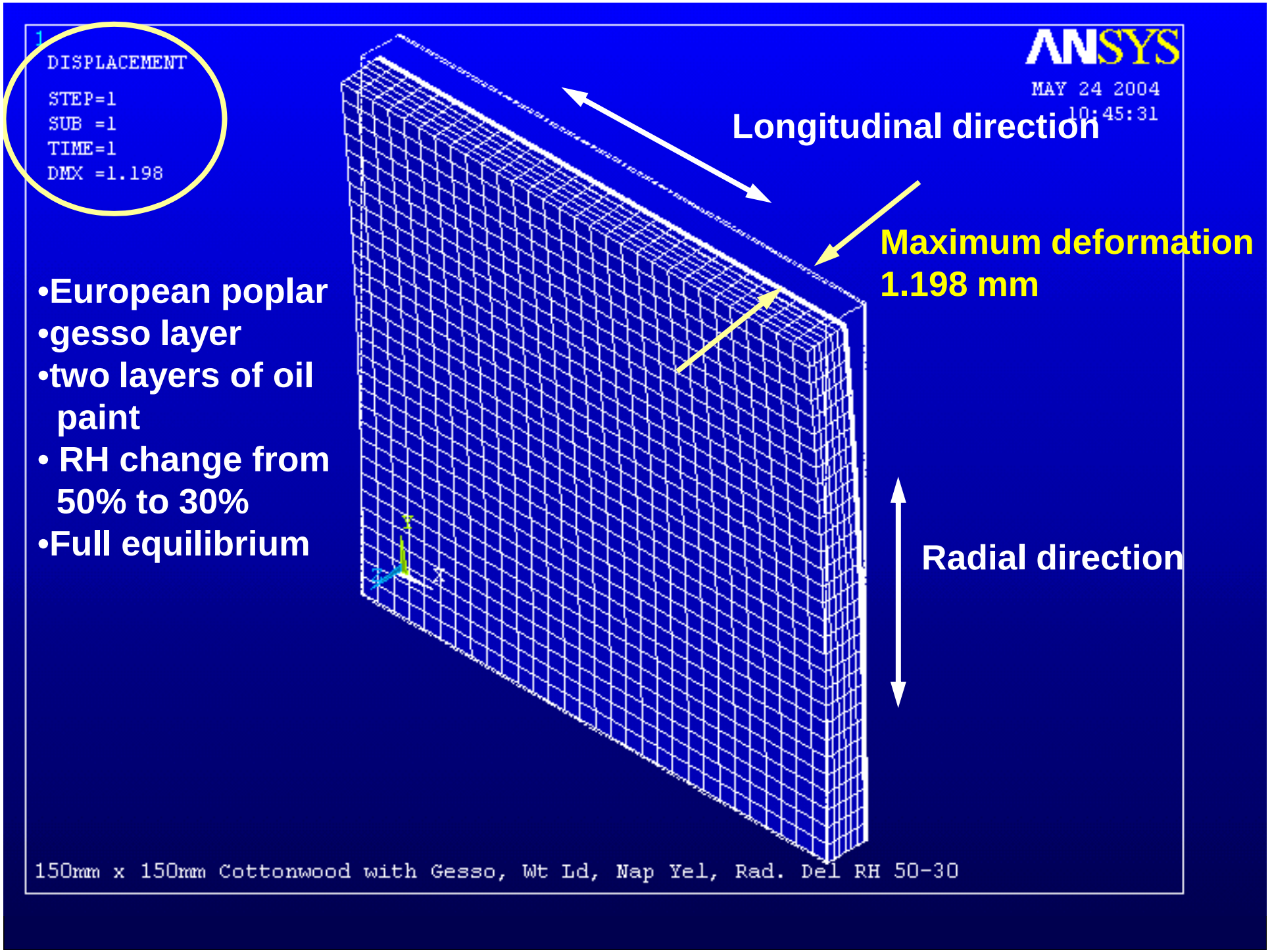
Determining the allowable RH using the established criteria.

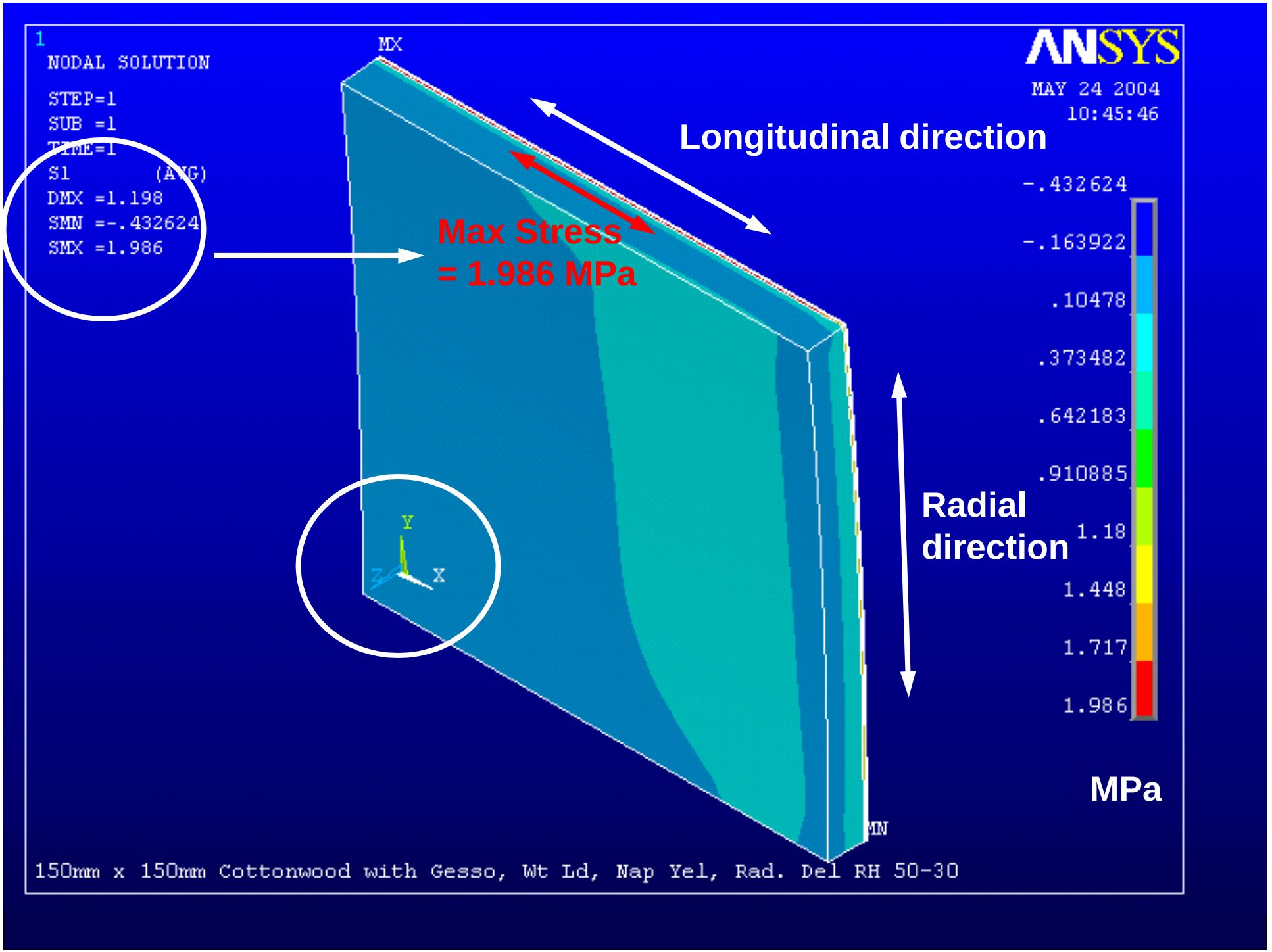


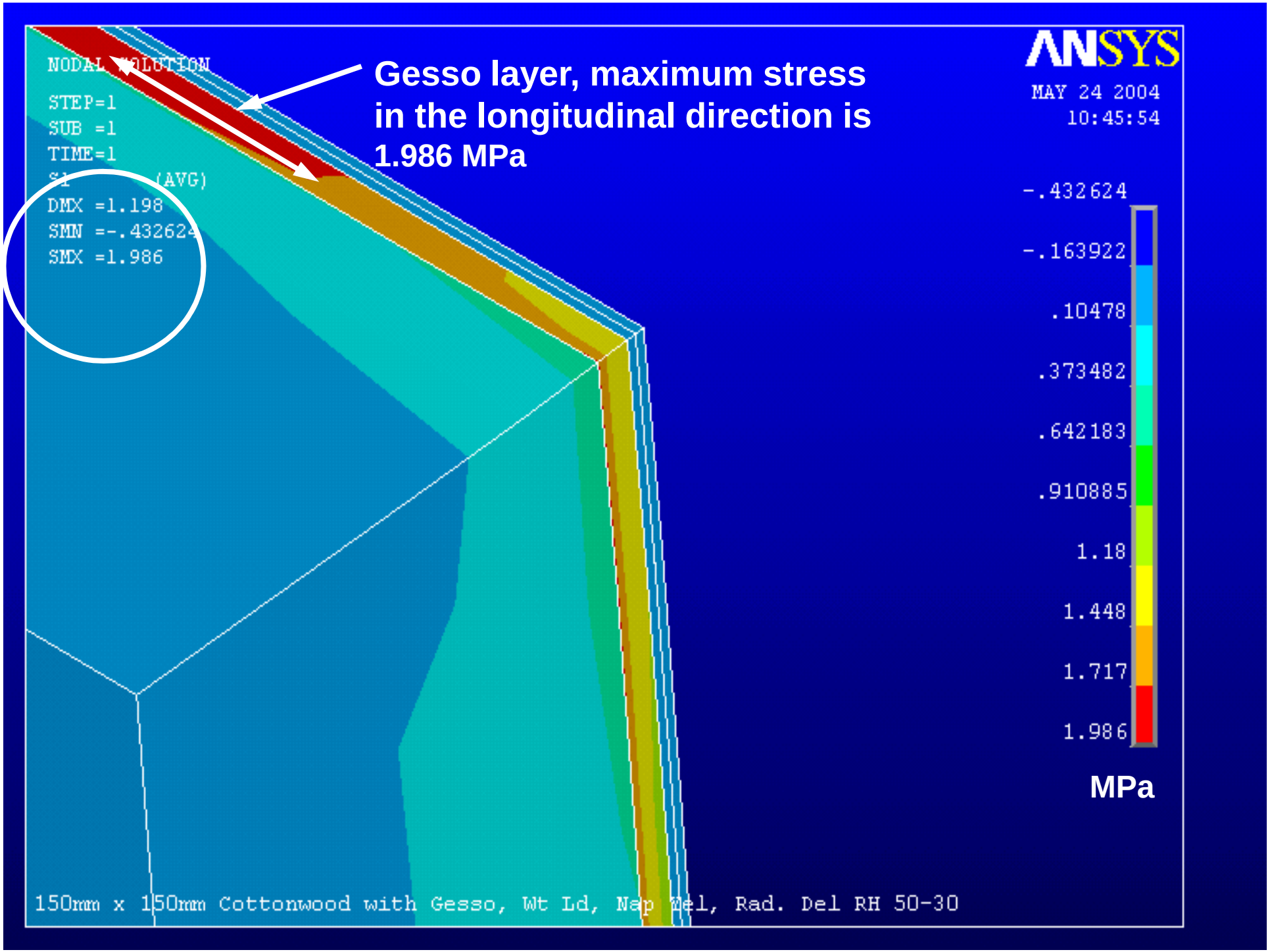

Cotton Wood, Tangential Direction
Free Swelling Strains
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0
20
40
60
80
100
Relative Humidity (%)
Current SI Guidelines
37% RH to 53% RH
+/-0.005
Allowable RH Range
30% RH to 62% RH

