MOISTURE PHYSICS AND PROCESS OF DRYING OF PRINTED CIRCUIT BOARDS

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

CONTENTS

1 MOTIVATION

The aim of this collection and interpretation is to develop an understanding of moisture in materials, especially in printed circuit boards, to know the effects on further processing and to be able to derive targeted corrective actions when moisture-related problems occur. In principle, the considerations are valid for all types of PCBs. Although these basic principles are of particular importance when working with flexible and rigid-flexible printed circuit boards; observing them can mean the difference between success or failure.

2 TECHNICAL TERMS AND ABBREVIATIONS

PCB	Printed Circuit Board
IPC	Global Association for Electronics Manufacturing
Tg	Glass Transition Temperature
CTE	Coefficient of Thermal Expansion / (material specific)
MBB	Moisture Barrier Bag
WVTR	Water Vapor Transmission Rate
RH/RF	Relative Humidity / maximum permissible moisture or critical moisture limit (refers to the resin only)

3 MOISTURE CONTENT – AN EQUILIBRIUM

Moisture is water in a molecularly dissolved form. With air humidity the water molecule is dissolved in air. The solubility varies depending on the conditions, for example the temperature of the air. If humid air cools down, the solubility of the water in the air decreases and the moisture condenses into water droplets. These form fog or free water in clouds; it rains, snows or even hails from these clouds.

In summer, when the sun is shining brightly, we can also observe the opposite in the sky: clouds dissolve because the temperature of the air and thus its water absorption rises. The cloud slowly disappears - the absolute humidity increases.

In the same way, water can dissolve as moisture in solids and thereby change the properties of the materials. Firewood, for example, is dried for days so that it burns better and soot-free. If dry firewood is stored in a damp environment, the wood absorbs moisture from the air, becomes heavier and burns poorly. The slowly developing wood moisture depends on the ambient conditions and represents the quasi-equilibrium between absorption and release (also called sorption equilibrium in the literature). The time it takes to reach equilibrium depends on pressure, temperature and the thickness of the wood.

A bottle of sparkling water provides an example of the influence of pressure on the solubility of gases. To create the fizzy drink, CO_2 is dissolved in water. When the bottle is opened for the first time, CO_2 gas escapes from the bottle, causing the pressure of the gas phase inside the bottle to drop and the desorption of the gas dissolved in the sparkling water. By opening the bottle, the previous equilibrium between the gas phase and the liquid phase has been altered. Now a new equilibrium is established with regard to the gas content of both phases according to the new conditions.

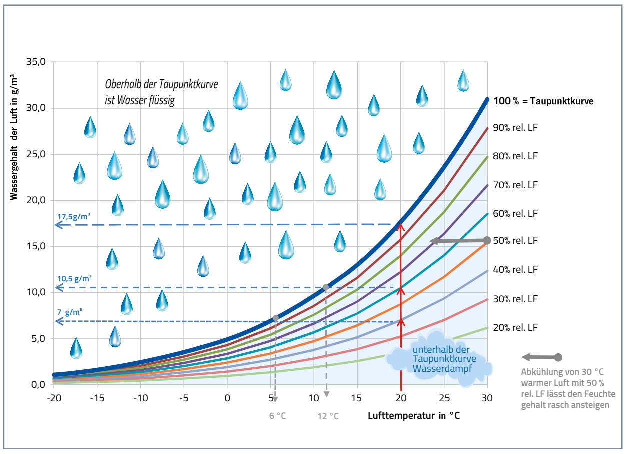


Figure 1: Water vapour content in air at different temperatures [14]

THESE SIMPLE EXAMPLES SHOW:

- Absorption and release of moisture are reversible processes.
- Material properties are changed by moisture.
- Dissolved moisture is not a water bubble in the material. Water can only collect in liquid form in pores and cavities.
- Depending on the conditions, moisture equilibria with the environment are established in materials.
- By deliberately changing the conditions, the equilibrium can be "shifted" until a new equilibrium is reached.
- This realisation of a new, desired equilibrium does not happen spontaneously, but rather takes time.
- The speed at which equilibrium is reached also depends on pressure and temperature.
- Sporadic or seasonal delamination during soldering can be an indication that the conditions in the warehouse or manufacturing environment are not controlled and regulated. There are rarely problems in winter when there is a low humidity!

3.1 PHYSICAL PROCESSES IN DETAIL

We consider a system consisting of a printed circuit board and its environment. The surface of the PCB represents the boundary layer in the PCB/environment system, the phases are gas phase, i.e. in this case the ambient air, and solid body, i.e. the PCB. Water molecules from the environment accumulate on the surface of the PCB (adsorption). At the same time, water molecules also detach from the surface, desorb and dissolve in the air. At equilibrium, the adsorption rate is equal to the desorption rate.

A different equilibrium is established inside the printed circuit board: Water molecules diffuse into the solid (absorption) and, in quasi-equilibrium, back out of the material to the surface in an equal amount, from where they can be absorbed or desorbed again. Basically, moisture in the form of water molecules is distributed evenly by diffusion very slowly in the solid, but depending on the substance-specific moisture absorption of the respective material in the different layers. However, moisture migration into the PCB through pores and capillaries (capillary condensation) as is found in building materials (plaster, concrete, wood or masonry) does not occur in professionally manufactured PCBs.

„The driving forces of diffusion are of different types, whereby a distinction is made between diffusion in an isothermal and non-isothermal system. In an isothermal system the diffusion process is based on mechanical driving forces; these are partial pressure or concentration gradients. Since" … an electronic system…" cannot be understood as an isothermal system, another effect must be taken into account - the thermal diffusion effect (Soret effect). The diffusion driving forces here additionally result from a temperature gradient…. The diffusion coefficient is a material constant that depends on partial pressure, temperature and concentration. " [1]

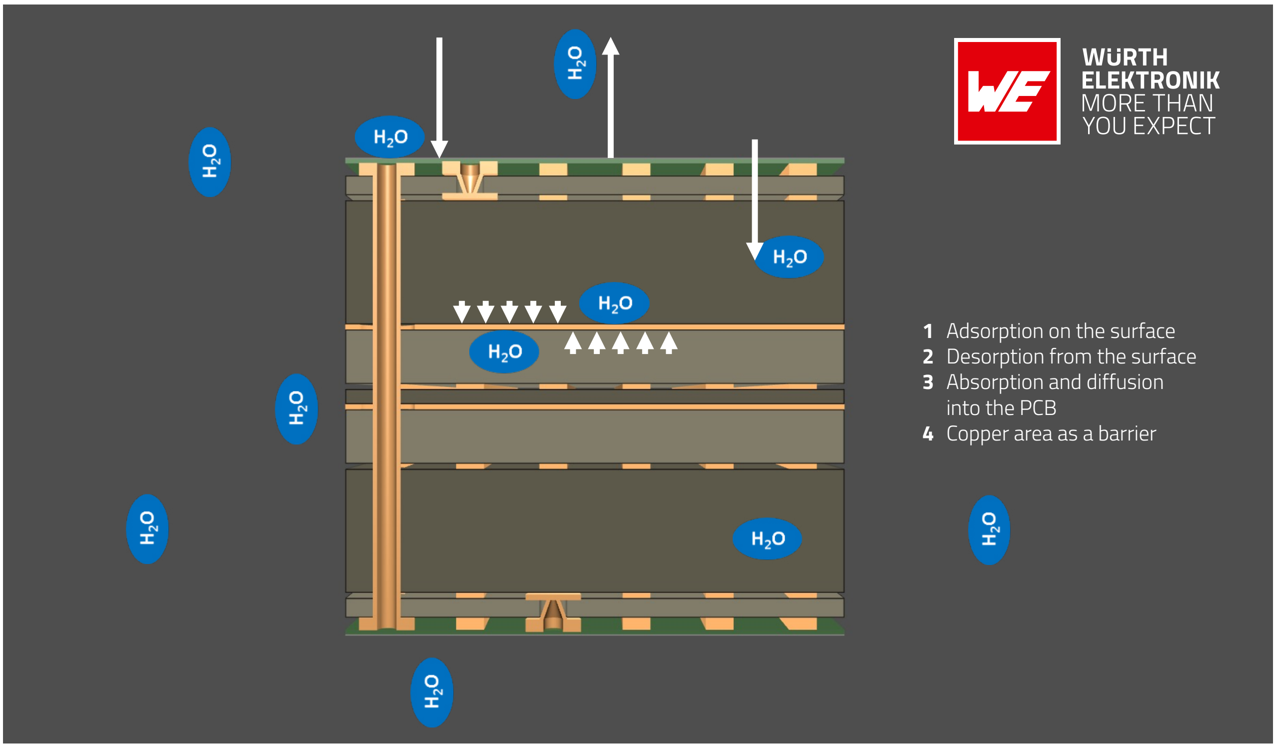


Figure 2: Moisture processes in the PCB - ambient air system

The diffusion rates of water molecules in a solid are very low, but can be increased by raising the temperature (Arrhenius law). Diffusion constants in resin are in the range of 10-8 cm^2/s. A change in pressure in the gas phase, for example by applying a vacuum, only has an effect at the boundary layer of the air - PCB phases, not inside the PCB. The diffusion rate in a solid cannot be influenced by this, but the desorption rate can.
Since the PCB consists of many different solid materials, there are many other boundary layers inside the solid. These become important further on under the aspect "Effect of moisture", chapter 4 (bonding processes and adhesive forces).

A special feature of these boundary layers is that moisture can preferentially accumulate on them. Due to their different nature and structure, the adjacent materials offer a certain "germination effect". This can have negative effects.

3.2. TARGETED CHANGES TO THE MOISTURE BALANCE

The Pressure Cooker Test (DIN EN 60749-33) is used as a material test or for accelerated simulation of environmental conditions. In the autoclave, hot pressure storage takes place in 100 % relative humidity at 121 ± 2 °C/ 202 kPa. This quickly detects weak points in terms of moisture resistance or signs of ageing in the material composite. High humidity and high pressure are the goal of this process.

To avoid damage during soldering processes, it may be necessary to dry PCBs in a suitable oven immediately before assembly. For drying, the moisture equilibrium must be shifted in the desired direction. Both equilibria described above must be considered:

- **Environment:**
The moisture content of the ambient air must be reduced so that the desorption rate becomes higher than the adsorption rate. This makes it understandable why a household oven, which is basically also suitable for steam cooking, cannot function for drying. Suitable drying equipment must have an exhaust air facility that allows or even promotes the escape of moisture from the drying chamber.

- **Drying material - PCB:**
A solid made of many different materials with boundary layers. The dimension thickness (z-axis) is small in relation to length and width. This ratio becomes crucial for the drying process if the diffusion path is obstructed in the z-axis.

FROM THESE CONSIDERATIONS WE CAN CONCLUDE:

➔

- For drying, both the moisture removal outside the PCB and also the moisture diffusion inside the PCB must be considered and influenced.
- Copper planes act as a diffusion barrier and can hinder moisture diffusion and therefore efficient dying.
- Different materials can exhibit different moisture absorption.
- Transitions from one material to another can form so-called boundary layers. Moisture can preferentially accumulate at such boundary layers.

4 MOISTURE IN PRINTED CIRCUIT BOARDS

4.1. WHEN ARE PRINTED CIRCUIT BOARDS DRY?

Strictly speaking, PCBs are never completely dry, i.e. without moisture. During the production of a PCB, it goes through many wet processes and is exposed to the humidity of the environment. Drying processes during production usually only aim to dry the surface for the subsequent process.

