Laboratory Calibration and Field Results of Wood Resistance Humidity Sensors

Kohta Ueno, Building Science Corporation[1]

John Straube, Ph.D., P.Eng., University of Waterloo[2]

ABSTRACT

In building enclosure monitoring, measurement of relative humidity within assemblies can be used to determine the risk of moisture-related failures. However, many commonly available relative humidity sensors fail during extended exposure to high relative humidity, especially condensing environments, and provide little resolution in the important high relative humidity region. Therefore, research was undertaken on the use of wood electrical resistance (moisture content-based) sensors as a surrogate measurement for humidity.

These sensors were first calibrated under laboratory conditions, which included measurement of response time, response to various humidity conditions, and repeatability and variability between sensors. This was followed by the installation and monitoring of these sensors in a variety of field applications over several years. These locations included brick space drainage cavities and stud bay cavities in above grade walls, interfaces between basement walls and insulation systems, and within masonry construction. During the field research, the test walls were disassembled; conditions within the wall were compared to measured data.

The calibration and field results show that these sensors are promising for building enclosure monitoring applications. The sensor shows a different response between saturated air (100% relative humidity) and the presence of liquid water (e.g., condensation). The moisture storage available in the wood sensor material results in a measurement that reflects the accumulation of moisture over time at an interface, which can be correlated to mold growth risks. The response of these sensors was found to be relatively slow as well as asymmetric (wetting vs. drying responses).

INTRODUCTION

In building enclosure monitoring, measurement of relative humidity (RH) within assemblies can be used to determine the risk of moisture-related failures. Previous field monitoring work has shown that common relative humidity sensors (e.g. thermoset polymer capacitive sensing element) will often fail after extended exposure to high relative humidity, especially condensing environments. Measuring the moisture content of masonry and concrete *in situ* is also very difficult. There are no low-cost sensors available commercially and the moisture region of interest is in the very high RH (over

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[1] Kohta Ueno is an associate at Building Science Corporation, Somerville, MA.

[2] John Straube is associate professor in the Civil Engineering Department, University of Waterloo, Waterloo, Ontario, Canada.

80%) capillary saturation region. Relative humidity sensors provide no resolution in the capillary zone at all.

In an effort to develop a long-term, low-cost, high-reliability measurement of moisture conditions, several types of wood moisture content surrogate sensors were developed for use in these challenging high RH conditions. Two form factors were used: a flat sensor meant to measure moisture conditions at a planar interface (referred to as a “wafer” sensor; see Figure 1), and a cylindrical sensor, intended for post-construction installation in a drilled hole in a solid material, such as masonry or brickwork (referred to as a “plug” sensor; see Figure 2). Both sensors have a pair of electrical leads that allow resistance measurement of the wood, when connected to data collection equipment. These sensors were calibrated under laboratory conditions, and then deployed at the field monitoring sites for several years. This paper covers the development, calibration, and field results of these sensors.

BACKGROUND

The moisture content (MC) of wood can be measured by electrical resistance; this technique has been well documented (Garrahan 1988, Straube et al. 2002). The formula that relates uncorrected moisture content of the reference species (Douglas Fir) to electrical resistance is stated in Straube et al. (2002) as follows:

$$\text{Log}_{10}\,(\text{Moisture content}) = 2.99 - 2.113\ \ (\log_{10}(\log_{10}(\text{Resistance}_{\text{wood}}))\qquad(1)$$

where:

moisture content is in mass %

resistance is in ohms (Ω).

Wood moisture content can be related to humidity levels; the relationship between the equilibrium moisture content of a porous medium and the environmental relative humidity is known as the sorption isotherm. The sorption isotherm for wood is shown in Figure 3. The sorption curve at 81°F (27°C) is highlighted in red; most building applications fall into a similar range (for comparison, see curves in the figure for 32°F/0°C and 120°F/49°C).

Note that at moderate humidity ranges (20-75%), the slope of the isotherm is relatively low; as a result, small errors in MC measurement can result in larger errors in humidity readings. In addition, the sorption isotherm shows some hysteresis behavior, which further impedes accuracy (average isotherm is shown in Figure 3). Carll and TenWolde (1996) tested wood-based sensors based on these relationship, and noted errors on the order of ±10% RH without pre-screening of sensors.

Below roughly 98% RH, water is stored in the vapor or adsorbed phase within the pores of the material; however, in contact with liquid water (100% RH, by definition), moisture content can rise to two or four times this amount (known as “capillary suction” behavior. In physical terms, in this regime, there is free water within the pores of the material.

Therefore, the material properties of wood result in sensors that have different responses to the presence of liquid water (such as condensation, or rainfall penetration) and 100% relative humidity environments. This distinction is of particular interest in light of work by Doll (2002) and Black (2006). These researchers have observed that mold growth in common building materials occurs much more readily in the presence of even a small amount of liquid water, rather than at high relative humidity conditions.

LABORATORY CALIBRATION

Step Change Calibration: The “wafer” and “plug” sensors were first run through similar calibration procedures: they were allowed to reach equilibrium in a controlled 66°F (18.8°C; ±2σ=4.0°F/2.2°C)/50% (±2σ=5.3%) relative humidity test facility, then moved to a 100% RH chamber (same temperature conditions), and then returned to the 50% RH test facility. This was done to record the response to these step changes, as well as to gauge sensor variability.

In the initial calibration stage, the sensors showed a moisture content value of approximately 11% (using the calibration equations and species correction factors from Straube et al. 2002), which maps to 55% RH, as per the sorption isotherm (Figure 3). Actual humidity was 45-55%; moisture content measurements were sporadic, as wood electrical resistance reaches the limit for consistent readings with the data collection equipment (1-2 GΩ range). Once placed into the humidity enclosure, moisture content values quickly rose to the 27-32% range (98%-100% RH), as shown in for the “wafer” sensors in Figure 4. There was some variation in the final moisture content measurements; average value was 29%, ±2-3%. In extended testing at 100% RH for 39 days, the resistance response of the "wafer" sensor continued to stay flat.

The results for a single representative "plug" sensor is also shown in Figure 4 for comparison; it had a noticeably slower response, which might be explained by the difference in sensor shape (surface area vs. volume).

Time constant (τ) curves were fitted to these results; although the sensor response curve did not exactly match the expected exponential ($1 - e^{-t/\tau}$) function (Wheeler and Ganji 2004), a value of τ=24 hours provided a reasonable match. At $t=4\tau$, a sensor’s output nominally reaches 98.2% of its final value.

