Phototools On The Move:
Dimensional changes of artwork.
August 2005

1. Introduction

In an ideal world your phototools would carry a design from your CAD/CAM station, through the photo plotter, through the photo resist, to the copper or to the solder mask without any distortion. Unfortunately the ideal world does not exist.

During creation, use and even during storage the information on your phototools will change.

Information is distorted or even lost due to the limitations of your plotter (accuracy, resolution, round-off, dimensional stability limitations, ...), the film (resolution, pinholes, fogging, light undercut, ...), the processing (emulsion pick-off, scratches, ...) and the use of the phototool (scratches, dust, ...). Correctly used modern systems will keep these losses to an acceptable level.

The dimensions of your phototool will change under the influence of changes in temperature, changes in humidity, mechanical tensions and ageing. Some dimensional changes are reversible others are not.

2. Dimensional changes
2.1. Dimensional changes caused by fluctuations in temperature

Most materials expand with increasing temperatures and phototools are no exception to that rule. The dimensions of all phototools in use today change with changing temperatures. The expansion is determined by C_T, the thermal expansion coefficient. C_T is a basic characteristic of a material; it is expressed in μm per metre per degree Centigrade. If the C_T of a material is 1, one metre of that material will expand 1μm when the temperature is raised by 1 degree Celsius. Likewise that material will shrink by 1μm per metre when the temperature is reduced by 1 degree Celsius.

The C_T of some materials:

Material	**C_T in μm/m °C**
Glass phototools	9
Polyester	18
Gelatine	18
Silver halide phototools on PET base	18
Diazo	18

Note:

The thermal expansion coefficient is independent of the thickness of the phototool.

The thermal expansion coefficient of PET (polyester)-based phototools is only valid in the range between -20 °C and 60 °C.

2.2. Dimensional changes caused by fluctuations in relative humidity in the range 30 to 70 %.

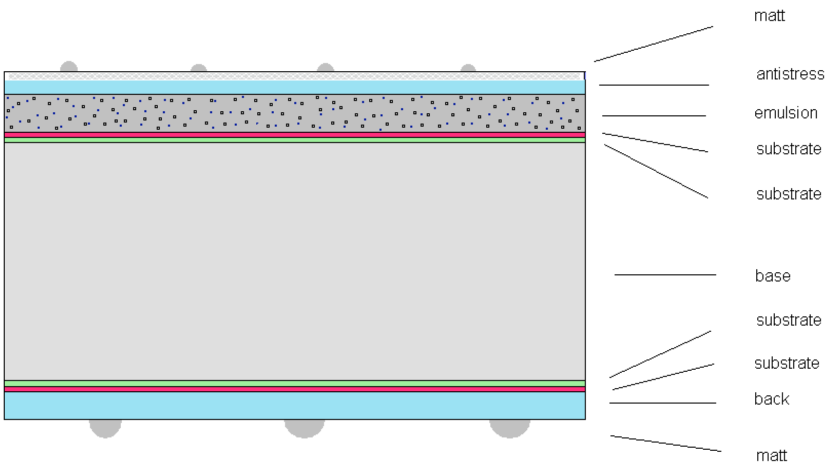
Most phototools absorb water and thus expand with increasing relative humidity. The expansion is determined by the C_{RH}, the relative humidity expansion coefficient, which also is a basic characteristic of the material. C_{RH} is expressed in µm per metre per % change in relative humidity. If the C_{RH} of a material is 1, one metre of that material will expand 1µm when the relative humidity increases by 1 %. Likewise the material will shrink as the relative humidity decreases.

The C_{RH} of some phototools:

Material	**C_{RH} in µm/m %**
Glass phototools	0
Polyester	8
Gelatine	Approx. 100
Silver halide phototools on a 175 µm PET base	Approx. 11
Diazo	9

Note:
The relative humidity expansion coefficient of PET (polyester) based phototools is only valid for a relative humidity between 30 and 60 %.

A phototool is composed of several layers in different materials. The C_{RH} of each of these materials is very different. The C_{RH} of PET is 8 µm/m %, the C_{RH} of a typical emulsion layer ranges between 70 and 150 µm/m %. When the relative humidity changes the different expansions causes extremely high tensions between the different layers. The adhesion layers between the PET and the gelatine layers absorb these tensions.



Structure of a silver halide phototool

The size off of a phototool at a given relative humidity is determined by the balance of forces applied by the gelatines and the polyester base. Due to the nature of the production process the characteristics (especially the elasticity modulus) of the polyester are different in the machining direction (the direction of production at factory) compared to across this direction. As a result a phototool will expand differently in length and width. The characteristics of polyester taken from the centre of the production web are also different from these from the borders. Also the proportion of the total area of film that is developed black influences the relative humidity expansion coefficient. The figure also depends on the relative humidity range in which it is measured. The figure 11, in the above-mentioned table, is an average value. It is a fair value to use in calculations.