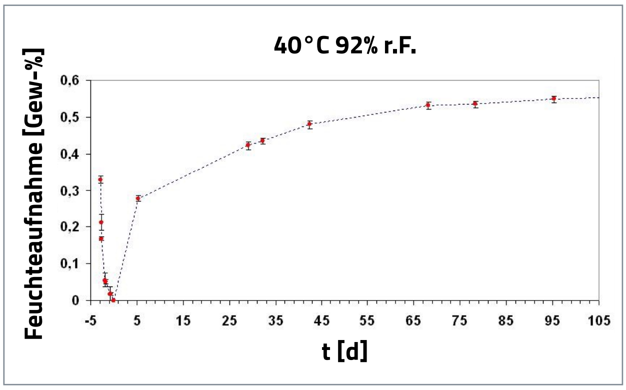


Figure 3: Drying and subsequent moisture absorption FR4 multilayer

From the production environment and processes, the PCB in the above example absorbed just under 0.2 percent moisture by weight. The dry weight was then determined by drying for 24 hours and then exposed to a humid climate.

If a PCB is dried in the right way, i.e. below the glass transition temperature Tg of the base material, there may still be a residual moisture bound in the epoxy resin that can only be removed above Tg [9]. On the other hand, a dried PCB also immediately absorbs moisture again as soon as it is removed from the drying equipment. Therefore, subsequent processes and their logistics must be perfectly coordinated with the drying process. Thin polyimide films have already reabsorbed most of the possible moisture after two hours!

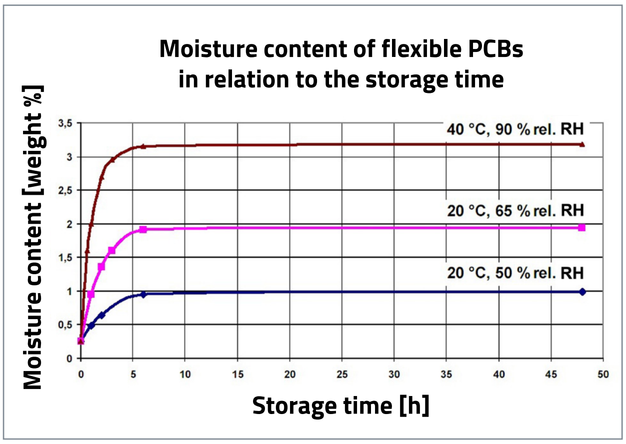


Figure 4: Moisture content of flexible printed circuit boards as a function of storage time, source: STN Atlas

4.2. MOISTURE MEASUREMENT

Moisture absorption, i.e. absorption of water, changes the weight of the PCB. This change in weight serves as a measure of the change in moisture content:

$$\text{Moisture absorption [weight \%]} = \frac{\text{weight (t=x days)-weight (t=0)}}{\text{weight (t=0)}}$$

- The dry weight is determined by drying for a long time until the point at which the weight practically no longer decreases.
- The maximum moisture absorption at certain conditions is determined by long humidification until the point at which the weight practically no longer increases

- Measurements are taken with a precision analytical balance, airflow must be eliminated because the weight differences are very small.

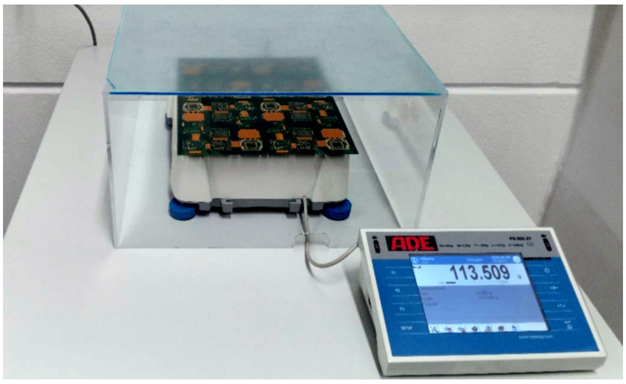


Figure 5: Precision fine balance with wind cover and test sample [12].

The following diagram shows the time periods over which moisture is absorbed even under extreme conditions, in this case a tropical climate of 40 °C and 92% relative humidity:

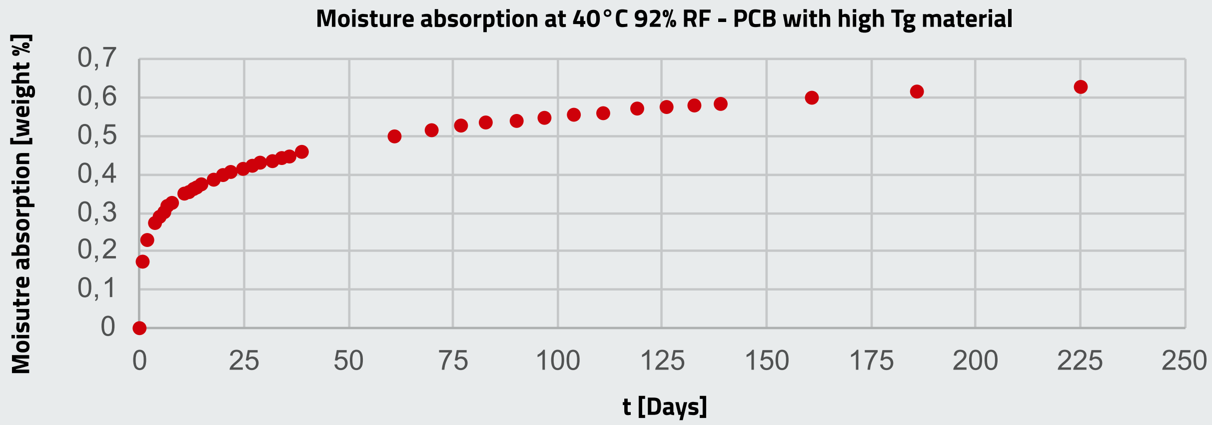


Figure 6: Typical course of moisture absorption over a long period of time

Even after half a year, moisture absorption is not yet complete, the moisture content is still increasing.

4.3. FACTORS INFLUENCING THE MOISTURE CONTENT IN PRINTED CIRCUIT BOARDS

THE AMOUNT OF MOISTURE ABSORBED DEPENDS ON MANY FACTORS:

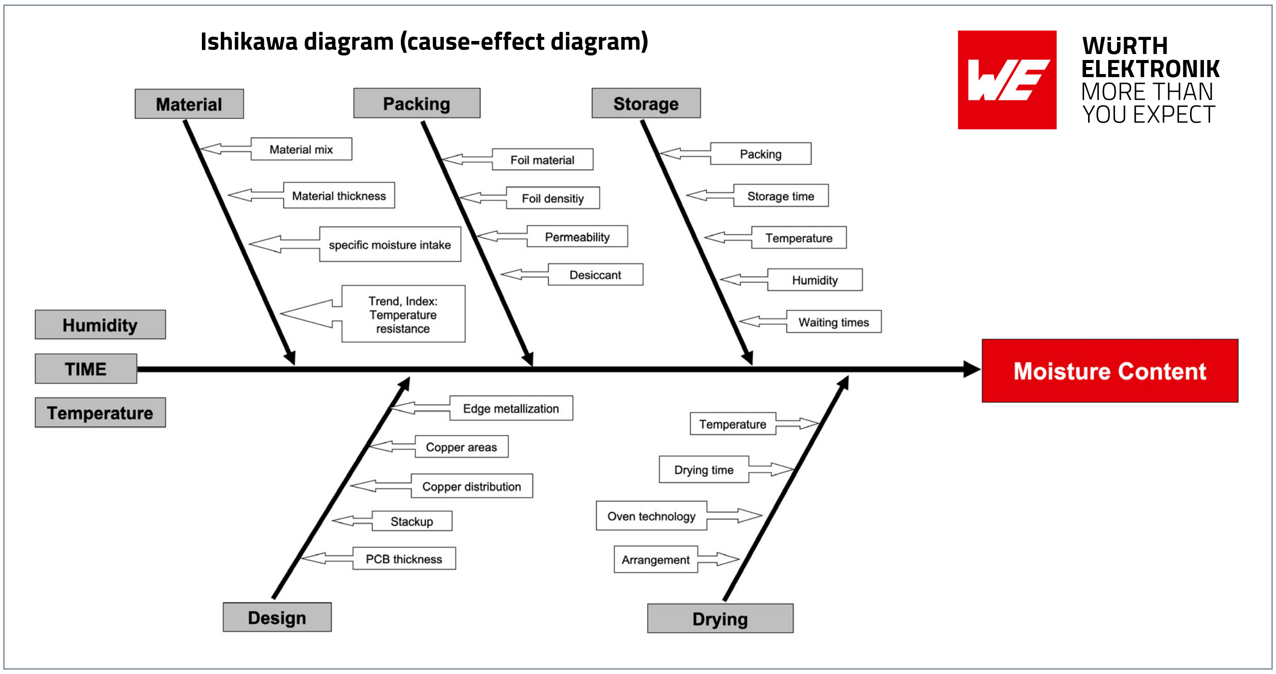


Figure 7: Ishikawa diagram (cause-effect diagram) "moisture content"

4.3.1. MATERIAL

In terms of moisture absorption and moisture permeability, the materials in a PCB differ, sometimes dramatically.

- Soldermask shows moisture absorption similar to epoxy and is not a barrier to moisture, it is virtually moisture transparent.
- Copper does not absorb moisture and provides a moisture barrier. However, a closed copper surface on the outer layers does not protect against moisture absorption - this is still possible via the open edges via longer pathways. For moisture absorption as well as for a drying process, a large copper surface always represents an obstacle, see also chapter 3.3.4 Layout.
- Plastics, such as the resins of the base material, vary greatly in moisture absorption, ranging from almost zero for LCP (Liquid Crystal Polymer) to approx. 0.4 percent by weight (wt.%) for standard epoxy to several percent by weight, for example for polyimide films. Different materials can be combined in a printed circuit board, for example in rigid-flex a combination of rigid base materials, flexible polyimide films and coverlays is used. The temperature resistance can be used as a first indicator for epoxy: Mid- and high-Tg materials typically show higher moisture absorption compared to Tg 135 °C epoxy.

- **Special feature of the material mix for flex and rigid-flex:**
  The more flexible layers and thus also adhesive layers and cover films are present in a multilayer structure, the higher the moisture absorption. The proportion of hygroscopic material is decisive for the amount of moisture and thus for the risk of damage if drying is not carried out or insufficient. It must also be taken into account that in flex-rigid PCBs the polyimide flex materials are also present in the rigid areas, i.e. they do not end at the flex-rigid transition, as is often erroneously assumed:

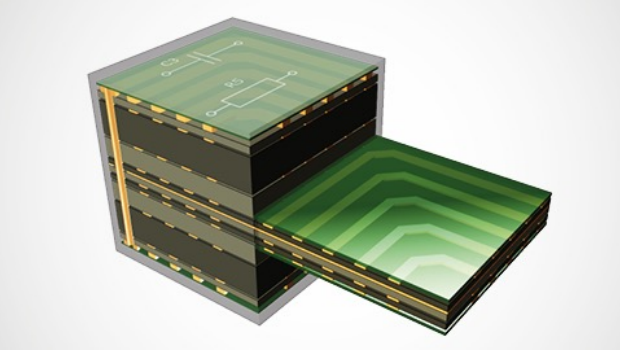


Figure 8: 3D representation of a rigid-flex printed circuit board with a 3Ri-4F-3Ri stack-up.

With internal flex foils, the diffusion distance in the rigid area to the surface is longer than with an external polyimide foil. Consequently, with rigid-flex printed circuit boards, the moisture critical outer flex foils dry faster.

- Fillers to achieve flame retardancy and a reduction in z-axis expansion.
- Reinforcing materials for the resins. Today, glass fabric is typically used, paper and aramid fibres are less common. The higher the glass content in a base material, the lower the resin content and thus the amount of absorbable moisture.
- Adhesive layers, for example acrylic or epoxy adhesive. Acrylic adhesives can absorb up to 4% moisture by weight, epoxy typically 0.3 to 0.5% by weight. These adhesive layers can be included in flexible base materials or multilayer constructions, in any case they are a constituent of coverlay and bondply films. Depending on the adhesive material used, rigid-flex or flex multilayers may behave differently in soldering processes. Basically, from this point of view
  - Adhesive-free flex materials are preferred
  - Rigid-flexible constructions with pre-pregs are cheaper than constructions with acrylic adhesive
  - Coverlays with epoxy adhesive or polyimide adhesive are preferable to those with acrylic adhesive.
- Depending on their properties, coatings or potting compounds can reduce moisture absorption.