Moving the sensors from the 100% RH chamber to the 50% RH test facility provided a measurement of the desorption or drying response, as shown in Figure 5. Two points are noted in this response.

First, the drying response is much faster than the wetting response: it reaches its equilibrium condition in approximately 40-50 hours, as opposed to 100-150 hours in Figure 4. It was not initially clear from this data whether this reflects an actual physical response, or an artifact of measuring the moisture content using electrical resistance. This issue is discussed in a following section.

Second, the variability of measurements at 100% RH is much higher than the variability at 50% RH. This might be due to the non-linear relationship between resistance and moisture content, as described in Equation 1. At 11% MC, a ±30% error in resistance measurement results in ±0.4% MC, while at 27% MC, a ±30% error in resistance results in ±1.4% MC . Although the absolute differences are small, the relative magnitude of the errors (factor of four) is consistent with standard deviation data at 100% vs. 50%. Calibration of the measurement equipment with reference resistors (from the GΩ to the kΩ range) indicated that resistance measurement errors were small; the uncertainty may lie instead in the variability of wood material properties.

Water Immersion Calibration: Another calibration test was to immerse six "plug" sensors in water for 48 hours while simultaneously monitoring moisture content, to determine their response to liquid water (Figure 6). The plot shows that measured moisture content goes up to the 40-45% range by the end of the immersion period, and it appears that the sensors have not yet achieved equilibrium. This is well above the 25-35% range for hygroscopic adsorption (100% RH environment, out to 39 days) found in previous tests.

The sensors were then removed from the water and allowed to dry in a 66°F (18.8°C)/50% RH environment. After removal from water, the samples dried at a variety of rates, but all eventually recovered to conditions in equilibrium with a 50% RH environment.

Although this demonstrates that these sensors can distinguish between liquid water wetting events and high humidity environments, absolute moisture contents are not very certain at higher levels. The resistance vs. moisture content relationship was developed for the 7-25% range, and extrapolation to 40% seems to provide reasonable results (Straube 2002). However, it is known that the equation will underpredict moisture content above 40% MC.

In addition, these sensors do not provide consistent measurements at lower humidity levels (when electrical resistance of the wood exceeds the measurement threshold of the data collection equipment). However, given that these are low-risk conditions for mold growth, this limitation has a minimal impact for the purpose of these sensors.

Concrete Cylinder Uptake Measurements: The intended installation technique for the "plug" sensor is embedment in a drilled hole in brickwork or masonry, to estimate the *in situ* moisture content. This application is conceptually similar to the measurement of internal relative humidity of concrete floor slabs, as per ASTM F 2170–02 (ASTM 2002).

This type of application allows the sensor to respond not only to water in vapor form, but water in capillary form. The moisture content of wood in direct contract with a capillary active material such as masonry should rise along with the masonry, although there will be a delay and the quantitative levels will be different. In most practical applications involving masonry or concrete, one is not concerned with relative humidity *per se*. Instead, damage functions occur at higher moisture content levels that allow capillary transport (and associated salt transport, resulting in efflorescence or subfluorescence) or levels near capillary saturation (and freeze-thaw damage).

In part of this experiment, the liquid water uptake response of these sensors was compared with RH sensors. Relative humidity and "plug" sensors were installed centered in 4" (100 mm) diameter concrete test cylinders; they were placed into a drilled hole perpendicular to the axis that was sealed with vapor impermeable urethane caulk and adhesive foil tape. The sides of the samples were wrapped in impermeable foil tape to force one-dimensional uptake, one end was immersed 1-2 mm (1/16”) into a water bath, and weight (water) gain over time was recorded.

Figure 7 shows uptake results for three “plug” sensors and one relative humidity sensor. The humidity sensor shows a reaction within 12 hours of immersion, and reaches saturation (100% RH) within 30 hours. The “plug” sensors start to react at the same time, but take much longer to react to the step change. They reach equilibrium after roughly 150 to 200 hours, which is consistent with the calibration experiments. Their final moisture contents are in the 28-32% MC range, which is consistent with 100% RH.

Part of this experiment was to determine if wicking from exposed end grain of the wood cylinders would cause non-uniform responses in installed “plug” sensors. Therefore, some of these sensors were coated with a layer of epoxy at their exposed end grain, while the remainder did not have this treatment. This testing showed no discernable difference between these groups.

One portion of the experiment was to cast sensors into wet concrete, and compare their response with sensors installed post-casting (as per the procedures described above). In general, the results from the “cast” sensors were erratic, showing sudden unexplained variations in measured moisture content that were unlikely to reflect actual changes in concrete conditions. Therefore, further work is recommended before using these sensors in this application.

Electrical Resistance and Gravimetric Measurement Comparison: As noted above, the sensors have an asymmetric wetting and drying response, even though the absolute vapor pressure difference is the same in both cases. It was important to determine if this is the actual behavior of the wood sensor, or an artifact of the measurement of moisture content using electrical resistance. For instance, it seems possible that moisture is only gradually diffusing through the thickness of the wafer to the resistance pin locations, causing this slow response.

A simple experiment was set up to determine the adsorption/desorption response of the wafer stock using gravimetric moisture content. Samples were moved from the 50% RH/66°F (18.8°C) controlled environment into a 100% RH chamber and the weights were periodically measured. After they had achieved their final weight, they were removed from the chamber, and again periodically weighed while desorbing moisture. After returning to equilibrium conditions with 50% RH, the wafers were then oven dried to 0% MC, as per ASTM D 4442-92 (ASTM 2003), to allow back-calculation of gravimetric moisture contents. This gravimetric adsorption and desorption responses are plotted in Figure 8 and Figure 9, respectively, with a typical resistance response for reference.

The adsorption response (Figure 8) clearly shows that the long time response of the sensor is a function of the slow increase in wood moisture content when placed in the 100% RH environment. Both gravimetric and resistance measurements have a slow response, taking 100 to 200 hours to reach final values. However, the ending gravimetric moisture content is consistently higher than the corresponding electrical resistance readings: the former are in the 38-41% range, while the latter are near 30%. This is consistent with the predicted error mentioned above (Straube 2002).

The gravimetric desorption response (Figure 9) also matches the electrical resistance readings very closely. The curve shows a similar time response (reaching equilibrium with 50% RH in 15-24 hours).

Hygrothermal Simulation Comparison: To gain some insight into the asymmetric adsorption/desorption response and the related moisture physics, one-dimensional hygrothermal simulations were run using WUFI 4.0 software. If this behavior could be duplicated in the simulation, the material property causing it might be isolated and identified.