2.3. Dimensional changes caused by mechanical tensions

Any phototool will expand to a certain extent under the influence of mechanical tension. The expansion is determined by the elasticity modulus ε, which is typical of the material. If the tension does not exceed a certain value, all changes will be reversible. In practice the phototool will be subject to only limited mechanical tensions and no irreversible dimensional changes will occur. Phototools do suffer from mechanical tensions induced by the loading system and the vacuum applied in the plotter and in the printer. The dimensional changes will be limited when the vacuum is gently built up all over the surface of the phototool.

In a normal PCB production process phototools can get localised irreversible deformations, for example around tooling holes and, for outer layers, around the wider drilled holes.

2.4. Dimensional changes due to ageing

The size of silver halide phototools may change over time. When a film is not processed correctly over time the film will tend to change back to the initial size it had prior to processing. These changes can take several months. When the phototool is processed correctly, according the so-called zero deviation processing, this change of size does not occur.

3. Dimensional changes: kinetics

The above theoretical story is often told and well understood in the industry. However, it is only part of the story. The above is all true and correct when you allow the phototool to adapt to the changed environment. That adaptation requires time.

In daily life the factors influencing size are constantly changing. The temperature of the phototool increases because of the heat of the printer lamps. Relative humidity is constantly changing because of the limitations of the air conditioning system, etc.

So, it is very important to understand the kinetics (the dimensional change in time) of phototools.

3.1. Dimensional changes caused by fluctuations in temperature

PET based phototools change rather fast when the temperature changes. The time constant for temperature changes (the time needed to reach 2/3 of the total change) is a few minutes. Glass phototools have a much larger time constant due to their higher thermal mass.

So, a PET based phototool will reach its new size in about ten minutes when the film is exposed to the environment from both sides. When several films are piled up, you have to add ten minutes for every sheet.

When a film is secured by a very strong vacuum that vacuum may hold the film and prevent it from changing size in response to changes in temperature or humidity. Although the temperature of the film changes the size will not for as long as the vacuum is applied. Once the vacuum is released, the film size will change instantly.

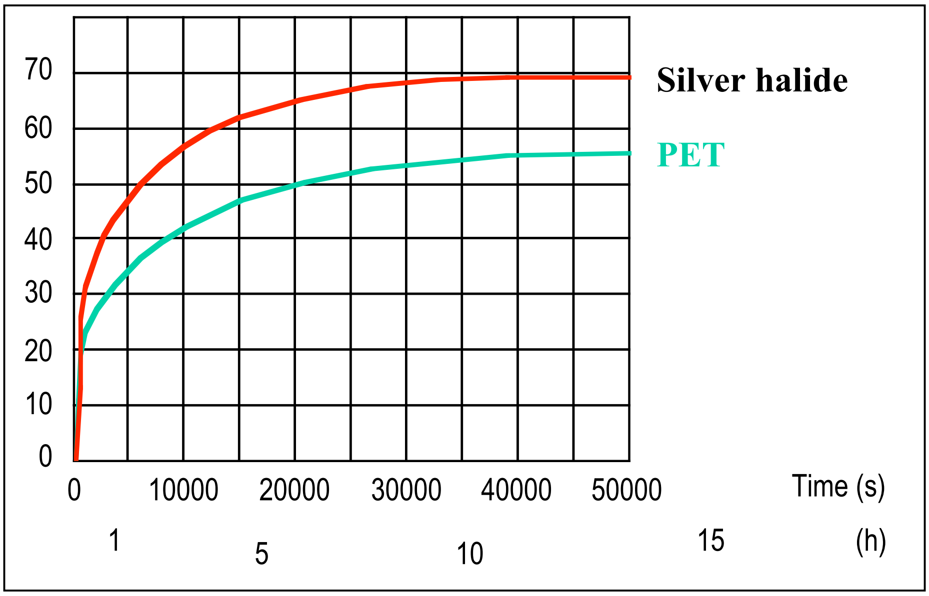
3.2. Dimensional changes caused by fluctuations in relative humidity in the range 30 to 70 %.

Silver halide phototools react in a more complex way to changes in relative humidity. The dimensional change is partly caused by the influence of the gelatines and partly by the influence of the PET.