The thickness of the PCB has an influence on the speed of moisture absorption.

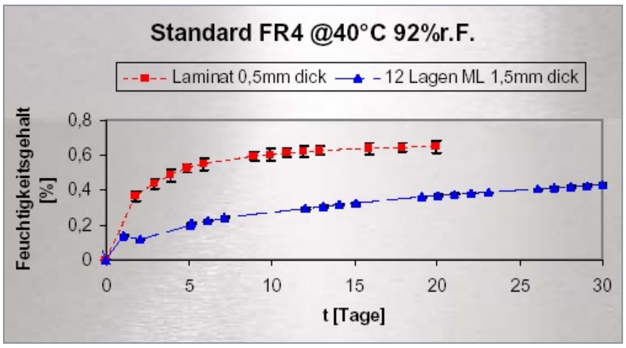


Figure 9: Moisture absorption with different material thicknesses

With increasing thickness, the diffusion lengths also increase, thus it takes longer to reach moisture equilibrium. When drying, it also takes longer for the moisture to diffuse to the surface and desorb.

The following diagram shows not only the influence of thickness but also that of resin quality:

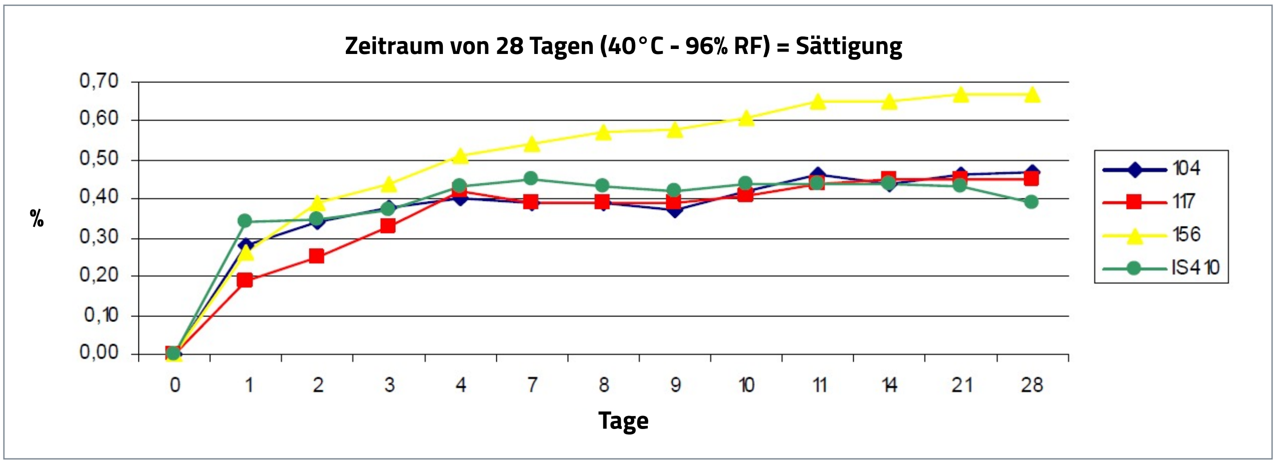


Figure 10: Moisture absorption of copper clad inner layers at different resin grades and thicknesses (0.2mm lower bundle of curves, 1.5mm upper bundle of curves), [15], modified

The curves „show the course of moisture absorption in an almost steam-saturated atmosphere (40 °C, 96% RF) over a period of 28 days. With the thin laminates of 0.2 mm thickness (fig. 1), weight constancy is almost achieved after 14 days and a weight increase of 0.4 to 0.7 %. In the case of laminates with a thickness of 1.5 mm (fig. 2), this is not fully achieved even after 28 days.

In a normal climate at 23 °C, 50% RF (no figure), the increase to constant weight remains limited to values between 0.25% and 0.35% for both material thicknesses. For the laminates of 1.5 mm thickness, saturation occurs after 3 months. " [15]

4.3.2. PACKAGING

The standard PCB packaging (PE shrink film) is not moisture-proof, and, in a similar way to solder resist, does not provide a barrier for moisture. Even additional packaging in a PE bag offers no protection against moisture absorption!

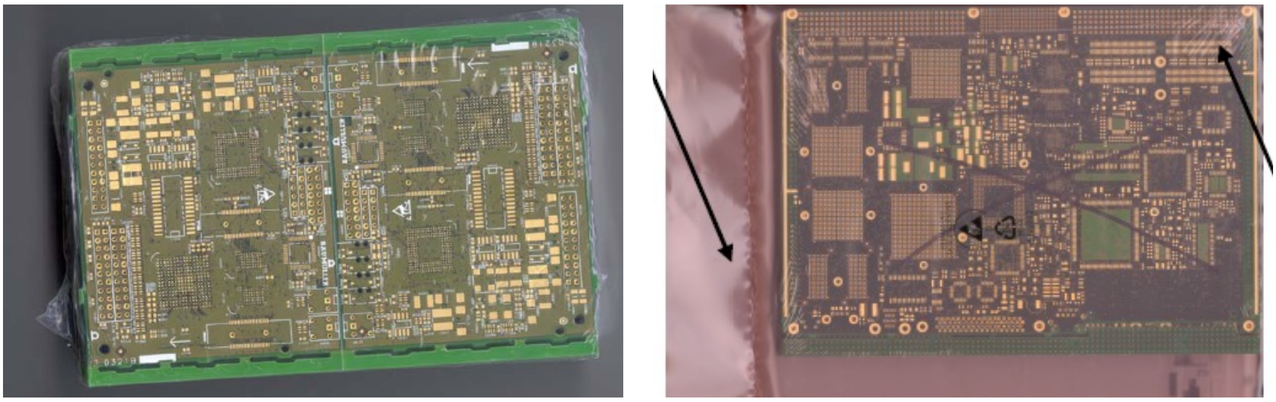


Figure 11: Packaged PCBs, left: in PE shrink film, right: in an additional 100µm thick PE bag.

Special packaging with aluminium coating and a defined MVTR value (Moisture Vapour Transmission Rate) is possible in principle, but is very costly in terms of time and material [9]. Damage to the MBB packaging (Moisture Barrier Bag) by the sharp PCB edges during transport must be reliably prevented through suitable measures. After opening the packaging and during any process-related waiting times, the dryness of the PCB must again be ensured through suitable measures.

For PCBs known to be moisture critical, such as flexible or rigid-flexible, the original packaging may be labelled as follows:

This is equivalent to MSL6 for components according to IPC/JEDEC J-STD-033, drying prior to further processing is mandatory.

4.3.3. STORAGE

If dry PCBs are exposed to a humid environment, a moisture equilibrium is reestablished. This process takes many weeks until saturation has occurred. In terms of humidity, it may make a big difference whether the PCBs are processed immediately after delivery or after half a year. Depending on the storage conditions, the PCBs may be considerably more humid or also drier if, for example, they are stored in a drying cabinet.

4.3.4. LAYOUT

Copper does not allow moisture to pass through, i.e. it is a moisture barrier. Copper surfaces therefore hinder the diffusion of water molecules during moisture absorption, but also during drying. While there is usually a lot of time available for moisture absorption, drying should go as quickly as possible. Therefore, it is essential to hatch copper surfaces or to provide them with openings so that the moisture can diffuse to the surface via a short route and does not have to take the long route over the edge, as is, for example, the case with full power/ground layers. The following investigation shows the correlation very clearly.

A test layout with different copper assignments A/B/C/D was examined as a double-sided PCB with a thickness of 1.6mm.

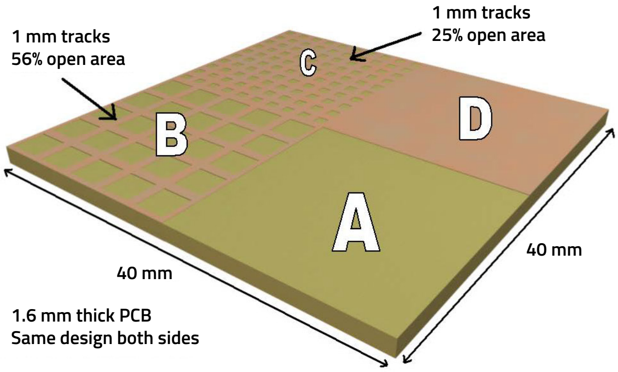
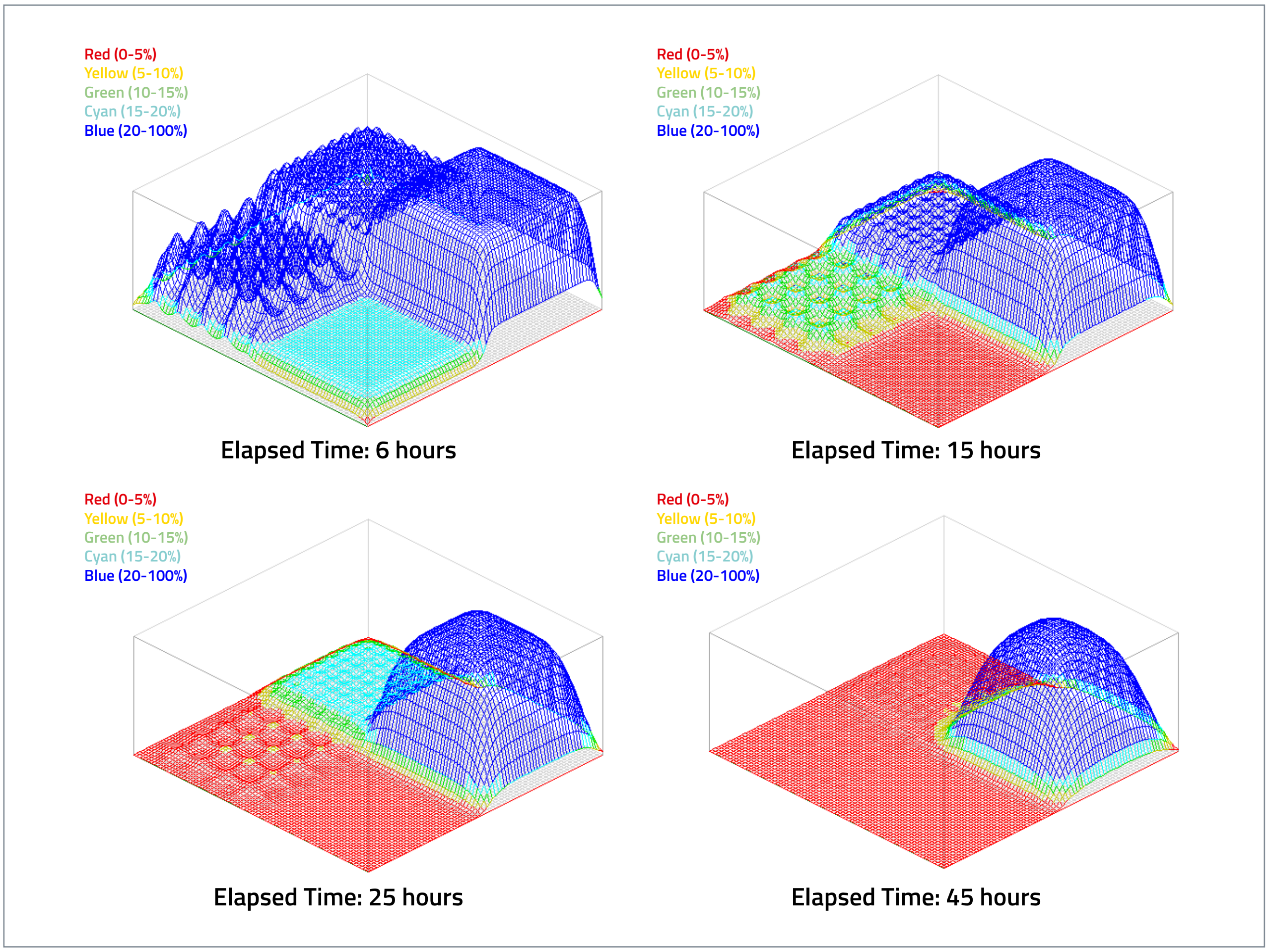


Figure 12: Layout with copper content A (0%) B (44%) C (75%) D (100%) on the top and bottom side [8].

