Study of hygroscopic expansion of anode read-out boards of gaseous detectors based on FR4

J. Bortfeldt, F. Dubinin, P. Iengo, J. Samarati

Introduction

Readout boards of modern gaseous detectors required to be very precise:

- Required accuracy $\lesssim 100\mu m$

FR4 been a standard base material of the PCBs is hygroscopic

- FR4 swells under humidity exposure
- For large-size boards as ones used in Micromegas the hygroscopic expansion can be crucial

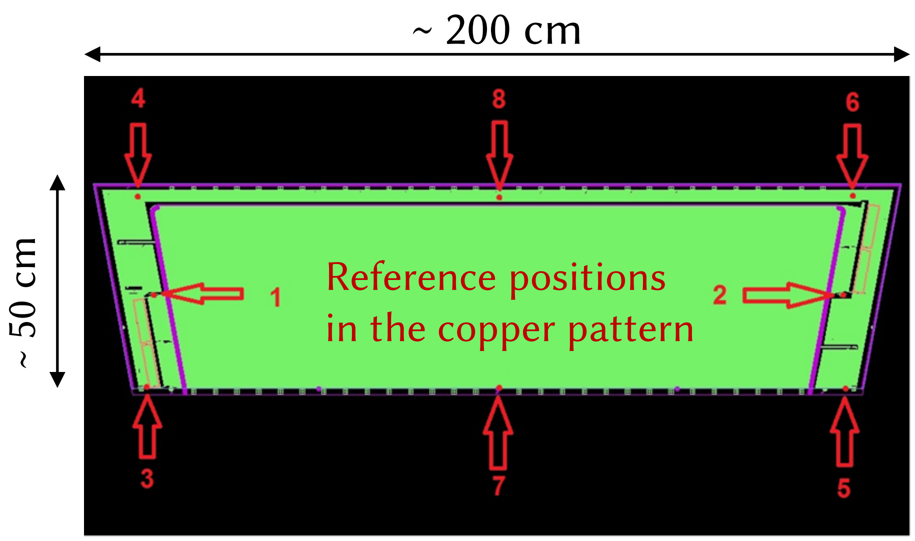
In the work the water absorption process by specific FR4 material is experimentally studied:

- Specifics of diffusion in FR4 are discussed
- Methods for measurements of expansion are considered
- Measurements with 2 FR4 samples are presented and discussed

Long-term measurements with ATLAS pre-series boards

The boards brought into the laboratory from outside

- stored for ~1 month
- without T & RH control
- with T & RH monitoring



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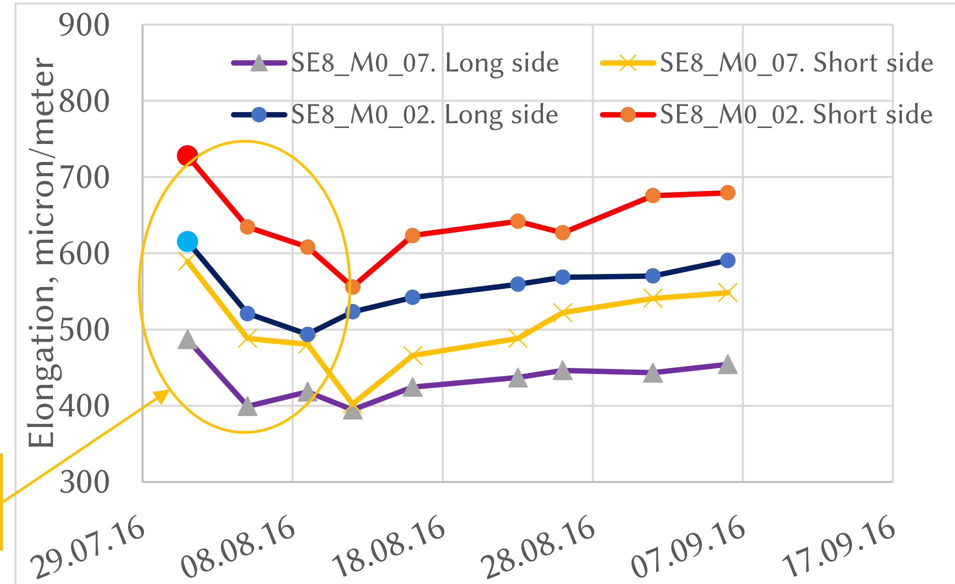
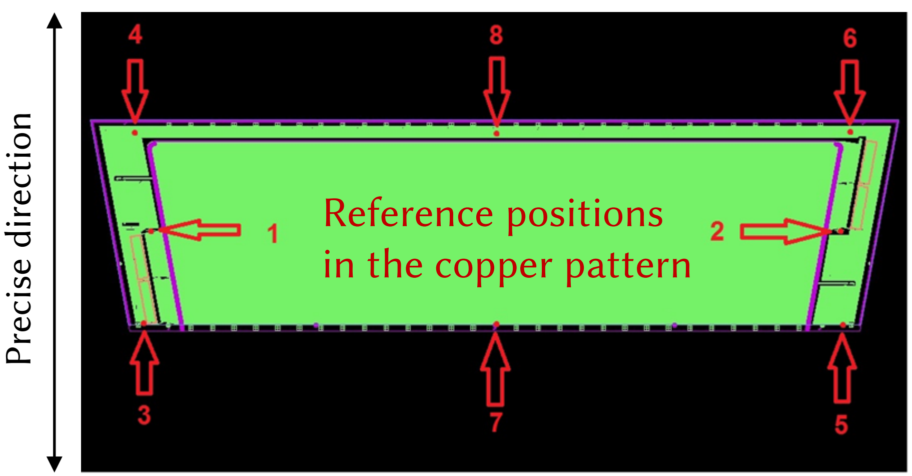
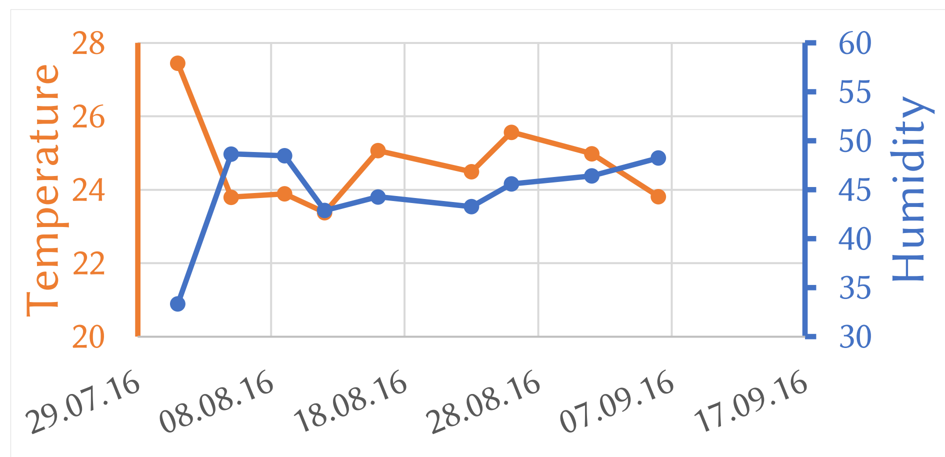
Results:
- Elongation up to 700 μm/m from nominal values



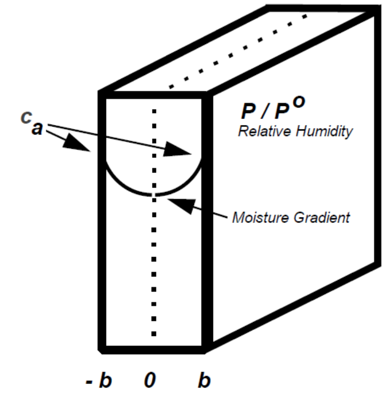
Conditioning in the laboratory atmosphere

Non-precise direction. Strips are parallel to the arrow.





