Effects of Moisture Diffusion in Sandwich Composites

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A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

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Outline

I. Brief summary of a UW numerical study funded by Boeing in 2003

II. Experimental studies at UW, 2008-09

III. Newly-funded JAMS-AMTAS project, initiated September 2015

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- Fick's diffusion equations → used to predict through thickness moisture content resulting from cyclic changes in external temperature and humidity
- Fourier heat conduction equation → used to predict steady-state through-thickness temperature profiles
- Clapeyron equations → used to predict dew point of water vapor in core (if current temperature < dew point, condensation occurs)
- Certain properties of core region estimated using rule-of-mixtures

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Overall Conclusions:

- Core humidity levels will increase with time…only question is time required
- Under realistic service conditions liquid water does not accumulate within core region of pristine structures due strictly to diffusion…*however*
- (For transport aircraft flight profiles) humidity increase implies water vapor will condense-freeze-thaw-evaporate during ascent-cruise-descent cycles

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Predicting Moisture Diffusion

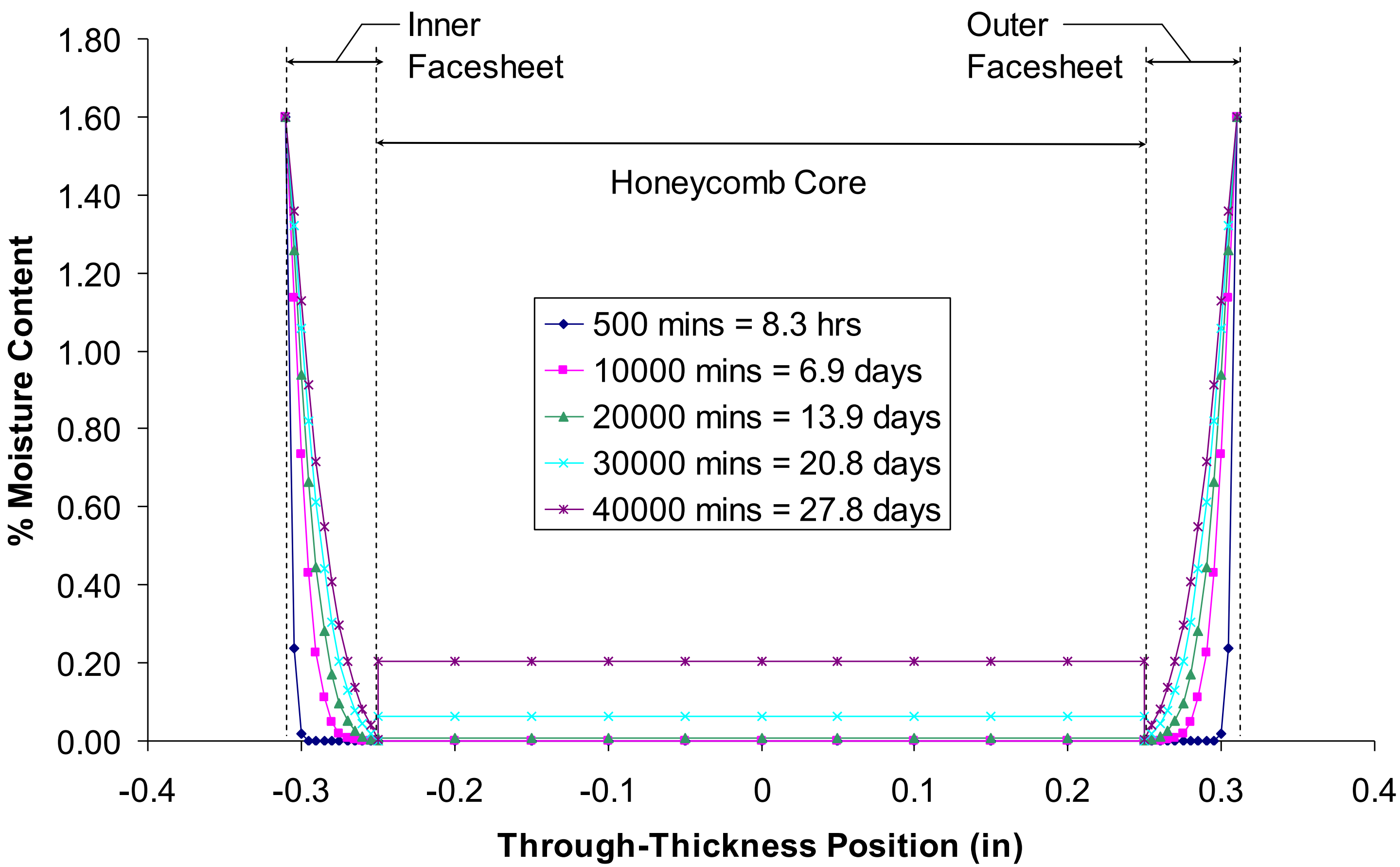
Typical Result: Constant Temperatures and Humidity

12-ply Gr/Ep inner and outer facesheets

0.50 in honeycomb core with 0.20 in cell size

T=90F (both faces; constant)

RH = 80% (both faces, constant)



Predicting Moisture Diffusion

Typical Result: Constant Temperatures and Humidity (cont'd)

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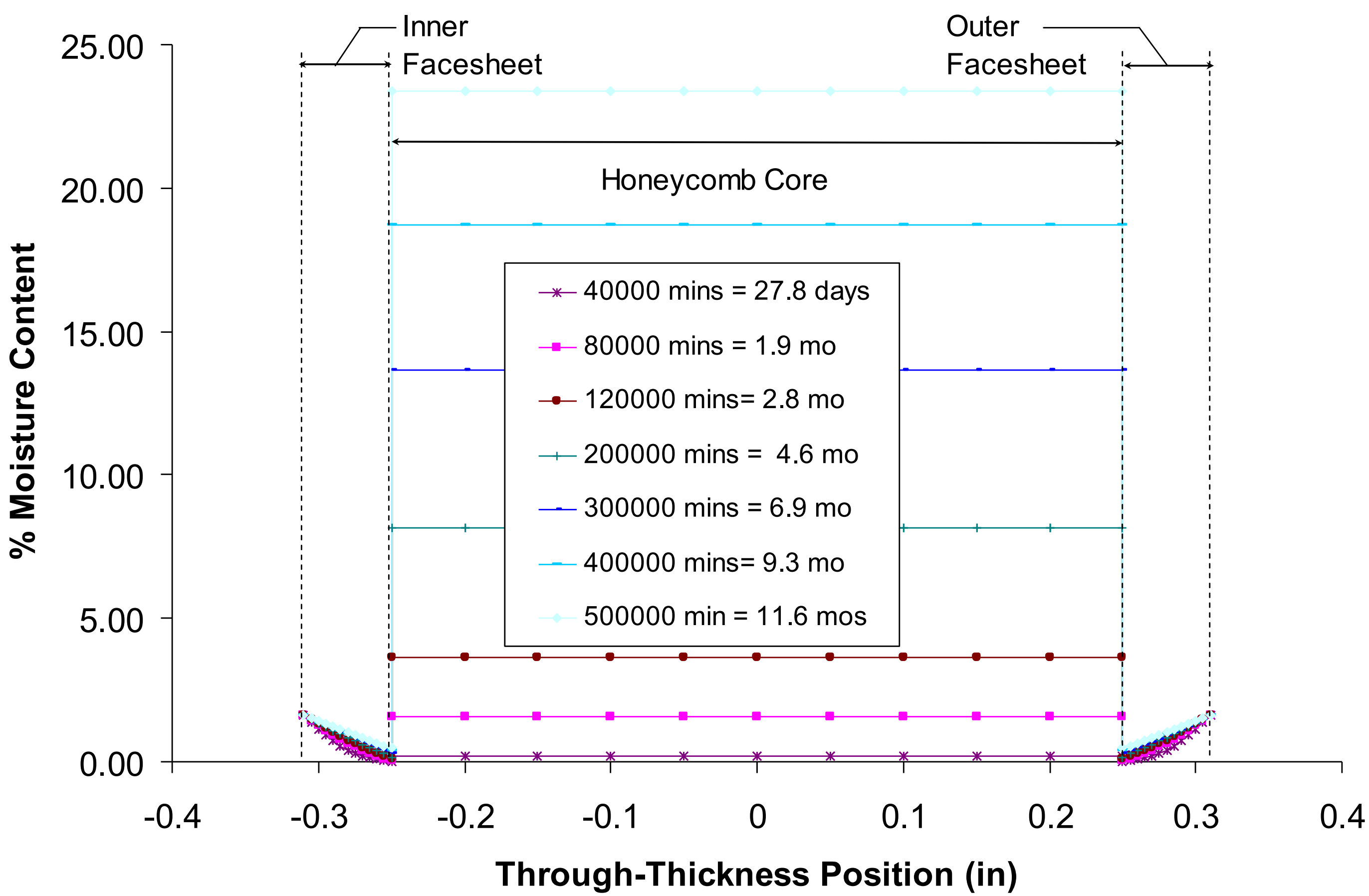

Numerical UW Study Funded by Boeing in 2003

Although reasonable predictions were obtained using program MOIST, no experimental measurements were available to validate analysis

The potential structural application of sandwich composites envisioned by Boeing engineers (in 2003) were not pursued, funding was discontinued, and the UW study ended.