After maximum moisture saturation, drying was carried out for 6/15/25/40 hours and the residual moisture was measured at 0.6mm depth in the 4 sectors.



Elapsed Time: 6 hours

Elapsed Time: 15 hours

Elapsed Time: 25 hours

Elapsed Time: 45 hours

Figure 13: Residual moisture in the PCB at 0.6mm depth after 6 / 15 / 25 / 40 hours of drying at 125 °C [8].

RESULT:

- Sector „A“ = pure base material without copper dries evenly and quickly. After 6 hours, less than 20% of the initial moisture is measurable.
- Sector „B“ with 44% copper coverage takes about twice as long.
- Sector „C“ with 75% copper coverage takes about four times as long.
- Sector „D“ with full copper covering dries only from the edges, even after 45 hours the moisture in the middle has only slightly decreased!

Such differences in copper coverage also exist in a single design. Power and logic areas, for example, can differ greatly, as the following example shows.

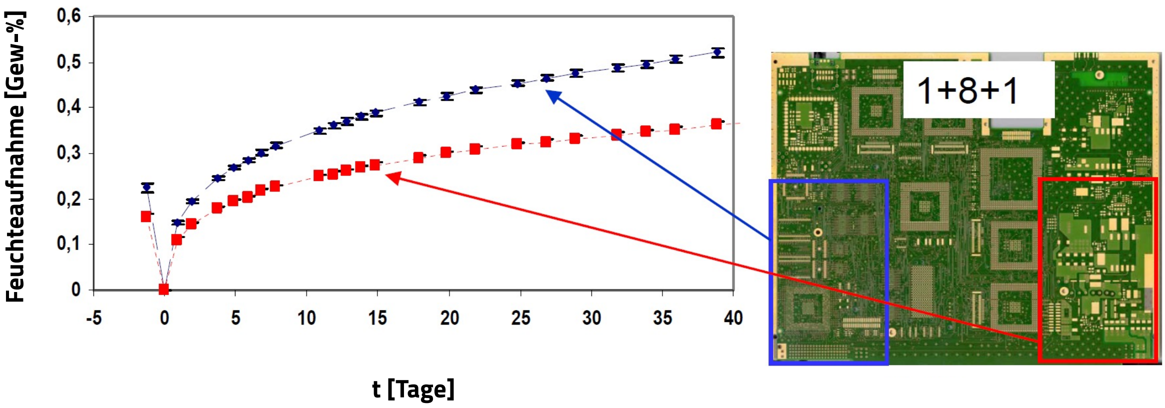
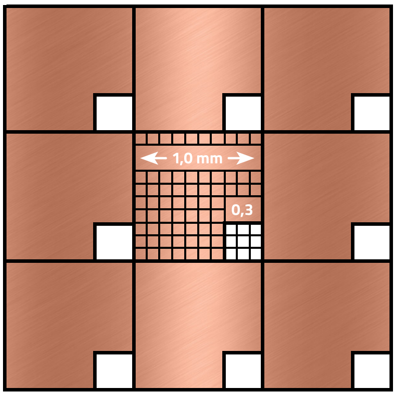


Figure 14: Moisture absorption on identical PCB at different locations [4].

The moisture absorption diagram shows that the red area with the higher copper coverage absorbed less moisture at the beginning of the experiment. After drying, the moisture absorption here was also significantly slower. However, if due to long storage sufficient time has passed until moisture saturation, drying must be continued in such a case until the red area is also sufficiently dry.

From a „design-for-drying" point of view, the following points thus arise:

- The largest contiguous copper area is the critical dimension for drying.
- Full copper layers without gaps should be avoided, even on inner layers.
- In the area of critical signals that require an undisturbed return current path on the reference layer, the openings can be removed accordingly or repositioned by the necessary amount.
- Even small openings in the copper represent diffusion channels for drying.
- Below is a design recommendation for copper openings from our design rules for rigid-flex: 0.3mm of 1mm copper length (up to 70µm base copper thickness):



4.3.5. DRYING

Drying is the reversal of moisture absorption. For this, the moisture in the material must diffuse to the surface, then be able to desorb from the surface. Since the diffusion rate is temperature-dependent, the PCBs are usually heated. For the drying process, see chapter 5.

5 EFFECTS OF MOISTURE IN PRINTED CIRCUIT BOARDS

Moisture leads to changes in the dielectric properties of the base material due to the dipole character of water. However, these influences will not be discussed further here. „Moisture absorption in the laminate causes the resin matrix to swell, which leads to a reduction in the glass transition temperature. Since swelling processes are reversible, the original glass transition temperature can be reached again after drying." [15]

„Moisture reduces the critical fracture toughness" and Young's modulus of polymers, favouring crack propagation. Likewise, the visco-elastic behaviour changes. [21]

Moisture in the PCB leads to damage, especially at high temperatures, with failure modes such as voids, delamination or cracks. The idea of a pressure cooker, for example during the soldering process, i.e. high water vapour pressures at high temperatures [4] above a liquid phase, does not correspond to reality.

Figure 15: Vapour pressure curve of water [3].

A water accumulation with a liquid/gaseous phase boundary or a change of the aggregate state from liquid to gaseous is only present if there are actually cavities in which the moisture could accumulate. In principle, however, the moisture is distributed in the form of water molecules in the polymer solid, depending on the moisture absorption of the respective material, but with accumulations at the boundary layers (see detailed explanation under chapter 2.1).

Moisture can thus be the cause of defect formation through outgassing or degradation of plastics: in the case of polyimide, it can lead to a deterioration of bonds through hydrolysis at the surface [5]. At boundary layers such as adhesive layers, the adhesive forces can be reduced, which can then also be the cause of delamination due to thermal stress and expansion.

5.1. CRITICAL MOISTURE LIMIT

Many PCB designs survive reflow soldering stresses without damage, whereby it should be noted here again that lowering the peak temperature by a few Kelvin already noticeably reduces the stress. Exceptions are generally critical designs and moisture-critical base materials, such as those used for flexible and rigid-flex PCBs. In such cases, the product- or design-specific critical moisture limit for the intended further processing should be determined by tests, see also chapter 6.4.

There is no generally valid critical moisture limit; it must be determined specifically for each PCB item. Basically, the following dependencies exist:

- Base material or base material mix used
- Layer structure for multilayer printed circuit boards
- Layout, i.e. copper design
- Soldering profiles and other thermal loads

If the determined critical moisture limit is exceeded, a controlled drying process is required before processes with high temperatures. IPC-TM-650 method 2.6.28 can be used to determine the actual moisture content.

The determination of a critical, product-specific moisture limit is only possible and makes sense if the copper design is suitable for drying. The measurement of moisture via the weight represents an arithmetic mean value as a result and makes no sense if moisture cannot escape at all under a large copper surface during drying, see chapter 4.3.4.

5.2. THERMAL LOADS

Due to the ban on lead and the change to lead-free soldering processes with higher soldering temperatures, the need for drying processes has noticeably increased even for „normal" multilayers made of FR4. The higher the temperature stress in the soldering process, the higher the risk of defects. This applies all the more to materials that are more sensitive to moisture or hygroscopic, i.e. that absorb more moisture than standard FR4. Examples are aramid fibres, high Tg FR4 or especially polyimide, as used in flexible and rigid-flexible printed circuit boards. For the latter, a dry PCB is mandatory before soldering, which is usually done by a drying process immediately before assembly.

Even small variations in the solder profile can, in borderline cases, be the difference between success or damage to the substrate. From this point of view, every well-intentioned „safety margin" in the soldering process must be regarded as critical. Thermal stresses also occur several times, depending on the type of assembly and further processing.

The following is an example of a possible combination of thermal stresses on a PCB:

a. Drying a peelable solder resist
b. Drying the PCB before the soldering process, e.g. 4 hours at 120 °C
c. 1st PCB preheating at 180 °C + reflow soldering at 230-250 °C
d. Adhesive curing for 2-sided SMD assembly
e. 2nd PCB preheating at 200 °C + reflow soldering at 230-250 °C
f. Wave soldering at 250-270 °C
g. Partial selective wave soldering
h. Rework (possibly hand soldering, particularly critical)
i. Repair soldering (possibly hand soldering, particularly critical)

At this point, it must be especially pointed out that sufficient dryness must also be ensured for rework and repair soldering processes. Usually the PCB has spent a lot of time in less than optimal (i.e. dry), ambient conditions up to this point. It may well have absorbed more moisture than an unassembled PCB in its as-delivered state after production.

Significant temperature increases in a material mix, which always occurs in every PCB, lead to stresses due to different thermal expansions. There is therefore a mismatch of the expansions, also called „CTE mismatch“ (CTE = Coefficient of Thermal Expansion). By reinforcing the epoxy resin with glass fibre fabric, FR4, for example, is well matched to the expansion of the copper in the x/y plane, but not in the z-axis. Here, the copper barrel of a metallised hole is subjected to strong stresses, for example during the soldering process. The stronger the mismatch and the higher the soldering temperatures, the higher the thermo-mechanical stress. This also affects the boundary layers.

5.3. FAILURE MODES

THE FOLLOWING ARE SOME TYPICAL MOISTURE-RELATED FAILURE MODES.

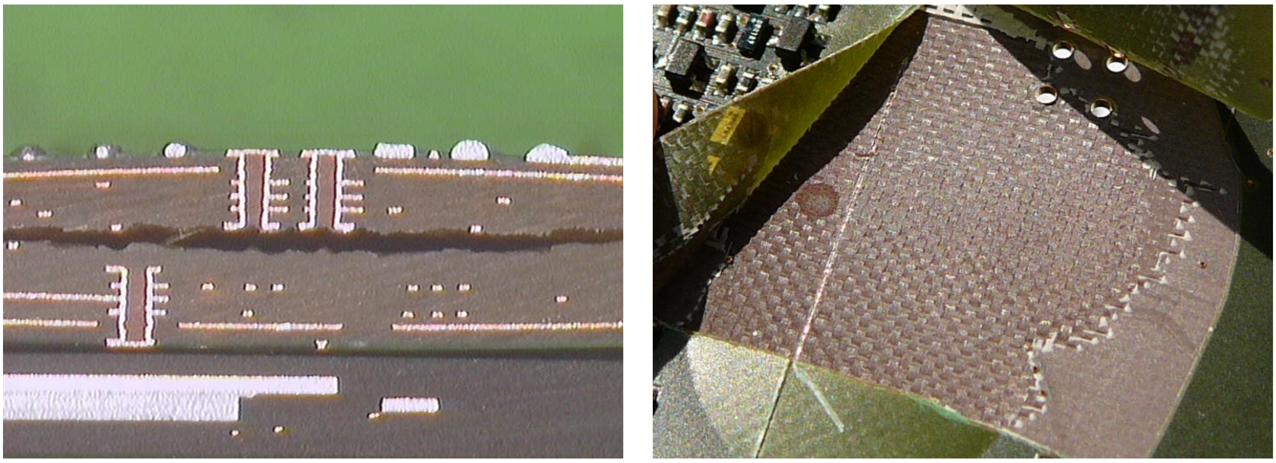


Figure 16: Massive delamination between two „sub-stacks“ (left), open blister (right)

