

A New Model for Mould Prediction and its Application on a Test Roof.

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1 ABSTRACT

Up to now the common methods to assess the risk of mould growth are based on steady boundary conditions. The newly developed model, describing the hygrothermal behavior of the spore, allows for the first time to encounter the changing surface temperatures and relative humidities for the prediction of mould growth. Special research is still necessary in order to receive the required hygrothermal material properties of the spore, like moisture retention curve and vapour resistance of the spore wall. Even though the capability of the biohygrothermal model to assess the risk of mould growth can be demonstrated impressively with the chosen example. A new basis has been built up to describe non-steady biological processes in mould spores, up to the start of the metabolism at least.

2 INTRODUCTION

Roofs covered with metal sheets have a very high vapour diffusion resistance, so that virtually no moisture can escape through the covering. Therefore, a sufficiently permeable inside vapour retarder must allow the moisture to dry out towards the room side, especially during the warm summer months. In order to compare different vapour retarders, extensive investigations were carried out in the outdoor-testing field of the Fraunhofer Institute for Building Physics (IBP). Fig. 1 shows an overview of the testing area in Holzkirchen (top) and the test house used for the investigations (bottom).

Because of the high insolation on the southern pane of the roof and the resulting high temperatures of the metal covering, so-called summer condensation occurs. This means that moisture diffuses from the hot outer parts of the roof assembly to the cooler room side and temporarily increases the humidity at the vapour retarder. The above mentioned outdoor tests show that a polyamide sheet results in the lowest wood moisture levels so that the proper function of this kind of vapour retarder could be confirmed. In the variant conducted with paper based vapour retarder, mouldy odor and patches of mould were found at the end of the investigations which showed that extensive mould growth had taken place in the roof assembly.

These damages due to mould were the motive to investigate in more detail the conditions which are necessary to allow or promote mould growth.

3 GROWTH CONDITIONS FOR MOULD

German literature often states a relative humidity of 80% at wall surfaces as the decisive criterion for mould growth, independent of temperature. Sometimes it is mentioned that many types of mould can also thrive at lower humidities (see for example the new draft of DIN 4108-X, Mould [1]). Other growth conditions, namely a suitable nutrient substrate and a temperature within the growth range are taken for granted on all types of building elements usually.

The growth conditions for mould may be described in so-called isopleth diagrams, as was already done by (mainly British) biologists in the sixties and seventies (Fig.2, left: spore germination; right: mycelium growth) [2, 3]. These diagrams are different for different types of mould and describe the germination times or growth rates. Beyond the lowest line every mould activity ceases, under these unfavorable temperature and humidity conditions spore germination or growth can be ruled out. The isopleths are determined under steady state conditions, i.e. constant temperature and relative humidity.

However, the temperatures and relative humidities encountered in buildings are usually unsteady. For this reason [4] performed extensive investigations with changing climate conditions. The experimental set-up for mould tests on rough surfaces (Fig. 3 top) allows to adjust the air and surface temperatures and humidities and to use different substrate materials. For the tests a spore suspension which consists of ten mould species was sprayed on the surfaces of the building material samples. With a microscope, the mould-infested areas on the sample surfaces were assessed according to growth intensity. As an example, Fig. 3 bottom shows the resulting mould growth intensity on different paint coats with and without contamination. Thus, for the first time test results are available which show the influence of different substrate materials on mould growth.

Table 1 lists all the parameters which influence the growth of mould [5, 6]. An assessment of these influences shows that temperature and humidity as well as nutrient supply of the substrate are the dominating factors for mould growth.

The influence factors light, oxygen and spore dissemination are allowed for in the predictions in that they are always assumed to constitute optimal growth conditions. Since mould also grows on smooth surfaces, the influence of surface roughness is ignored. As the model aims at preventing growth of all mould species, it is irrelevant whether one mould species is superseded by another one. Biotic influences can therefore be ignored.