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Experimental Studies at UW

Conducted over 2008-09

Objectives:

Measure relative humidity in core region of a flat sandwich panel exposed to constant external temperature and humidity on both sides

Compare measurements with MOIST predictions

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Sandwich panel internally instrumented with:

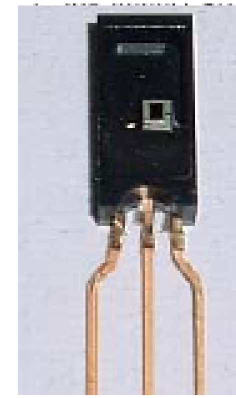
- 2 type K thermocouples
- 2 Ohmic Instruments Model HC-610 capacitive humidity sensors:
  - 5-95 %RH
  - -40 to 185ºF operating range

Test begun on 5 Aug 2008:

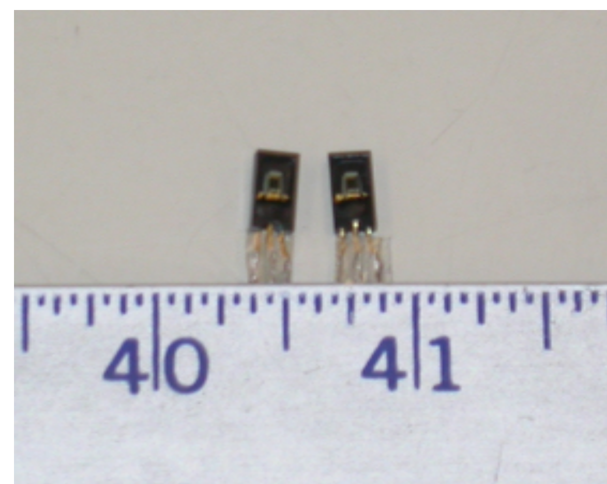
- Temperature set @ 40ºC (104ºF)
- Humidity level 55%RH
- Data recorded every 30 mins (using Labview)

HC-610 Thermoset polymer capacitive humidity sensor. Hybrid electronics. Linear output. Range 5 to 95 %RH 2%. Temp. – 40 to 185 ºF. Supply voltage 4.0 - 5.8 VDC

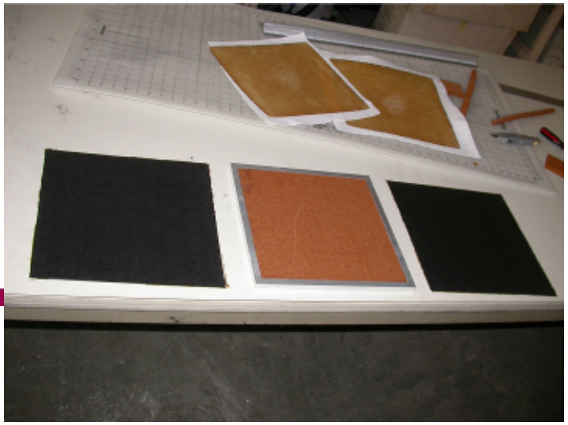
PDF Data | PDF Man/Instructions



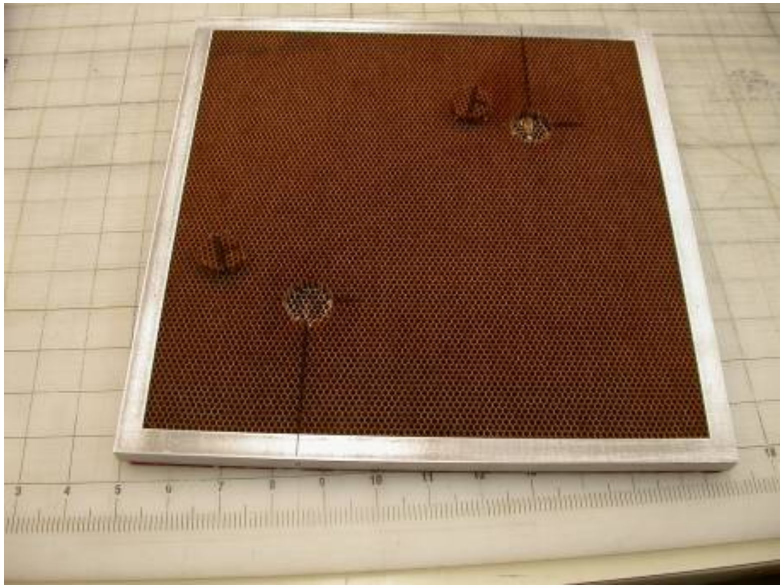
www.ohmicinstruments.com/



Test Panel Fabrication



- Type 410 Nomex honeycomb core
- $[0/45/90/-45]_s$ Gr/Ep facesheets
- Core sized to fit within aluminum frame to insure 1-D, through-thickness diffusion

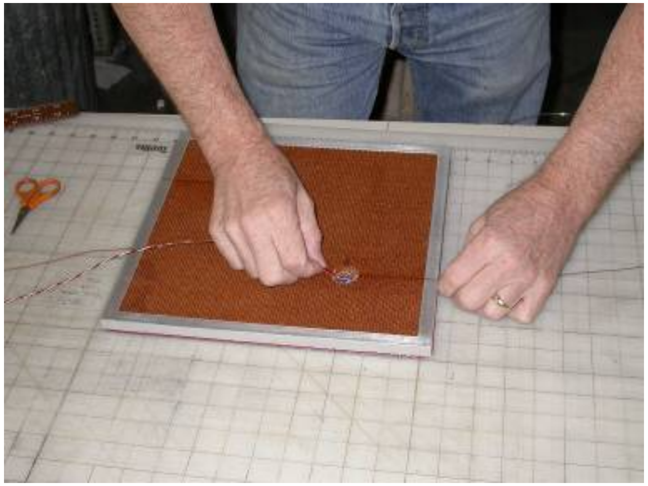


- First facesheet bonded to one side of panel using thin-film adhesive

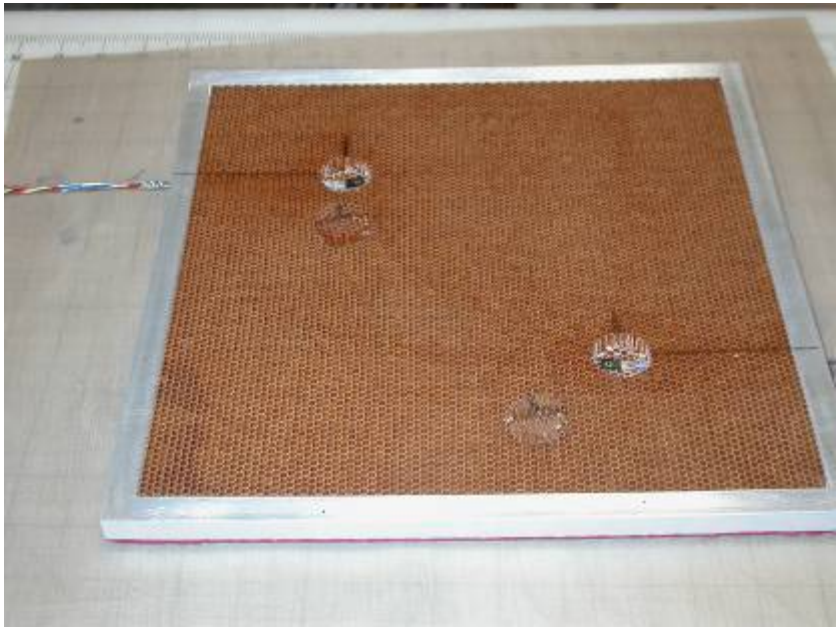
- Pocket for embedded humidity sensors and thermocouples milled in core