Mathematics of diffusion



$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2},$$

$$C = C_a, x = b, t > 0,$$

$$C = C_0, x < b, t = 0.$$

C - concentration

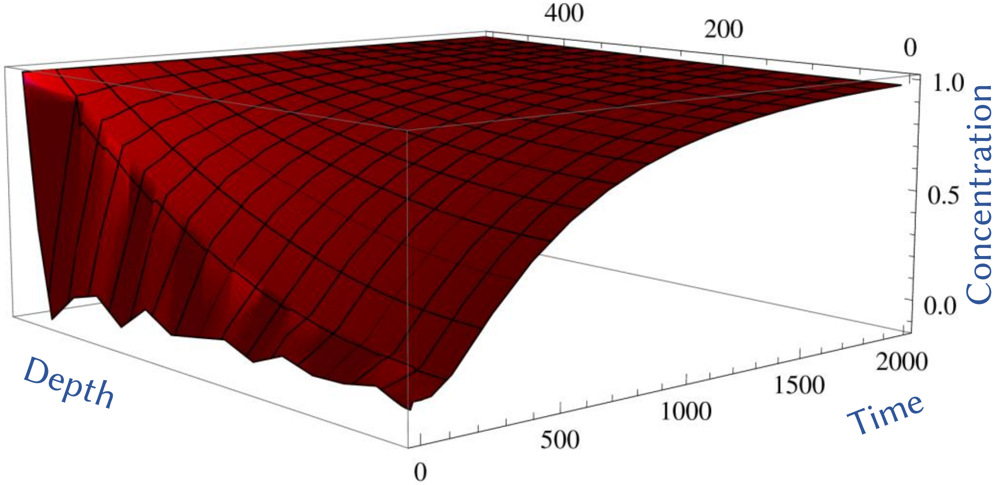
D – diffusion coefficient

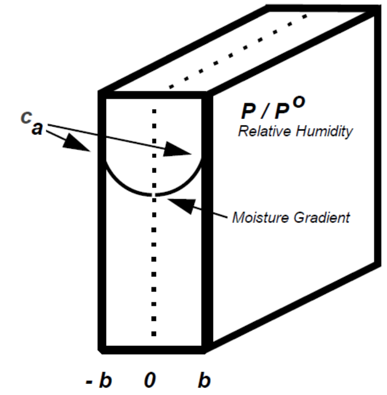
$2b$ – thickness

Mathematics of diffusion

The corresponding solution of the Cauchy problem for diffusion in a plane sheet (1D case) is

$$\frac{C(x,t)-C_0}{C_a-C_0} = 1-\frac{4}{\pi}\sum_{0}^{\infty}\frac{(-1)^n}{2n+1}\exp\left\{-\frac{D(2n+1)^2\pi^2 t}{4b^2}\right\}\cos\frac{(2n+1)\pi x}{2b}.$$





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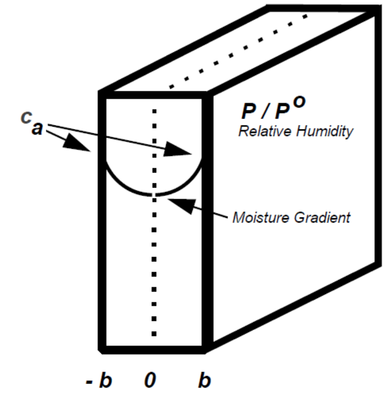

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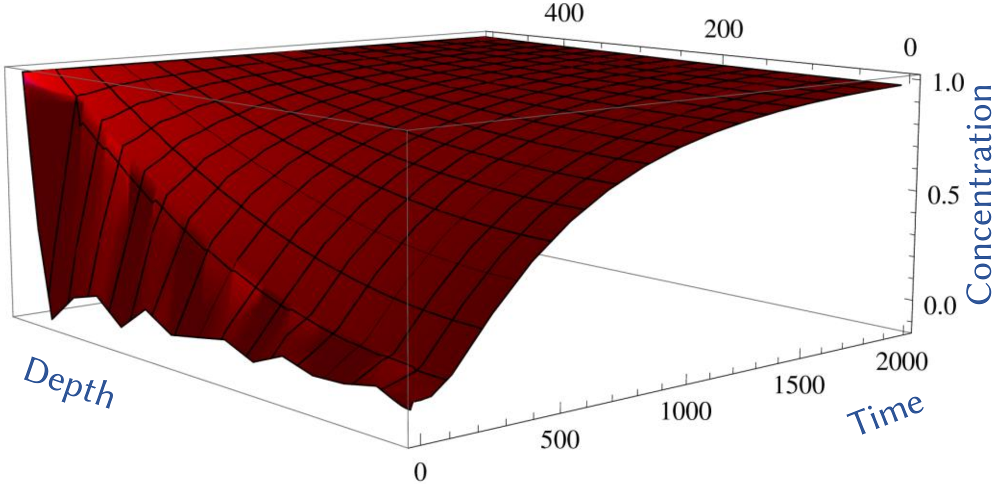
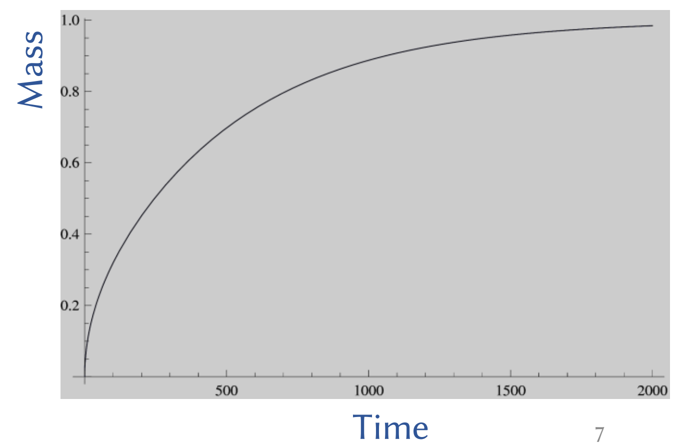


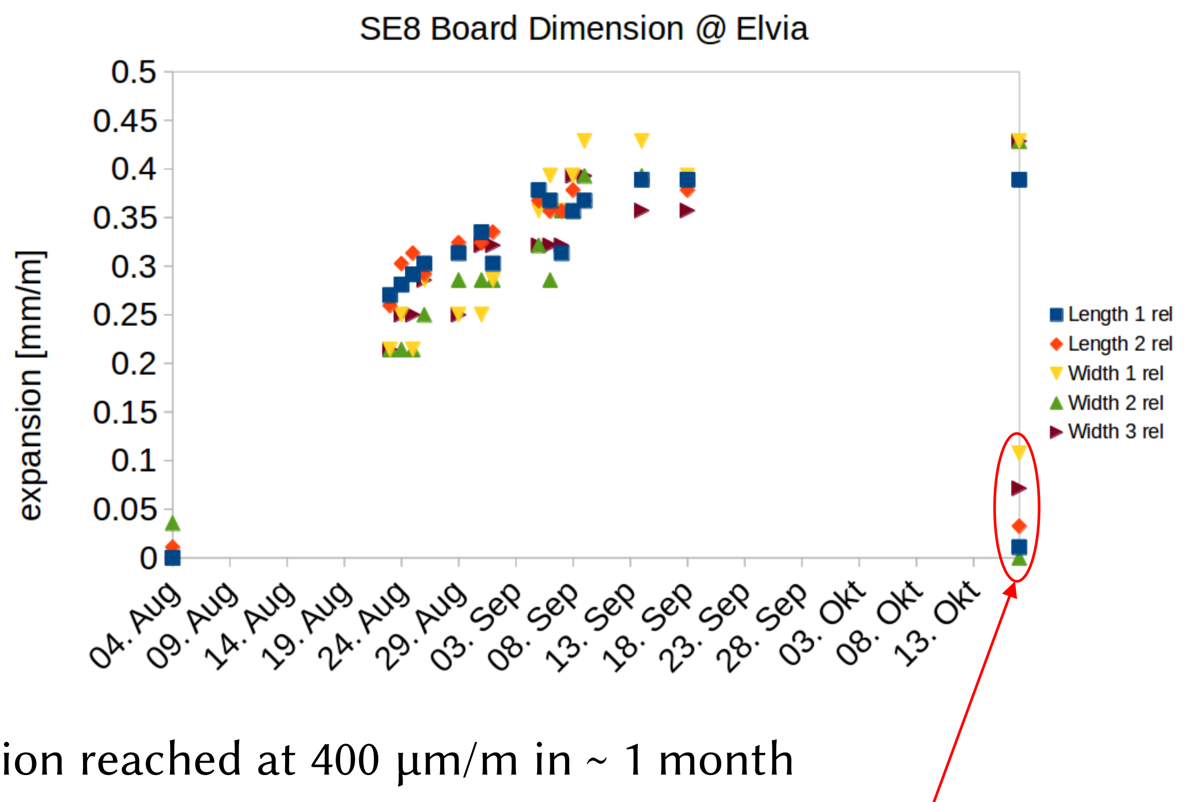
Integrating along the depth direction one gets the function corresponding to the water mass uptake:

$$\frac{M(t)}{M_\infty}=1-\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{D(2n+1)^2\pi^2}{4b^2}t\right].$$



*More information one can find in [1].

Long-term measurements by ELVIA at 50% RH

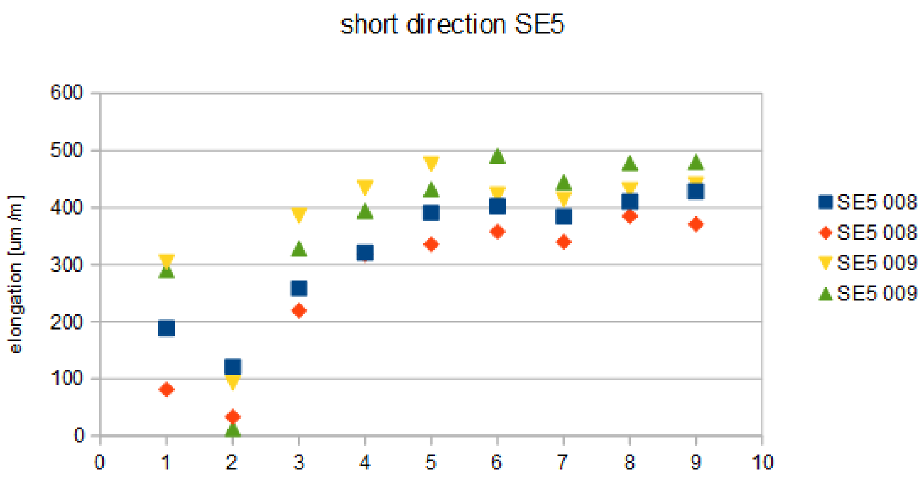


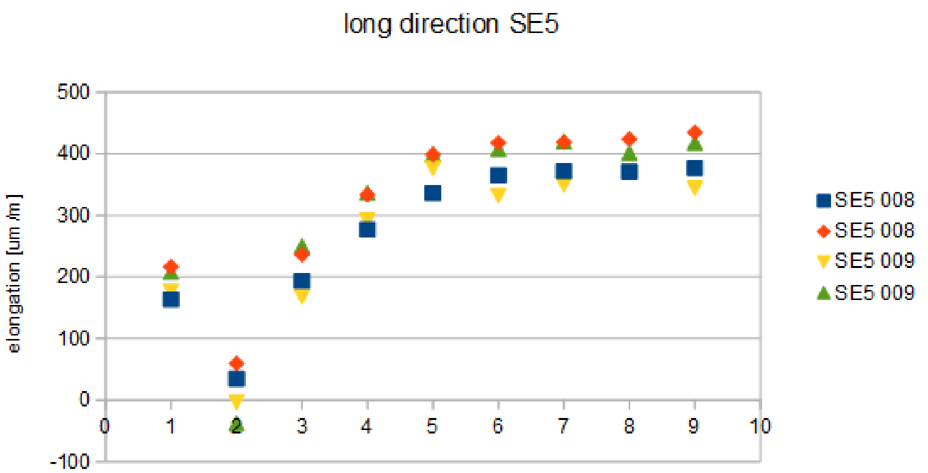
- Saturation reached at 400 µm/m in ~ 1 month
- Consequential heating up to 130°C resulting in recovering of the board

Solution adopted by ATLAS is to rescale the mask of the initial copper image

- Applied scaling factor for ELVIA boards is ~ 400 µm/m

Long-term measurements by ELTOS at 50% RH



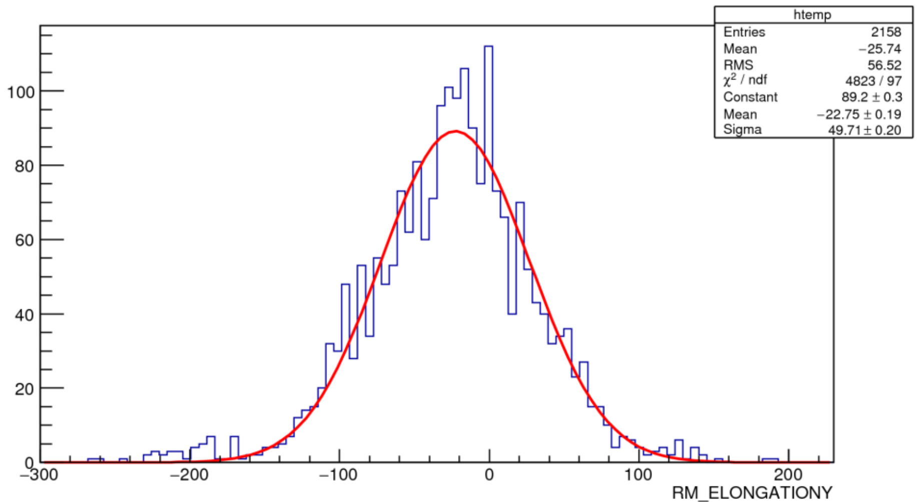


- ➢Saturation along strips was reached at ~390 μm/m
- ➢Across strips – at ~430 μm/m

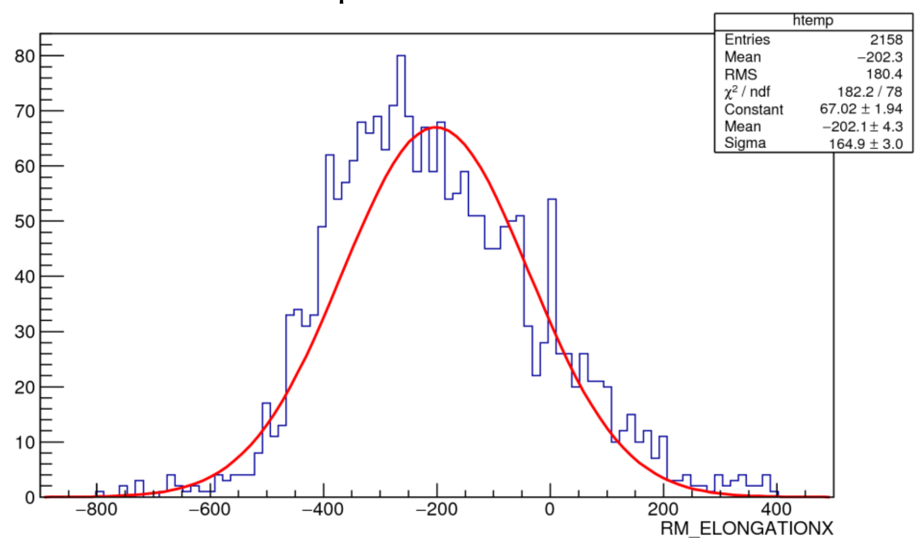
- ➢Applied scaling factor for ELTOS boards is ~ 430 μm/m in both directions

Statistics on series anode PCBs

Precision direction



Non-precision direction



- The measurements done during QA/QC procedure at CERN using the specific optical tool

Specified tolerance

- Precise direction: ±100 μm
- Non-precise direction: ±500 μm

Precise direction:

- Average elongation: -25.74 μm
- Uniformity (sigma): 56.52 μm

Non-precise direction:

- Average elongation : -202.3 μm
- Uniformity: 180.4 μm

Rescaling worked well!