Analytical tools

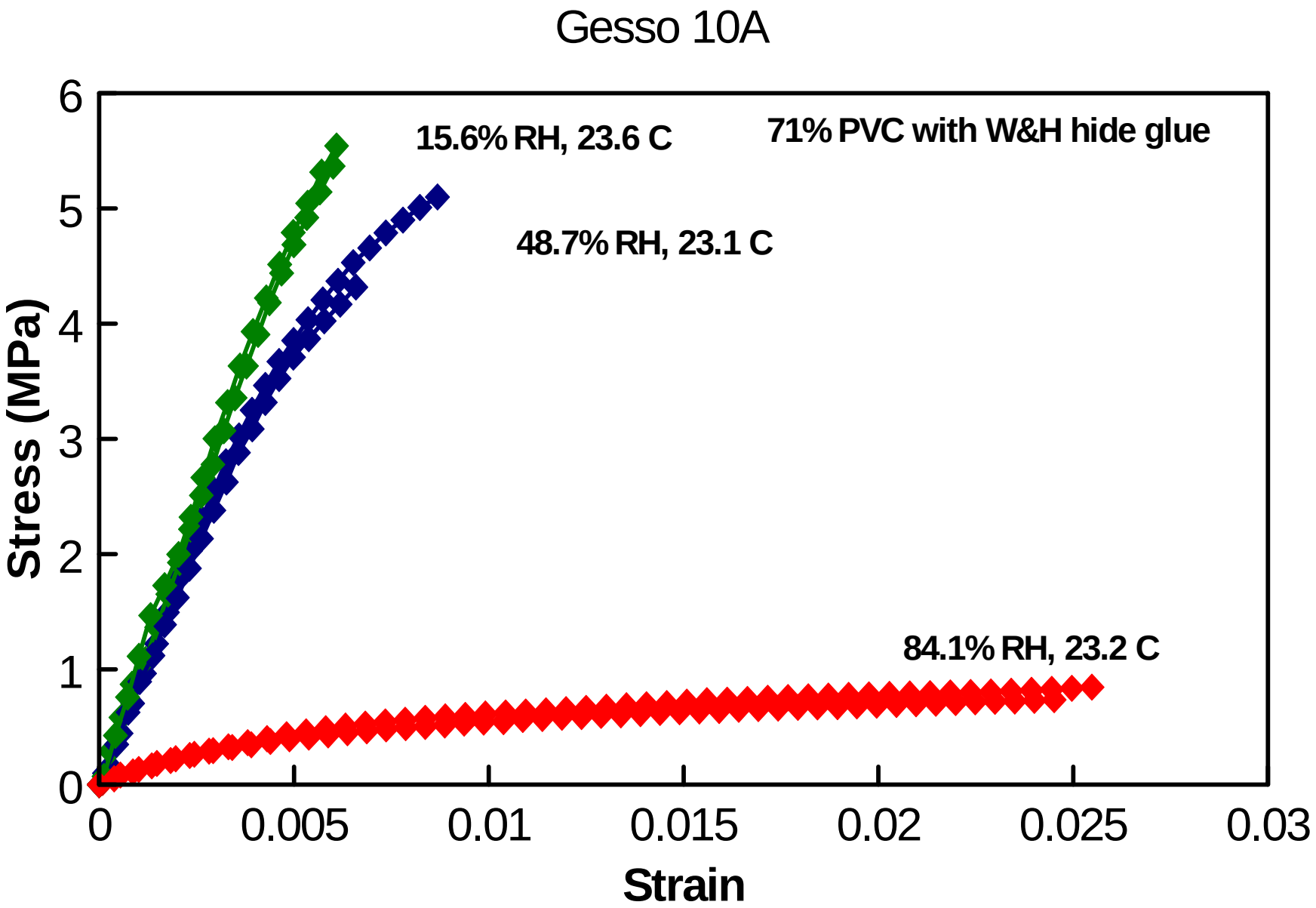
Computer modeling


1
DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =1.198
ANSYS
MAY 24 2004
10:45:31
Longitudinal direction
Maximum deformation
1.198 mm
•European poplar
•gesso layer
•two layers of oil paint
• RH change from 50% to 30%
•Full equilibrium
Radial direction
150mm x 150mm Cottonwood with Gesso, Wt Ld, Nap Yel, Rad. Del RH 50-30


1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
S1 (AVG)
DMX =1.198
SMN =-.432624
SMX =1.986
MX
MN
ANSYS
MAY 24 2004
10:45:46
Longitudinal direction
Max Stress
= 1.986 MPa
Radial
direction
-.432624
-.163922
.10478
.373482
.642183
.910885
1.18
1.448
1.717
1.986
MPa
Y
X
Z
150mm x 150mm Cottonwood with Gesso, Wt Ld, Nap Yel, Rad. Del RH 50-30

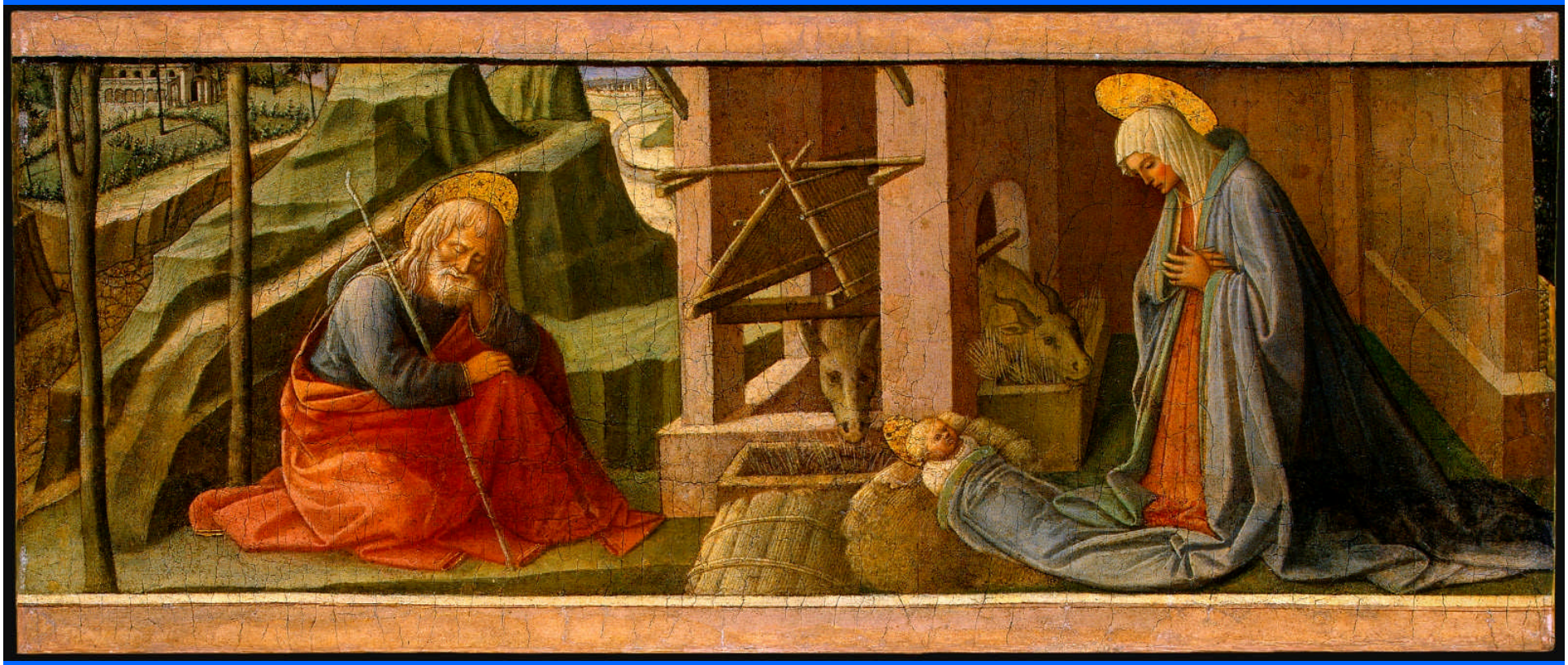

Gesso layer, maximum stress in the longitudinal direction is 1.986 MPa
ANSYS
MAY 24 2004
10:45:54
STEP=1
SUB =1
TIME=1
(AVG)
DMX =1.198
SMN =-.432624
SMX =1.986
-.432624
-.163922
.10478
.373482
.642183
.910885
1.18
1.448
1.717
1.986
MPa
150mm x 150mm Cottonwood with Gesso, Wt Ld, Nap Rel, Rad. Del RH 50-30

It is now possible to compare actual material test data to the computer model results.


Gesso 10A
15.6% RH, 23.6 C
71% PVC with W&H hide glue
48.7% RH, 23.1 C
84.1% RH, 23.2 C
Stress (MPa)
Strain
0
1
2
3
4
5
6
0
0.005
0.01
0.015
0.02
0.025
0.03

Gentile da Fabriano, Marchigian, c. 1370-1427, Madonna and Child Enthroned, c 1420, Tempera on panel, 37 11/16 in. x 22 ¼ in. (95.7 x 56.5 cm), Samuel H. Kress Collection, 1939.1.255.
(Courtesy of the National Gallery of Art, Washington, D.C.)

All of the cracks originated in the gesso layer and are perpendicular To the grain of the wood. The environmental ranges in RH had to have exceeded 70% to 20% for this damage to occur. The wood is acting as a restraint to the gesso layer.



Fra Lippo Lippi and workshop, Florentine, c. 1406-1469, The Nativity, probably c 1445, oil and tempera (?) on panel, 9 1/8 in. x 21 ¾ in. (23.2 x 55.3 cm), Samuel H. Kress Collection, 1939.1.279. (courtesy of the National Gallery of Art, Washington, D.C.)

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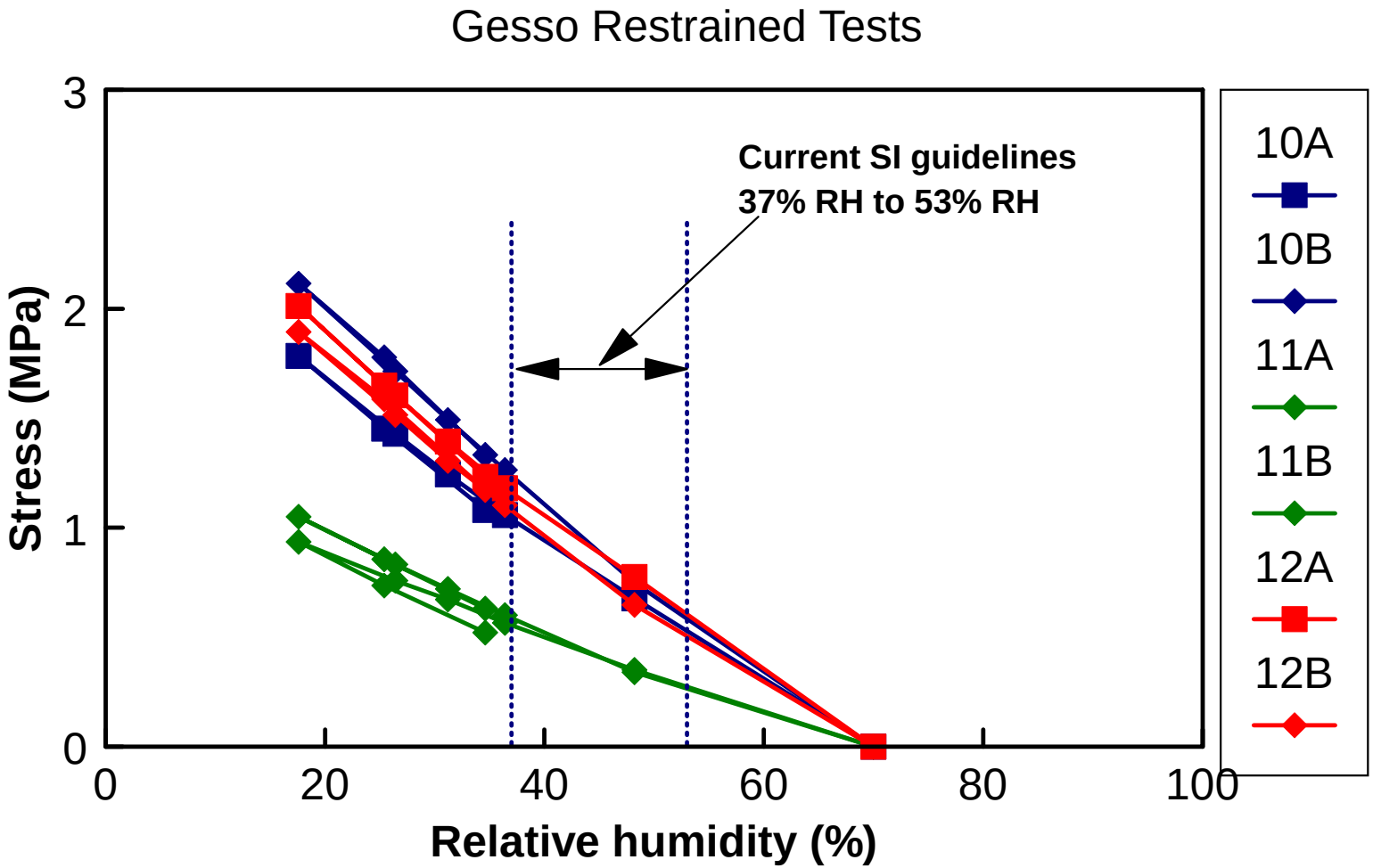

Gesso Restrained Tests
Current SI guidelines
37% RH to 53% RH
Stress (MPa)
Relative humidity (%)
0
1
2
3
0
20
40
60
80
100
10A
10B
11A
11B
12A
12B