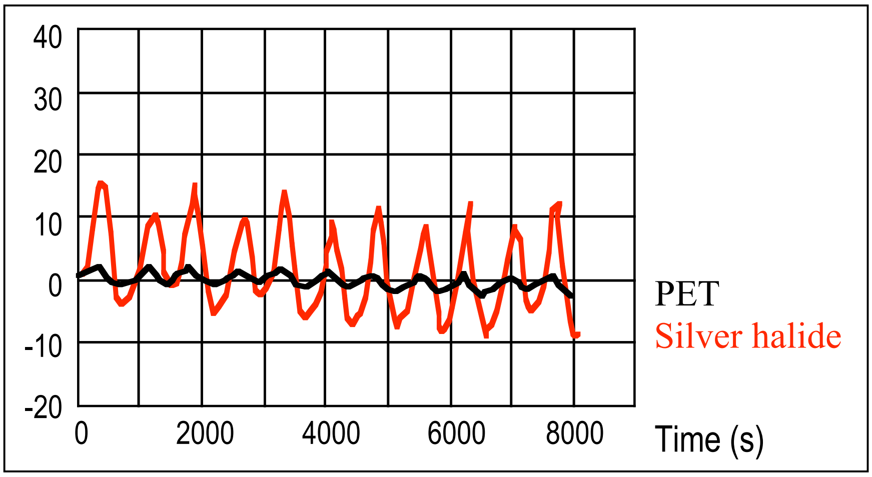
Gelatines have a time constant for relative humidity changes of only tenths of a second: they act like a sponge. They absorb and desorb much water and do so extremely fast. PET has a time constant for relative humidity changes of several hours: it absorbs or desorbs only a little water and does so very slowly.

Approximately 50% of the dimensional change of a silver halide phototool due to fluctuations in relative humidity happens within a second. This is due to the gelatines. The remaining 50 % of the total dimensional change takes literally hours and hours. That’s why we recommend waiting for eight hours for a film to be acclimatised after a change in relative humidity. This timing is only valid when the film is exposed to the environment from both sides. However, when the film is piled up the inner sheets will **never** reach the new size. The outer films shield the inner ones from the influence of the humidity. The polyester of the outer films can be seen as a humidity barrier.

Also here, when a film is secured by a too strong vacuum, that vacuum may hold the film and prevent it from changing its size.



Dimensional change of PET and a silver halide phototool as a function of a change in RH



Dimensional change of PET and a silver halide phototool as a function of an oscillating RH

3.3. Dimensional changes caused by mechanical tension

Mechanical tensions cause an immediate change in the size of silver halide phototools. The size is directly related to the strength of the tension. Examples of mechanical tensions are the forces generated by: the loading and unloading system of the photo plotter, the transport system in the processor, the mounting on the printer and the vacuum system of the printer. In praxis phototools may be deformed around the tooling holes since that is the area where the forces are concentrated.

3.4. Dimensional changes due to ageing

Dimensional changes of silver halide phototools due to ageing occur over long periods of time, i.e. months to years. The dimensional changes due to ageing can be ignored if you do not archive the phototools.

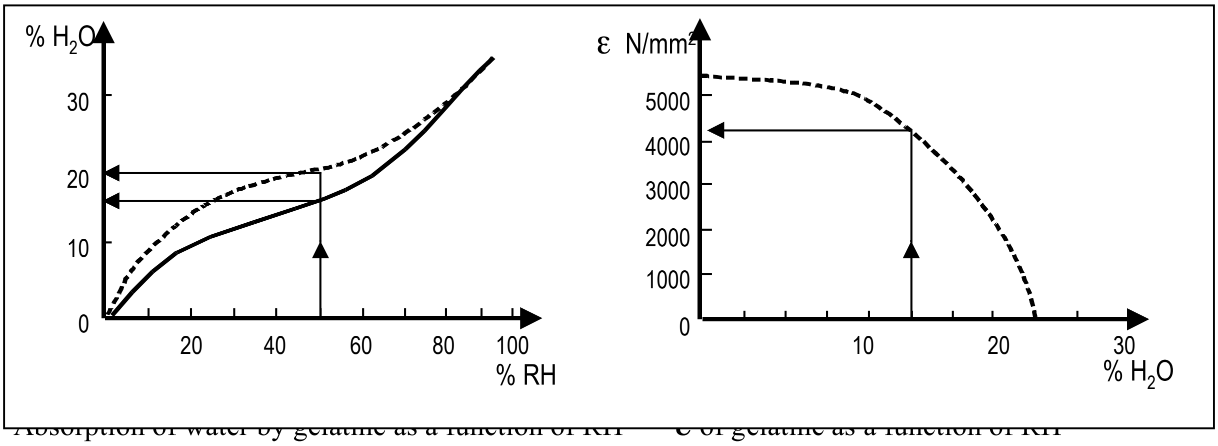
4. Reversible dimensional changes.