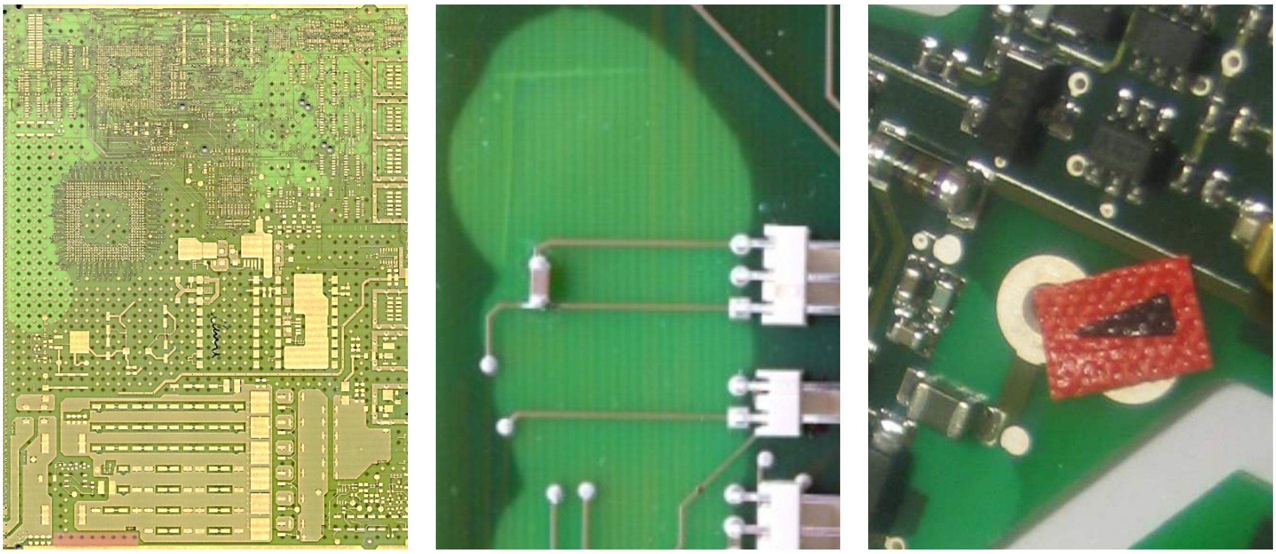


Figure 17: Light areas indicate possible delamination

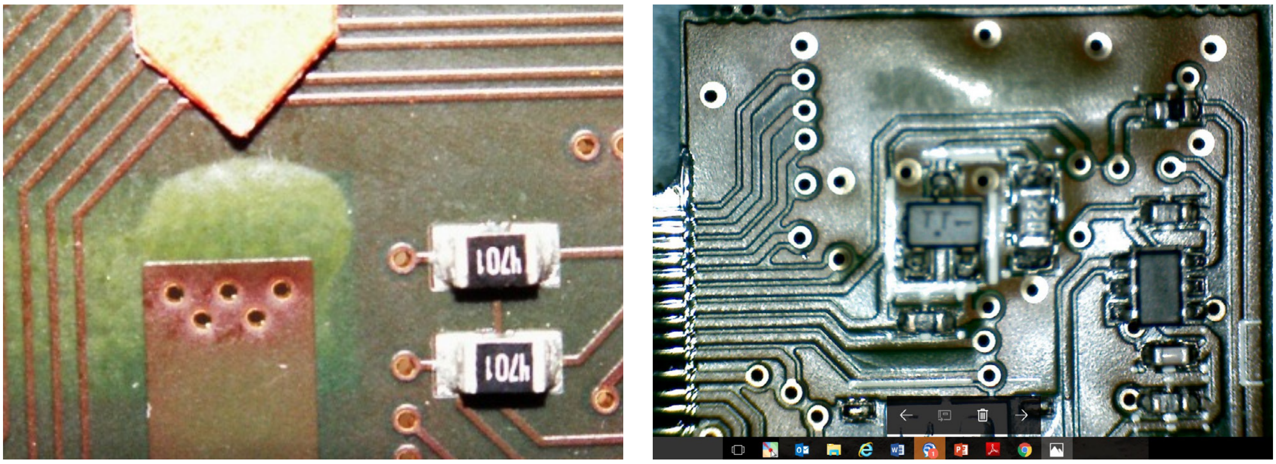


Figure 18: The large copper surfaces are certainly not entirely without blame in relation to these delamination blisters

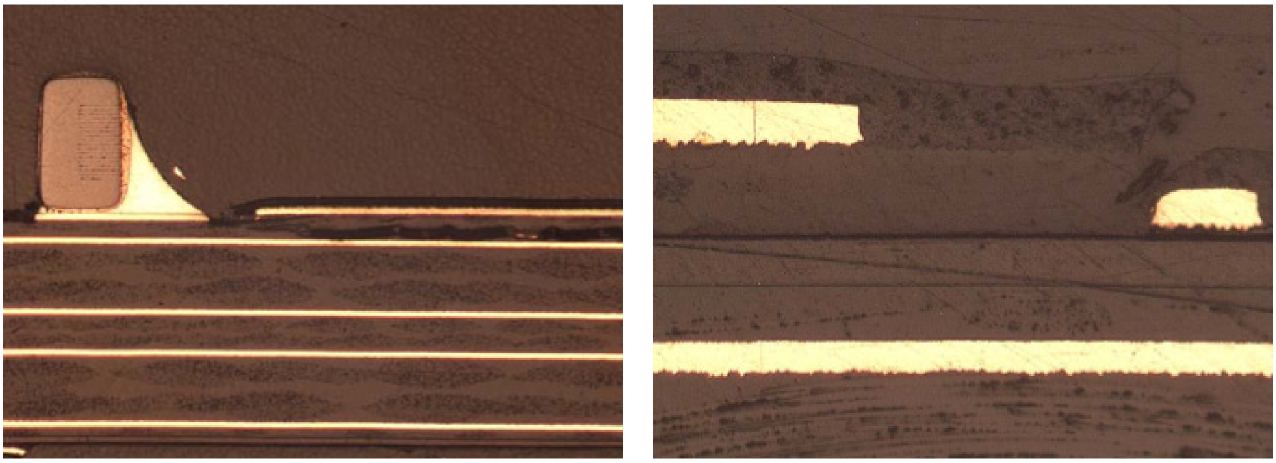


Figure 19: Separation in the material composite – pre-preg (left) and adhesive-based outer layer flex (right)

Round, light, bubble-like geometries are an indication of damage to the material bond. There is a material separation, which usually runs along the boundary layers.

6 THE DRYING PROCESS

For a drying process, both the moisture removal outside the PCB and the moisture diffusion inside the PCB must be considered and influenced.

There are different types of drying equipment, which are presented in detail below (chapter 6.2). Reduced to the physical relationships, all drying processes differ only in the following parameters:

- **Temperature** and temperature transfer to the dry material. The temperature has a great influence on the diffusion speed in the PCB.
- **Humidity** and possibility of dehumidification. The lower the humidity in the drying room, the higher the desorption rate from the surface of the PCB. The lower the moisture content absorbed by the PCB, the faster the critical moisture content can be undershot.
- **Time**, i.e. necessary drying time. The drying time is the result of temperature and humidity in the drying process.

6.1. DEFINITION OF DRYING AND TEMPERING

We understand „drying" to mean the removal of moisture, while „tempering" stands for „heating the material with increased temperatures", „a process to change the material properties of solids. In printed circuit board technology, tempering is used ... to reduce internal stresses, which are manifested in warping and twisting" [2]. For tempering temperatures above the glass transition point Tg of the resins must be selected, while drying usually takes place at lower temperatures below Tg.

In English, the term „BAKING" (for example IPC-1602) or „Pre-Bake" is also common.

➔ **Drying Temperature < Tg (Resin System) < Tempering Temperature**

6.2. EQUIPMENT

Regardless of the drying process, great attention must be paid to cleanliness, because contamination such as condensate deposits in the baking oven can deposit on the PCB surface and unnecessarily deteriorate the solderability of the surfaces in a noticeable way.

6.2.1. CIRCULATING AIR DRYING CABINET

The forced convection drying oven has both good heat transfer to the material to be dried and good moisture removal from the surface of the material to be dried, provided this is accessible. Because of the fast heat through, these units are very efficient and are used for both drying and tempering. With fresh air supply and guided exhaust air, the moisture content of the air can be kept low. IPC-1602 3.4.2, a maximum of 5% RH is permissible.

The following diagram shows the normalised representation of drying curves of identical PCBs at different temperatures in a circulating air drying oven:

There is a major difference between 80°C and 125°C. A further temperature increase to 150°C brings practically no improvement, but greatly increases the temperature load. A fundamental disadvantage is the risk of deformation of the PCBs at such high temperatures. „Drying at 130°C caused warping in all types of PCBs...“ [13]. More on this in chapter 5.5. Another disadvantage is that the PCBs have to cool down after removal from the hot oven before they can be transferred to the assembly machines.

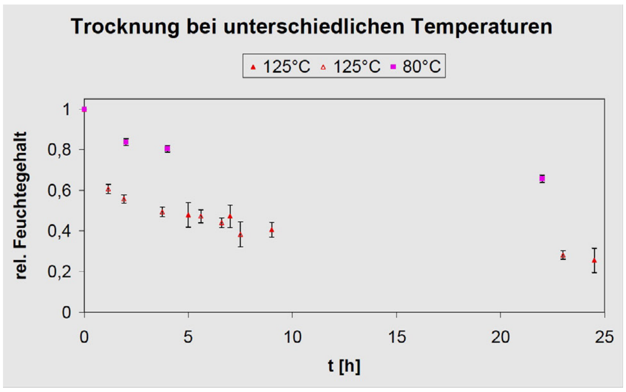


Figure 20: Drying curves at different temperatures [8].

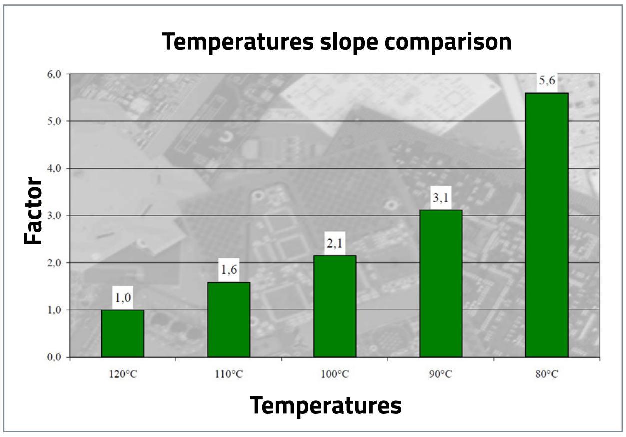


Figure 22: Comparison of drying time factors at different temperatures [6].

Figure 21: Example of a small circulating air drying cabinet [7].

6.2.2. VACUUM DRYING OVEN

Vacuum only takes effect when the water molecules are at the surface. In this respect, diagrams showing low boiling points of water when pressure is reduced are misleading because this "pot of water" does not exist. At best, the vacuum leads to a higher desorption rate.

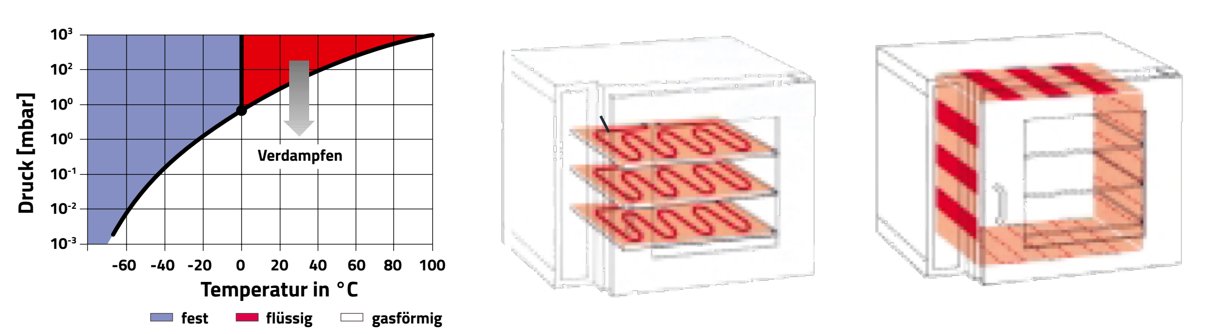


Figure 23: Boiling point reduction by vacuum, plate and jacket heating (from left to right) [7].