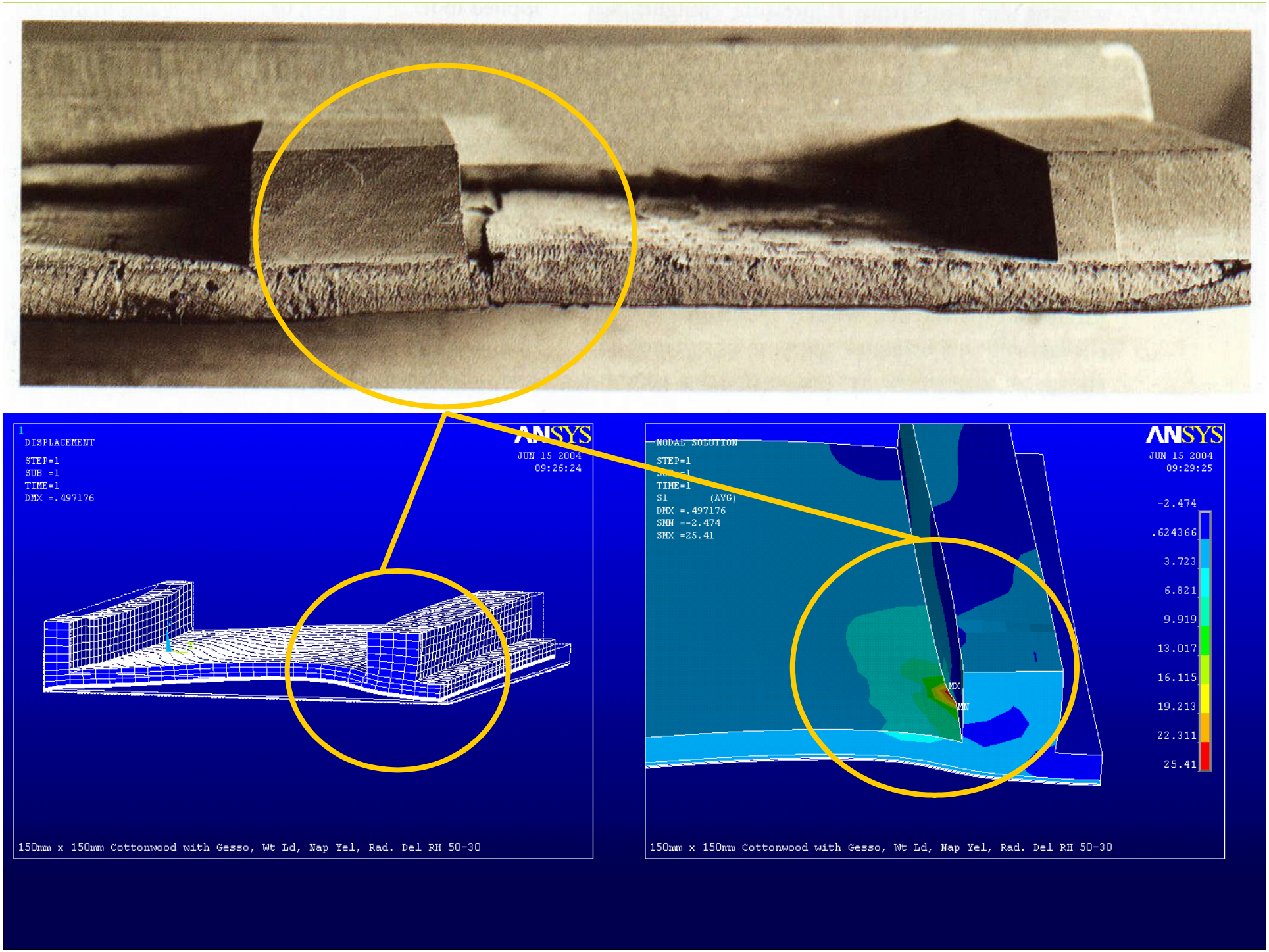
For those materials that are fully restrained and are allowed a strain variation of +/- 0.005, with an initial stress of zero, the RH range results are as follows.

Material	From	To
Woods in general	30-32%	62%
Hide glue	30%	60%
Ivory	26%	67%
Gesso	18%	72%
White Lead Paint	0%	100%
Titanium White Paint	28%	66%
Zinc White Paint	16%	63%
Earth Color Paints	30%	64%

For those materials fully restrained and already under stress:

Woods	30%	80%
Gesso	20%	70%
Linen	10%	90%
Hide glue	30%	70%
White lead Paint	20%	75%
Naples Yellow Paint	20%	75%

If constraint of materials and large humidity swings occur together then damage will result.


1
DISPLACEMENT
STEP=1
SUB =1
TIME=1
DMX =.497176
ANSYS
JUN 15 2004
09:26:24
150mm x 150mm Cottonwood with Gesso, Wt Ld, Nap Yel, Rad. Del RH 50-30
NODAL SOLUTION
STEP=1
TIME=1
S1 (AVG)
DMX =.497176
SMN =-2.474
SMX =25.41
ANSYS
JUN 15 2004
09:29:25
-2.474
.624366
3.723
6.821
9.919
13.017
16.115
19.213
22.311
25.41
MX
MN
150mm x 150mm Cottonwood with Gesso, Wt Ld, Nap Yel, Rad. Del RH 50-30

What About Pre-tensioned Objects Such as Canvas Paintings?

The traditional canvas supported oil painting

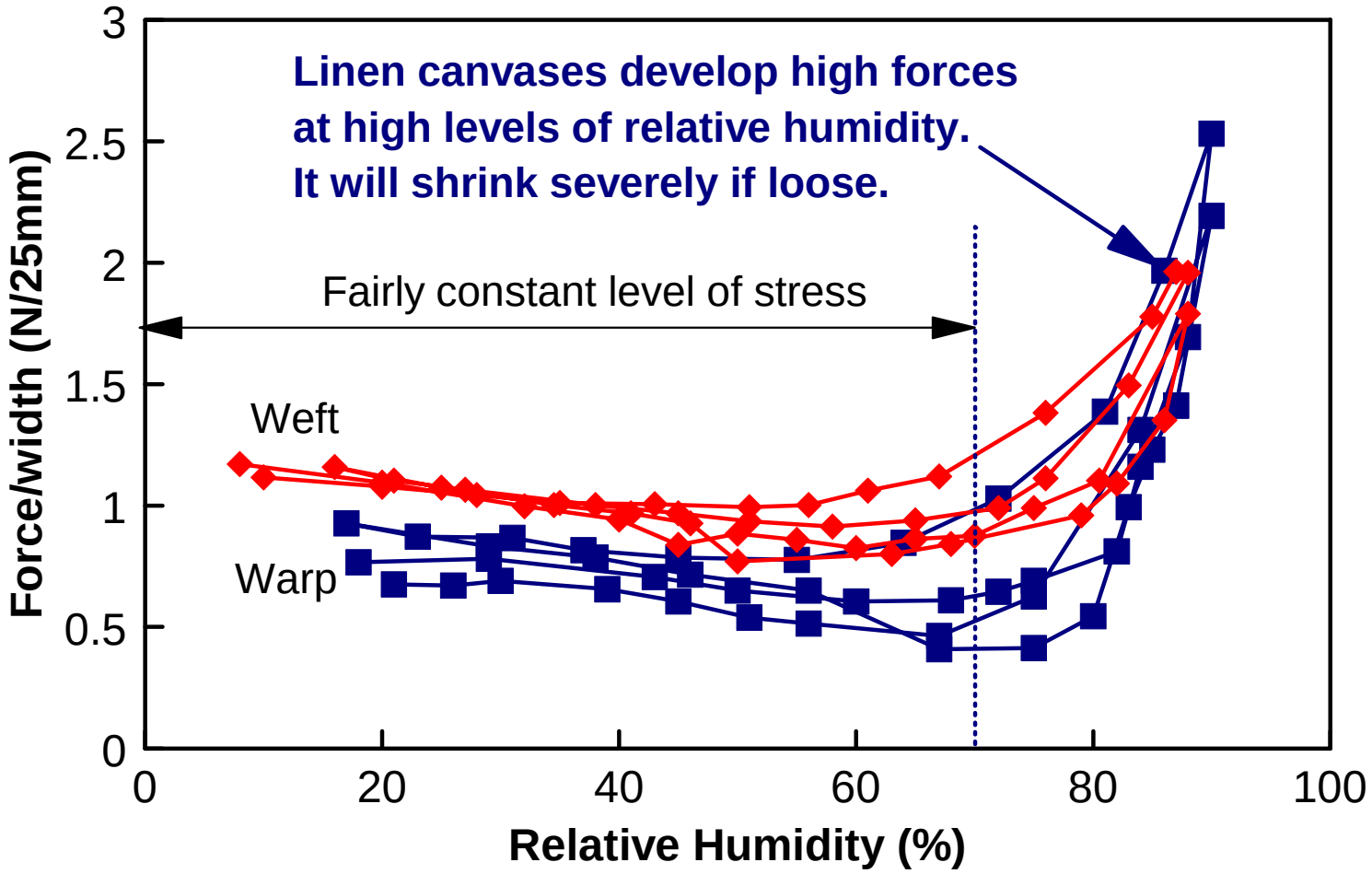
Slide and photo courtesy of Melvin J. Wachowiak

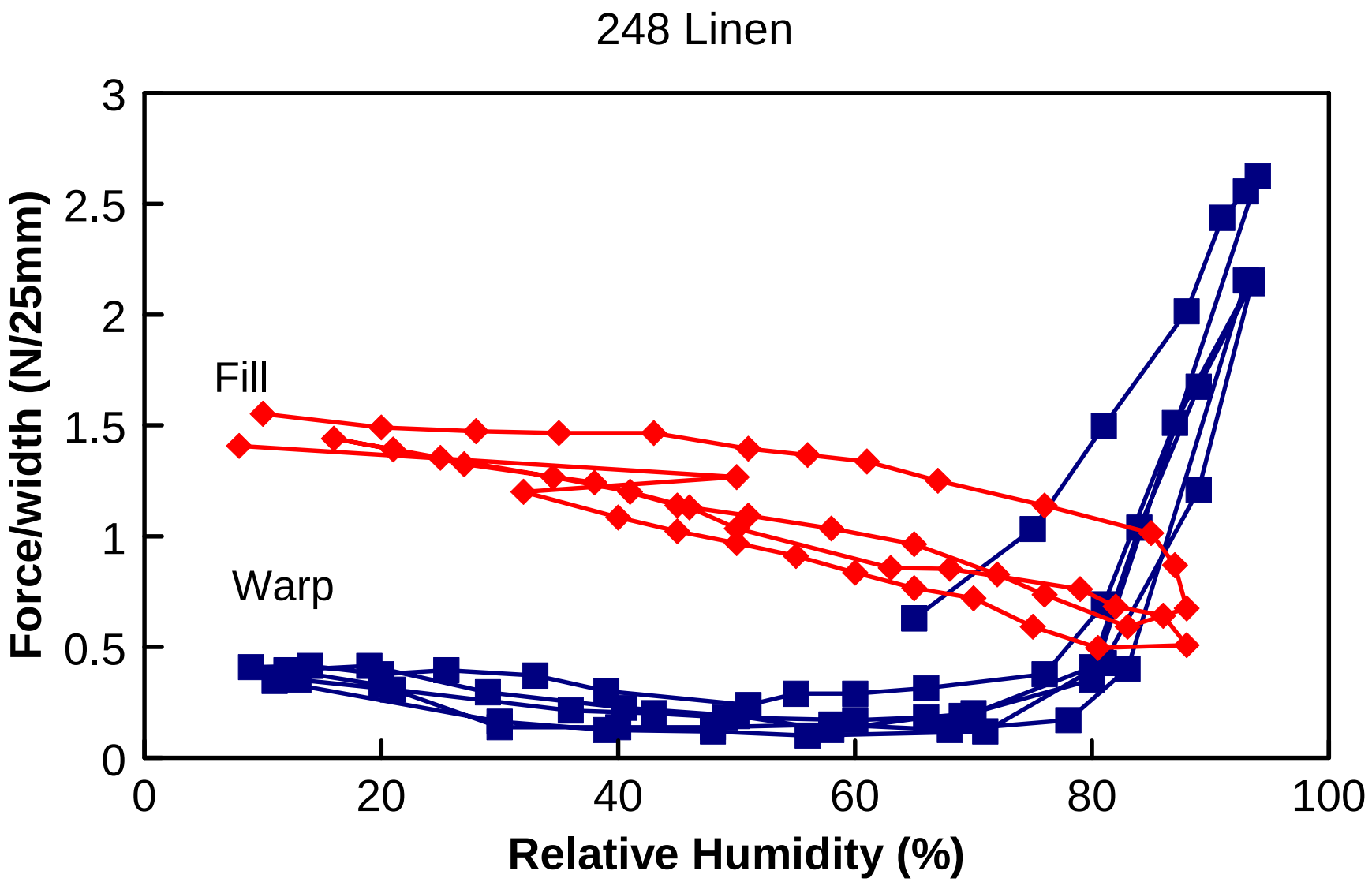
In order to examine the response of canvas painting to changes in relative humidity analysis of the materials under restraint is necessary.