Test Panel Fabrication

- Leadwires inserted through honeycomb and aluminum frame

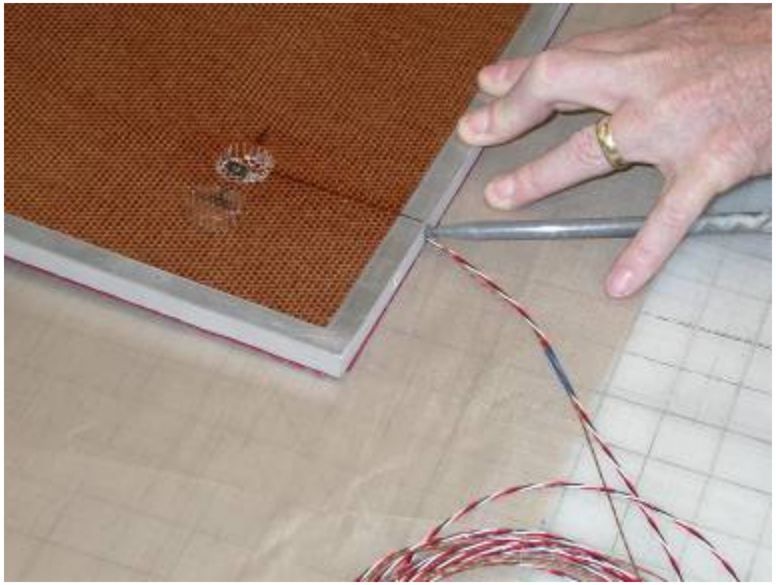


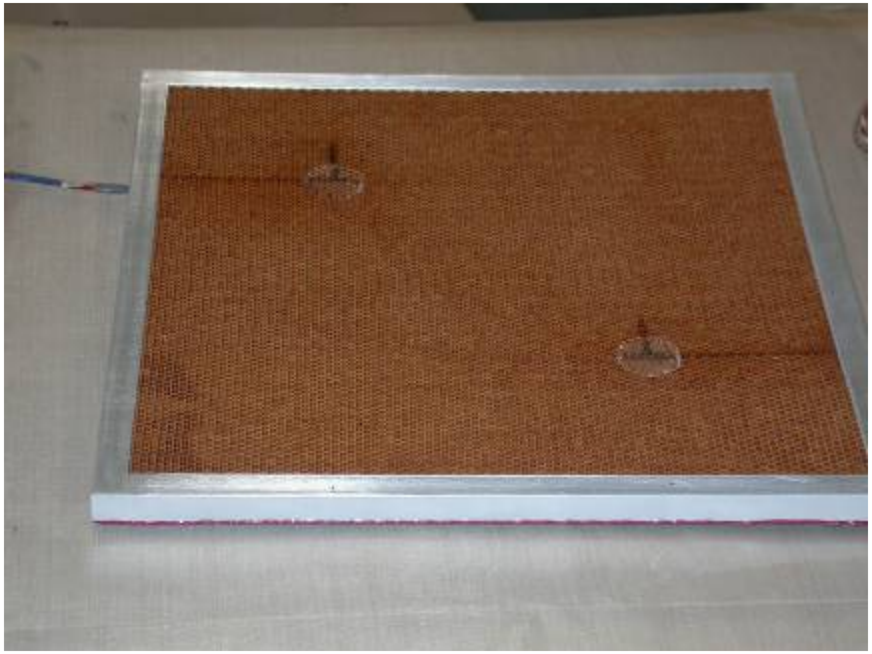
- Initial installation of embedded sensors



Test Panel Fabrication

- Leadwire passage in aluminum frame sealed with epoxy

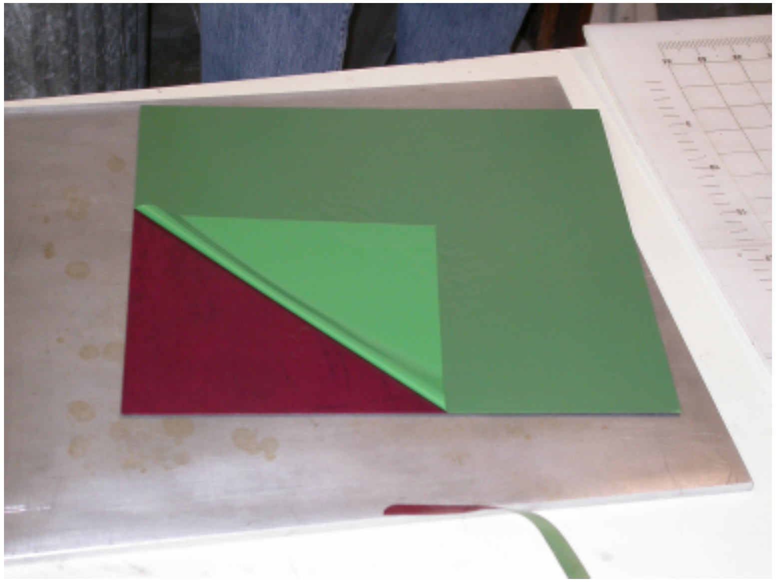




- Honeycomb ‘caps’ placed over instrumented sites

Test Panel Fabrication

- Second facesheet bonded to panel using thin-film adhesive…

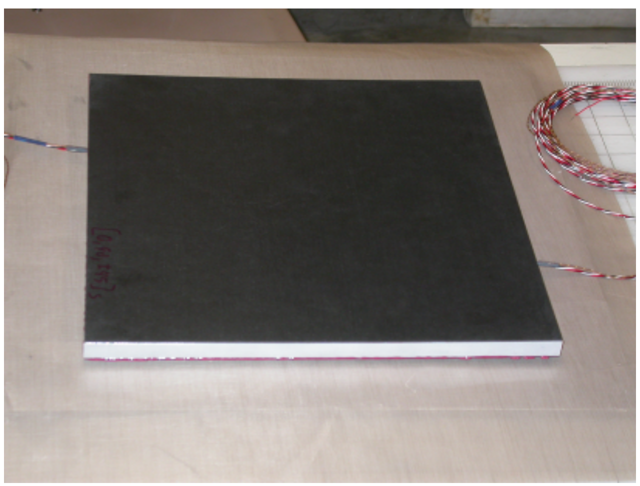


…and hot press

Test Panel Fabrication

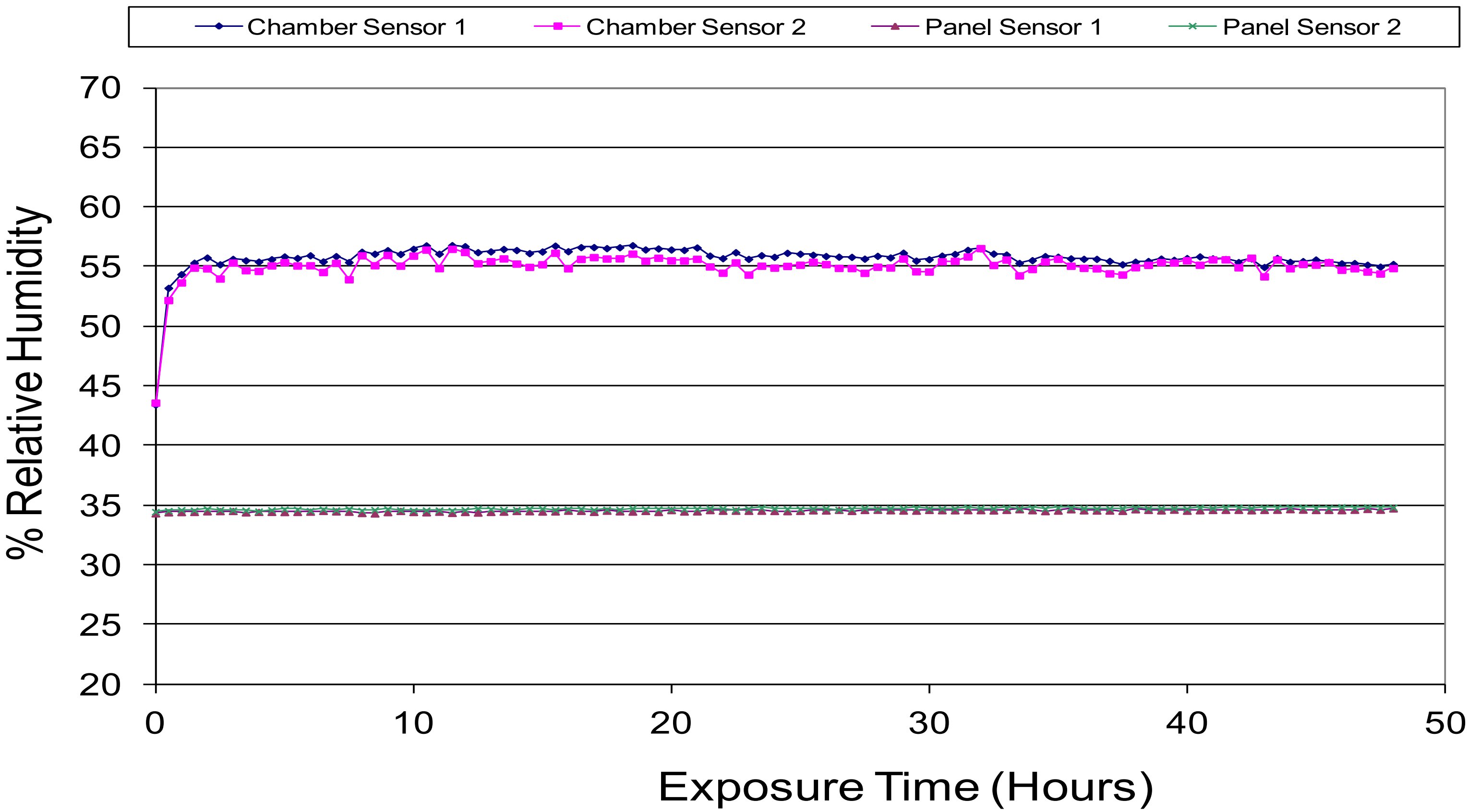
- Completed panel mounted in test chamber; exposure began on 5 Aug 2008

- Initial measurements (40ºC = 104ºF):
  Panel hum sensor 1: 25.0 %RH
  Panel hum sensor 2: 23.4 %RH
  (…higher than anticipated in ’03…)



Typical Measurements

Humidity data from 7:50am 3 Nov to 7:50am 5 Nov (48 hr period, about 3 months after test initiated)