A wood layer matching the thinnest dimension of the wafer (3/16” or 4.75 mm) was exposed to step changes similar to the calibration experiments: 68°F (20°C), and alternating between 50% and 100%, at 1000-hour intervals. Two wood materials from the database were tested; it was found that one of them (softwood from the IBP database) replicated the behavior (asymmetric adsorption/desorption), while the other (“pine transverse direction” from the NTNU database) had a symmetric response instead. The material properties of these two wood samples were then compared, to try to find the critical difference.

The key difference was found in the sorption isotherm (i.e., moisture storage function): below 95% RH, the curves were similar. However, the IBP softwood has a sharp “hook” rising from 97 to100% RH, to a maximum corresponding moisture content 144%. In contrast, the maximum moisture content of the NTNU material is 36% MC at 98% RH. The "hook" in the IBP data is likely from pressure plate measurements (not sorption isotherm data), which is a technique more easily controlled than very high RH sorption tests. However, adding this "hook" to the NTNU data, results in the asymmetric behavior seen in the IBP material, matching the experimental results.

FIELD OBSERVATIONS

“Wafer” and “plug” sensors were used in several in-situ building enclosure monitoring projects for multiple years. Two installations placed a “wafer” sensor in parallel with a relative humidity sensor; these results could be plotted against each other to gauge the accuracy and response characteristics of these sensors. In addition, wafers were placed in both above- and below-grade walls at the interface between the insulation and the interior vapor control layer (e.g., polyethylene), to gauge the magnitude of moisture accumulation due to inward vapor drives. Furthermore, several “plug” sensors were installed in an above grade brick masonry veneer wall to measure moisture conditions in the brick wythe.

Brick Cavity Space: The ventilation/drainage cavity in a brick veneer (single wythe) wall is a particularly challenging environment for relative humidity sensors. The space is at or near 100% RH for much of the year, experiences liquid water intrusion (capillary rain penetration through mortar joint cracks), and sees a wide range of temperatures. Therefore, in recent research on six wood frame walls in a southern Ontario (Canada) climate with brick cladding, “wafer” sensors were installed in this space in parallel with the relative humidity/ temperature sensors to provide redundant measurements. The examined data covers a period of over two years. The overall results of this research are discussed in Wilkinson et al. (2007).

The relative humidity data was first examined (not plotted here): during the colder seasons (October to May, typical), the measured relative humidity was 90-100%. During the summer months, humidity levels dropped to 40-60% (south) or 80% (north). This environment caused many sensor failures: several gave intermittent data, suddenly dropping to ~30% RH and then jumping to 100%; this lack of reliable data reduced overall confidence in the remaining results. Overall, only four of the six sensors remained functional at the end of the monitoring.

In contrast, the "wafer" sensors returned consistent data throughout the monitoring period. They showed patterns basically consistent with the relative humidity sensors, with a similar seasonal swing and differentiation between north and south walls.

To determine the correlation between these two sets of sensors, the relative humidity and moisture content measurements from the "wafer" sensors were plotted against each other. This required the removal of obviously incorrect relative humidity data; the daily average values are plotted in Figure 10. In addition, the sorption isotherm for wood (from Straube and Burnett 2005) is also plotted; the response of the sensors should ideally follow this line.

The plot shows relatively good agreement; much of the data seems to lie within ±5% RH of the sorption isotherm, as shown by the dotted grey lines. If the values for the N3 sensor are omitted, it reduces the number of data points outside of this range.

It should be noted that the data tends to be biased low, relative to the ideal correlation at the sorption isotherm. The significance of this trend will be discussed later.

These plots assume that the relative humidity sensors are maintaining their accuracy over time: given the history of erratic results from the RH sensors, it is entirely possible that their accuracy is drifting. The specifications for the RH sensors are stated as ±2% RH accuracy in non-condensing environments, with ±5% interchangeability in the 0-60% RH range, but ±8% at 90% RH. Given the extended exposure to high humidity levels, there is substantial potential for sensor degradation.

Basement Wall Concrete-Insulation Interface: Four basement interior wall insulation systems in a southern Ontario (Canada) climate were installed and monitored in a research project detailed in Ueno et al. (2007). Relative humidity was measured at the insulation-concrete interface, in order to determine accumulation of moisture in the assemblies; the sensors were installed at mid-height of the wall, roughly 3 feet (0.9 meters) below grade. Again, due to the expected high humidity conditions, all relative humidity sensors were doubled by "wafer" sensors.

Similar to the previous analysis, relative humidity and moisture content measurements were plotted against each other, with the sorption isotherm for wood superimposed (see Figure 12). One of the four walls had a failed RH sensor, so only three channels are shown. The three remaining walls are 2" of extruded polystyrene directly applied to the concrete wall ("XPS Interface"), a stud frame wall with fiberglass batt insulation and gypsum board with permeable latex paint ("FG-Latex Interface"), and a single-piece polyethylene basement insulation roll blanket ("Roll Blanket interface").

When the plot is examined, the three assemblies are clearly ranked in order of the vapor permeability: the polyethylene roll blanket (0.06 perms or 3.4 ng/Pa·m·s^2) remains at the highest relative humidity levels, the XPS wall is in the middle (0.55 perm or 31 ng/Pa·m·s^2), and the latex paint wall is the driest (2.6 to 18 perms or 150 to 1000 ng/Pa·m·s^2). The results shows good agreement between the two sensors: almost all of the data falls within ±5% RH of the sorption curve.

In contrast to the previous brick cavity data, these results are distributed above and below the sorption isotherm almost equally. This might be explained by the sensor response time and the conditions of these two projects. In the basement monitoring, temperature and relative humidity conditions changed very slowly (seasonally), so sensor time response would not be a strong factor. In contrast, the brickwork cavity would see a diurnal swing as well as rapid day-to-day changes based on weather conditions. The slow adsorption/fast desorption response of the sensor would cause a reduced number of observations at higher wood moisture contents, as seen in the data (biased below the isotherm).