Photo courtesy of Melvin J. Wachowiak

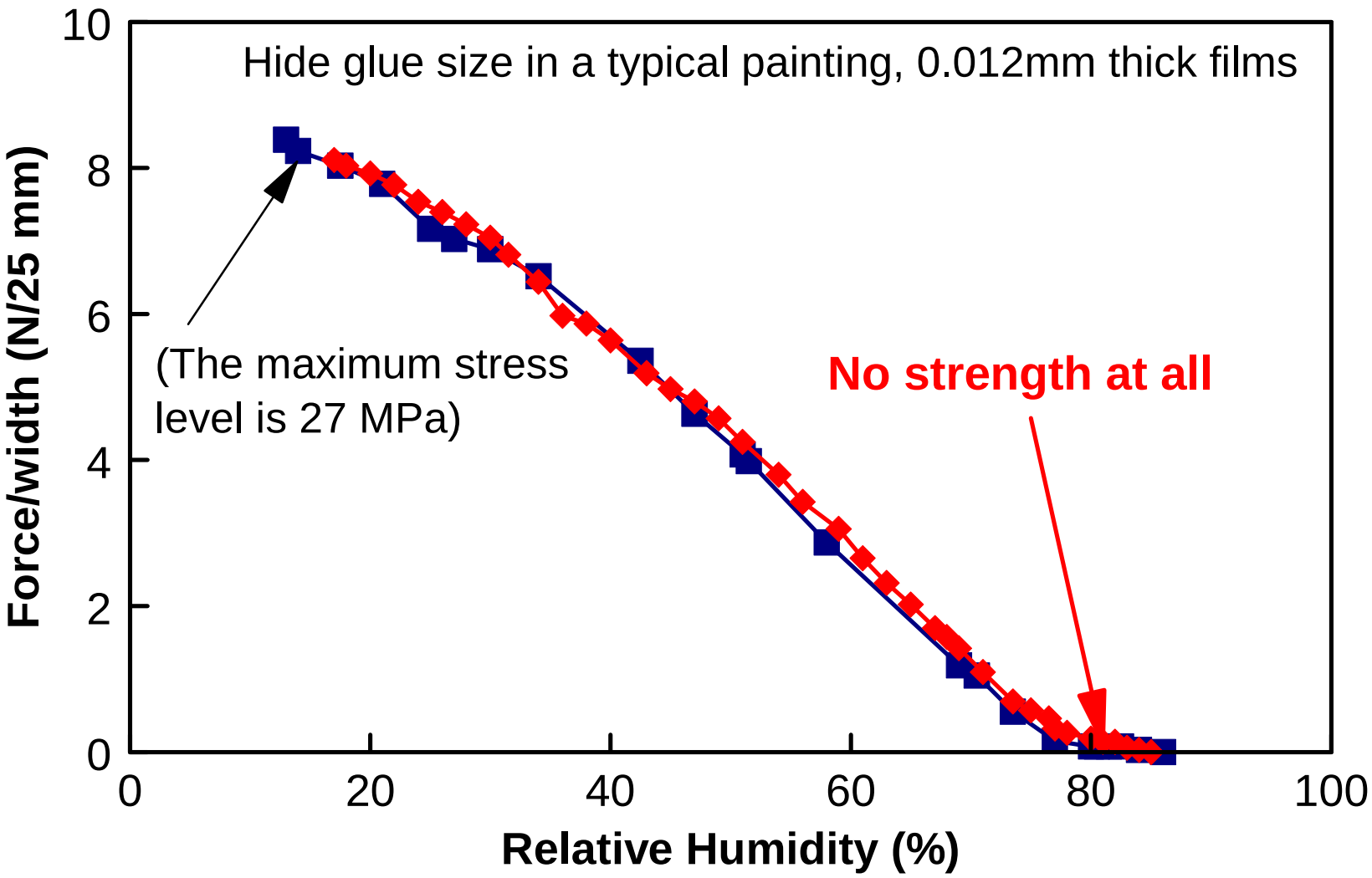
Restrained testing and the principle of superposition.

All layers of canvas painting are under stress nearly all of the time.

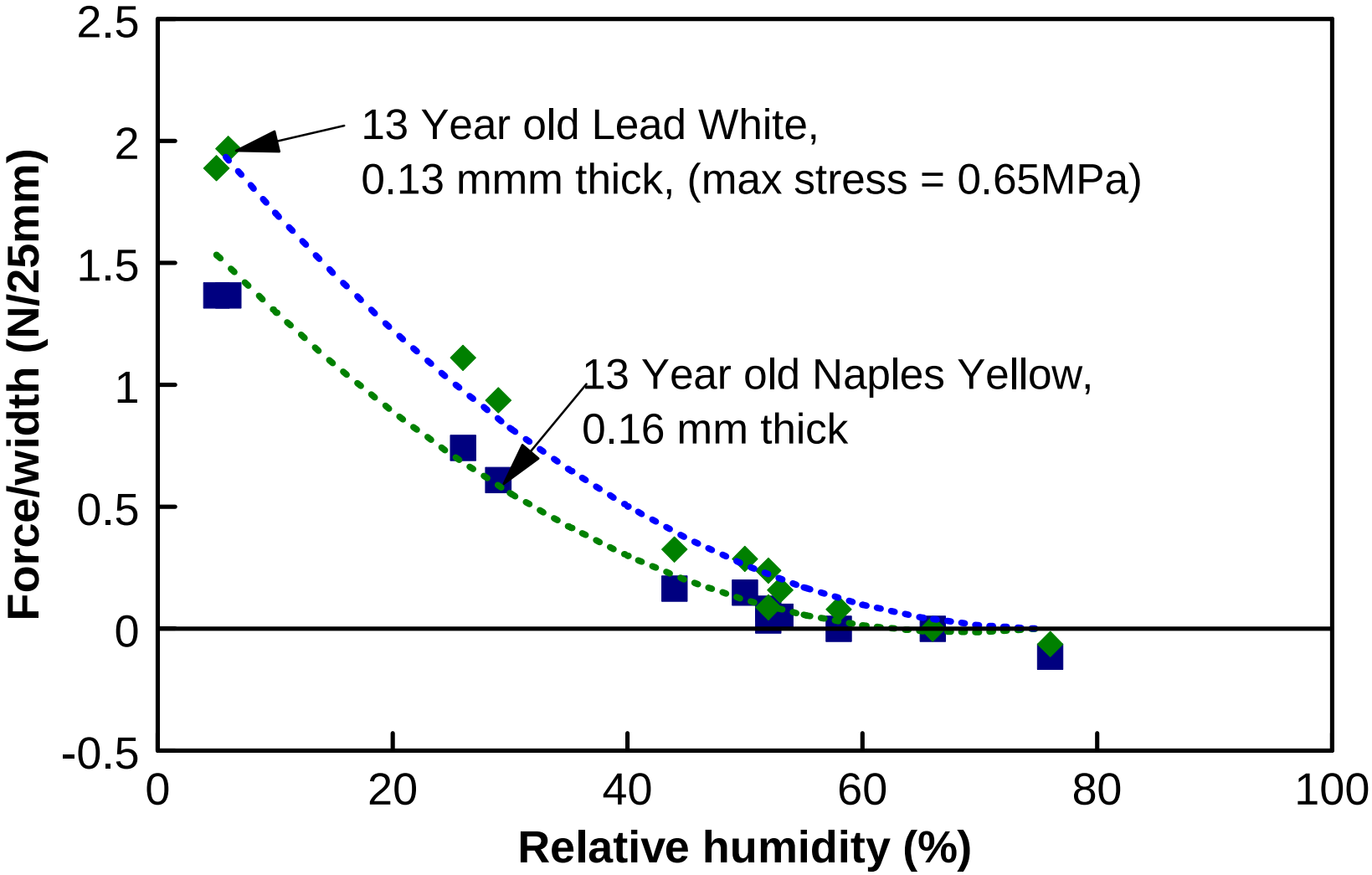



248 Linen
Force/width (N/25mm)
3
2.5
2
1.5
1
0.5
0
Fill
Warp
0
20
40
60
80
100
Relative Humidity (%)

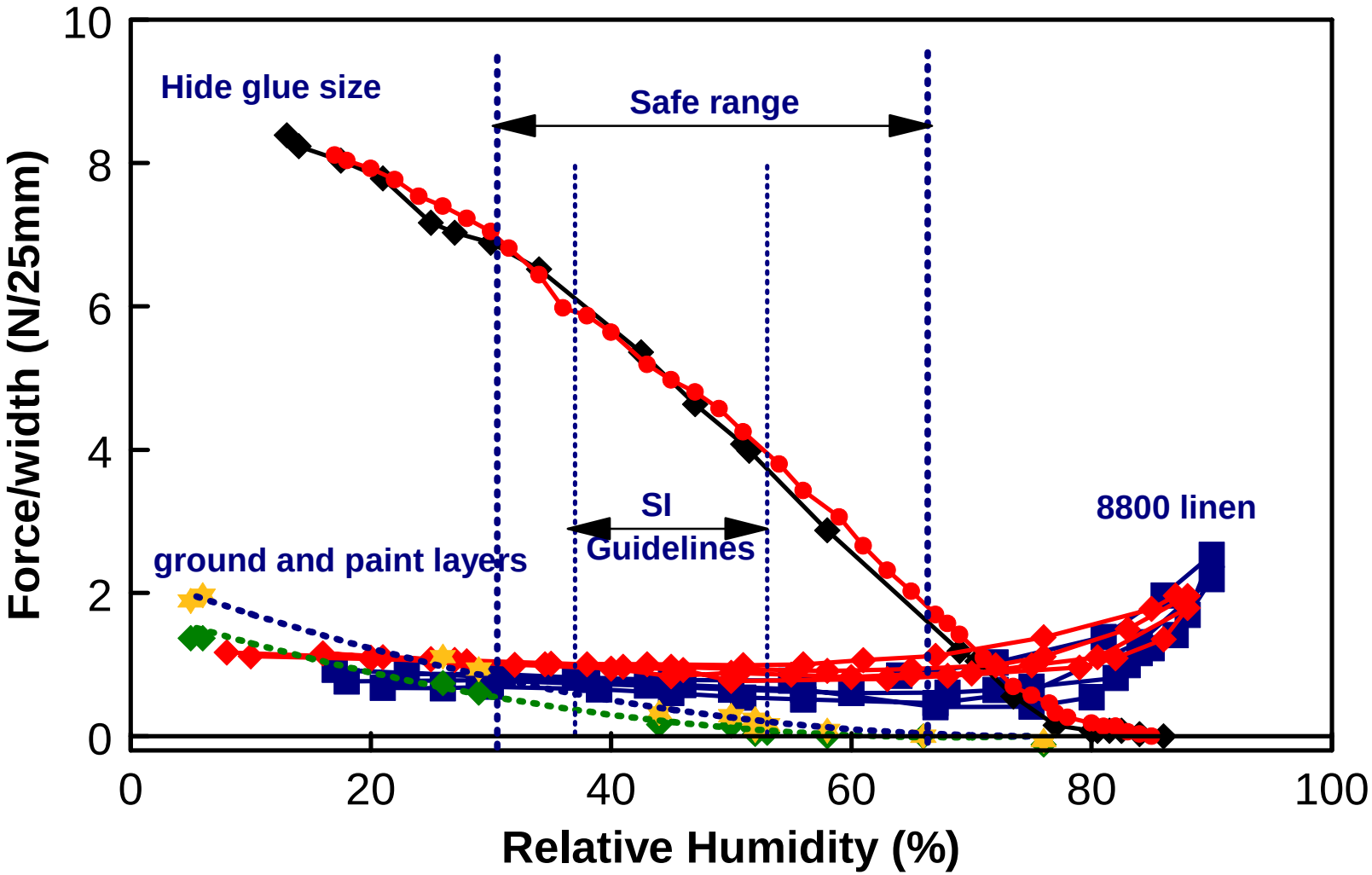
Restrained desiccation of hide glue.