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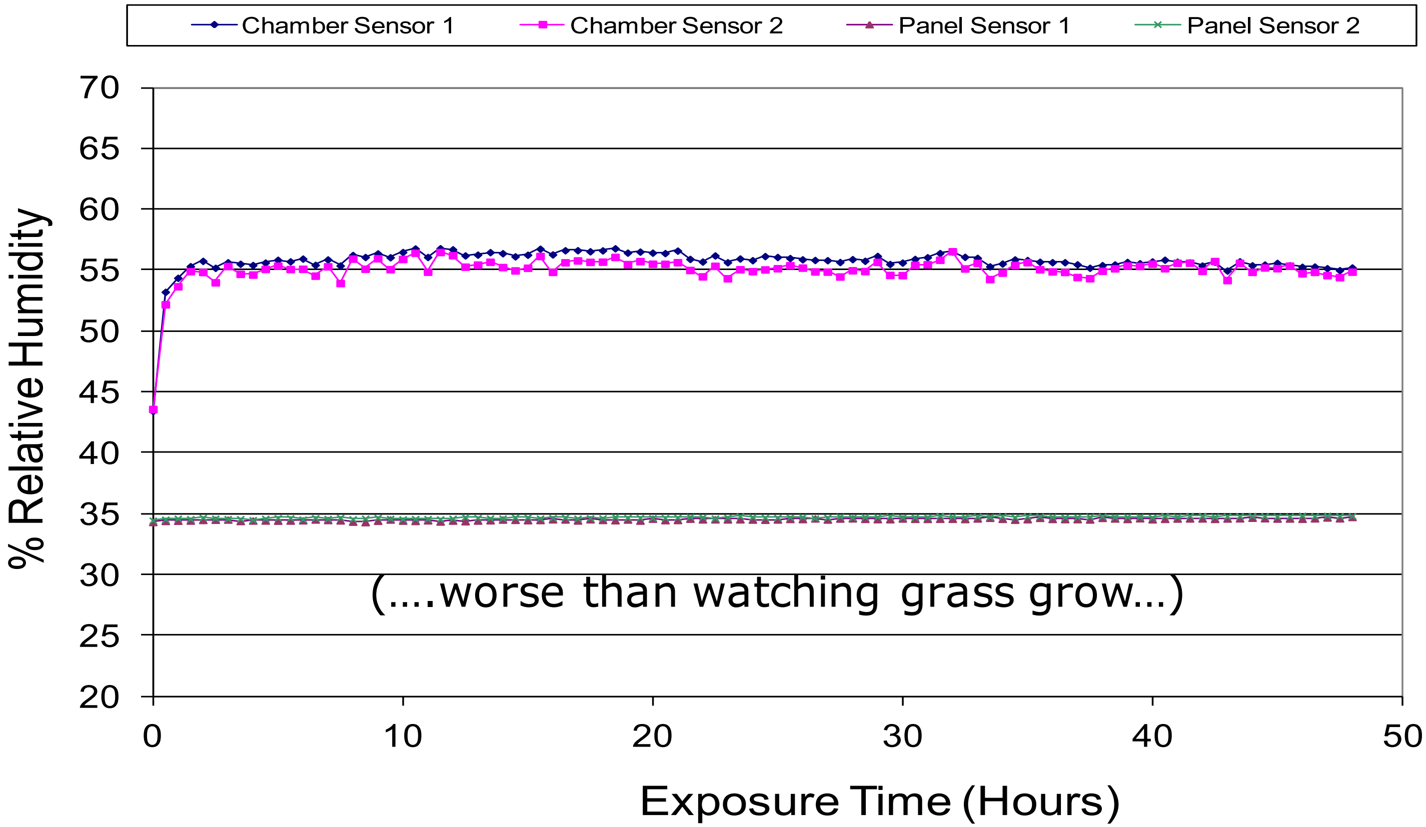
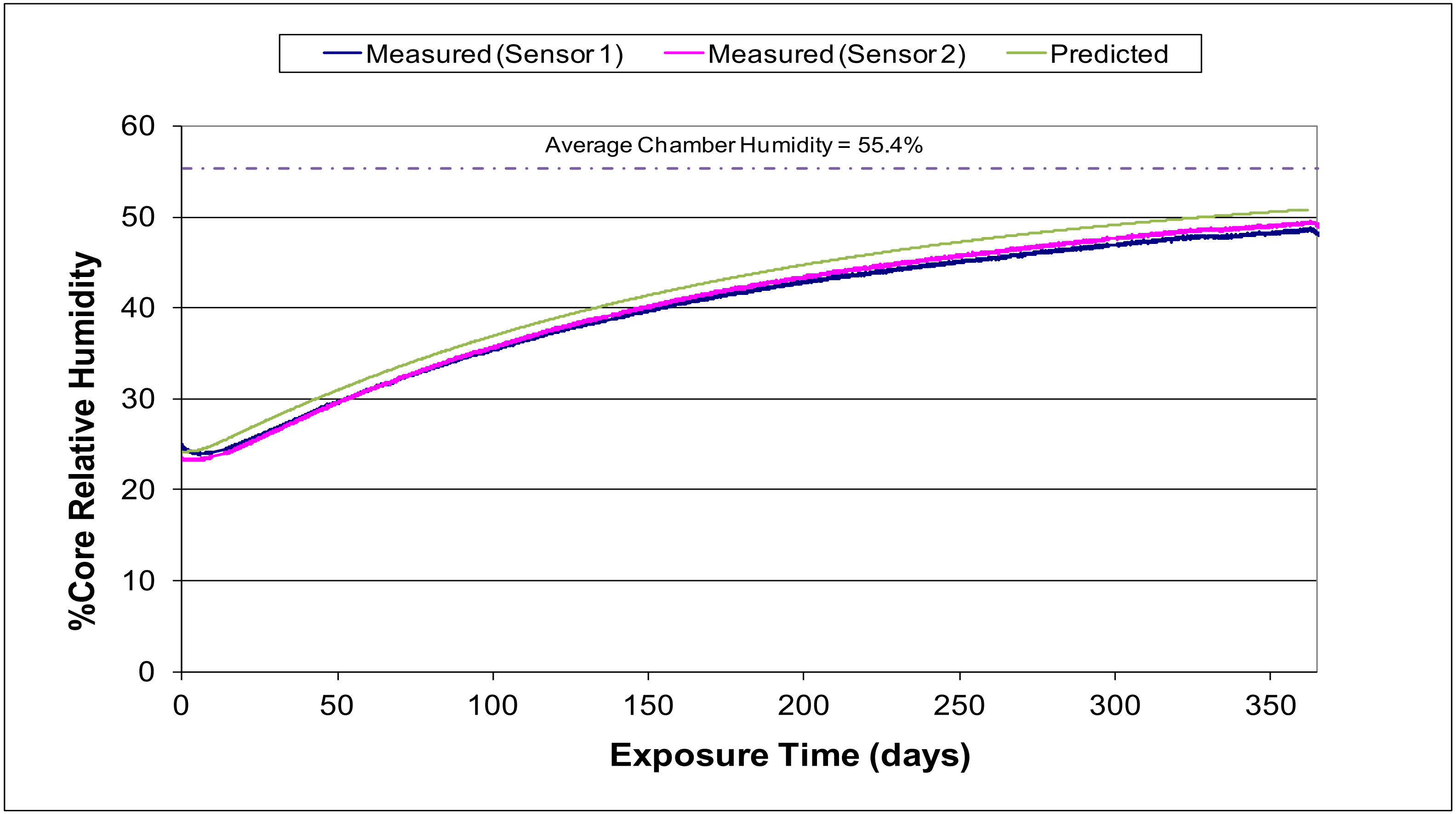


Measurement vs Prediction

Obtained between 5 Aug '08 to 4 Aug '09 = 365 days



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- Change in bending stiffness, EI_{eff} (measure using 4-pt bend test)
- Change in G_I (measure using methods being developed by CMH-17 group)

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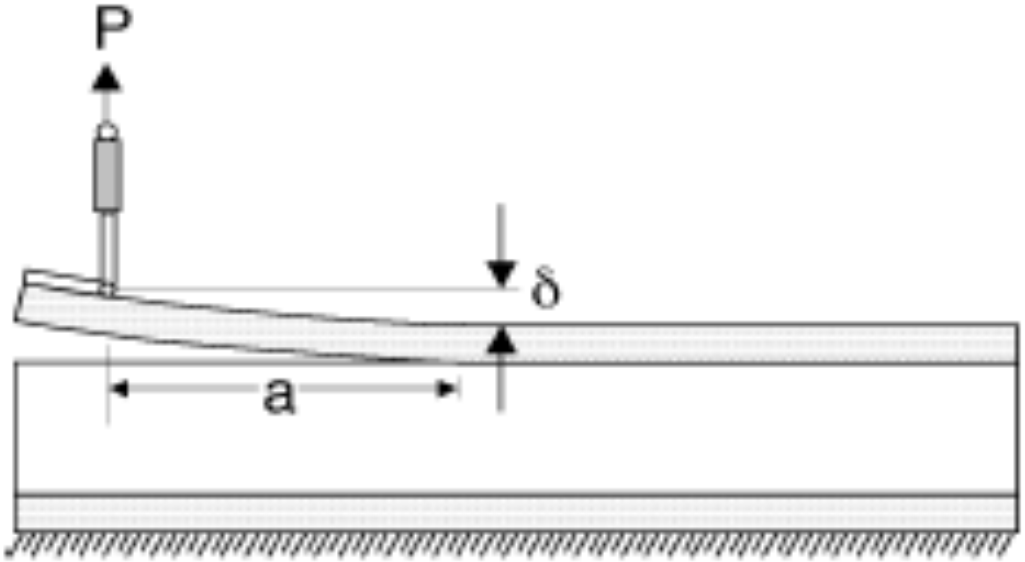
Schematic of experimental arrangement to measure G_I for sandwich panels (under development by CMH-17 working group)