Principles of water absorption in FR4

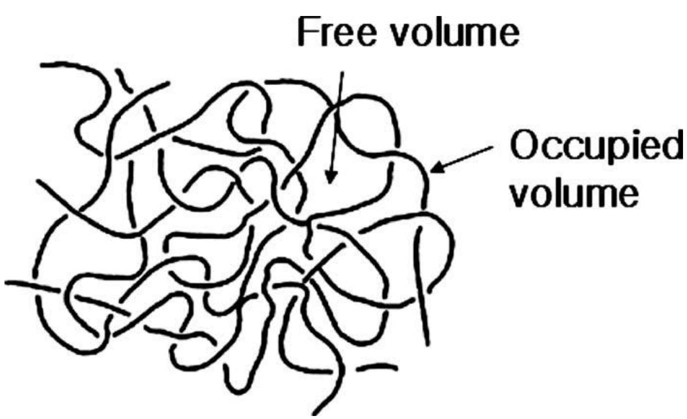
FR4 is a composite material: fiberglass grid layers filled with epoxy, pressed and cured.

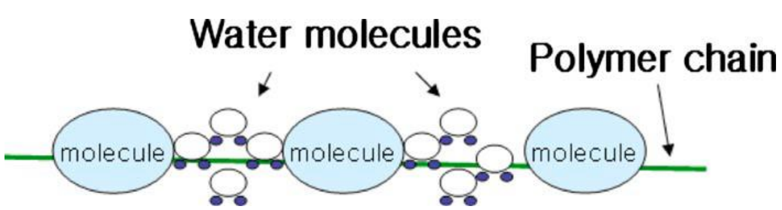
Epoxy consists of polymer chains with free spaces between them.

- Fiberglass doesn't absorb water
- Epoxy can absorb water

Absorption into free volume between chains does not affect on specimen size.

Molecules of water can create hydrogen bounds with polymer that leads to swelling of the material.



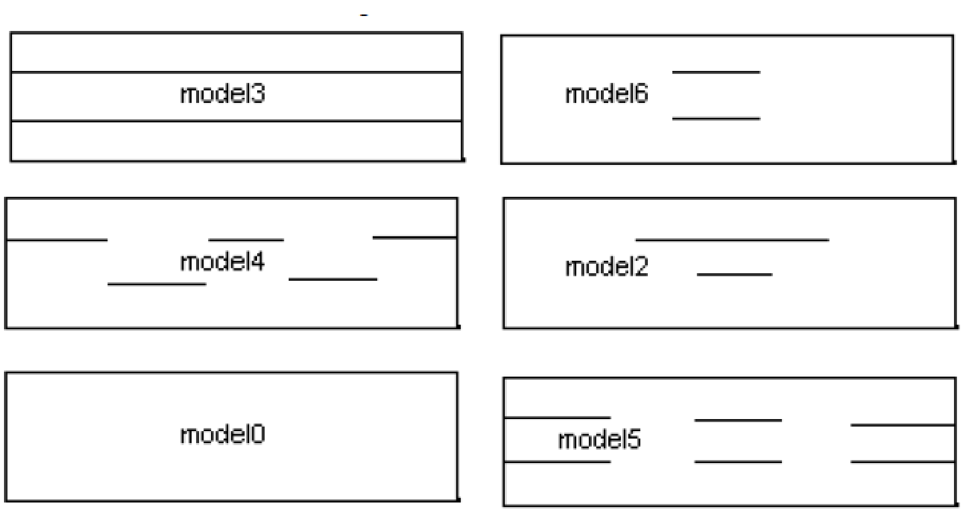


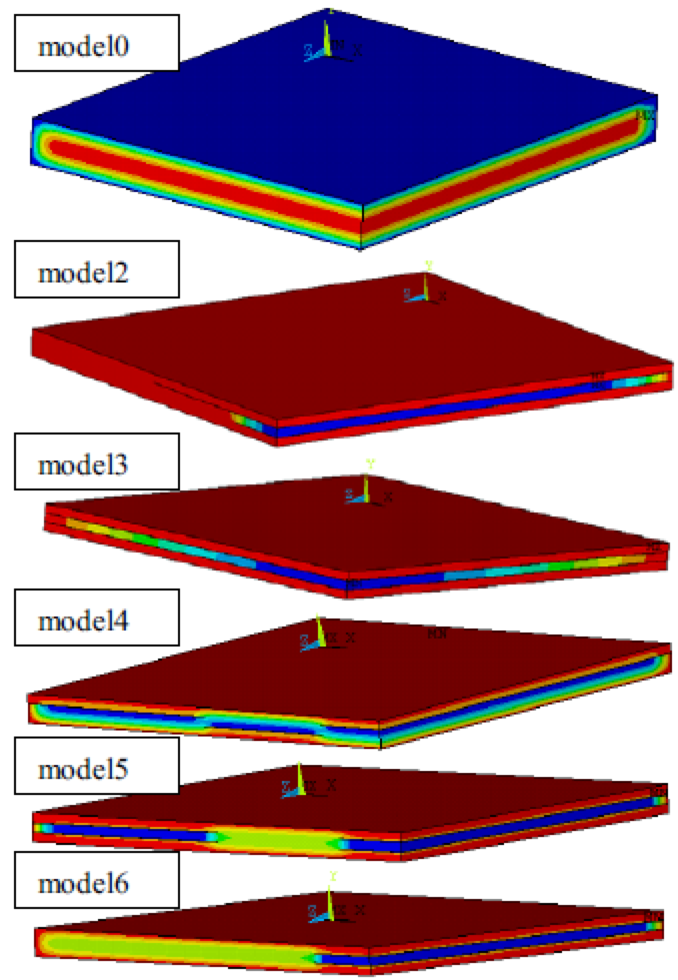
Influence of copper layers [2]

- Copper layers act as a barrier to water
- Experimental results confirmed by modeling

Here on the pictures:

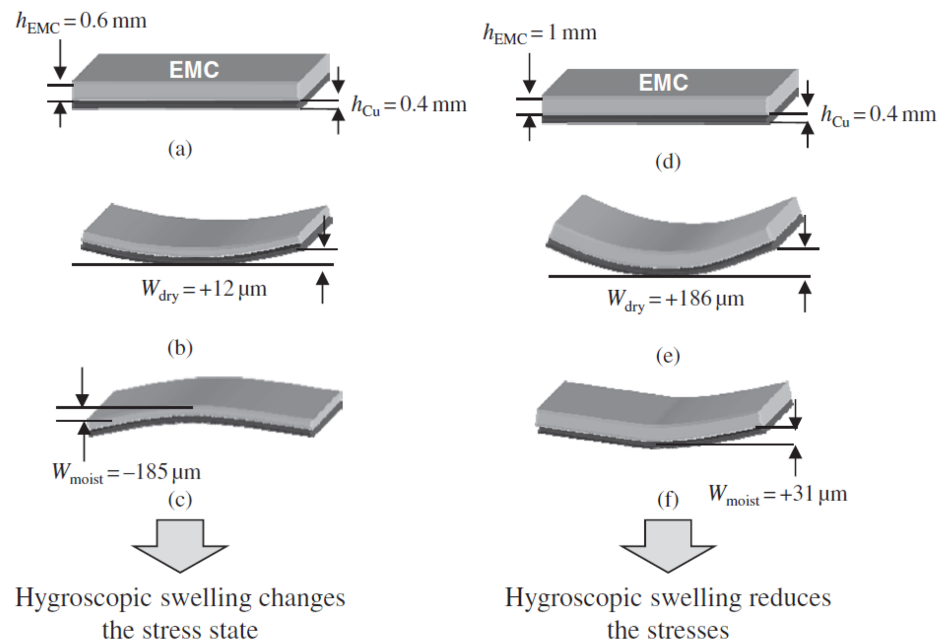
- Red – 0% RH
- Blue – 100% RH





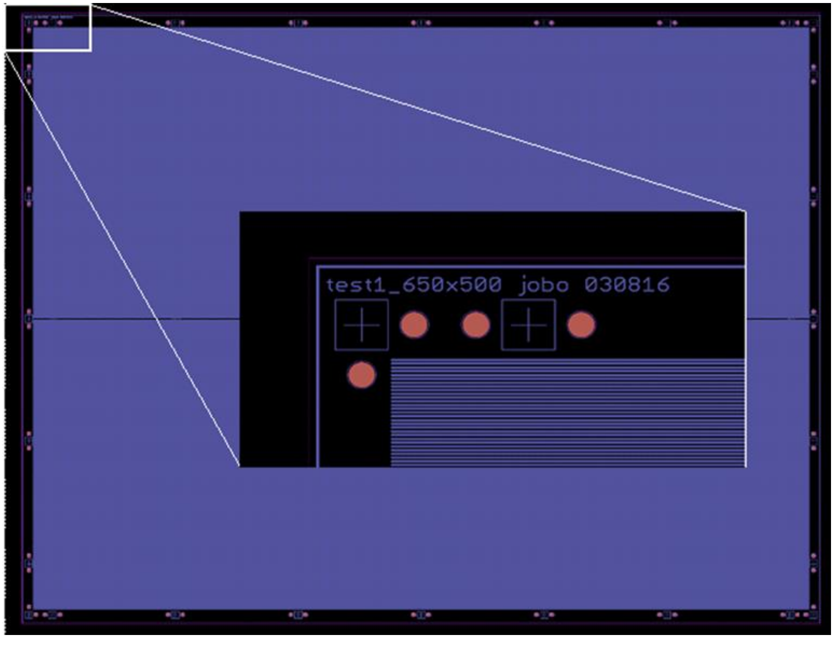
Methods for swelling estimation

- Using micrometer [3]
- Moiré interferometry [4]
  - submicron accuracy
- Thermomechanical analysis [5]
  - only desorption process can be studied
- Warpage Measurement of Bi-material sample [5]
  - can be compared with modeling of internal stresses in a specimen



The methods can be applied only to small-size specimens.

Experimental technique



Two samples:

- 650x500x0.5 mm
- Fiberglass FR4 EM-370DDM
- Copper layers of 18 µm thick
- 1024 copper strips on face side
- 1st sample has no copper on back side
- 2nd sample has entire layer of copper on back side

- Standard test by supplier showed less than 0.1% change of the mass of the dry sample
- We didn’t find any reference study on the expansion of this material

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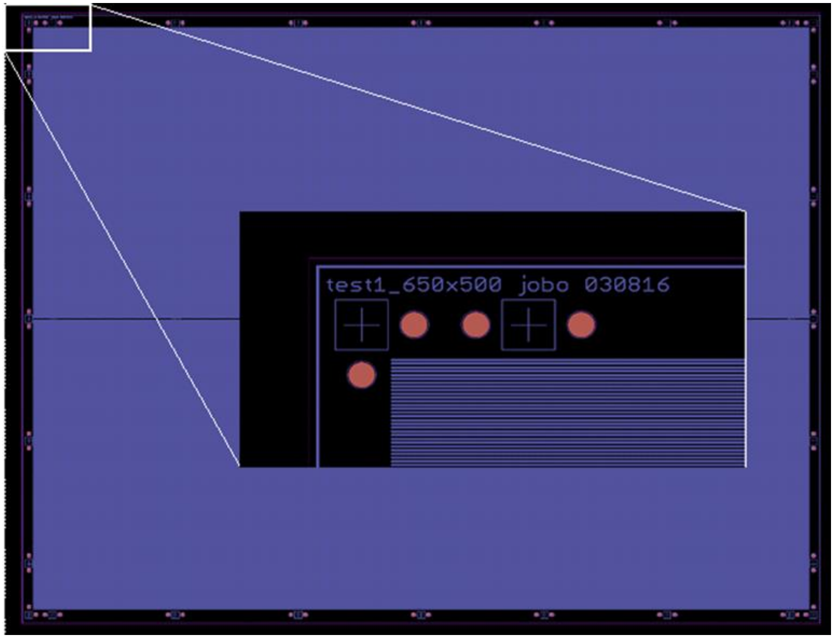

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- Preconditioned at 130°C for 24h

Moisture conditioning done using the climatic chamber at CERN

Table 1. Initial dimensions of the samples.

Sample	**Along strips, mm**			**Across strips, mm**		
	Top	**Middle**	**Bottom**	**Left**	**Middle**	**Right**
1	638.068	638.062	638.071	484.079	484.075	484.062
2	638.082	638.036	638.034	484.032	484.022	484.020

- Measurements done using precise glass ruler outside the chamber
- σ_{inst} = 5 µm
- Elongation expressed as
- $L = (l_t - l_0)/l_0 \cdot 10^6$ µm/m

Elongation at 50% RH and 21°C

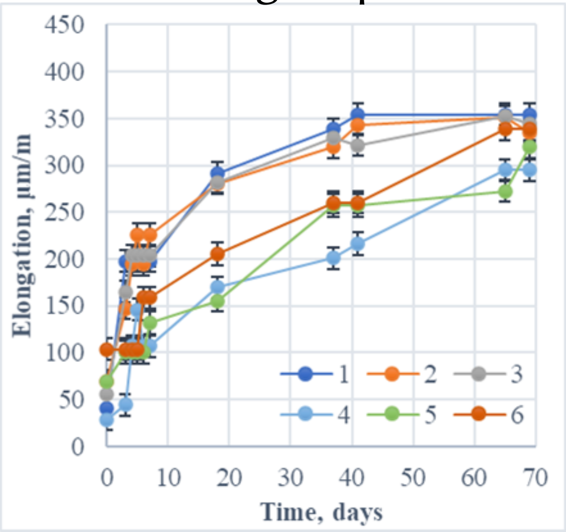
- The samples (almost) reached saturation
- Measurements at different positions are consistent
- Values for the sample 2 are less consistent

➢ Rate is different for the two samples but **not** for different directions

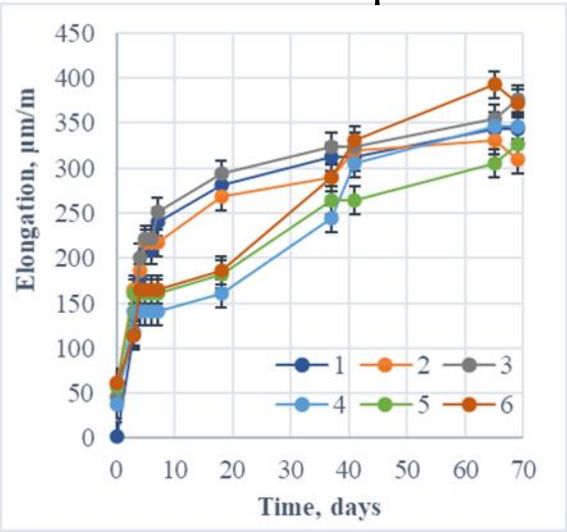
➢ Saturation value is approximately the **same** for both samples