Inward Vapor Drive Accumulation: In both of these previous projects, “wafer” sensors were also used at the interface between the cavity/stud bay insulation and the interior vapor control material (e.g., polyethylene), on the exterior-facing side. This was done to measure the magnitude of condensation on the polyethylene due to inward vapor drives, caused by an inward thermal gradient and a hygroscopic (reservoir) cladding (brick or concrete). This problem is discussed by Lstiburek (2006), and Straube & Burnett (2005), among others. Placing a relative humidity sensor at this location would have been of limited use: first, there is the reduction of sensor reliability in a condensing environment. Second, the ability of the “wafer” sensor to differentiate high humidity and liquid water conditions allow detection of condensation, similar to leaf wetness resistance or similar sensors. In both projects, the walls were disassembled after the monitoring period, allowing visual correlation between the degradation (if any) of the assembly and measured data.

In the above-grade research described in Wilkinson et al. (2007), the most telling results came from the south-facing above-grade brick wall with fiberglass insulation and a polyethylene vapor barrier. During the summer, the relative humidity in the mid-thickness of the stud bay rose to the 80-90% level. The moisture content of the wafer (at the fiberglass-polyethylene interface) rose concurrently, reaching a peak of 45% MC, which is substantially above the adsorbed 100% RH level of 27-32% MC, as per earlier calibrations. This response was compared with the exterior temperature: it became clear that when exterior temperatures rose above interior setpoint, causing an inward thermal gradient, the wafer began to accumulate moisture as condensation formed on the vapor barrier. When the thermal gradient shifted outward at the end of the summer, the moisture content fell to 10%, and remained there through the winter.

In late summer (September), the wall was disassembled for inspection. Liquid water was visible at the polyethylene vapor barrier, and the sill plate was noticeably wetted by condensation rundown. This is consistent with the results of the “wafer” sensor, indicating the presence of liquid water. There was mold growth evident on the framing, especially on the interior side of the bottom plate: moisture content measurements at that location ranged from 25% to over 30% (off the scale of the handheld meter).

In addition, the wafer sensor itself showed noticeable surface mold growth, which was a useful secondary indication of the sensor if the experiment concludes with disassembly of the test specimen.

It was useful to compare these results with the adjacent wall, which was built identically, but without the polyethylene sheet. The wafer at the fiberglass batt-drywall interface in the south-facing wall had peak values mostly in the 10-15% MC range, indicating that inward vapor drives could dry by diffusion to the interior, instead of condensing. This was confirmed during disassembly: the exterior (cavity) side of the gypsum board showed no damage or mold growth.

In the below-grade research described in Ueno et al. (2007), inward vapor drives were similarly demonstrated in the “roll blanket,” using a wafer sensor at the above-grade portion of the wall, at the insulation-polyethylene interface. Moisture contents of the wafer in that wall peaked at 40%, indicating liquid water condensation at the interface. Builders and consultants have reported this type of summertime condensation and rundown/accumulation as a homeowner complaint (Swinton and Karagiozis 1995). As with the previous case, wetting and drying behavior was linked to an inward temperature gradient. Inspection of the wall after a year of operation showed some residual mold spotting on the wafer, and some brown discoloration of the fiberglass insulation (typically linked with wetting of the insulation).

Masonry Wall: Several “plug” sensors were installed in an above grade brick masonry veneer wall in an east-facing wall of a research test hut. The sensors were installed in holes drilled into the mortar joints from the interior side of the assembly; they were located at three heights (“low,” “mid,” and “high”).

The data from this project is plotted in Figure 13; it includes calculated driving rain on the east face of the test hut, derived from hourly weather station data using the methodology presented in Straube and Burnett (2005). The plot shows approximately two years of data.

Several patterns can be discerned in the plot. During the colder seasons (fall, winter, and spring), the sensors typically show moisture contents in the 25-35% range, indicating RH levels close to 100%. In the summer, as outdoor temperatures rise, some drying starts to occur. However, quick jumps in moisture content (even rising into the liquid water range) interrupt this drying. These jumps are typically (but not entirely) linked to driving rain events on that face of the building. The correlation is very notable in the summer of 2007: a dry summer resulted in greater drying of the brick layer (10% MC “plug” reading). A rainstorm with substantial driving rain caused a quick jump in this measurement, followed by further wetting and drying cycles.

The sensor locations in the wall can be correlated with a discernable pattern, particularly in the summer of 2007. The wetness follows a height-related gradient, growing wetter going from the top to the bottom of the wall. This is consistent with observations of the test hut wall during rain events: the upper portion was partially sheltered by the roof overhang and drip edge, while the lowest portions received both incident rain and some splashback from the ground.

Both epoxy and non-epoxy coated sensors were used in this project. As mentioned earlier, no difference between the sets of sensors was noted, which is consistent with the laboratory results described earlier.

CONCLUSIONS

Taking this laboratory calibration and field installation work together, several conclusions can be drawn in regards to the use of these wood surrogate moisture content sensors:

- In steady-state laboratory calibration measurements, these sensors showed accuracy of ±3% RH at 100% RH (27-32% MC as measured by electrical resistance).
- In dynamic field installations, the results agreed with relative humidity measurements within ±10% RH or better, and more typically ±5% RH. This data showed good correspondence with the sorption isotherm for wood; the relative humidity can be estimated from moisture content using a curve fit of the isotherm, as long as the magnitude of the error margin is acknowledged.
- The sensors have a very slow wetting response, responding to a step change from 50% RH to 100% RH over a course of 100-150 hours. However, drying occurs at a much faster rate. This reflects the actual moisture response of the wafer material itself, not an artifact of the measurement method.
- This response suggests that these sensors are not a good indicator of diurnal or more rapid phenomena, and should instead be used to capture longer-term (i.e., seasonal) wetting or drying.
- Laboratory calibration measurements demonstrate that these sensors can distinguish between liquid water wetting events and high humidity environments (adsorbed moisture).
- Similarly, field measurements showed a distinct response when condensation wetting events occurred in interstitial building assembly spaces, as verified by disassembly of the components.
- These sensors showed good reliability and performance in environments challenging for many electronic relative humidity sensors.
- Inserting wood sensors into capillary active materials such as masonry and concrete allows for the measurement of relative wetness.

Overall, these results show that these sensors are promising for building enclosure monitoring applications, especially in locations that remain at high humidity or condensing conditions for extended periods, and for *in situ* monitoring of masonry or brick.