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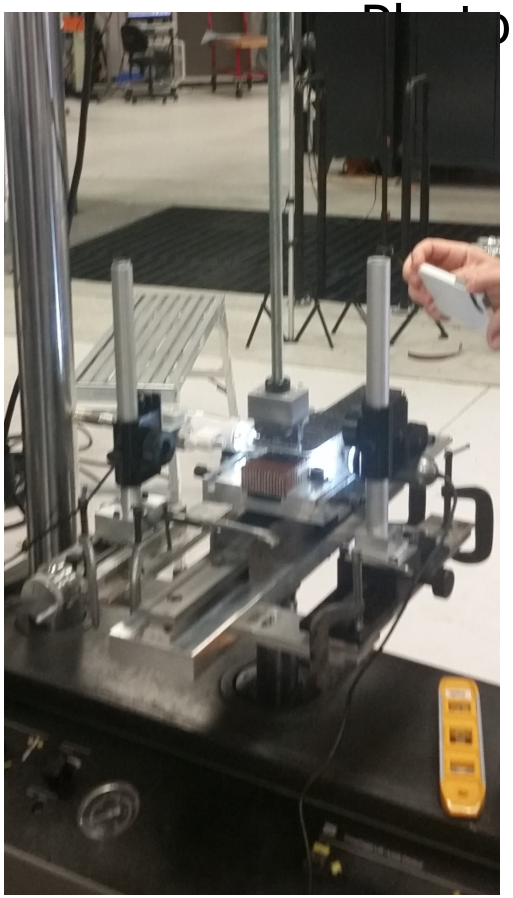
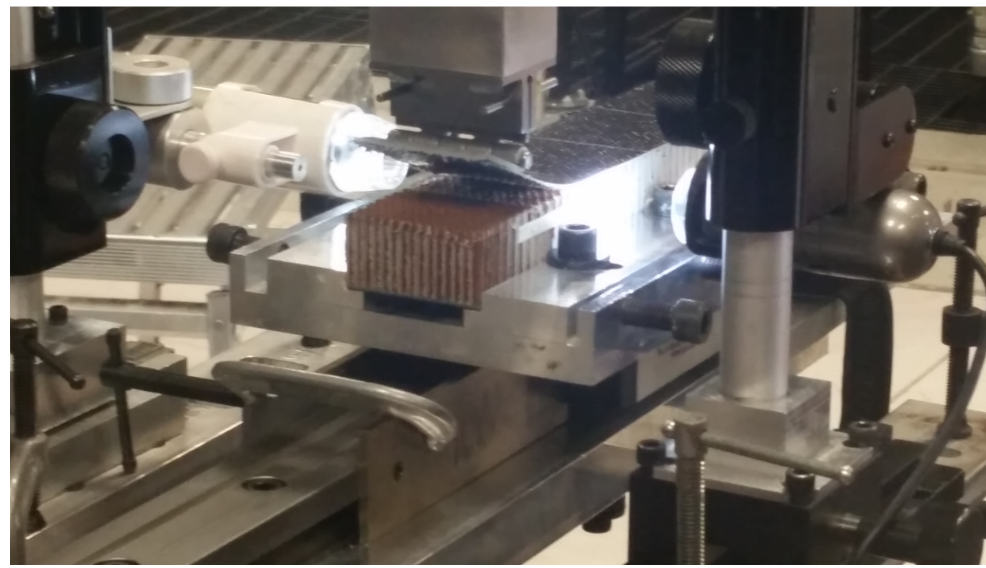
Photos of test setup at NIAR





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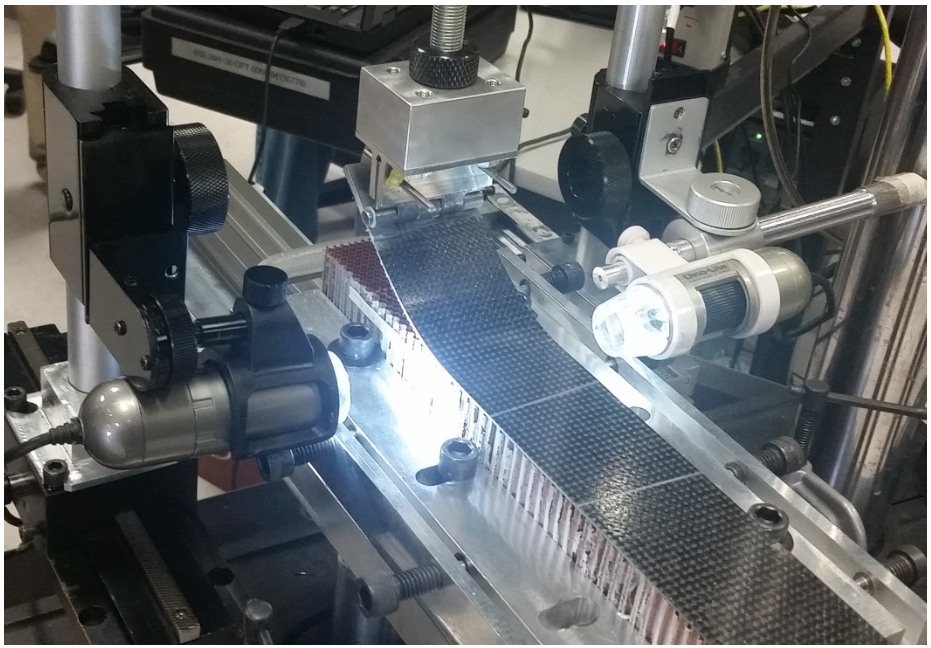

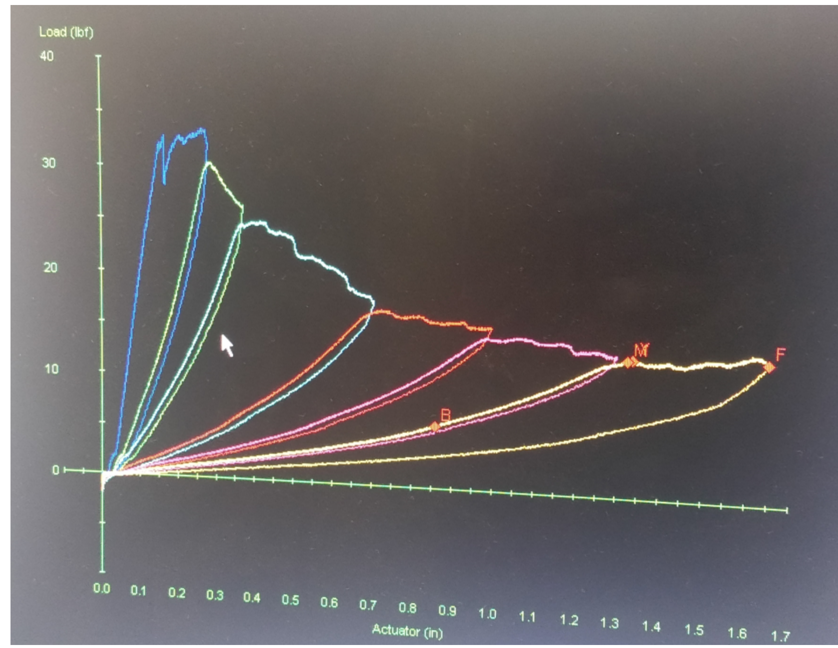

Thank You!

Comments/Questions/Suggestions?