Phototools change their size reversible when the relative humidity ranging from 30 % to 70 %. Within this reversible range the changing length of a phototool can easily be calculated. The temperature (the warmer the longer) and the relative humidity (the wetter the longer) influence the length. The length of a film is determined by the combination of the changes in the base material (polyester) and the gelatine layers. The base material expands 18 micron/meter per degree C change and reacts rapidly (within a couple of minutes). The gelatine layers have a very similar reaction to the temperature changes. The base material expands 8 micron/meter per % RH change and does so extremely slowly (over several hours). The gelatine layers expand typically a 100 of micron/meter per % RH change and do so extremely rapidly (tenths of seconds). The gelatines layers are bound together well with the base material so they cannot move independently. The dimensional changes of a phototool in total are a combination of that of the base material and the gelatine layers. Modern phototools have a coefficient of thermal expansion of 18 micron/meter per degree C change and a coefficient of relative change expansion of (on average) 11 micron/meter per % RH change).

The phototool suppliers offer easy to use programs or tables that make the dimensional change calculations. All these calculations are only valid in the reversible range (30 to 70 % RH) (e.g. seen http://phototooling.agfa.com).

5. Irreversible dimensional changes.

Irreversible dimensional changes occur when the relative humidity has been below 30% or above 70%. At higher relative humidities irreversible dimensional changes occur due to recovery. At lower relative humidities irreversible dimensional changes occur due to relaxation.



Absorption of water by gelatine as a function of RH   ε of gelatine as a function of RH

5 1. Recovery.

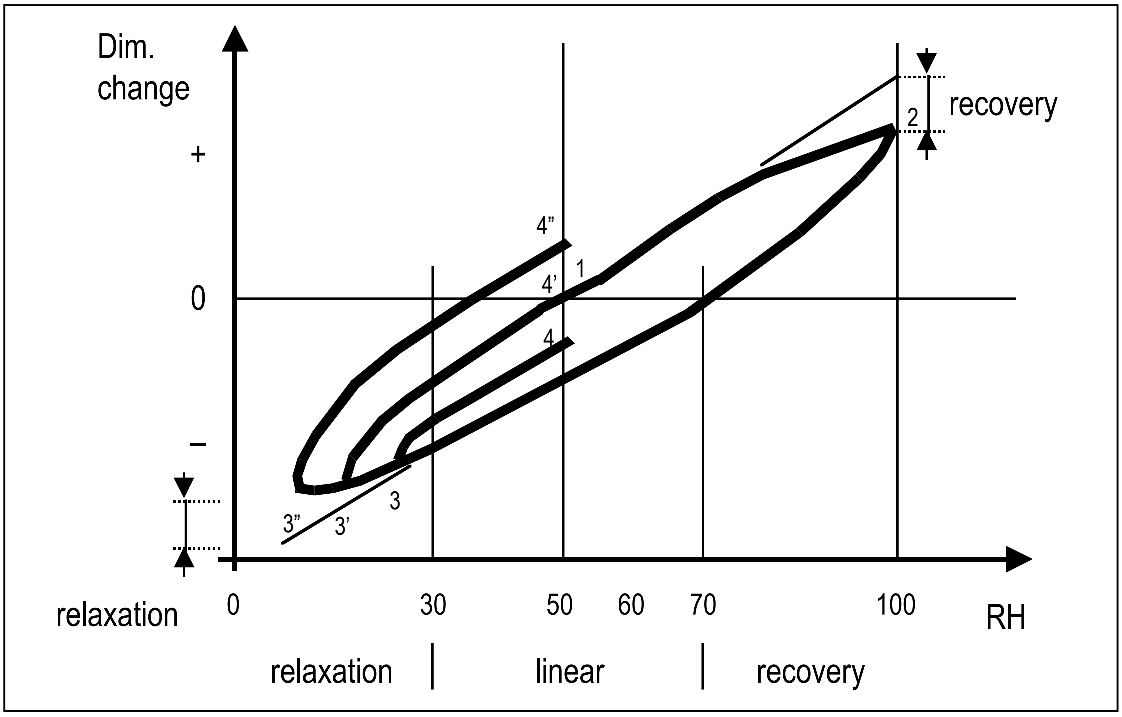
Film is manufactured and packaged at a RH of 50%. When a film is brought into an environment with a RH higher than 70%, the gelatines become so wet that they lose strength. One could say that the gelatines chains are separated by that much water that they loose contact one with another and cannot apply their influence any longer. The effect of the gelatines on the dimensional change becomes weaker. As a result the film expands less. This loss of length increase is permanent. Even when the RH of the environment will later return to below 70 %, the film will remain shorter. This phenomenon is called recovery.

5 2. Relaxation.

When a film is brought in an environment with less than 30 % RH, the gelatines loose so much water by evaporation that the gelatine chains touch one another. Hydrogen bridges are formed between the gelatine chains and these bridges absorb the mechanical tensions the gelatines would otherwise apply to the polyester. As a result, the effect of the gelatines on the dimensional change weakens. The film shrinks less. This loss of shrinkage remains, even if the RH of the environment rises above 30 % again. This phenomenon is called relaxation.

5 3. Processing.