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FIGURES

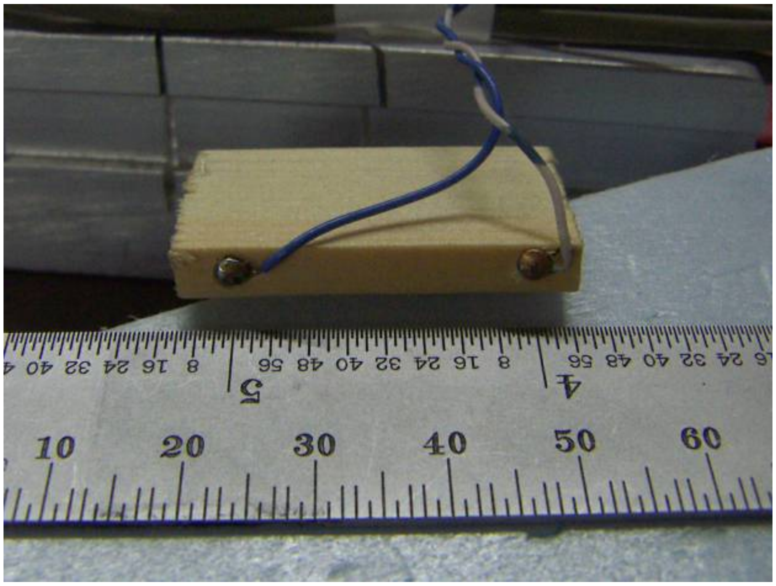

Figure 1: Close-up of “wafer” sensor

Figure 2: Close-up of “plug” sensor

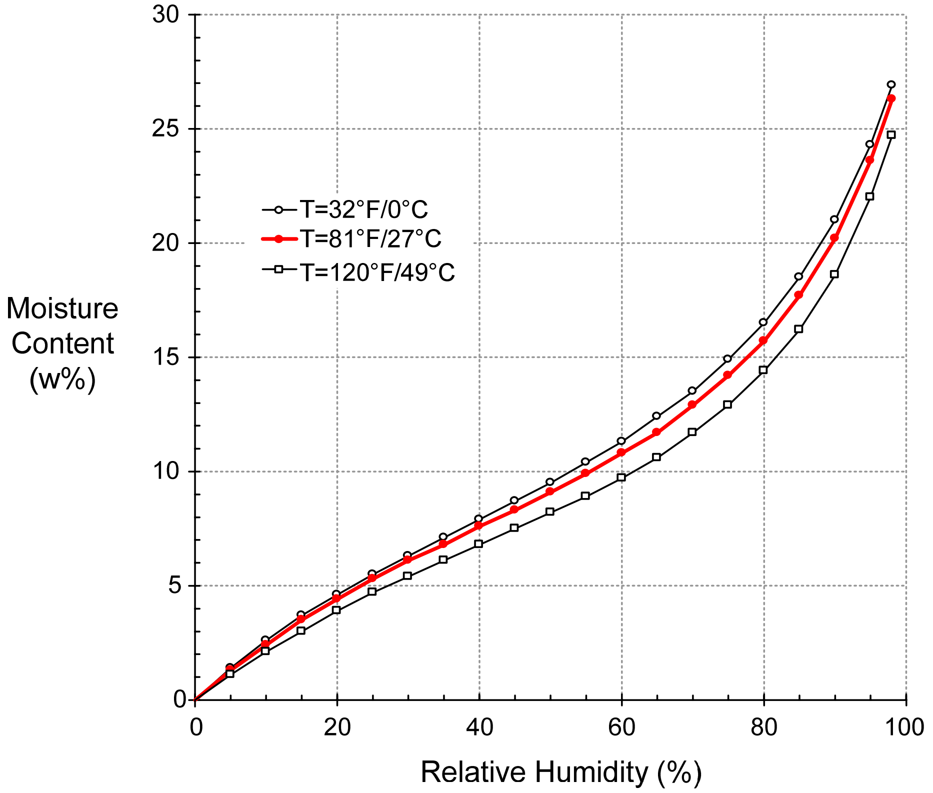

Figure 3: Average sorption isotherm for wood (Straube and Burnett 2005), with annotations