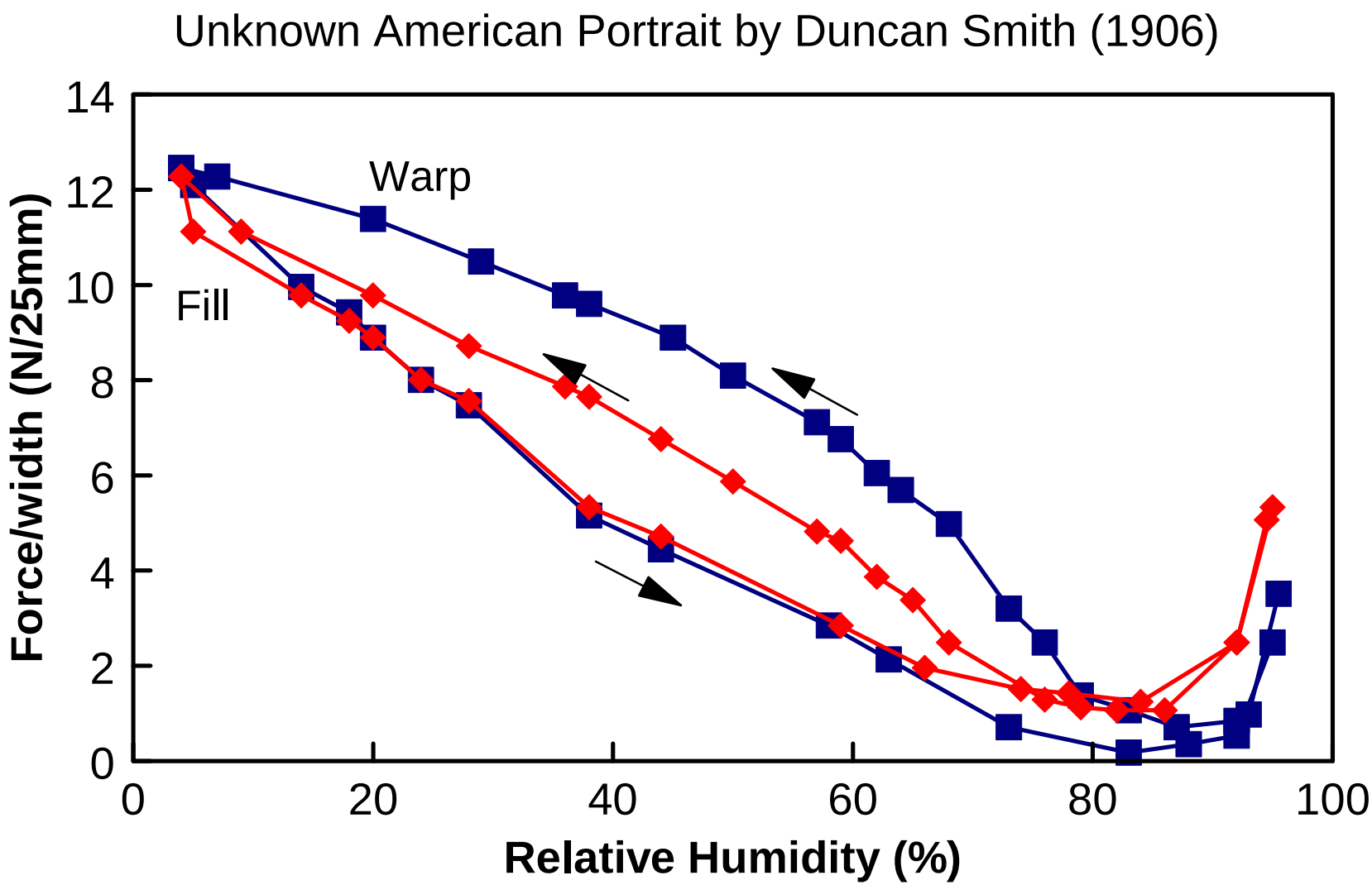


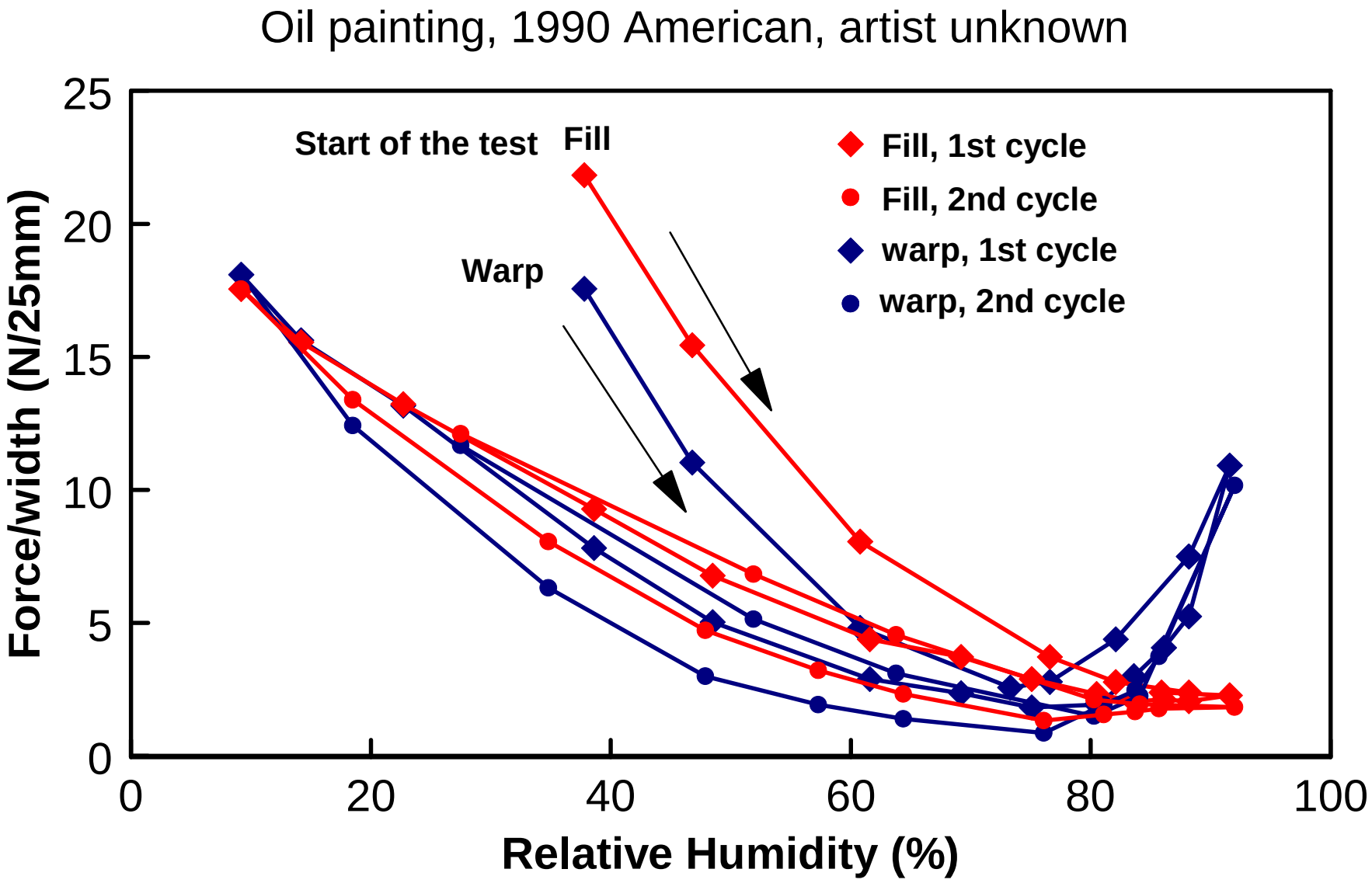
Restrained desiccation of oil paints.



The constructed composite painting




Unknown American Portrait by Duncan Smith (1906)
Warp
Fill
Force/width (N/25mm)
Relative Humidity (%)
0
2
4
6
8
10
12
14
0
20
40
60
80
100

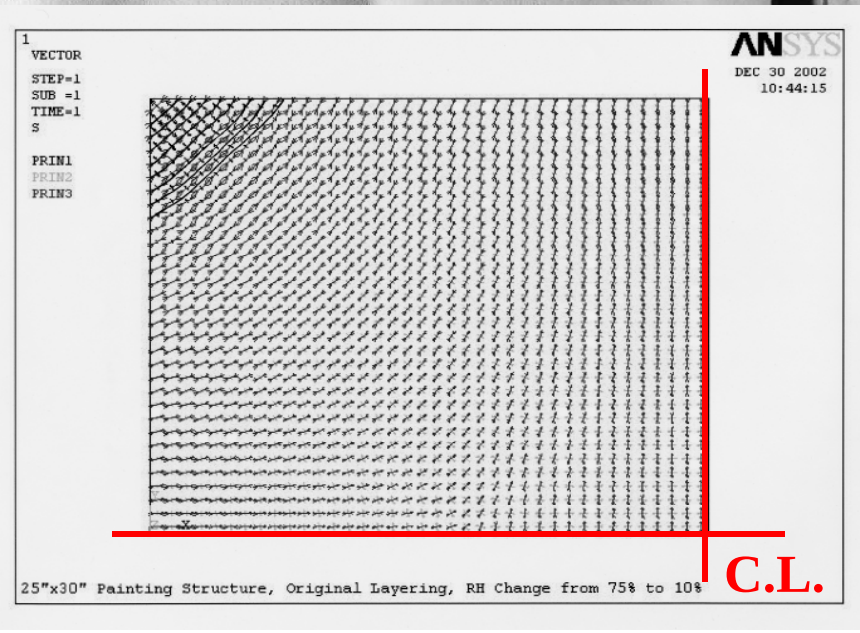

Oil painting, 1990 American, artist unknown
Start of the test
Fill
Warp
Fill, 1st cycle
Fill, 2nd cycle
warp, 1st cycle
warp, 2nd cycle
Force/width (N/25mm)
Relative Humidity (%)
0
5
10
15
20
25
0
20
40
60
80
100

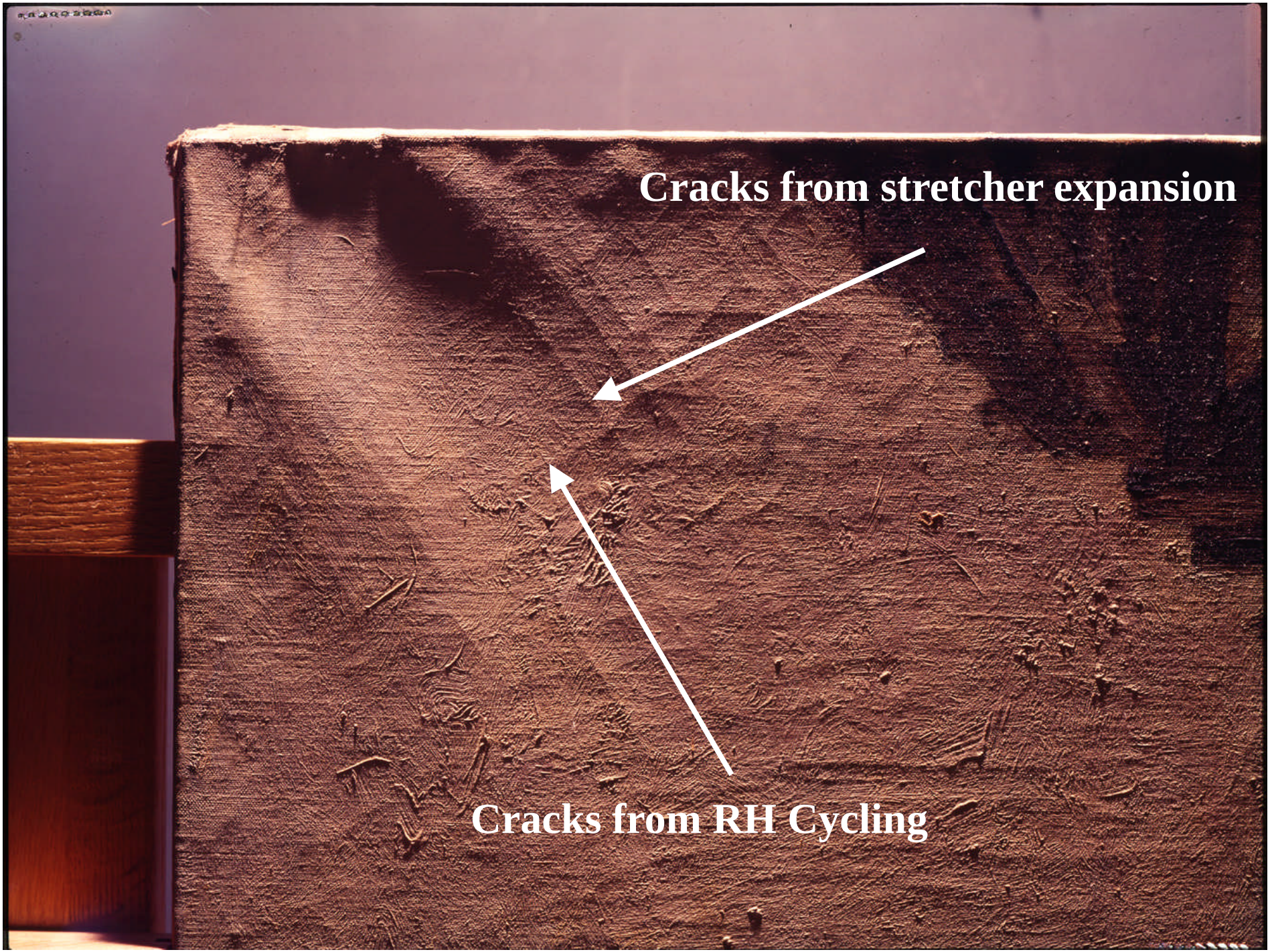
Cycling painting in large RH ranges.