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Backup Slides

Effects of Moisture Diffusion in Sandwich Composites

American Autoclave featuring 42 in dia x 96 in working chamber

Effects of Moisture Diffusion in Sandwich Composites

Blue-M Model POM-246F
Lab Oven

Wabash Model G50H-24-BCLX
50-ton hot press

Effects of Moisture Diffusion in Sandwich Composites

Cincinnati Sub-Zero "Tundra"
Environmental Conditioning Chamber

Effects of Moisture Diffusion in Sandwich Composites

Thermotron Model S.12 Temperature Chamber

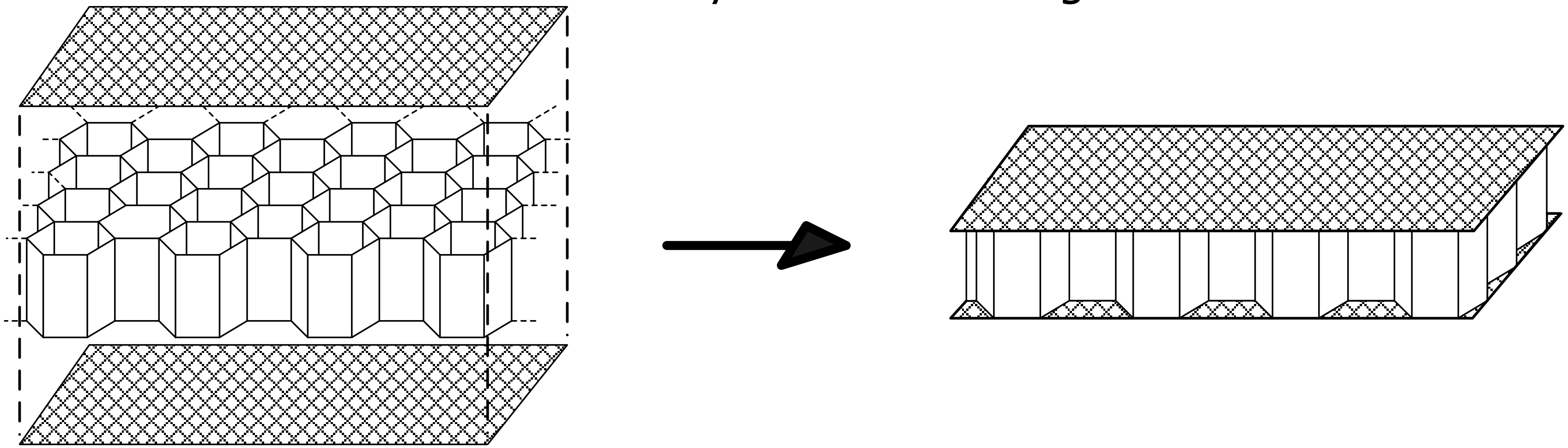
Effects of Moisture Diffusion in Sandwich Composites

Instron Model 8511 hydraulic test frame

Synopsis: Numerical UW Study Funded by Boeing in 2003

<u>Assumptions</u>:

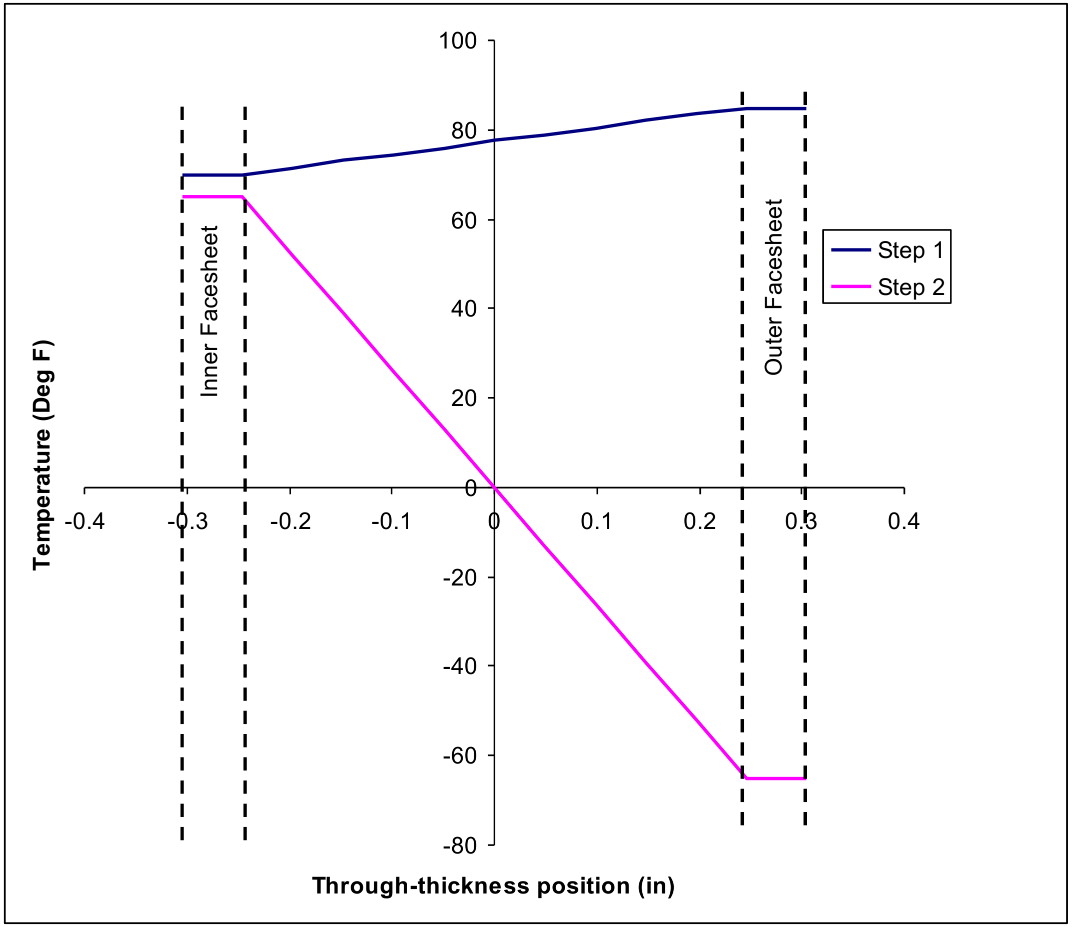
- 'Pristine' (undamaged) sandwich structure; moisture ingression solely due to diffusion
- Core = Nomex honeycomb
- Initial moisture content = 0% . This implies:
  - Initial moisture content of composite face sheets = 0%
  - Initial relative humidity within core region = 0%



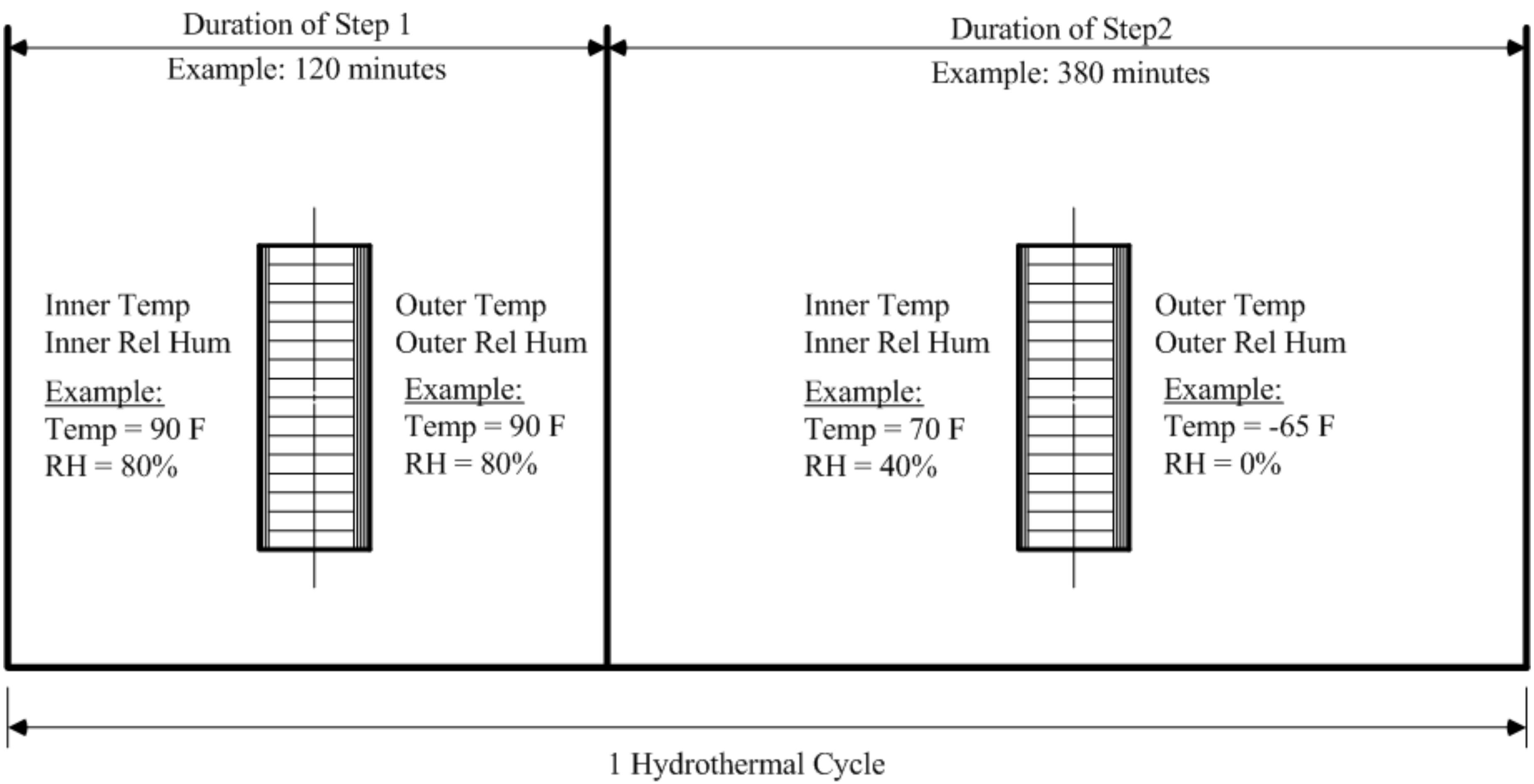
Typical Predicted Steady-State Temperature Profiles

- 12-ply Gr-Ep facesheets (0.060 in thick)
- Nomex honeycomb core (0.50 in thick)
- <u>Step 1:</u>
  Inside temp = 70F
  Outside temp = 85F