➢ Reached at ~350 µm/m

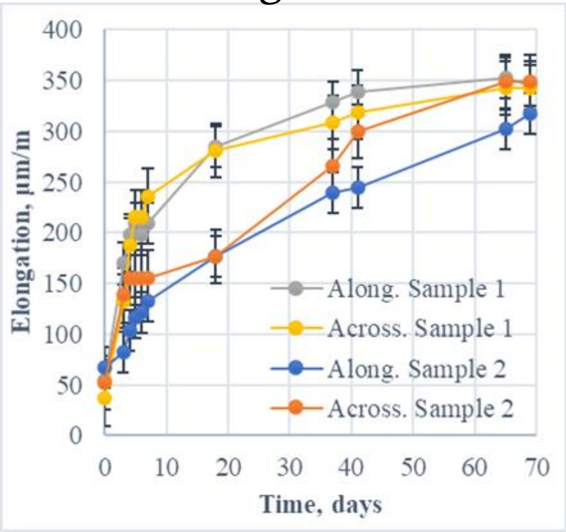
Along strips



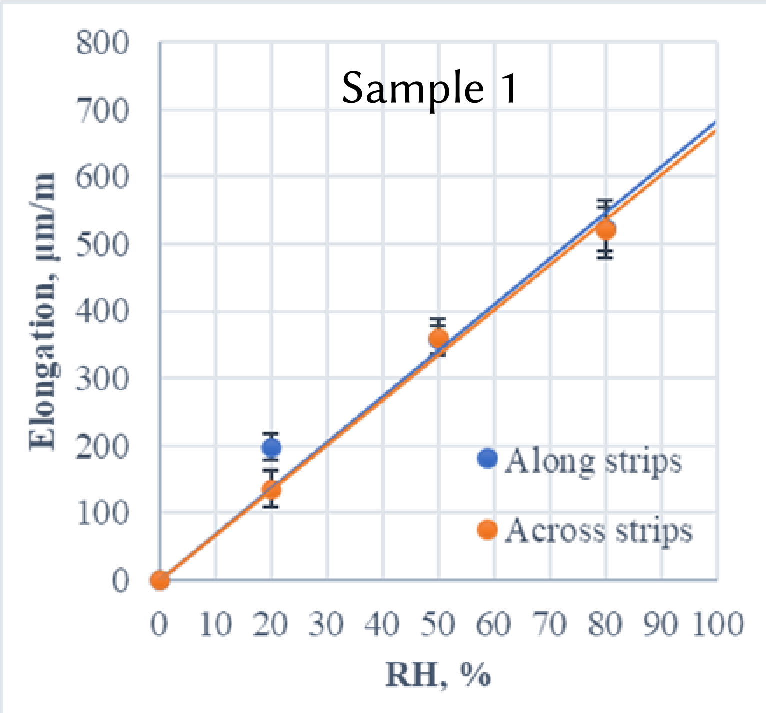
Across strips



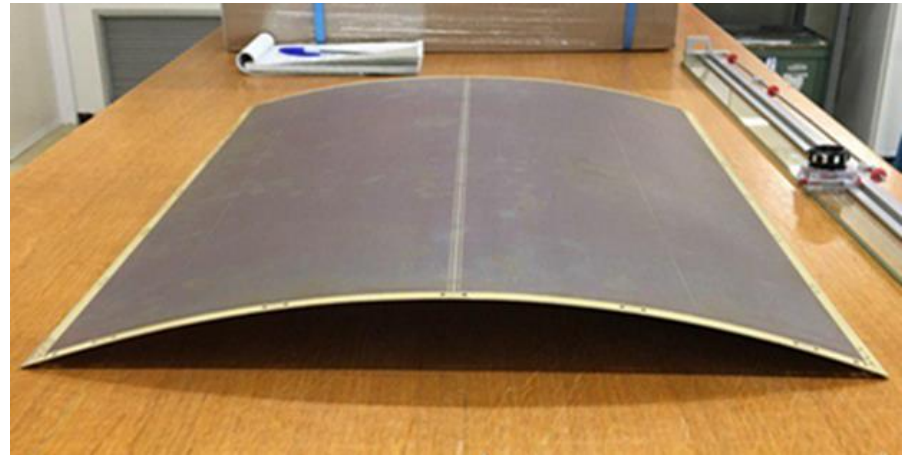
Average values



Coefficient of linear expansion



Sample 2



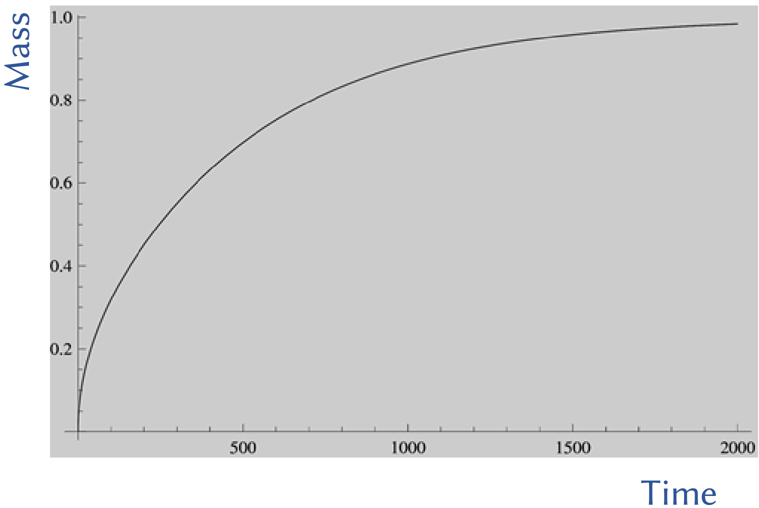
The measurements done only for sample 1

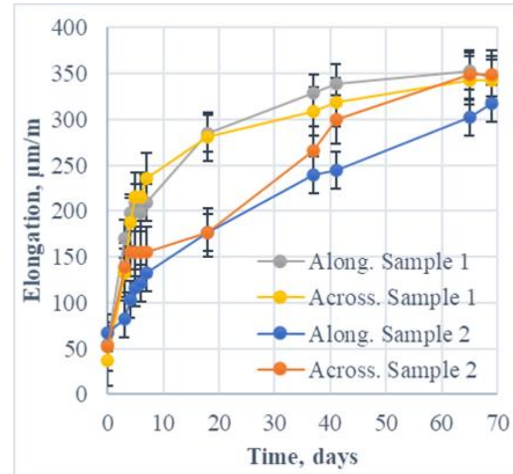
- $\beta_{||} = (7.1 \pm 0.3)$ µm/m/%
- $\beta_{\perp} = (6.9 \pm 0.4)$ µm/m/%

$\langle\beta\rangle = (7.0 \pm 0.2)$ µm/m/%

- Large board bended affected by moisture
- Shape recovered after drying the board

Characterization of expansion rate. Partial diffusion coefficient.





$$\frac{L(t)}{L_\infty} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{D'(2n+1)^2\pi^2}{4b^2}t\right]$$