Heating the material to be dried in a vacuum is more difficult: jacket or plate heaters are necessary, heat transfer by convection cannot take place on principle. A process with alternating heating and vacuum phases is also possible. A disadvantage, is the high cost of the complex vacuum technology; an advantage is the avoidance of oxidation in the vacuum, which protects the soldering surface and material.

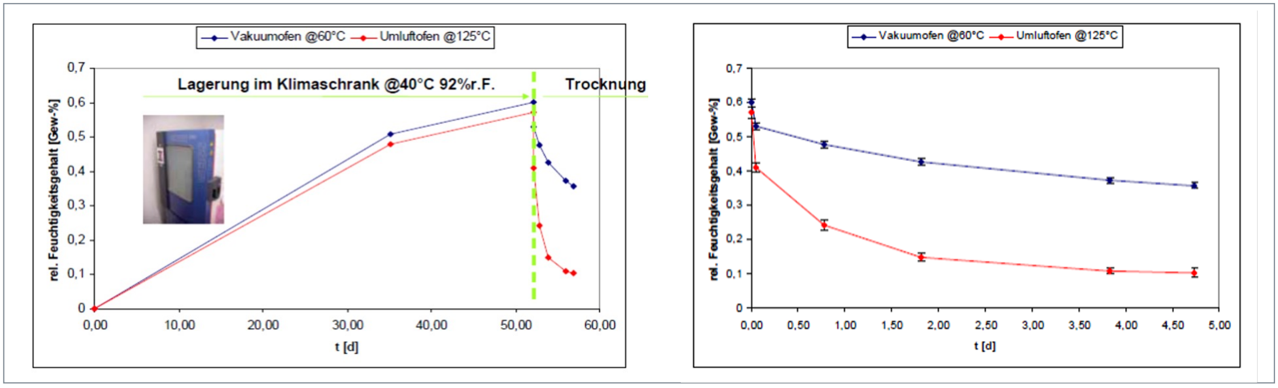


Figure 24: Comparison of drying with vacuum versus circulating air of unclad FR4 1.5mm thick

The lower temperature in the vacuum oven is directly reflected in slower drying. Only an increase in temperature to also 125 °C leads to similarly fast drying, whereby the weight loss is lower in the first hours, which should be due to the slower heating of the material to be dried in the vacuum.

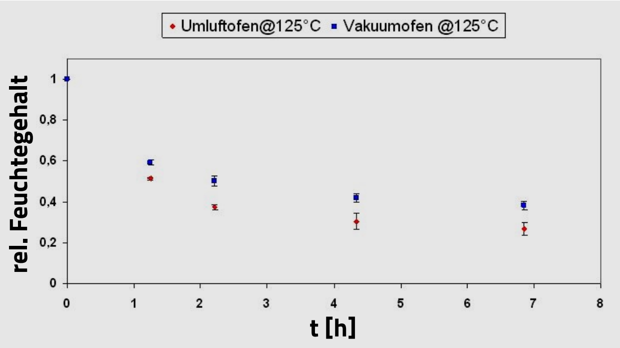


Figure 25: Comparison of vacuum with circulating air at 125 °C

6.2.3. DRY STORAGE CABINET

Dry storage cabinets dehumidify the air in the cabinet using desiccants. Various humidity levels, e.g. 10 / 5 / 2 / 1% RF, can be set via the control. Continuous operation is possible through automatic regeneration of the desiccant. Advantages are the low operating costs and the lack of temperature stress. This means that printed circuit boards can also be stored in the dry cabinet in their original packaging.

If necessary, the temperature can be increased to 45 °C or 60 °C, which results in a significantly faster drying (higher diffusion speed and higher desorption rate).

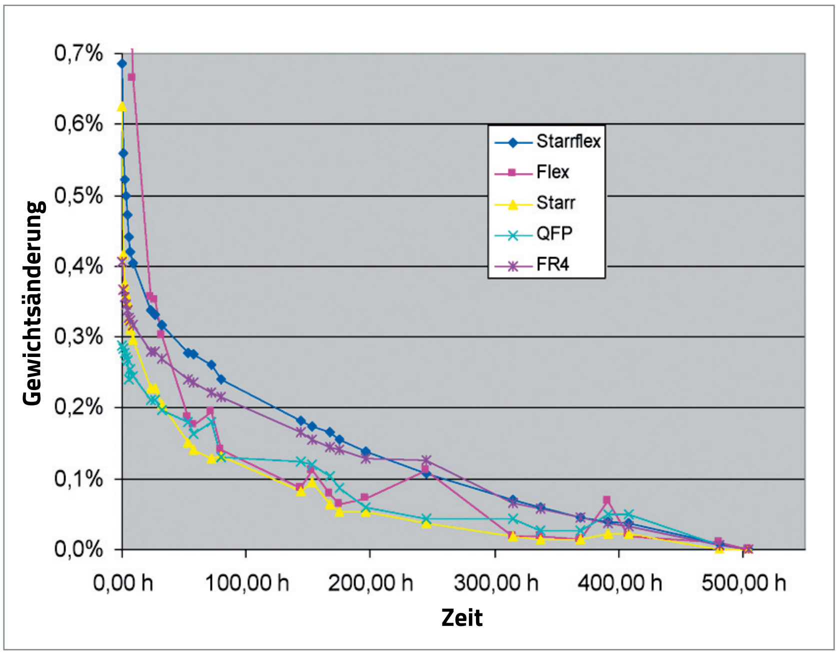


Figure 26: Drying curve in the drying storage cabinet, 45 °C/<1%RH after saturation in 85/85 climate [13].

Figure 27: Example of a dry storage cabinet [8]

The drying efficiency is described by one manufacturer for FR4 as follows [8]:

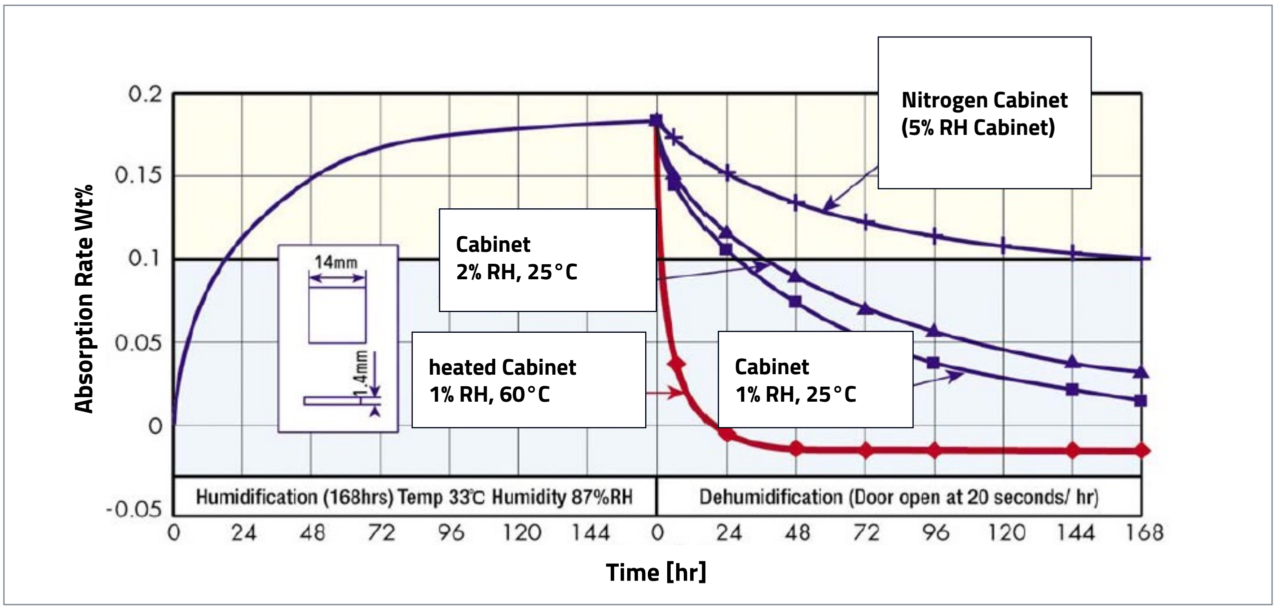
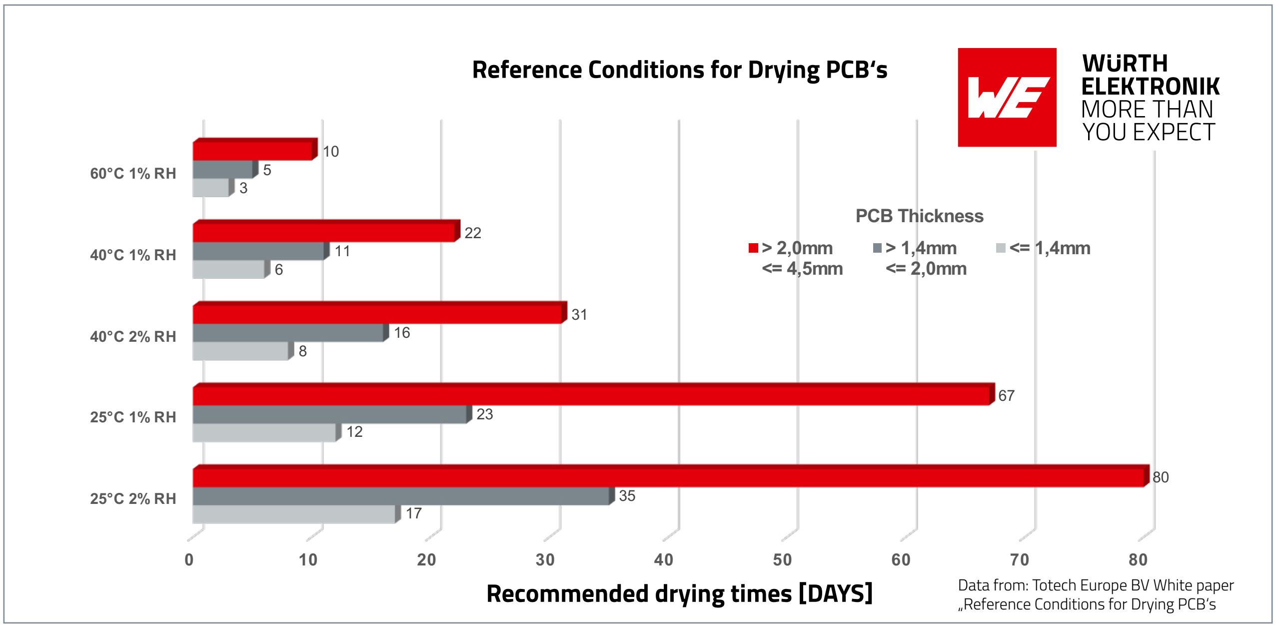


Figure 28: Drying of FR4 1.4mm thick in the dry storage cabinet [8].

The graph shows a few interesting aspects:

- Nitrogen storage (nitrogen cabinet) is unsuitable for drying printed circuit boards.
- The level of humidity in the drying storage cabinet has an influence on the desorption rate.
- As expected, the temperature shows a great influence via the higher diffusion rate.
- The samples were not dried before humidification. The dry weight is therefore lower than the initial weight, the moisture content is negative.

Finally, there is a graph created by the author based on data from Totech Europe BV:



Data from: Totech Europe BV White paper
„Reference Conditions for Drying PCB's

Please note that the times for drying are in the measurement unit "days"!