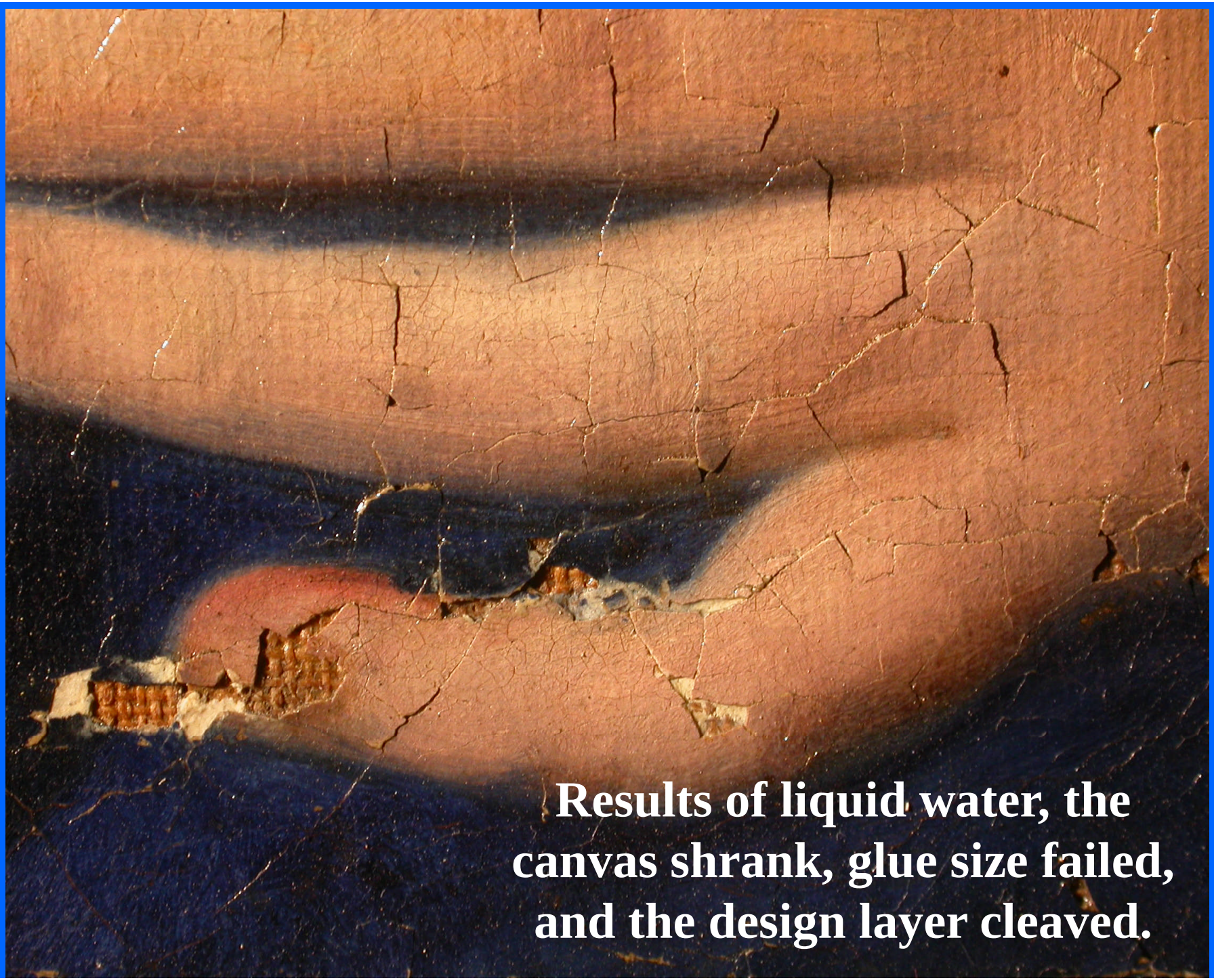
75 mm

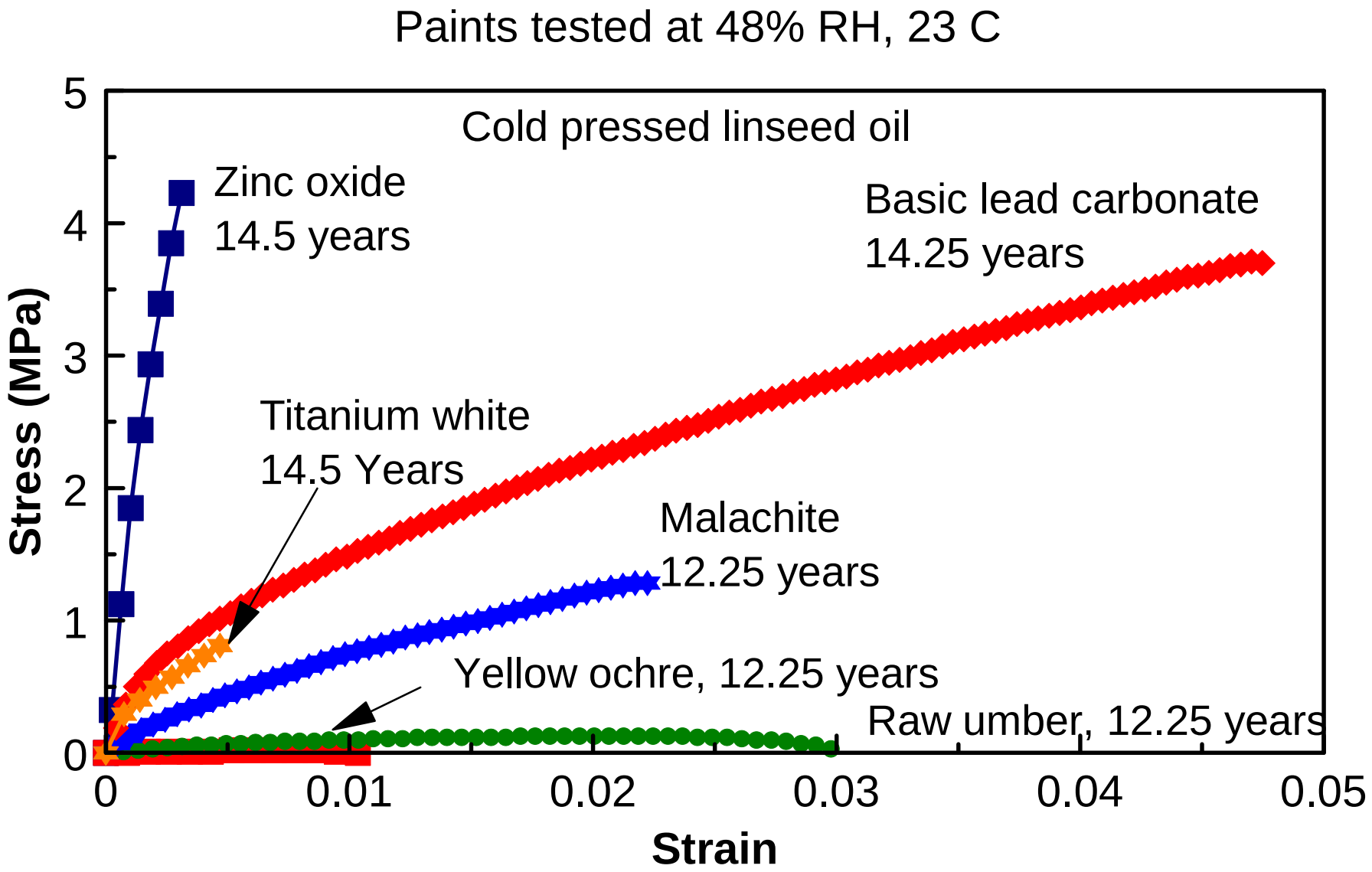
9 CYCLES

90% TO 35% RH

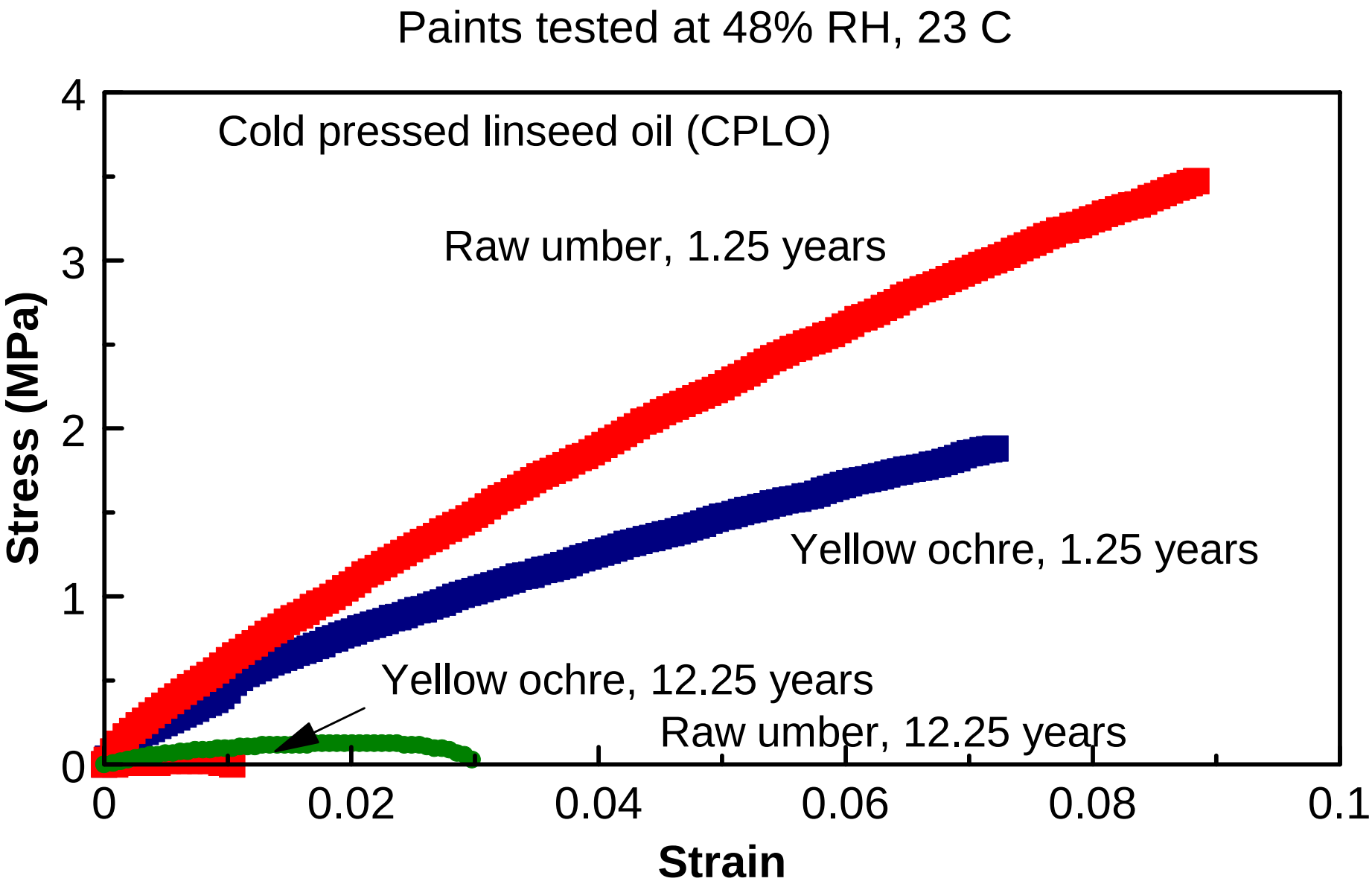


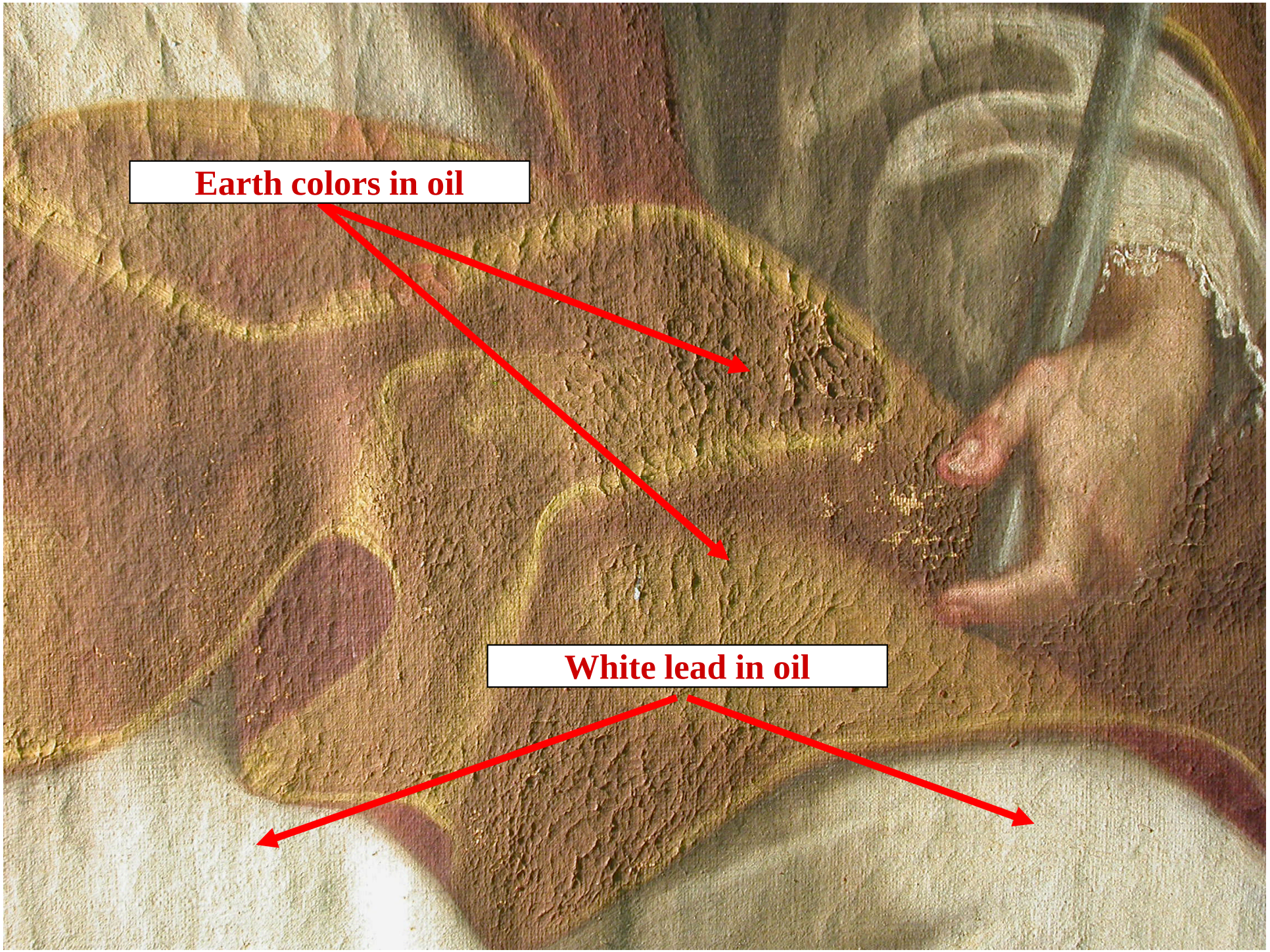

Cracks from stretcher expansion
Cracks from RH Cycling


Results of liquid water, the
canvas shrank, glue size failed,
and the design layer cleaved.