For $L(t)/L_\infty < 0.55$:

$$\frac{L(t)}{L_\infty} = \frac{4}{2b}\sqrt{\frac{D'}{\pi}}\sqrt{t},$$

where D' is **partial** diffusion coefficient

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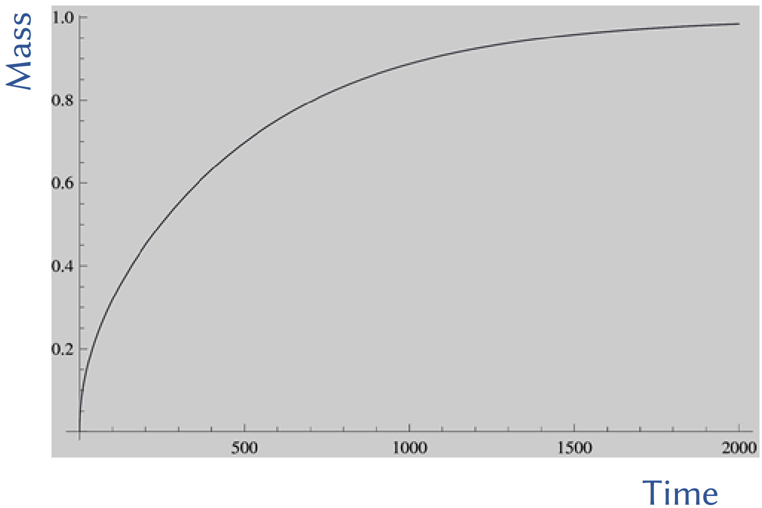

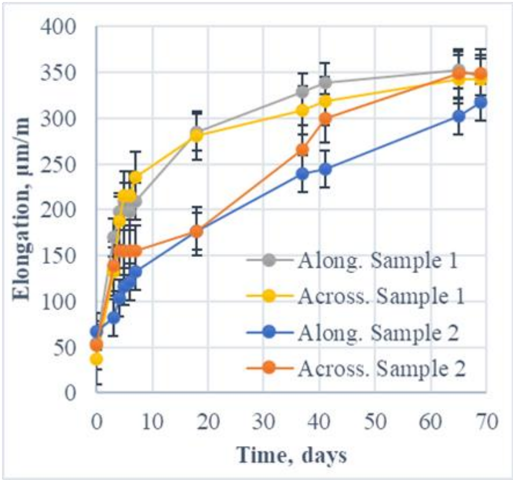

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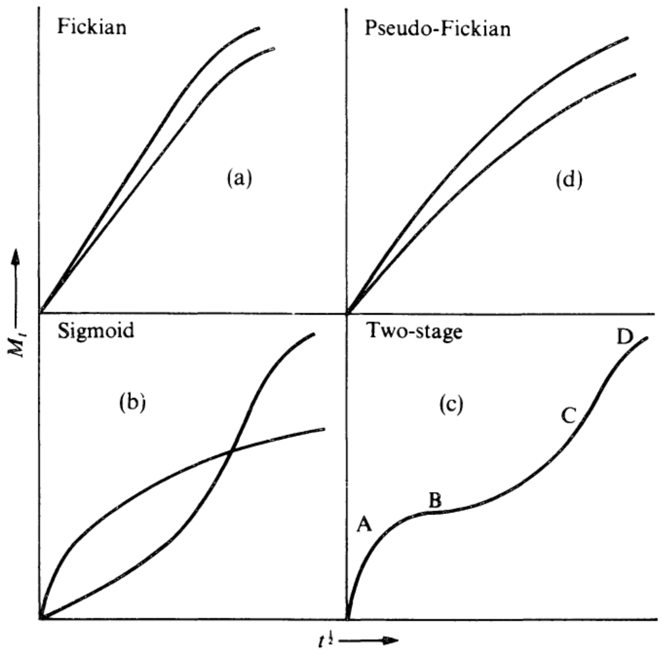
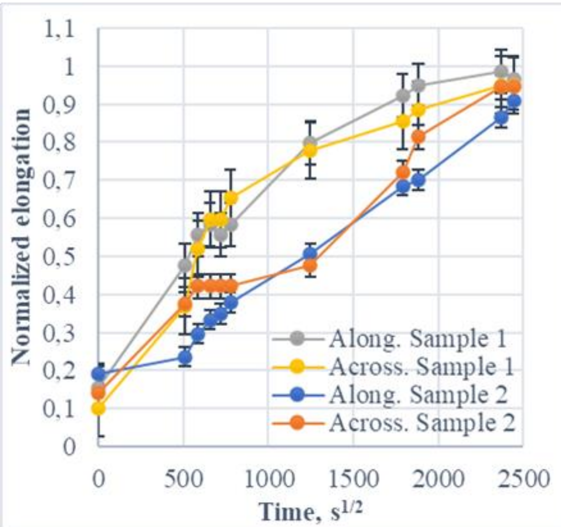
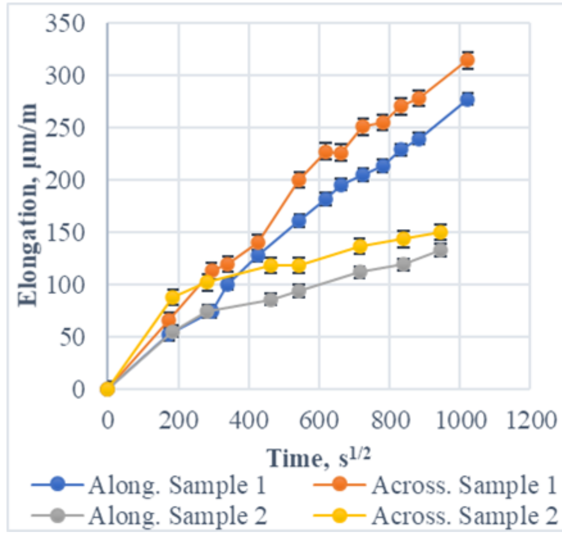


Partial diffusion coefficient

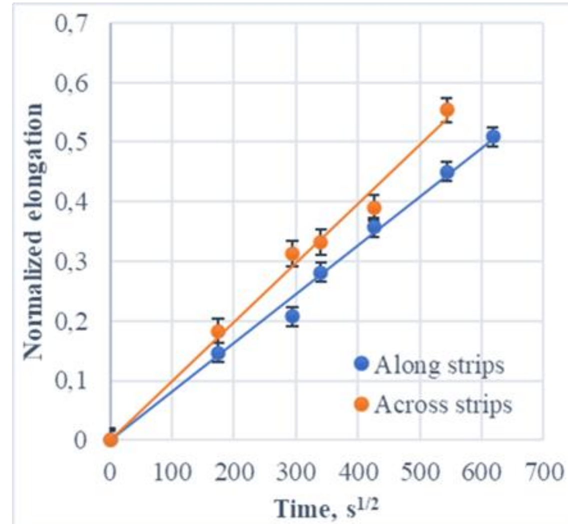
L(t^{1/2}) coordinates



L(t^{1/2}) coordinates. Remeasured



1st sample. Linear fit



- Difference between the samples is obvious in $L(t^{1/2})$ coordinates
- During the first two days the samples expand simultaneously

At 21°C and 50% RH the partial diffusion coefficients for the sample w/o full copper layer measured to be

- $D'_{\parallel} = (3.4 \pm 0.2)\times 10^{-2}$ μm²/s
- $D'_{\perp} = (4.7 \pm 0.5)\times 10^{-2}$ μm²/s

Conclusion

- Rates of elongation of both samples differ from each other as well as in directions along and across strips of each sample.
  - This difference is accounted for the different copper pattern of the samples.
- The equilibrium elongation in both directions of both samples is consistent within the measurement errors.
- The linear swelling coefficient for the sample w/o full copper layer is
  - $\beta = (7.0 \pm 0.2)$ µm/m/%.
- The swelling of the sample w/o full copper layer is described by the solution of the Fick's equation for an infinite sheet. Partial diffusion coefficients at 21°C/50% RH along and across the copper strips is
  - $D'_{\parallel} = (3.4 \pm 0.2)\times 10^{-2}$ µm^2/s
  - $D'_{\perp} = (4.7 \pm 0.5)\times 10^{-2}$ µm^2/s
- For the sample with copper layer on back side, the elongation curves cannot be described by the solution of the Fick's equation.

Acknowledgments

We would like to express gratitude to Rui De Oliveira and CERN PCB Production Workshop for the production of the samples and the valuable discussions, and the CERN Bond Lab for the usage of the climatic chamber and the working space in the clean room of the lab.