Both recovery and relaxation happen during processing.
The graph shows the dimensional changes of a phototool during processing.



When the film, with latent image, leaves the plotter it is at 50 % (the correct environment humidity) and has a length which is correct (we assume the plotter is set correctly). The film is at point 1 in the above graph.
During the wet stage (developing, fixing and washing) the film absorbs water and grows, first linear and reversible. As from 70 % the film goes on expanding but at a lower pace due to recovery. This size change happens within a second. Only the gelatines are responsible for the change. The polyester absorbs water far too slowly to have any effect.
When the phototool leaves the wet section (point 2) it is fed into the dryer. The low relative humidity in the dryer section will dry the film. Firstly that shrinkage is not linear and not reversible. Between 70 and 30 % the shrinkage is linear and reversible. Below 30 % the shrinkage goes on but at a lower rate due to relaxation. The relative humidity in the dryer can be controlled by the dryer temperature setting. When the dryer is set correctly the phototool has a dimensional change corresponding with point 3'. When the dryer was set too cold the relative humidity is too high and the phototool ends shorter (point 3), when the dryer was set too warm the relative humidity is too low and the phototool ends up longer (point 3'').
The phototool then leaves the processor and starts absorbing water from the environment and it expand, first not linear and not reversible, later linear and reversible. When the film was dried correctly the

phototool ends at exactly the right size. If dried too cold the phototool end sup too short, if dried too warm the phototool ends up too long.

Ideally a film is processed in such a way that the recovery is fully compensated by the relaxation. This can be achieved by selecting the correct dryer temperature. Then the internal tensions in the film (polyester and gelatines) are the same before and after processing. This is desirable to ensure the phototool is best able to minimize further the dimensional changes during the copy to resist or solder mask process and to avoid dimensional changes due to ageing. This is also referred to as zero-deviation-processing.

6. Dimensional stability: hidden factors

The size of a phototool changes because of 4 reasons: changing temperature, changing relative humidity, by ageing and under the influence of mechanical tensions.
If a phototool doesn't fit or doesn't fit no more the root cause is to be found in the above mentioned reasons.
Often phototools users experience dimensional changes without being able to specify the exact cause. Many parameters have an indirect effect on the dimensional behaviour of a phototool. These parameters we call hidden factors.
If a dimensional change occurs we advise to check these hidden factors.

6.1 Before and after processing:

The dimensional stability behaviour of a film due relative humidity changes is different before compared to after processing. During processing many components are rinsed out during fixing and washing. So the composition of the film changes and thus the characteristics, amongst them the dimensional stability for relative humidity.
As a result: film before processing changes its size more compared to after processing. The difference is +/- 10 %.

6.2 Development time:

The longer the development time the more the film can warm up in the wet section. This means that the film is kind of preheated and thus will dry faster. On top of that when the development time is extended also the time the film is in the dryer sections is extended and thus the drying is more profound.
The extension of the development time has no impact on the water absorption. The gelatine layers absorb the water extremely fast. Remaining some longer in the wet section doesn't change anything. The PET of the base material on the other absorbs water that slowly that a couple of seconds longer does not have any effect.
As a result: when the development time increases the film will expand.

6.3 Developer and fixer temperature:

The higher the developer and / or fixer temperature the more the film can warm up. This means that the film is kind of preheated and thus will dry faster.
As a result: when the developer and / or fixer temperature increases the film will expand.

6.4 Wash water temperature:

The higher the wash water temperature the more the film can warm up. This means that the film is kind of preheated and thus will dry faster.
Often the temperature of the wash water is not controlled. In many cases the first couple of litres is warmed up by the environment whereas the wash water then becomes colder and colder. Often the temperature of the wash water is different in the winter compared to the summer. This results in different film sizes. The solution for both cases is easy and cheap: install next to the processor a tank (content e.g. 50 litres) that acts as a buffer. The thermal mass of the tank and the water will flatten out the wash water and flatten out
As a result: when the wash water temperature increases the film will expand.

6.5 Dryer temperature:

The higher the dryer temperature the more the film will dry and end up longer.
Over time the airflow will reduce. The fan will cumulate dust and loose efficiency. The entrance air filter will also cumulate dust and limit the air flow. Also the air guides may become rougher when loaded with dirt resulting in a lower flow.
When the airflow reduces the temperature of the air goes up and the distribution of the air over the film will get worse. The centre part of the film will be dried too much and the boarders too little.
As a result: over time the flow, the temperature and distribution of the drying air will deteriorate and the film will deform.

6.6 Developer environment:

When the relative humidity of the room in which the processor is placed changes the drying characteristics changes too. When the relative humidity goes up the air at the entrance of the dryer contains more water. The air is then wetter and will not dry as good. On top of that the water is to be warmed up by the dryer too. The heat to warm up the water is not available to heat the air, resulting in a lower drying capacity.
As a result: when the relative humidity of the environment of the processor goes up the film will remain shorter.