Paints tested at 48% RH, 23 C
Cold pressed linseed oil
Zinc oxide
14.5 years
Basic lead carbonate
14.25 years
Titanium white
14.5 Years
Malachite
12.25 years
Yellow ochre, 12.25 years
Raw umber, 12.25 years
Stress (MPa)
Strain
0
1
2
3
4
5
0
0.01
0.02
0.03
0.04
0.05

Hydrolyzed paints lose strength with time

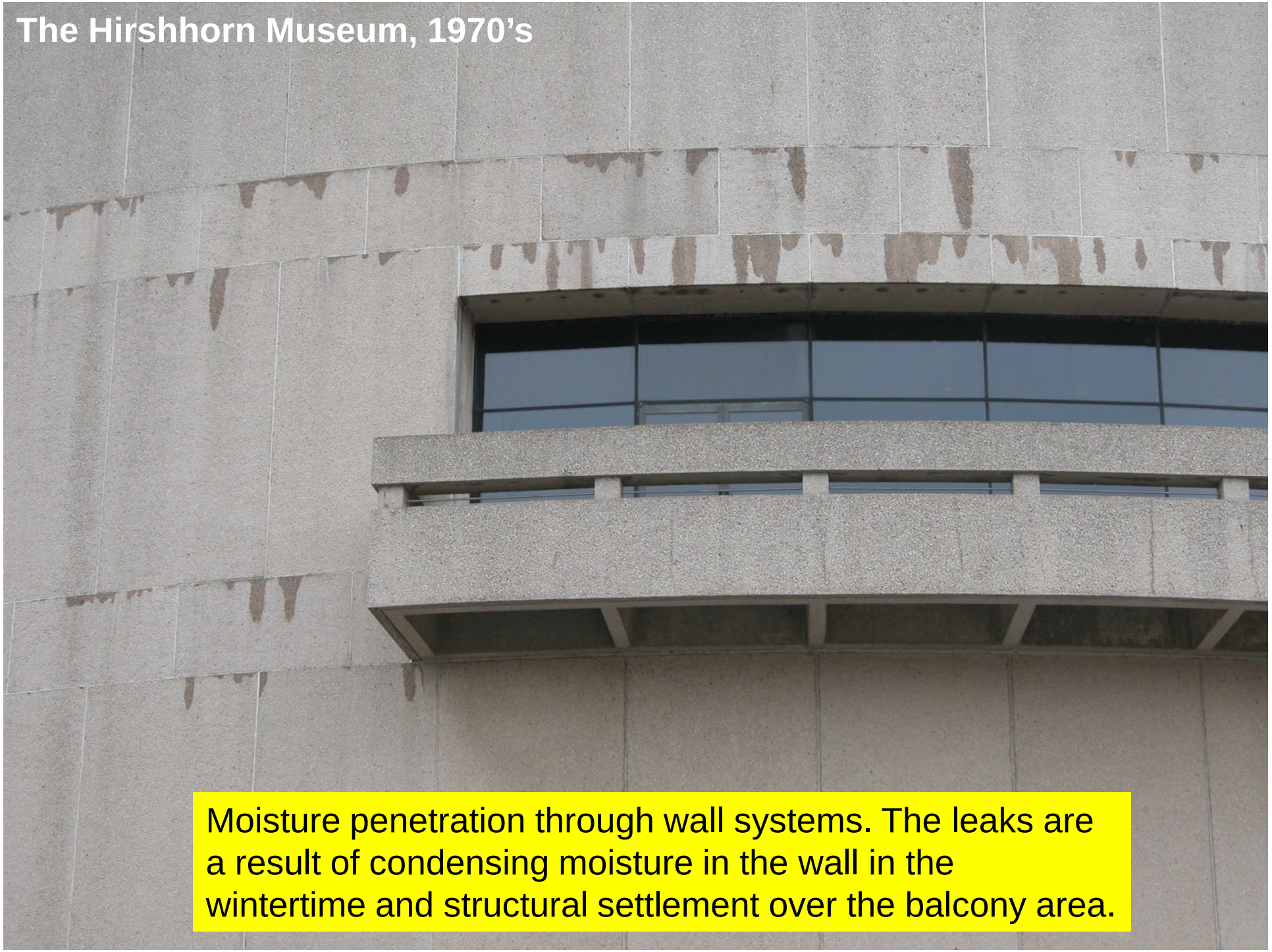



Earth colors in oil
White lead in oil

Building Preservation and Energy Consumption

The Renwick Gallery, c. 1860

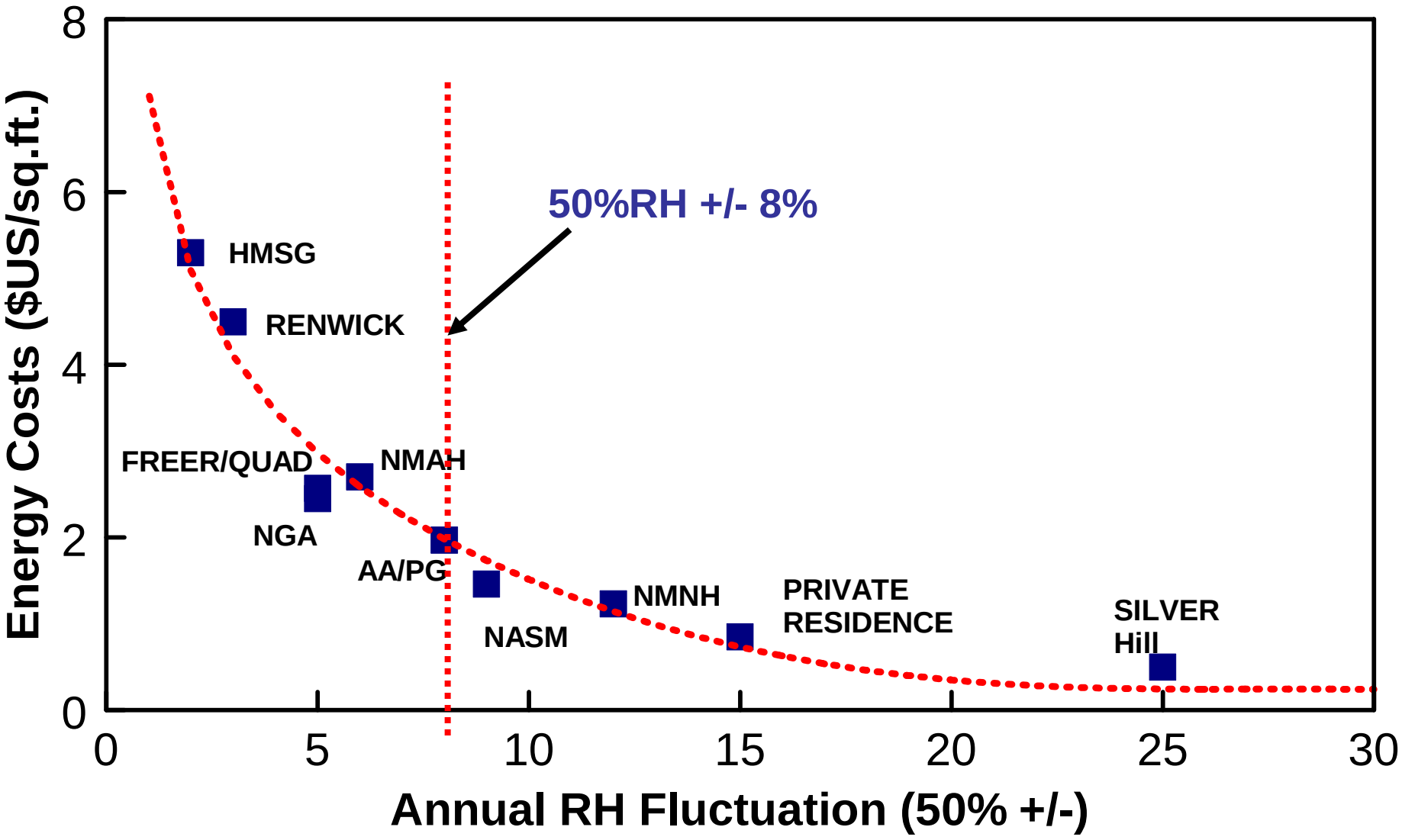
Moisture condensation on the walls in cold winters. Indoor ambient relative humidity was 50%. In the summertime the RH behind paintings can drop to 35%.


The Hirshhorn Museum, 1970’s
Moisture penetration through wall systems. The leaks are a result of condensing moisture in the wall in the wintertime and structural settlement over the balcony area.


The National Museum of American History, c 1960’s
Condensing moisture due to high relative humidity
In the wintertime.

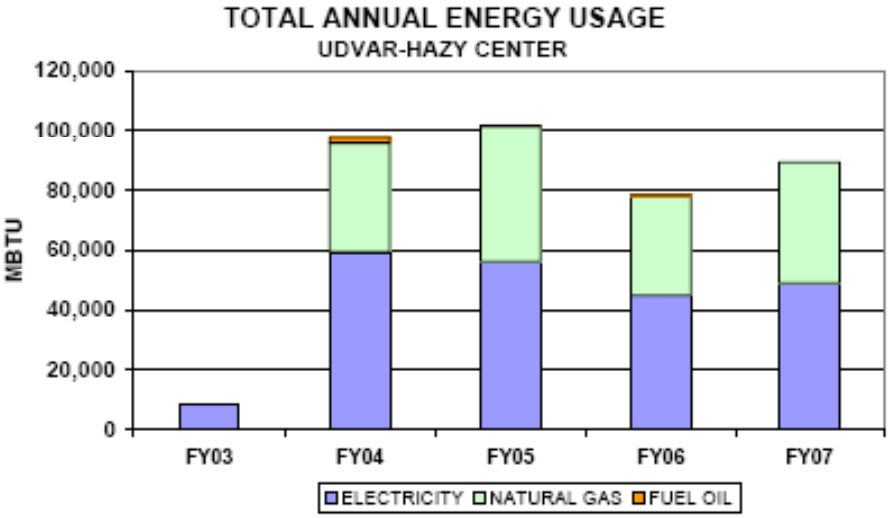
In 1994 we knew that energy savings were possible. If the annual RH range could be expanded even a small amount then there would be considerable energy savings.

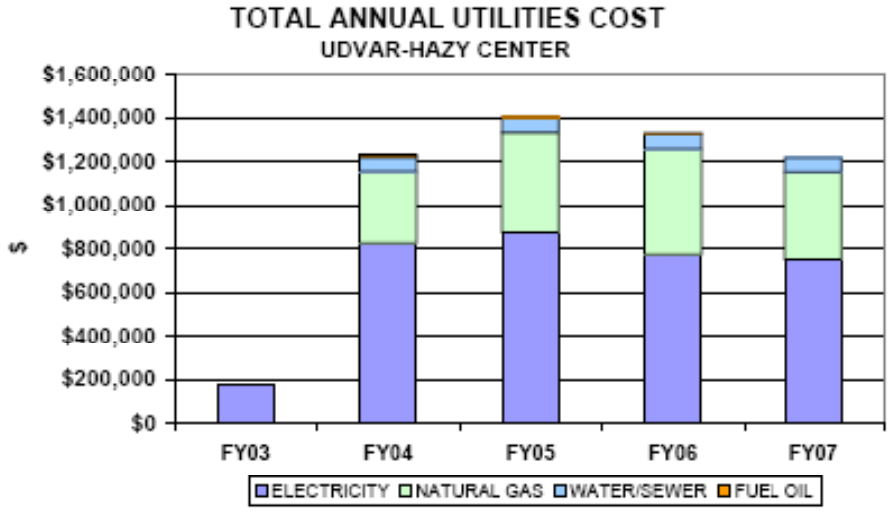
FY 1993, SMITHSONIAN ENERGY COSTS



Opened Dec. 2003
adjusted

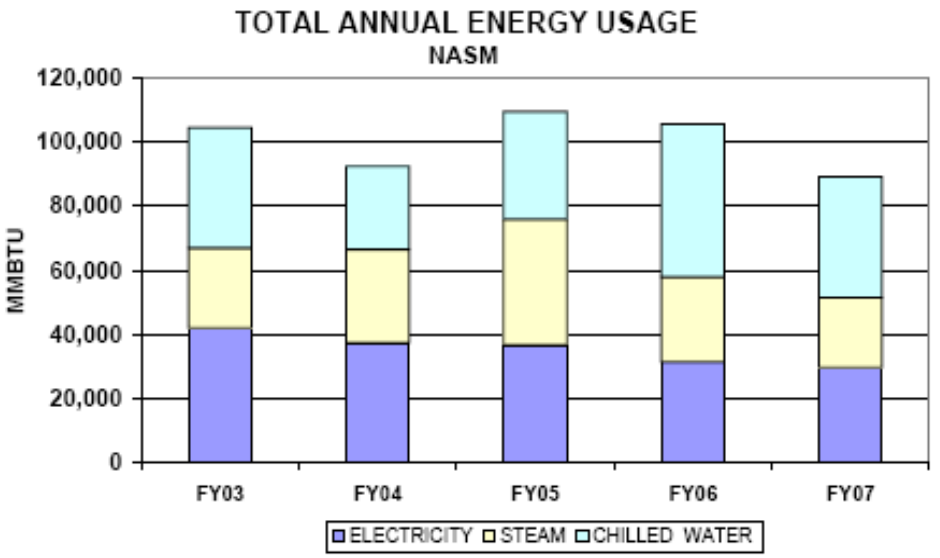
FY07 projected
after three quarters.