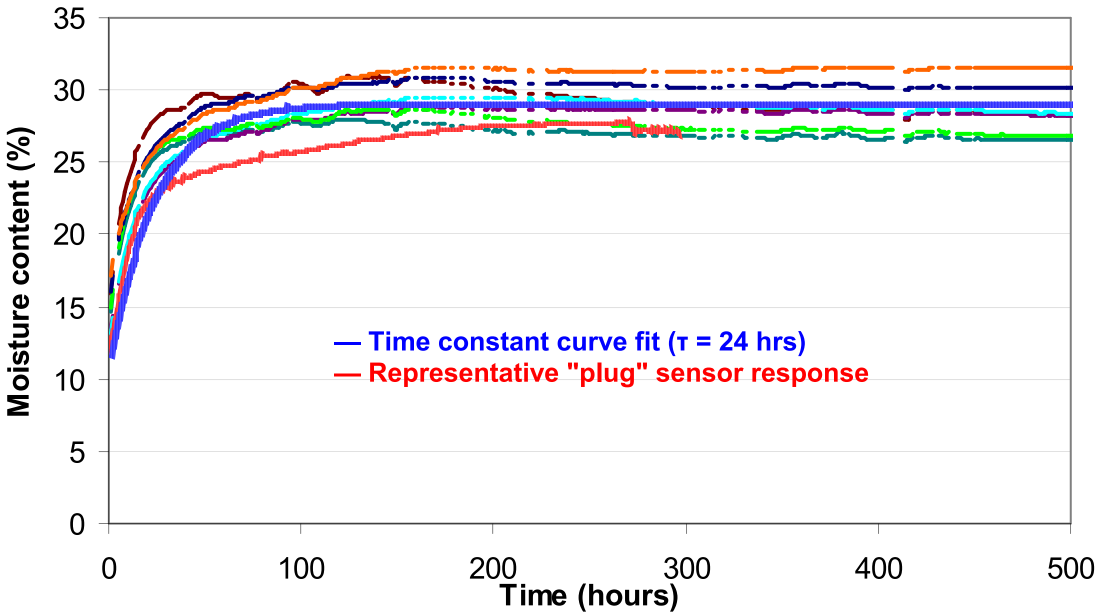

Figure 4: Wafer sensor response after placement in humidity enclosure

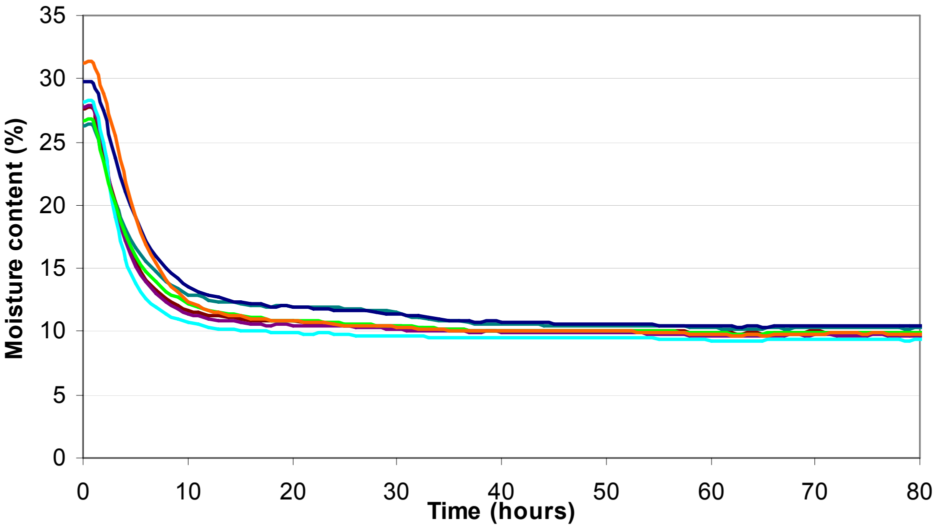

Figure 5: Wafer sensor response after removal from humidity enclosure

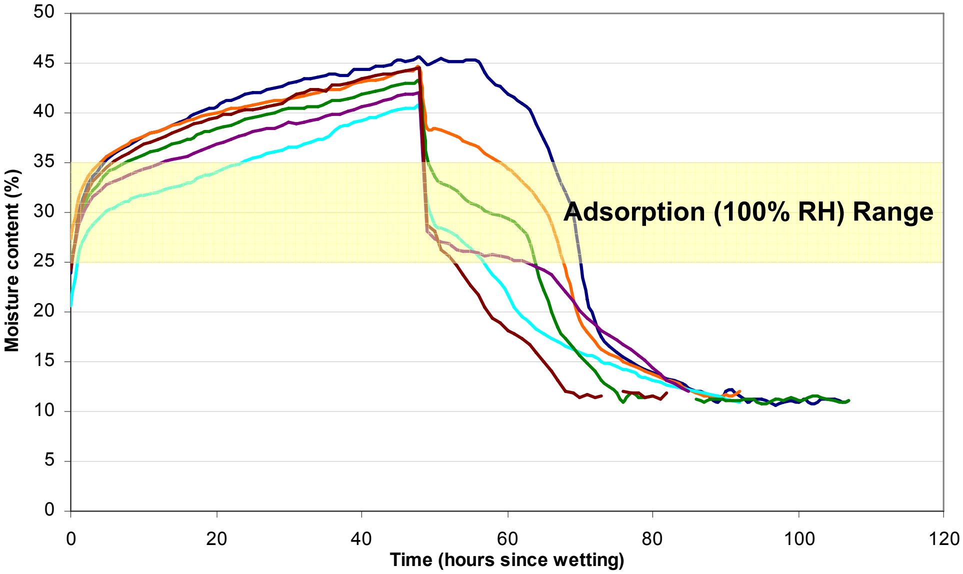

Figure 6: Plug sensor response to water immersion test and drying

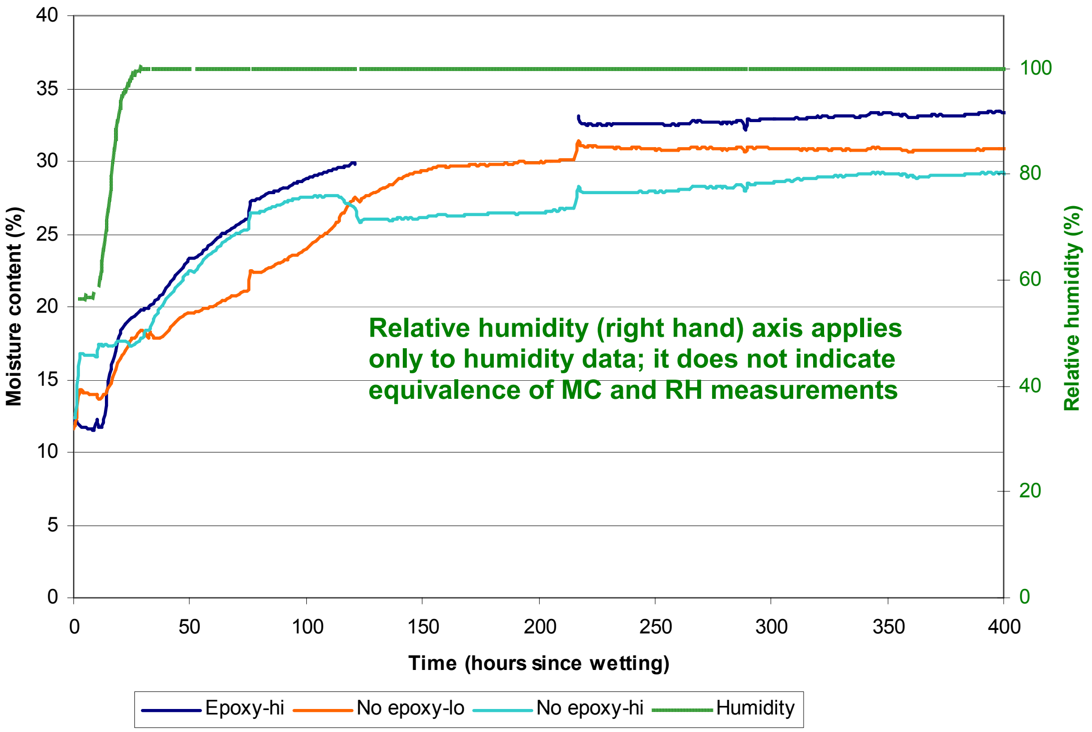

Figure 7: Liquid water uptake into a concrete cylinder: plug and RH sensor results