References

1. J. Crank, *The Mathematics of Diffusion*, Oxford, U.K: Oxford Univ.Press, 1975.

2. K. Weide-Zaage, W. Horaud and H. Frémont, *Moisture diffusion in Printed Circuit Boards: Measurements and Finite-Element-Simulations*, *Microelectronics Reliability*, Vol. **45**, Issues **9–11** (2005), p. 1662-1667.

3. Adamson, M.J., *Thermal expansion and swelling of cured epoxy resin used in graphite/epoxy composite materials, J Mater Sci 15*, 1736–1745 (1980).

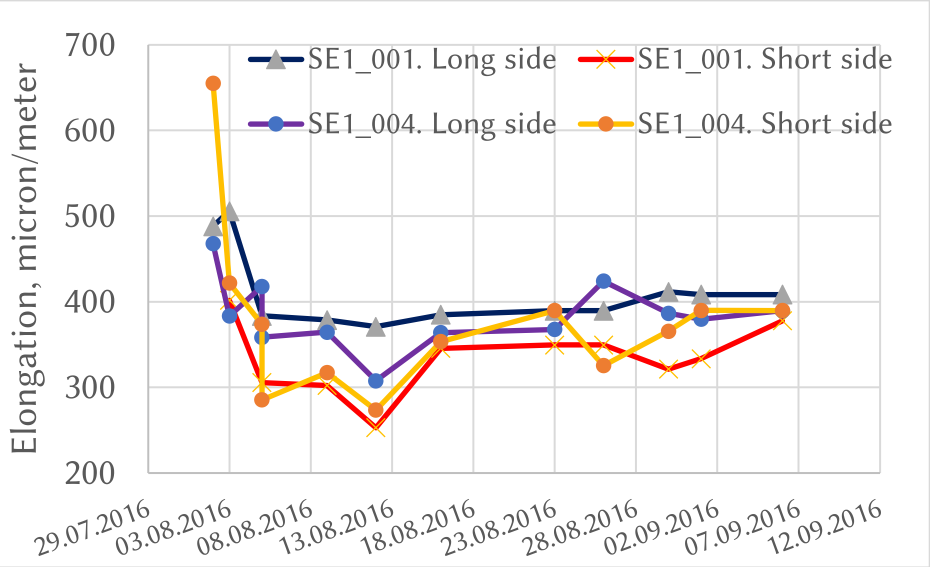
4. Yoon, J., Kim, I. and Lee, S., *Measurement and Characterization of the Moisture-Induced Properties of ACF Package*, *ASME. J. Electron. Packag.* 2009, 131(2): 021012.

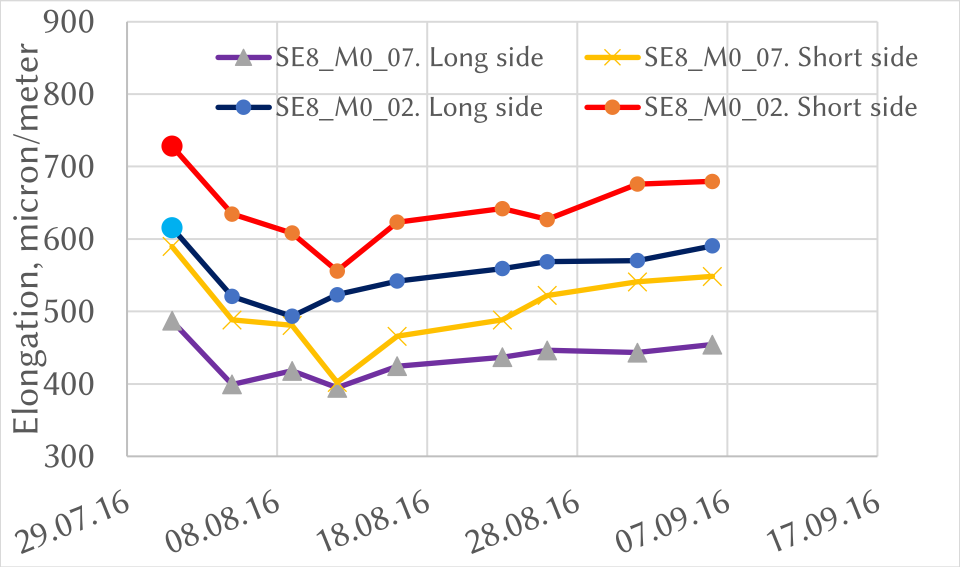
5. Shirangi M.H. and Michel B. *Mechanism of Moisture Diffusion, Hygroscopic Swelling, and Adhesion Degradation in Epoxy Molding Compounds*, In: Fan X., Suhir E. (eds) *Moisture Sensitivity of Plastic Packages of IC Devices, Micro- and Opto-Electronic Materials, Structures, and Systems*, Springer, Boston, MA, 2010.

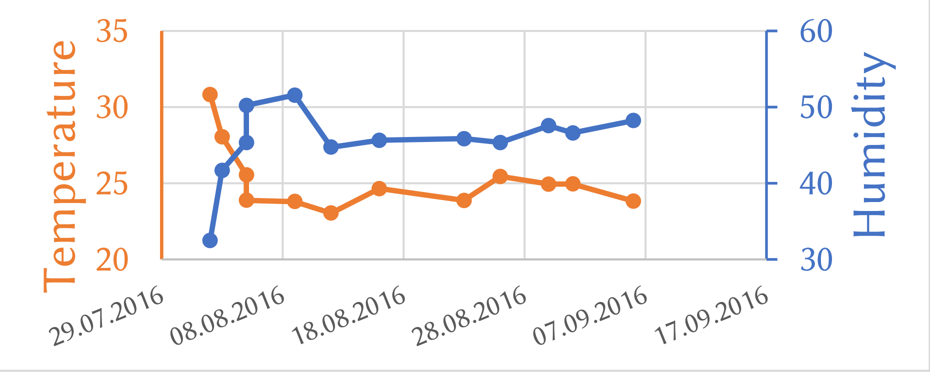
Back-up

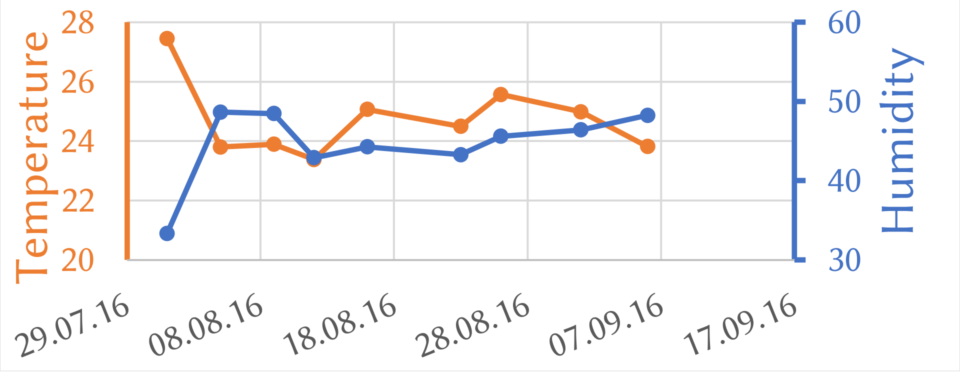
Long-term measurements with pre-series boards

boards kept in the room with neither t nor RH control









Dimensional Inspection

absolute width & length

- six rasmasks per board

boards too large: 0.4mm/m
→large problems with precision, edges & holes

distortions

- registration of strip position in center + rasmasks

- nine contact CCDs on granite table
- surveyors resting on pairs of precision spheres O(30µm), glued onto table
- fast measurement and analysis with custom GUI with direct interface to QC form (Pavia, Tokyo)
- flexible configuration