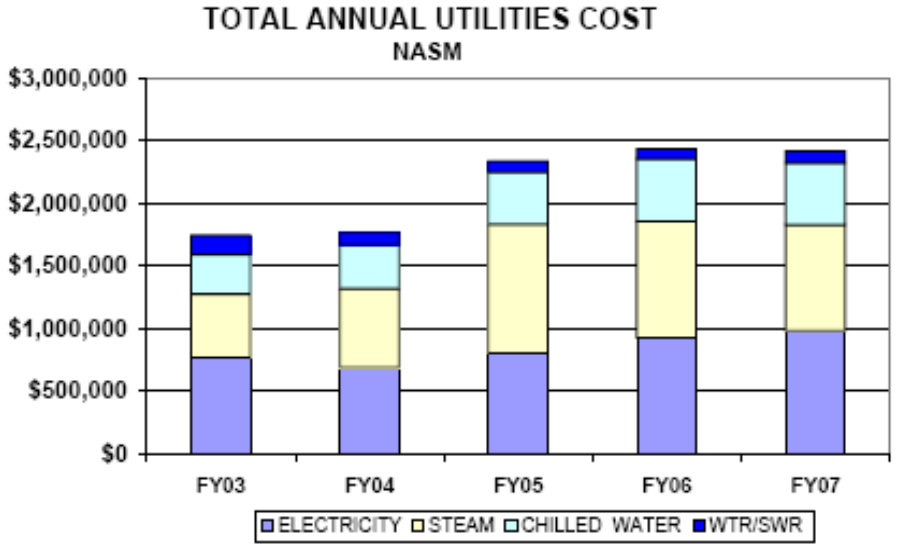




Adjusted in 2005

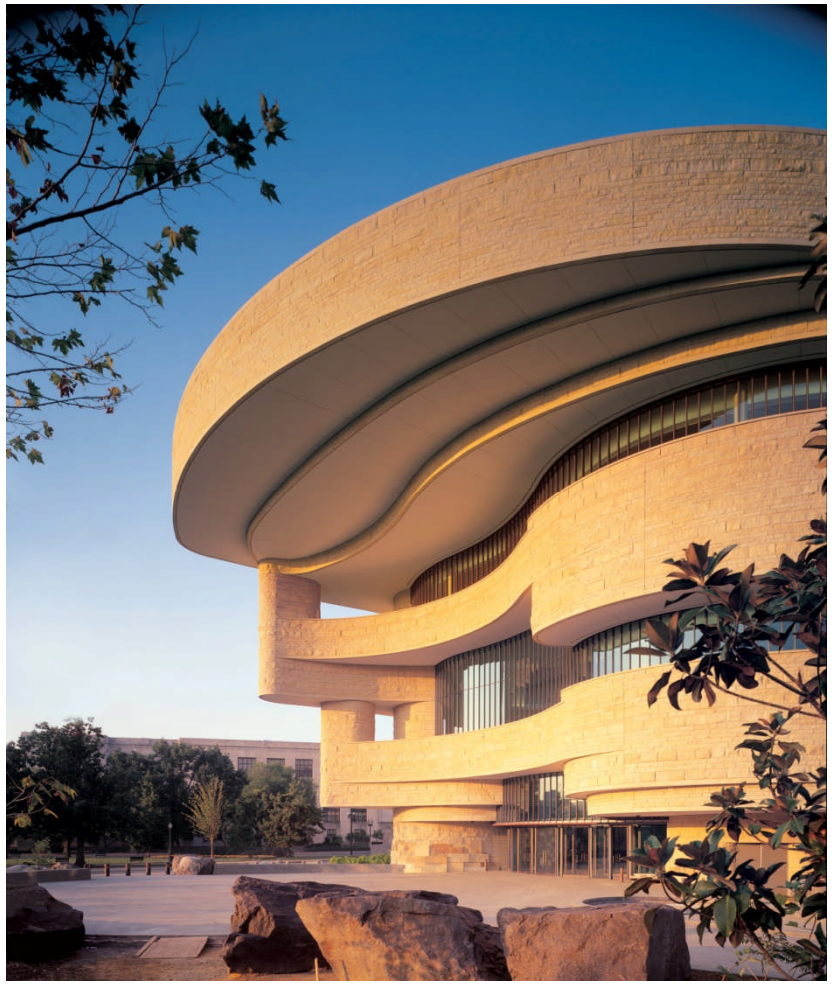
FY07 projected after three quarters.

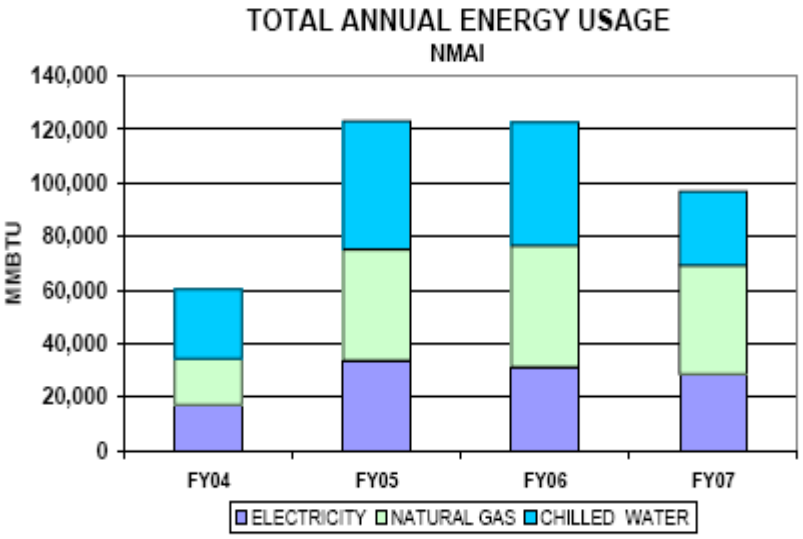


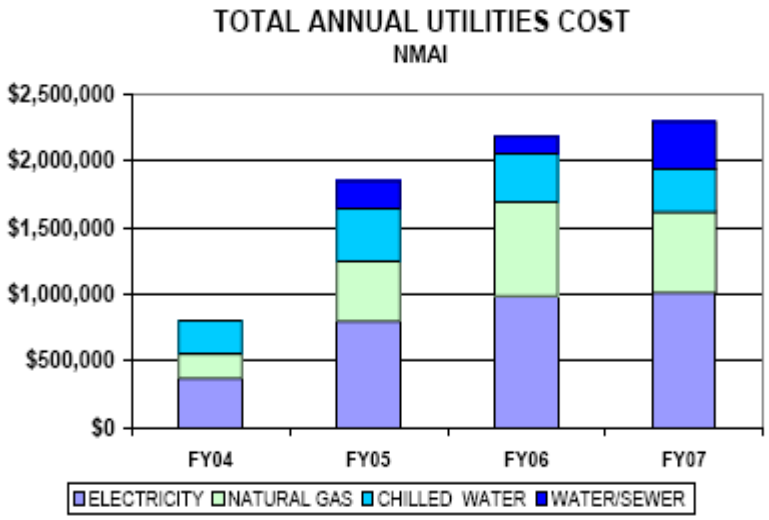


Opened 2004
not fully adjusted

FY07 projected
after three quarters.

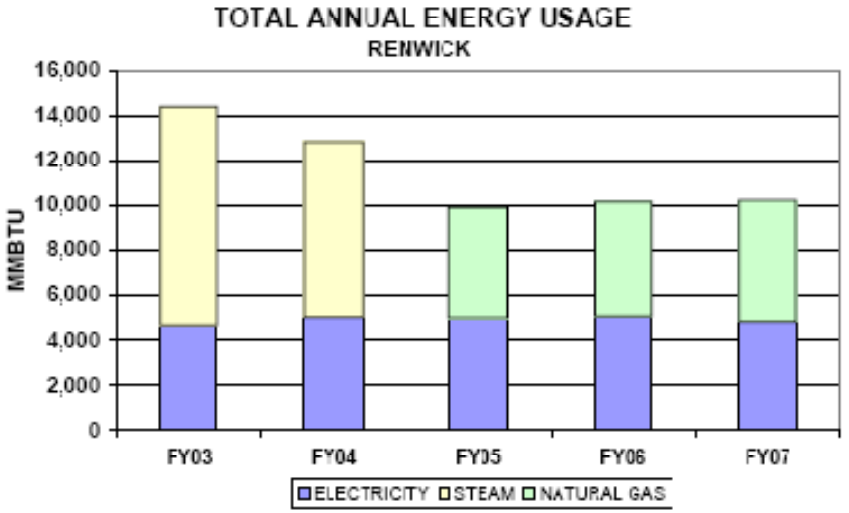


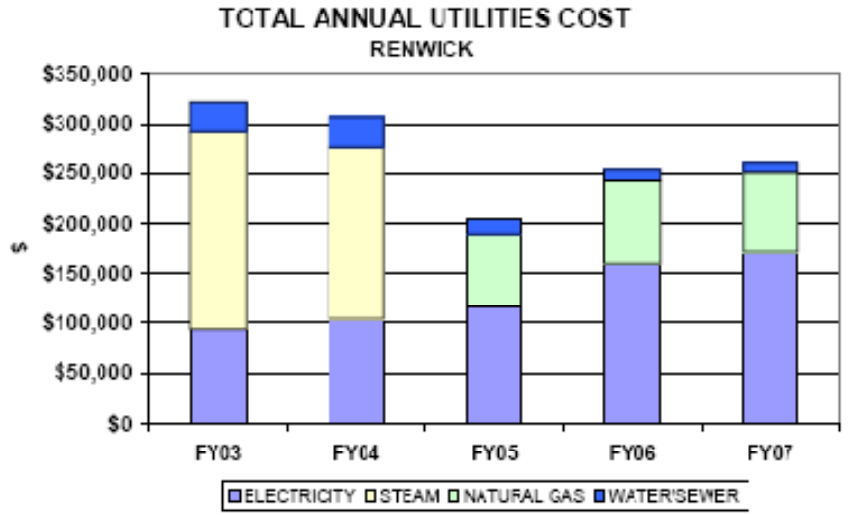




One of the buildings that got early attention

FY07 projected after three quarters.





Some of the energy conservation measures at the SI

Blue – Taking advantage of passive behavior and building "inertia"

- **HVAC - running smaller/less boilers in the summer**
- **HVAC - secured/setback air handling equipment during unoccupied hours**
- **HVAC - raised chilled water supply set point; lowered boiler supply set point**
- **HVAC - secured outside air and exhaust during unoccupied hours**
- **HVAC - raised space temperature set point**
- **Hot water - lowered supply temperature; secured during unoccupied hours**
- **Power- secured non-essential pumps where appropriate**
- **Lighting – dimmed, secured, disconnected, removed exterior/interior lighting**
- **Lighting – rescheduled to shut off during unoccupied hours**
- **Lighting – installation of LED exit signs and occupancy sensors.**

Did we actually save any money?

“We saved $2.7 million in the last half of FY 2006, and about $1.5 million in the first quarter of FY 2007, mainly through changes in HVAC operations.

The temperature and humidity guidelines help us because they are credible……and because they are broad and flexible enough to accommodate energy-saving strategies.”

David Hauk, Chief Energy Management Branch
OFEO

This is about a 17% savings on an annual basis.

Any materials that have been chemically or biologically degraded to the point where the strains to failure are less than a strain of 0.005. This is especially true for materials with high RH related dimensional response such as woods, ivory, paper. These materials should never be restrained. They should be exhibited in buffered cases or frames.

Those objects having crossed grain assemblies or wood veneers where the bonding adhesive has degraded.

This especially true for wood panel paintings that have cross grain battens glued to the reverse. Use caution in hanging paintings, especially on the inside surfaces of exterior walls in older buildings

Those wooden or ivory objects having metal or stone inlays. This recommendation in part reflects the adhesives used in bonding the materials together.

Those objects having very high pre-existing stresses such as hide drum heads and oriental paper or silk screens. It would be prudent to keep drum heads loose. Pastes such as Japanese wheat starch pasts are actually fairly strong, about half that of the hide glues.

If you have any questions contact me at mecklenburgm@si.edu

For additional information see the following links.

http://www.si.edu/mci/downloads/reports/Mecklenburg-Part1-RH.pdf
http://www.si.edu/mci/downloads/reports/Mecklenburg-Part2-Temp.pdf