6.7 Air flow over the baths:

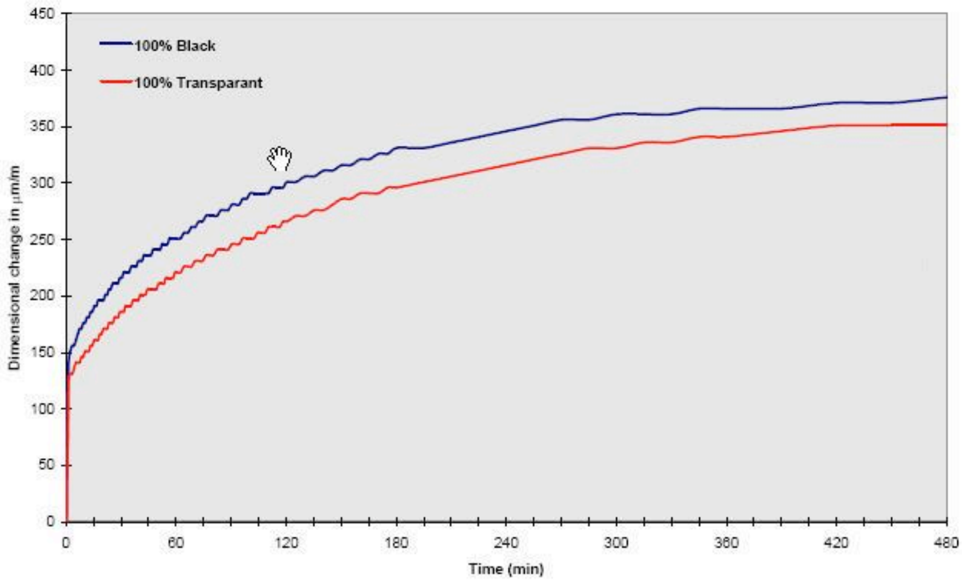
In many cases the processor is built through the wall. The feed in table is in the plotter room. The rest of the processor is in another room. In normal circumstances the plotter room is in overpressure. When that overpressure increases the airflow over the baths increases too. This not only results in an increased oxidation of the chemistry and with a increased risk of crystal build up and possible scratches as a result but it also disturbs the dryer airflow.
As a result: when the airflow over the baths changes the size of the films may change.

6.8 Processor throughput:

When the throughput of a processor is irregular the films may end up with different sizes. When a film is processed by a cold machine (just started or standing idle for some time) a considerable amount of the heat generated by the dryer is absorbed by the machine itself. The air is wetter and will not dry the film as well.
As a result: films processed in a cold machine are too short.

6.9 Blackness:

In the fixer the silver in the transparent areas of a film is dissolved and washed out. As a consequence the layer has a different structure. Since dimensional stability comes in with the balance of forces between the gelatine layers and the base material it is clear that a different layer has different dimensional stability characteristics. The difference between a full transparent film and a full black film is 3 % (when a transparent film expands 100 µm, a black film will, in the same circumstances, expand 103 µm).
As a result: the blacker the film the more it will changes it size