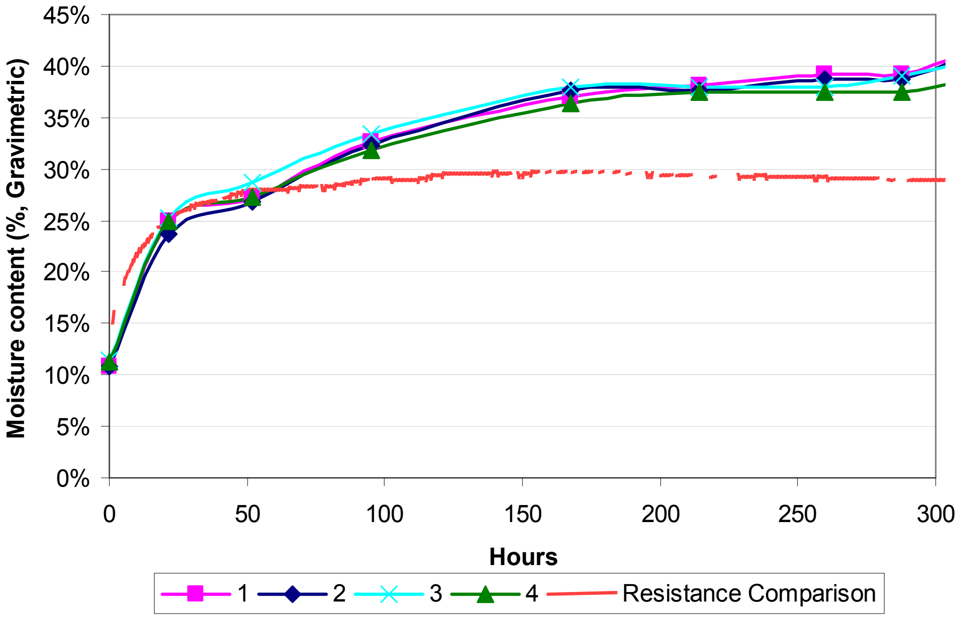

Figure 8: Gravimetric adsorption response of wafers

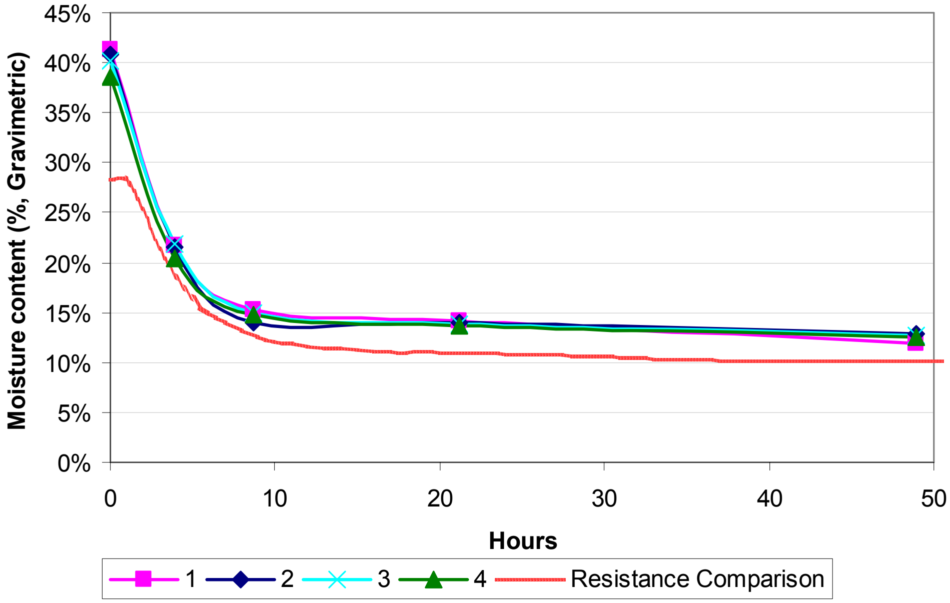

Figure 9: Gravimetric desorption response of wafers

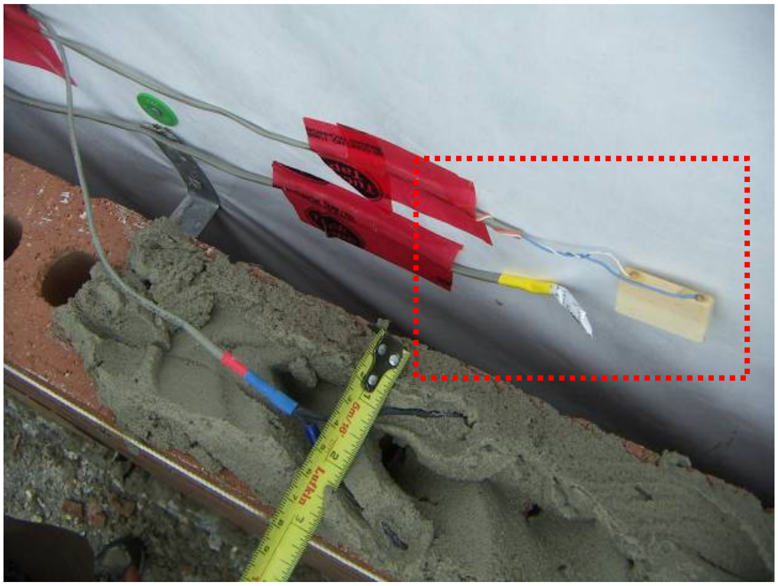

Figure 10: RH sensor and wafer sensor in brick space cavity

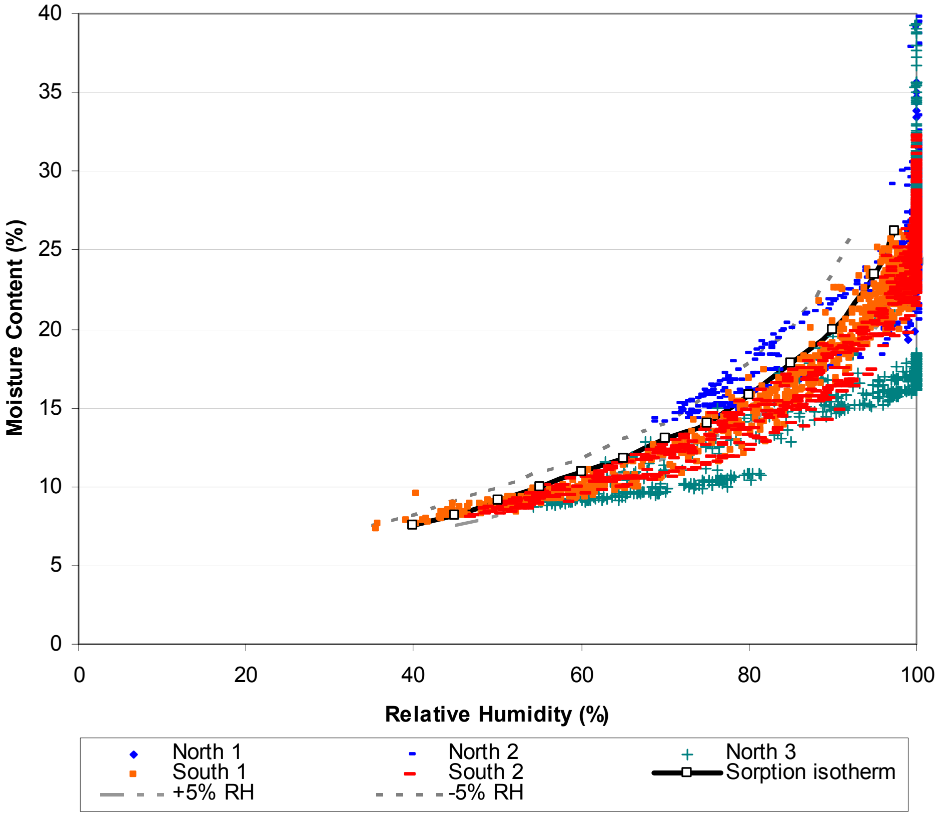