  <u>Step 2:</u>
  Inside temp = 65F
  Outside temp = -65F



Definition of a Cycle



Typical Analysis
Cyclic Changes in Temperature and Humidity

- Step 1:
  Duration: 120 minutes
  Inside: temp = 90F; RH = 80%
  Outside: temp = 90F; RH = 80%
- Step 2:
  Duration: 380 minutes
  Inside: temp = 70F; RH = 40%
  Outside: temp = -65F; RH = 0%
- (Total cycle time = 500 minutes = 8.3 hrs)
- 12-ply Gr-Ep facesheets (0.060 in thick)
- Nomex honeycomb core (0.50 in thick)
- Initial moisture content assumed = 0%

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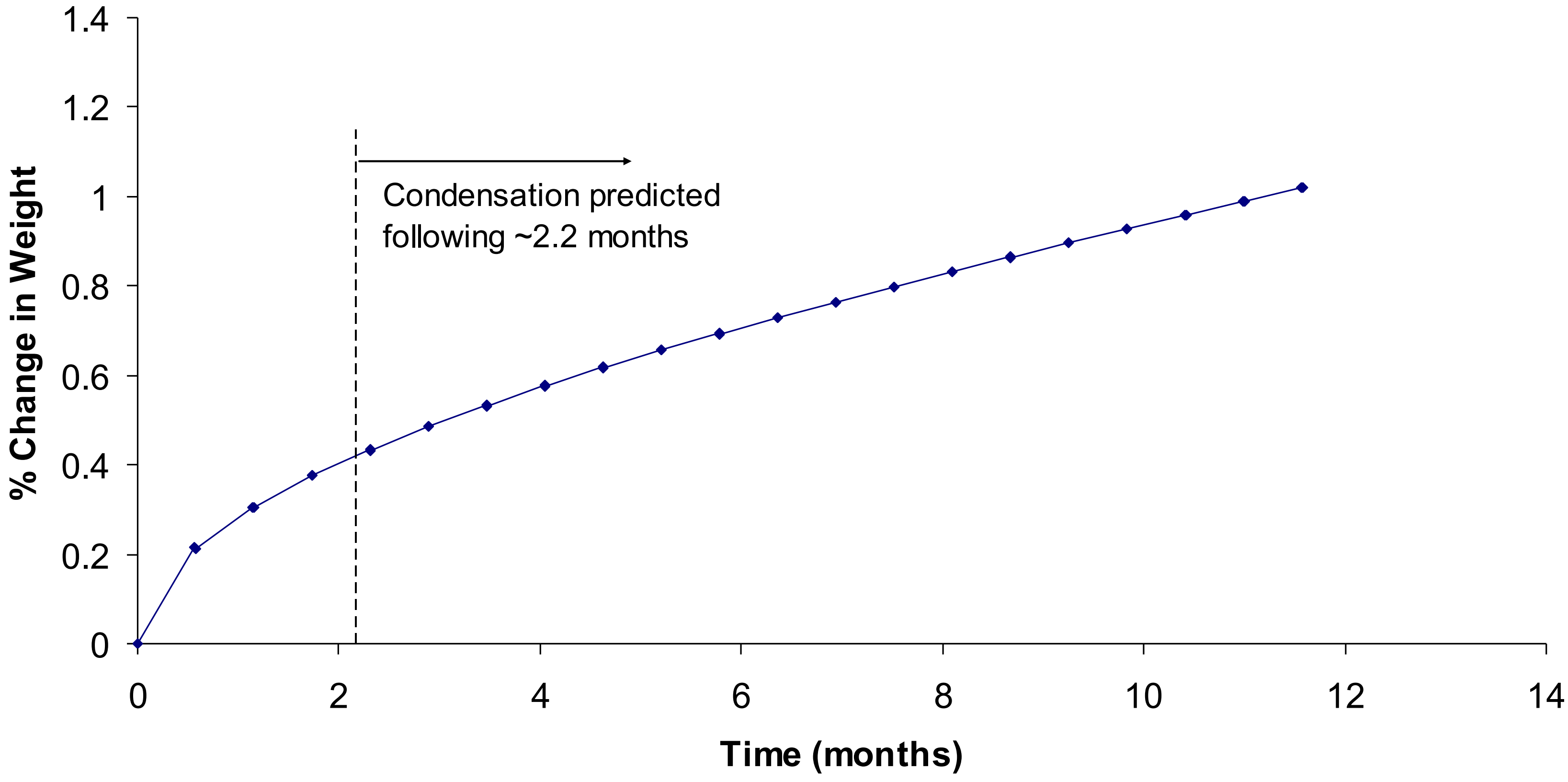
Cyclic Changes in Temperature and Humidity



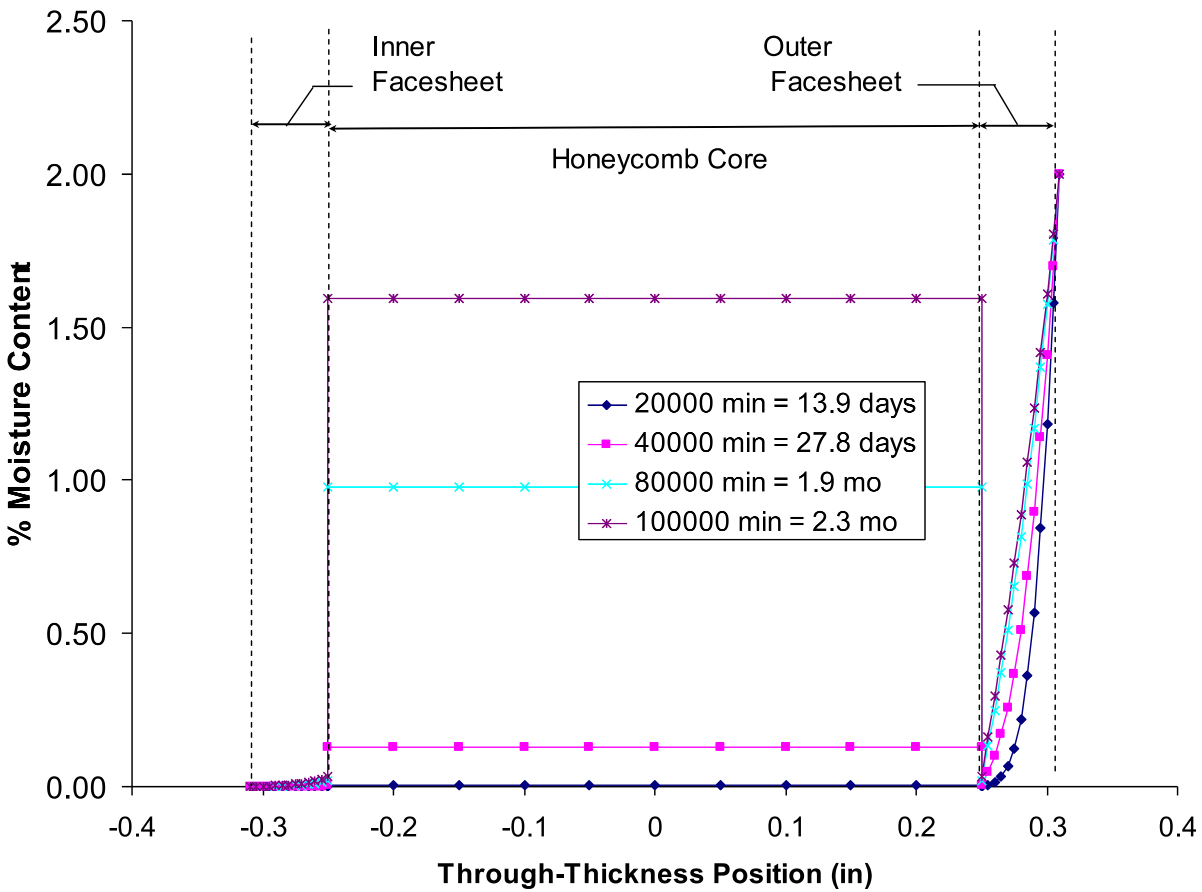
Typical Analysis
Constant Temperatures, Non-uniform Humidity

12-ply Gr/Ep inner and outer facesheets

0.50 in honeycomb core with 0.20 in cell size

Outer: T=90F; RH = 100% (constant)

Inner: T=90F; RH = 0% (constant)



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Temperature predictions

- Through-thickness temperature distribution assumed to be governed by the Fourier heat conduction equation:

$$\frac{\partial Q}{\partial t} = -K_z A \frac{\partial T}{\partial z}$$

where:

$\partial Q / \partial t$ = heat transfer rate

K_z = thermal conductivity (z - direction)