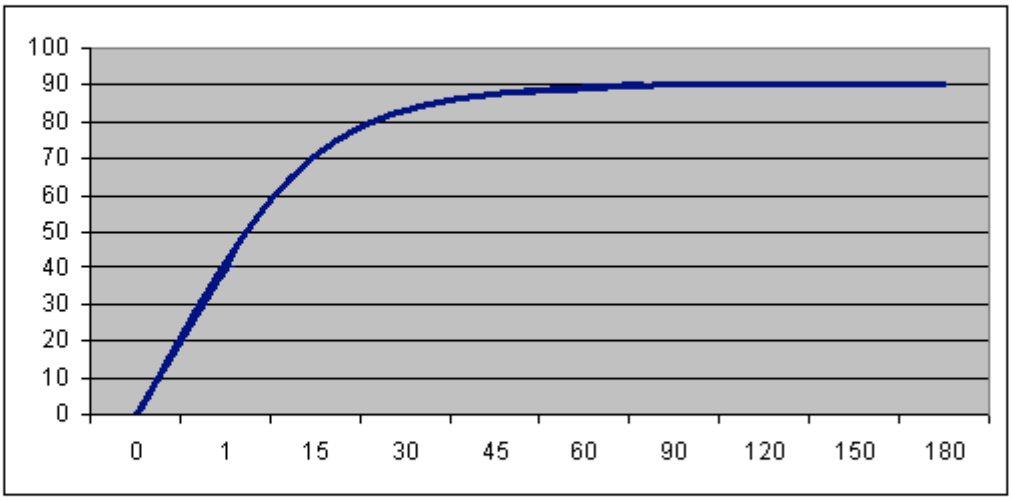


6.10 Loading, unloading and mounting:

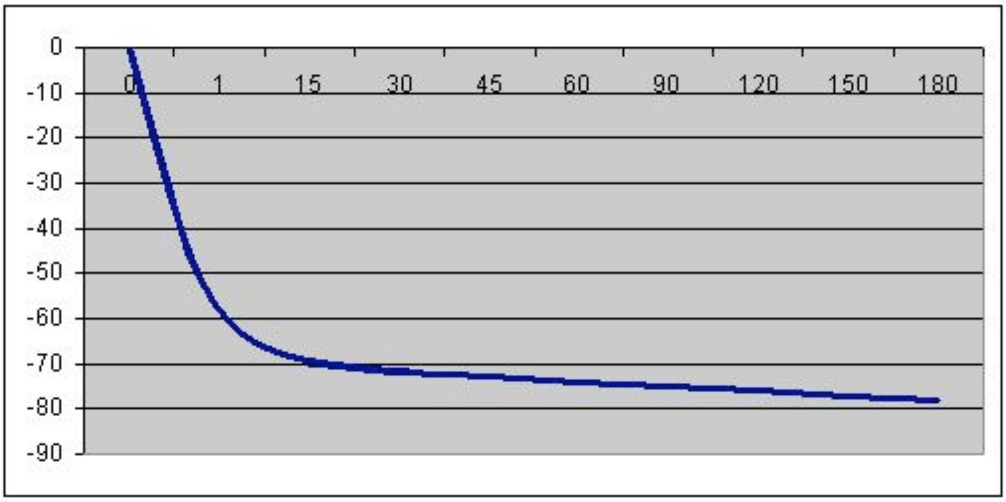
Mechanical tensions, induces by loading and unloading or by mounting with the aid of vacuum in the plotter and in the printer, may changes the internal tensions in both the gelatine layers and the base material. In normal circumstances the forces are that small that the size changes they generate are small and fully reversible. Yet when these parameters change the film may show a different size. If so the system (plotter, processor, film) has to be recalibrate.
As a result: when the loading unloading or mounting changes a film may change size.

7. Size changes during printing.

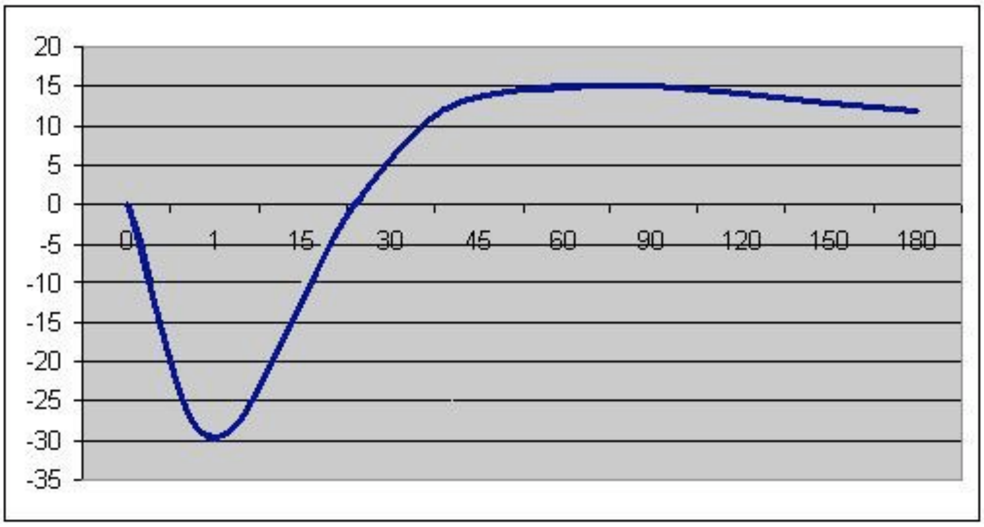
During printing a phototool changes its size. As a result the size of the image on the panel changes from panel to panel too.
Let us assume the phototool has the correct size when mounting and that the mounting itself does not deform the artwork. Let us also assume that the printer is installed in an environment of 20 °C and 50 % RH and that these circumstances do not change. We further assume that the vacuum applied does not dry the phototool and that the when the printer is closed there is no humidity exchange with the environment. Let us have a look how the film size is changing when the heath of the lamps increase the temperature with 5 °C.
Because of the temperature change the phototool will grow (we assume the mounting does not block the artwork) with 90 µm per meter (C_T = 18 μm/m °C). This size change happens rather fast.