6.3. COMPARISON OF OVEN TYPES AND CONCLUSION

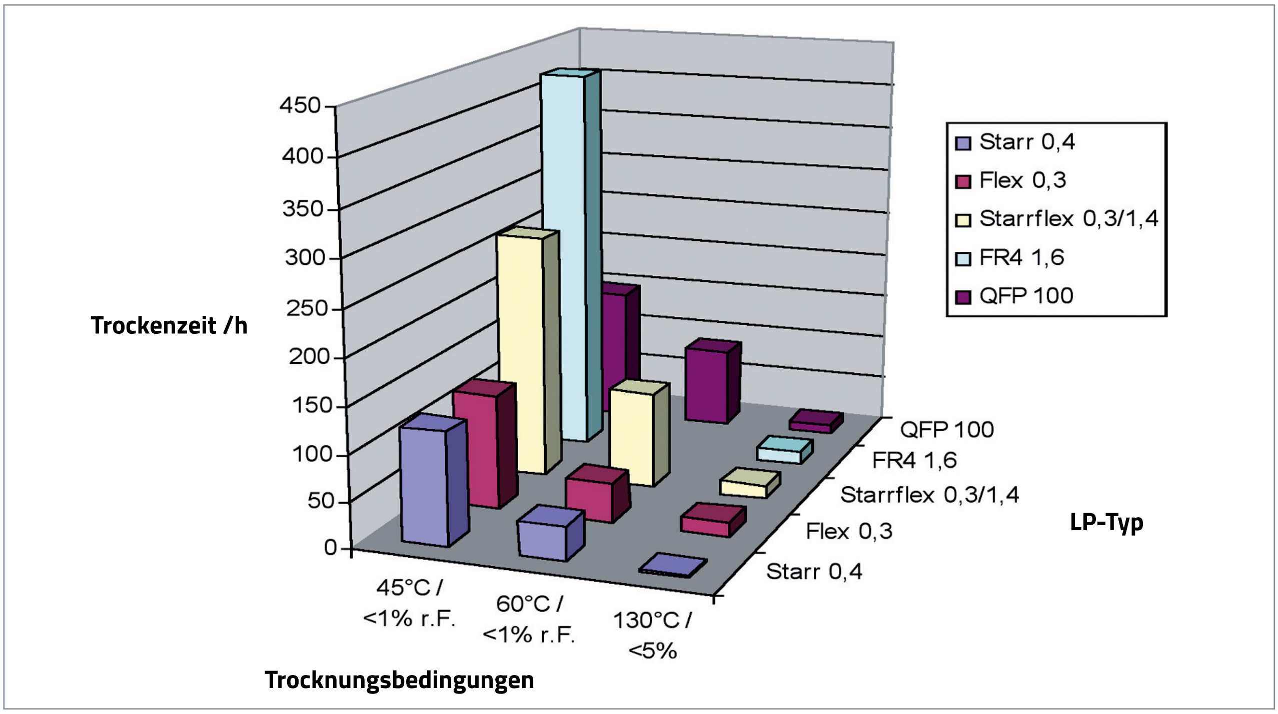


Figure 29: Comparison of drying times at different drying temperatures [13].

In the introduction of the individual oven types, many features, performance differences and parameters have already been outlined. Lastly, there is a final comparison between the two preferred drying methods, the circulating air drying cabinet and the dry storage cabinet.

„Drying of four different types of PCBs in the dry cabinet (correct: „dry storage cabinet", editor's note) and in the oven (correct: „circulating air drying cabinet „, editor's note) show that the three methods of PCB drying at 45 °C/<1%RH, 60 °C/<1%RH and 130 °C/<5%RH have a clear systematic staggering of drying time according to PCB thickness and drying conditions." [13]

IN CONCLUSION, IT CAN BE SUMMARISED:

- Due to the low diffusion speeds in the solid state PCB, the temperature influence of the preheating in the soldering process is not sufficient for drying.
- Climatic test chambers, vacuum ovens and nitrogen storage chambers are not suitable for a drying process suitable for series production and have high maintenance costs associated with them.
- Drying in a circulating air drying cabinet at 120 °C is very efficient and fast, but places a high thermal load and ageing on the solder surface. The risk of deformation of the PCBs also exists and must be taken into account when arranging the PCBs in the oven, see later.
- The dry storage cabinet is „...well suited for the gentle drying of components." [13]. This also applies to printed circuit boards. However, longer drying times must be planned for. The dry storage cabinet is also the first choice for bridging waiting times for goods that have already been dried.

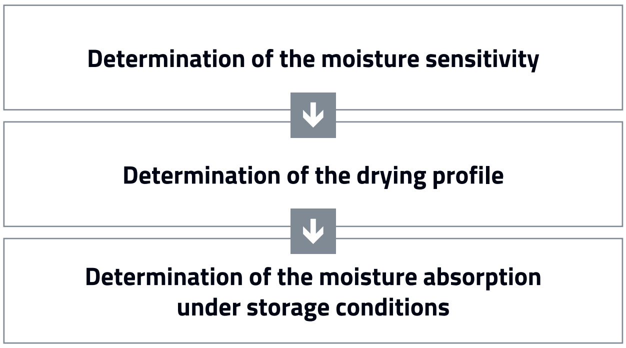
6.4. DRYING PARAMETERS

Drying parameters depend on many factors, as already explained. The PCB design and the history of the PCB's "moisture life" play a role.

- How much moisture has the PCB absorbed?
- What dehumidification must take place so that the following temperature stress does not cause damage?
- What are the drying properties of the base material or material mix used?
- What does the PCB design look like in terms of moisture absorption and dehumidification?
  - PCB thickness
  - Placement and size of copper planes, also reference planes
  - Power and ground layers
  - Edge plating
- What time without moisture protection is permissible?

Drying parameters from PCB manufacturers can only be understood as reference values or rough recommendations, because both the design influences and the specific ambient, drying and soldering conditions with the associated logistics play a decisive role and are usually not even known to the PCB manufacturer.

Consequently, product-specific drying parameters must be determined by the PCB assembler via the following process:



6.4.1. DETERMINATION OF THE MOISTURE SENSITIVITY

First, the moisture content at which a PCB is damaged in a particular soldering process is to be determined. IPC-1601A 3.3.6: The sensitivity of a particular design to moisture-induced delamination may be characterized by thermal stress testing. The preferred method for thermal stress testing is IPC-TM-650 test method 2.6.27. Additional reflow cycles may be specified, or samples may be cycled through thermal stress to the point of failure to provide useful data or validate design margin. For most designs, the maximum acceptable moisture content, or MAMC, will be between 0.1% and 0.5% of moisture weight to resin weight.

At this point, it should be expressly pointed out once again that a suitable copper layout is a prerequisite for drying. Large copper surfaces must be made permeable to moisture through copper openings, see also Chapter 4.3.4.Layout.

6.4.2. DETERMINATION OF THE DRYING PROFILE

Layout-specific drying parameters can be defined by determining drying curves. For this purpose, the PCBs are saturated with moisture and then dried in a controlled manner until the weight no longer changes and the PCB is „bone dry". It is important that the parameter determination takes place using equipment that is both suitable and planned for the series production. The drying parameters should be selected in such a way that they meet the requirements of the material and the production. Among other things, the ageing of the soldering surface must be taken into account.

6.4.3. DETERMINATION OF THE MOISTURE ABSORPTION UNDER STORAGE CONDITIONS

Starting from a "bone-dry" PCB, it is determined how quickly a PCB absorbs moisture. The IPC-TM-650 method 2.6.28 can be used for this purpose. When interpreting the results, it should be noted that moisture is not absorbed by copper or glass fibres. The moisture content in the resin can therefore only be calculated if the weight of copper and glass fibres is known and subtracted from the weight.

The determined absorption rate is used to specify the maximum time that the PCBs may be processed or stored unprotected. A common recommendation is a maximum of two hours.

6.4.4. A NOTE ON TEMPERATURE

Investigations have however also shown that with epoxy a certain amount of moisture can only be expelled above the Tg of the base material. [9] According to our definition, see chapter 5.1, we no longer speak of drying but of tempering. Since this is chemically bound moisture, it does not play a role with regard to the sensitivity described in 6.4.1.

6.4.5. DRYING TIME, BREAKS, WAITING TIMES

In manufacturing practice, neither the actual humidity nor the dry weight of the PCBs are available. Through the process described above in the course of series qualification, the required drying times can be determined for daily manufacturing practice, taking into account the ambient conditions and the processes and process flows of the respective production.

Ensuring that damage is avoided during the soldering and temperature processes is thus ensured by adhering to the specified drying processes and production sequences. This also includes the time for breaks and waiting periods during which the PCBs are unprotected from moisture.

6.5. ARRANGEMENT OF THE CIRCUIT BOARDS IN THE DRYING OVEN

In addition to the drying temperature and time, the arrangement of the material to be dried, i.e. the PCBs in this case, is an essential parameter for the drying efficiency. If boards are dried in a stack, it takes longer for the ones inside to reach drying temperature. As a result, the degree of drying decreases the deeper the PCB is situated in the stack. The variation in the quality of the soldering result can be correspondingly large, from „OK" to „extensively delaminated". The drying parameters in the stack are determined by the central specimen.

If, on the other hand, panels are dried individually standing upright in a slotted carrier board, then each panel can be heated quickly and also desorption can take place in an optimal manner: the drying is more efficient.

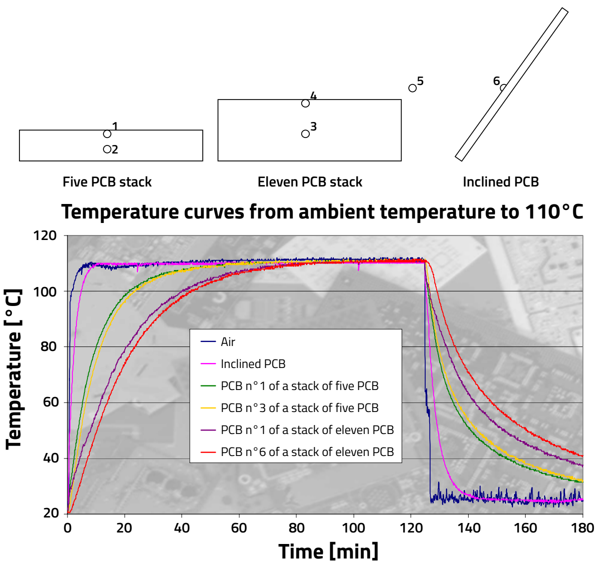


Figure 30: Temperature curves for stacks of 5 / 11 or individually in a slotted carrier board [6].

The higher the stack and thus the thermal mass of the stack becomes, the slower the entire stack heats up. Interestingly, the temperature differences between the inner and outer specimens are quite small.

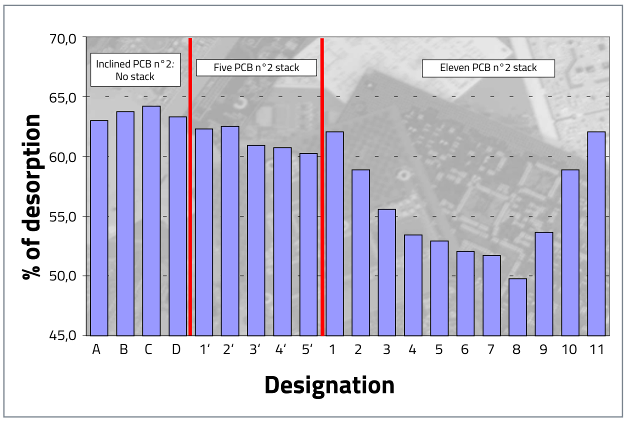


Figure 31: Degree of dryness in a slotted carrier board or in stacks of 5 / 11 [6].

The drying efficiency in the stack of 5 is slightly lower than individually in the slotted carrier board, but the result is similarly uniform. In the stack of 11, however, there are large differences within the stack, a correspondingly long process duration would be the consequence in order to also dry the inner laying specimens sufficiently and to achieve a uniform result.