A = area

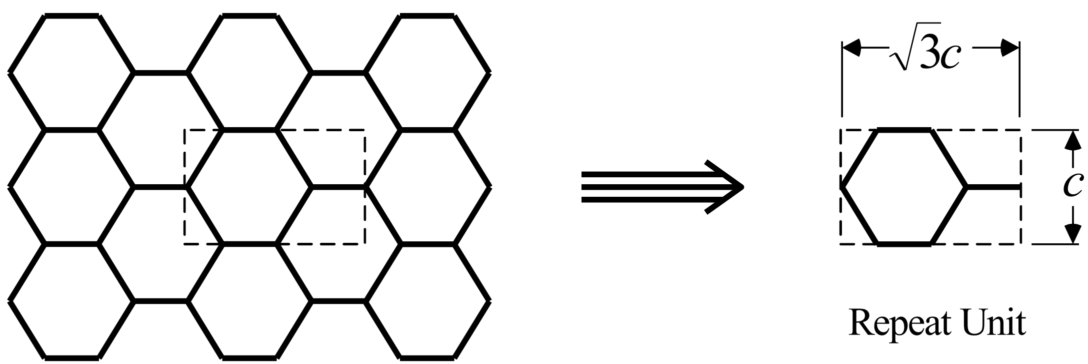
T = temperature

t = time

- Material properties allowed to vary through thickness; heat conduction equation solved numerically using finite-differences

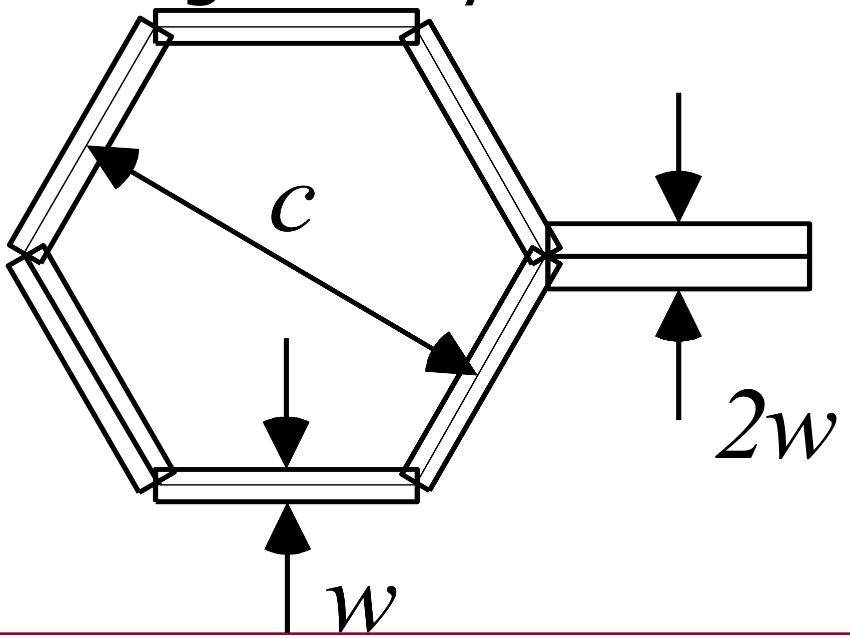
Core Thermal Conductivity

- K_{core} estimated using rule-of-mixture approach
- Volume fractions of air and paper within the core calculated using hexagonal repeat unit



Core Thermal Conductivity

- Given the cell size (c), paper ribbon thickness (w), and core thickness (t), it can be shown that the volume fractions are given by:



$$V_{air} = \frac{(3c - 8w)}{3c}$$

$$V_{paper} = \frac{8w}{3c}$$

Core Thermal Conductivity

Example: $$K_{core} = (V_{air})(K_{air}) + (V_{paper})(K_{paper})$$

Honeycomb core with 0.20 in cell size, produced using 2-mil thick DuPont Type 410 Nomex paper:

K_{paper} = 0.715 BTU-in/hr-ft²-°R
K_{air} = 0.166 BTU-in/hr-ft²-°R

Calculated quantities:

V_{paper} = 0.027
V_{air} = 0.973

K_{core} =0.181 BTU-in/hr-ft²-°R

* Nomex properties: http://www.matweb.com
Air properties: *Marks' Standard Handbook for Mechanical Engineers*, 8th Ed (1978)

Typical Properties

Material	Thermal Conductivity, K (BTU-in/hr-ft^2-°R)	Thickness (in)
Graphite/Epoxy	4.0*	0.005 (ply)
Honeycomb Core	0.181	0.50

* Note: Typical through-thickness K for Gr/Ep is listed; in-plane K values typically > 400 BTU-in/hr-ft2-ºR

Predicting Moisture Diffusion

- Through-thickness (1-D) diffusion of moisture assumed to be governed by Fick's first and second laws:

$$\phi = D_z \frac{\partial c}{\partial z} \qquad \frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left[D_z \frac{\partial c}{\partial z}\right]$$

ϕ = rate of diffusion ("moisture flux") : units = mass/(area * time)

c = concentration : units = (mass/volume)

D_z = diffusivity : units = area/time

z = direction of diffusion : unit = length

t = time

Predicting Moisture Diffusion

- From an experimental point of view it is easier to deal with percent moisture by weight (*M*), rather than the concentration of moisture (*c*). Fick's first and second laws are restated as:

$$\phi = \frac{D_z \rho}{100} \frac{\partial M}{\partial z} \qquad \frac{\partial M}{\partial t} = D_z \frac{\partial^2 M}{\partial z^2}$$

$\rho = \text{density, mass/volume}$

$M = \text{"moisture content"}$

$$M = \frac{\text{(current weight) - (dry weight)}}{\text{(dry weight)}} \text{ X } 100\%$$

Predicting Moisture Diffusion

- Temperature dependency of diffusion coefficient for solids (i.e., ply and core paper) assumed to follow a Arrhenius-type relationship:

$$D = D_o \exp\left(-\frac{E}{T}\right)$$

where: D_o, E = known material constants (differ for ply and core paper)

T = absolute temperature

Predicting Moisture Diffusion

- Temperature dependency of diffusion of H_20 vapor in air assumed to follow a power law of the form*:

$$D_{air} = 0.03376\left(\frac{T(^\circ R)}{491.67(^\circ R)}\right)^{1.81} \frac{in^2}{\sec}$$

* Massman, W.J., *Atmospheric Environment*, Vol 32 (6),
pp 1111-1127 (1998).

Predicting Moisture Diffusion

Estimated Core Density and Diffusivity

$$\rho_{core} = (V_{air})(\rho_{air}) + (V_{paper})(\rho_{paper})$$

$$D_{core} = (V_{air})(D_{air}) + (V_{paper})(D_{paper})$$

Predicting Moisture Diffusion

The moisture content (M) of any surface layer in contact with air can be related to the relative humidity according to (Springer, 1980):

$$M = M_u \left(\frac{\%RH}{100} \right)^b$$

- constant M_u = material property
- exponent b = 1 for most materials
- relationship used to define the boundary condition at all ply interfaces

Predicting Moisture Diffusion

Preceding relations allows forward-difference solution to Fick's equations; summary

- (At all interior ply interfaces) moisture flux leaving ply *k* must equal moisture flux entering ply *k+1*

$$M = M_u\left(\frac{\%RH}{100}\right)$$

- (Boundary conditions):
- (Initial conditions): Initial through-thickness moisture content assumed uniform (assumed = zero in '03)
- Time step increment of 1 minute

Predicting Moisture Diffusion

Properties Used in '03

Property	Gr/Ep (typical values)	Type 410, 2-mil Nomex (www.matweb.com)
D_o	0.010 *in²/sec* (see note)	0.006 *in²/sec*
E	10300 °*R*	9000 °*R*
M_u	0.02	0.03
Density, ρ	0.054 lbm/in^3	0.026 lbm/in^3

Note: Properties reported for Gr/Ep vary widely. For example:

$$0.005 < D_o < 0.040 \; in^2/sec$$

Predicting Condensation

Having calculated the moisture content and temperature within core following Step 1, then

1. Calculate relative humidity within core volume (based on rule of mixtures approximation)

$$\%RH = M_{core} / M_u^{core} = \left(\frac{M_{core}}{V_{air} + M_u^{pap} V_{pap}} \right)$$

Predicting Condensation (cont'd)

2. Use Clapeyron equation to estimate saturated vapor pressure (P_{svp}) at Step 1 core temperatures

T_{cor}^{s1}

$$P_{svp} \approx P_{svp}^{ref} \exp\left[\frac{h_{fg}(T_{cor}^{s1} - T^{ref})}{(RT^{ref})T_{cor}^{s1}}\right]$$

T^{ref} = ref temperature (e.g., T^{ref} = 70°F = 529.67°R)

P_{svp}^{ref} = saturated vapor pressure at T^{ref}

= 0.3632 psi at $T^{ref} = 529.67°R$

h_{fg} = enthalpy of vaporization at T^{ref}

= 1054 BTU/lbm = $820E3\ ft-lbf/lbm$ at $T^{ref} = 529.67°R$

R = gas constant for water vapor = $85.76\ ft-lbf/lbm-R$

Predicting Condensation (cont'd)

3. Calculate partial pressure of water vapor at Step 1 temperatures:

$$P_{pp} = (\%RH)(P_{svp})$$

Predicting Condensation (cont'd)

4. Calculate dew point temperature based on reference temperature and partial pressure at step 1 temperatures:

$$T_{dewpt} = \frac{h_{fg} T^{ref}}{h_{fg} - \ln\left(\frac{P_{pp}}{P_{svp}^{ref}}\right) R T^{ref}}$$

Predicting Condensation (cont'd)

5. Finally, condensation is predicted if core temperatures during step 2 become lower than calculated dew point temperature

$$T_{cor}^{s2} < T_{dewpt} \Rightarrow \text{Condensation}$$