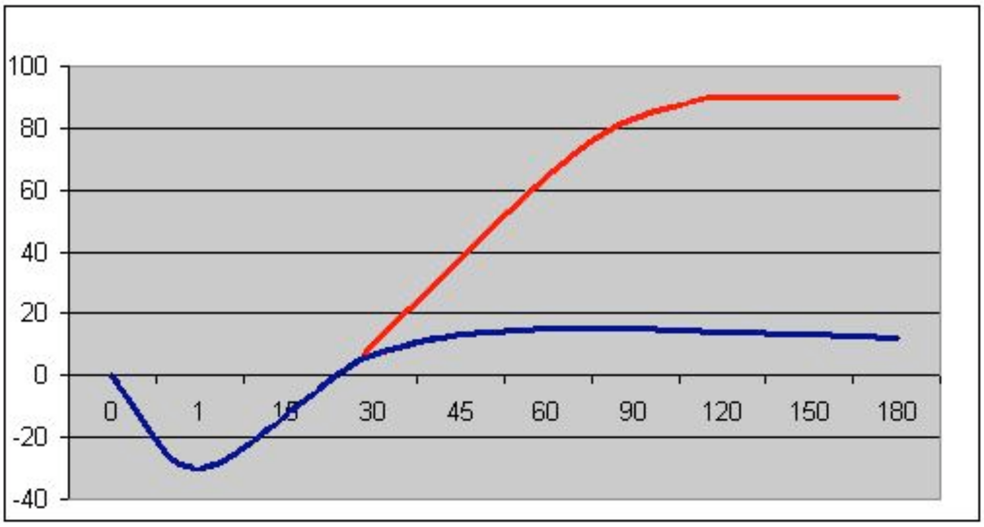
Due to the temperature change and the fact that no humidity from the environment can be added the relative humidity drops. At 20 °C and 50 % RH the air contains 7.26 grams of water per kilogram of air. Since there is no humidity exchange the air at 25 °C contains the same 7.26 grams of water per kilogram of air. At that temperature the relative humidity is 36,9 %. Because of that relative humidity change the phototool will shrink (we assume the mounting does not block the artwork) with 143 µm per meter (C_{RH} = 11 μm/m %). Half of this size change happens very fast, the other half very slowly.



Of course both changes happen simultaneously result in a change like this.



When we take this one step further and assume that during printing there is air leak then the humidity brought in by that air will increase the humidity and thus stretch the film. In the case the humidity compensates completely the relative humidity drop the curve will look like this.



In praxis many more factor influence the artwork size making things even more complex. Herewith a typical diagram showing the position changes of fiducials between the first and the tenth panel. This data is courtesy of AT&S Leoben Austria. AT&S experienced that the size changes during the first 10 panels are most pronounced and that after 60 panels the phototool does not change no more.

8. Best practice

It is of major importance to start correctly. Prior to plotting the film must be in equilibrium with the environment of the plotter (and printer) room). If not the size of the film is changing while it is in the plotter. It is our experience that a correct start, with a film that is well acclimatised, eliminates half of the problems.

There for we advise to acclimatise the film, prior to loading in the plotter in its original packaging, for a least 8 hours to an environment of 21 °C and 50 % (the standard conditions that are also applied during packaging). During that time the film can get at the right temperature without any humidity exchange. When then the film is at the right temperature the inner packaging can be opened There then will be no humidity difference between the film and the environment so no humidity will be exchanged and thus no size changes.

Protecting your phototools from irreversible dimensional changes is not that difficult. Make sure the plotter is calibrated correctly. Then make sure the processor is set correctly so no irreversible dimensional changes occur there. Then acclimatise each phototool to the right conditions for at least 20 minutes **from both sides**. Then protect the phototools from the environment by packing them in humidity-tight bags (pushing out all air to make sure that no humidity exchange can happen inside the bag) and seal the bag.

Before using the phototools to print you also must to take care that the package (phototools and bag) is acclimatised at the correct temperature. When the package has been acclimatised at the correct temperature for 8 hours, you can open it, and no dimensional changes will occurre.

9. Phototools in extreme circumstances.

Best practice advises us to prevent phototools from being held in an environment which causes irreversible changes. That is not always possible. Some phototools are shipped over long distances under unknown circumstances. If shipped by air the phototools stored in the cargo bay may become as cold as minus 20 degree C with a relative humidity below 10 %.

During transportation irreversible changes can be prevented when the phototools are correctly packed at the right temperature and relative humidity. When a phototool is packed in a humidity-tight bag it cannot evaporate nor absorb any water, so dimensional changes due to variations in RH will not occur. The only dimensional change that can happen will be caused by changes in temperature. Low, even extremely low temperatures such as in a cargo bay, does not result in irreversible dimensional changes.

On the other hand at temperatures above 60°C the polyester starts to deform. These deformations are permanent and very obvious (such a deformed film will never make it to the printer). These temperatures may not seem a realistic possibility, yet they may be reached in the trunk of a dark car when parked in the sun for a longer period of time.

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