The risk of deformation at high temperatures has already been mentioned. Here are a few examples to illustrate this:

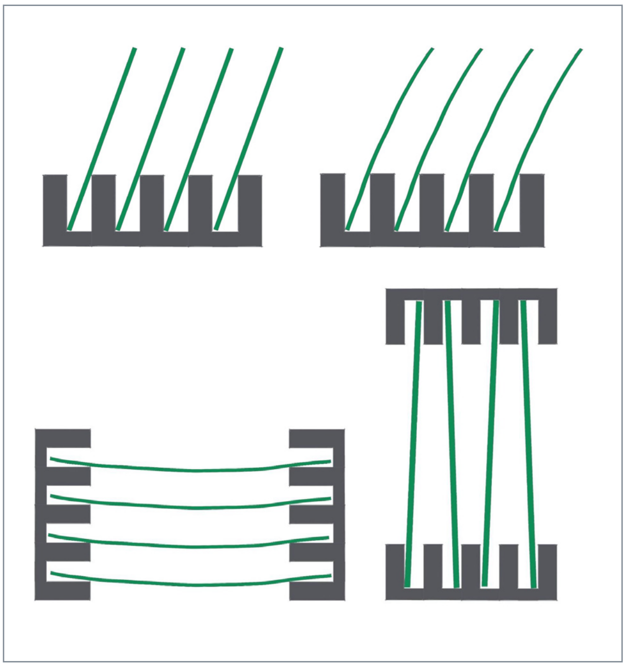


Figure 32: Various fanned arrangements, some risk of bowing [12].

From a series production point of view, stack drying should be considered, but some points must be taken into account [12]:

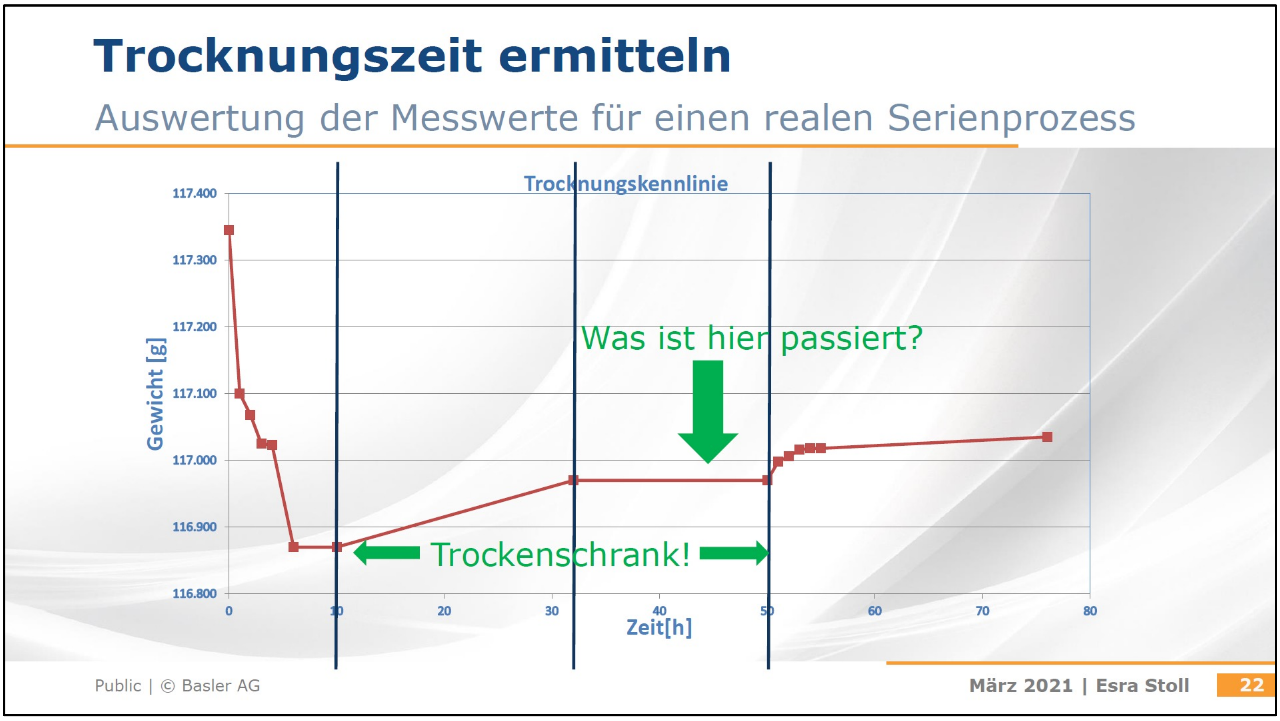
- Even drying through?
- No “transfer printing” between the PCBs?
- Labels (adhesive bleeding?)
- Surface scratches?

6.6. A PRACTICAL EXAMPLE

Mr. Esra Stoll, from the company BASLER, gave a presentation in a FED webinar on 10 March 2021 on the subject of "Handling Rigid-Flex, a user report", see also source [12]. Thankfully, I have the presentation and am permitted to quote from it!

BASLER processes rigid-flex printed circuit boards with a 3Ri-2F-3Ri structure in large quantities and has developed a drying process suitable for series production.

- Determining the drying time
  - Moisture penetration of the PCB panel
  - Logged drying in a circulating air drying cabinet at 120°C
  - Remove, weigh and record: every 30 minutes
  - Until no weight loss is measured several times in a row.
- Storage in dry storage cabinet, 5% RH, logging. After reaching equilibrium, removal.
- Determination of moisture absorption in the production environment
  - Weighing and logging: every 30 minutes
  - Determination of the MSL



Trocknungszeit ermitteln

Auswertung der Messwerte für einen realen Serienprozess

Was ist hier passiert?

Trockenschrank!

Public | © Basler AG

März 2021 | Esra Stoll

22

Figure 33: Moisture content throughout the drying processes [12]

Due to the prevalent humidity of 5%RH in the dry storage cabinet, the „bone-dry" PCBs first reabsorb some moisture, this takes a little more than 30 hours to reach equilibrium.

BASLER derived the following drying process from the measured values:

- Drying in circulating air drying cabinet @120 °C: 4 hours.
- Transfer to drying storage cabinet @23 °C without cooling.
- Processing from the drying storage cabinet at 5%RH is possible.
- The PCBs may be processed unprotected for two hours. If processing is not possible within two hours, the PCBs must be temporarily stored in the dry storage cabinet.
- A reflow pass resets the time to zero.
- Production is organised like a kanban: as soon as there is space in the drying storage cabinet, the goods are delivered and dried again.

The drying process is used for more than 50 different rigid-flex designs with similar layer stacks and profiles, and is stable over a long time with different supply batches and suppliers.

Abbildung 34: Serial process drying stage 1 in the circulating air drying cabinet at BASLER [12].

The following table shows a uniform drying:

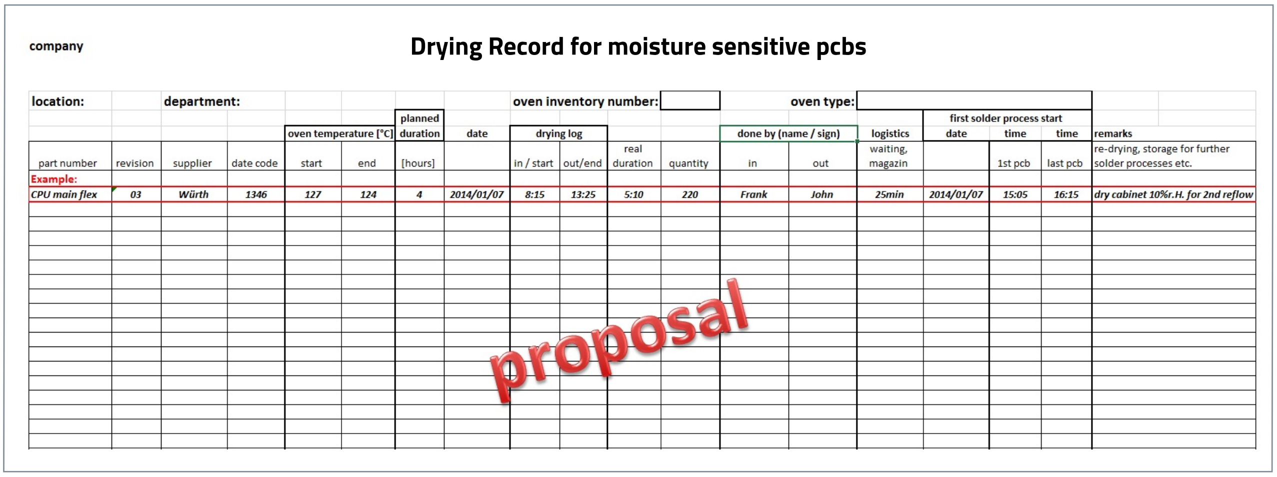
Zeitpunkt	Top [g]	Middle [g]	Bottom [g]
After opening	122.106	123.556	121.709
09:45	122.125	123.577	121.728
13:50	121.816	123.246	121.410
Delta 4 hours	0.309	0.331	0.318
Weight loss	0.253%	0.268%	0.261%

Figure 35: Drying data in the stack, company BASLER [12 , translated].

6.7. LOGISTICS IN THE DRYING PROCESS, DRYING RECORD

Waiting times should be kept as short as possible, ideally a maximum of two hours.

It is recommended to keep a record at least for the establishment of the drying process. This makes it easier to find the causes of abnormalities. The following is a suggestion for a drying record.



company

Drying Record for moisture sensitive pcbs

location:		**department:**						**oven inventory number:**					**oven type:**					
						planned									**first solder process start**			
				oven temperature [°C]		**duration**	**date**	**drying log**				**done by (name / sign)**		**logistics**	**date**	**time**	**time**	**remarks**
part number	revision	supplier	date code	start	end	[hours]		in / start	out/end	real duration	quantity	in	out	waiting, magazin		1st pcb	last pcb	re-drying, storage for further solder processes etc.
Example:																		
CPU main flex	***03***	***Würth***	***1346***	***127***	***124***	***4***	***2014/01/07***	***8:15***	***13:25***	***5:10***	***220***	***Frank***	***John***	***25min***	***2014/01/07***	***15:05***	***16:15***	***dry cabinet 10%r.H. for 2nd reflow***

6.8. TYPICAL MISTAKES DURING DRYING

Figure 36: Two serious errors: Stack of rigid-flex PCBs clearly too thick and unsuitable oven

Drying in a conventional oven cannot work because the maximum permissible relative humidity <5%RH required by IPC-1602 is not possible. On the other hand, I would not wish to eat a dust-dry cake baked in a circulating air drying cabinet.

6.9. EFFECTS OF DRYING ON SOLDERABILITY

Basically, any temperature stress after application of the solder surface represents accelerated ageing. The effects can be seen in a reduction of the specified storage times due to a deterioration of the solderability. Solderability can be determined in trials by wetting tests and spreading tests. The ENIG surface (Electroless Nickel Immersion Gold), which is now widely used, is considered to be very robust and can also be dried several times without affecting the solderability.

7 SUMMARY

In principle, PCBs already contain a certain moisture content directly after manufacture due to the manufacturing processes and ambient conditions. They are therefore never free of moisture that has diffused into the dielectric materials without special treatment. Over the storage period, the moisture content can increase further under unfavourable storage conditions.

To avoid damage during the soldering processes, it may be necessary to dry the PCBs in a suitable oven immediately before assembly or to store them in a dry atmosphere for a longer period of time (dry storage cabinet). **For flexible and rigid-flex PCBs, this drying is mandatory before soldering!** Process planning for the processing of flexible and rigid-flex PCBs and also other moisture-sensitive materials must take adequate drying into account, including its effects on solderability.

Solder profiles should be designed to be as gentle as possible. Even a few Kelvin lower peak temperatures in the solder profile are advantageous.

The necessary drying parameters depend on the PCB design (copper areas), the drying equipment and the arrangement of the PCBs in it, the PCB material, the soldering process and the soldering parameters, which can possibly also be multiple and combined from reflow, wave and partial soldering techniques. These drying parameters must be determined and verified by the PCB assembler. Particular importance must also be attached to logistics and, in particular, waiting times between processes, as the dried PCBs reabsorb moisture from the environment. Packaging the PCBs in a moisture barrier bag (MBB) for the supply chain and storage is not sufficient.

Alternatives in the material stack-up and design of the PCB should be used consistently to optimise the drying behaviour.

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