Figure 11: Brick space cavity relative humidity vs. wafer moisture content

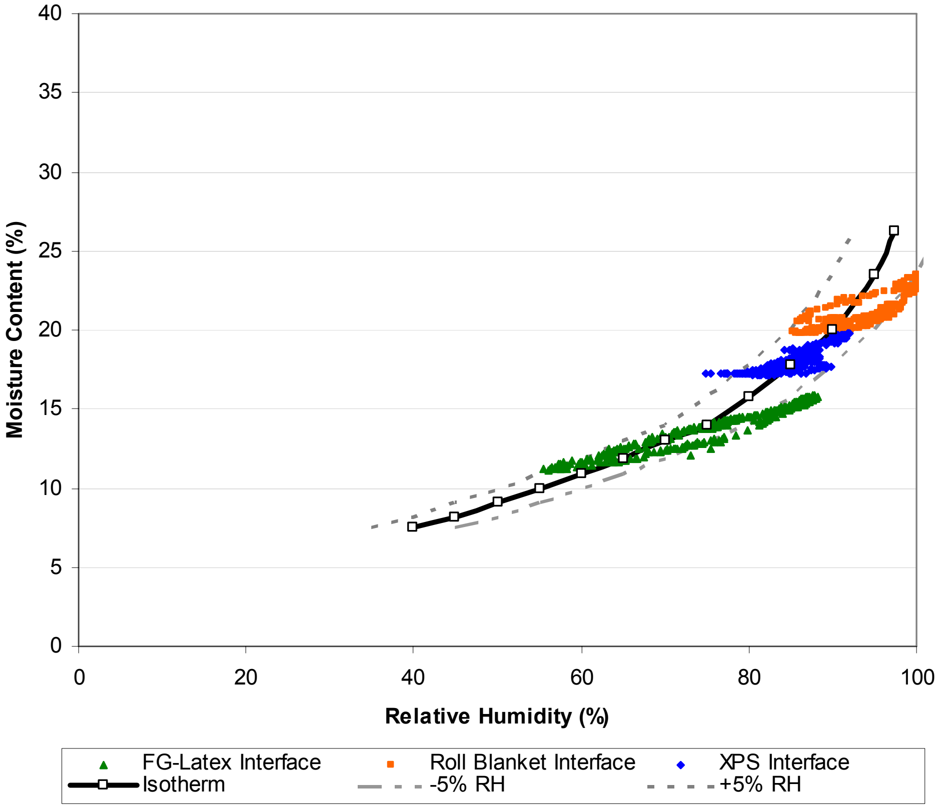

Figure 12: Basement wall-insulation interface relative humidity vs. wafer moisture content

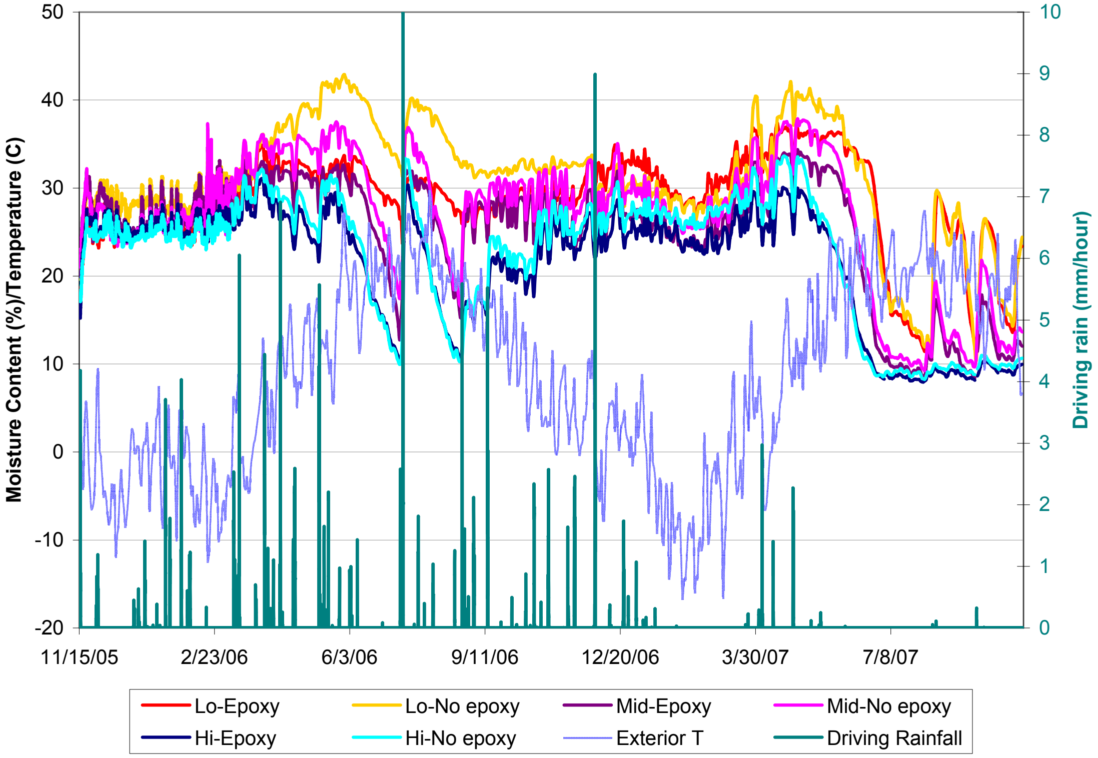

Figure 13: "Plug" sensor response in brick wythe with driving rain & exterior temperature