4 OBJECTIVE

The three factors required for growth – nutrients, temperature and humidity – must exist simultaneously for a certain period of time; this is the reason why time is one of the most important influence factors (see Fig. 4). Therefore a genuinely non-steady simulation of the occurring processes is necessary, which allows for moisture absorption as well as the drying-out under deteriorating growth conditions. Modern simulation methods allow very

precise determination of the unsteady temperatures and relative humidities of interior surfaces in different geometries. A model remains to be developed which describes in a realistic manner the development of a mould fungus as dependent on the external unsteady boundary conditions.

5 NEW APPROACHES FOR PREDICTING MOULD GROWTH

All populations of microorganisms follow a growth curve. The life cycle of a fungus colony can be divided into three phases. During the first two phases (spore germination, mycelium growth) vegetative growth takes place, while reproduction occurs in the third phase (sporulation). In order to reliably rule out any health risks due to mould, the very beginnings of mould growth, i.e. spore germination, must be prevented, which also assures that other harmful microorganisms with higher demands on growth conditions cannot flourish [7].

In order to reliably prevent spore germination or mycelium growth, even on optimal substrates, one considers the combined growth conditions of all fungus species (using the respective fungus-specific isopleths) and determines the lowest occurring limit of growth, the so-called Lowest Isopleth for Mould (LIM), as shown in Fig. 5 for spore germination (top) and mycelium growth (bottom). Only temperatures in the range from ca. 5°C to 25°C are being considered, which is the hygrothermally relevant range for indoor conditions. The LIM for spore germination and mycelium growth turn out to be different, with the LIM for spore germination being only a few % RH greater than the LIM for mycelium growth. This means that spore germination can only occur if subsequently mycelium growth is possible.

6 NEW CALCULATIVE METHOD FOR PREDICTING MOULD GROWTH

The decisive condition for the germination of the spores is the ambient humidity which determines the moisture content within a spore. The objective of the biohygrothermal model is to predict this moisture balance in dependence of realistic unsteady boundary conditions as found in buildings, in order to permit predictions of growth probabilities.

Of course, the moisture content of a spore is also determined by biological processes, but the current knowledge is far from sufficient to allow modelling of these. It is safe to assume that only above a certain minimum moisture content the spore begins to germinate and no biological metabolic processes occur before that. Until then, the spore may be considered as an abiotic material whose properties are subject to purely physical principles. The biohygrothermal model only describes the development of the spore up to this point.

Due to the small size of the spore an isothermal model is sufficient, so that liquid transport processes (such as capillary suction) can be lumped together with diffusion transport. Under these assumptions only the moisture storage function of the spore and the moisture-dependent vapour diffusion resistance of the spore wall are needed as material parameters in order to enable the calculation of the moisture balance of a spore.

Extensive theoretical and experimental investigations of moisture transport in building materials and building elements have resulted in a thoroughly validated computer model (Wärme- und Feuchtettransport instationär; WUFI), which allows realistic calculation of these processes [8, 9]. This model includes diffusion, liquid transport and moisture storage processes.

Fig. 6, top, shows a schematic wall assembly, with a spore adhering to its surface (strongly magnified). In the biohygrothermal model the spore itself is treated as a 'biological' wall assembly in order to make it accessible to a WUFI calculation (Fig. 6, middle). However, in the one-dimensional calculations the spore cannot be treated as a separate material layer in front of the wall, since this would introduce an unrealistically high diffusion resistance between the wall surface and the indoor air. Therefore the wall and the spore cannot be modelled simultaneously. In a first step, the moisture balance of the wall only is computed. In the second step, the resulting climate data for the wall surface are then used as boundary conditions for the biohygrothermal computation of the model spore (Fig. 6, bottom). The

prediction model assumes that germination occurs in the spore above a certain limiting moisture content. When this moisture content in the spore is reached or exceeded, mould growth is to be expected.

7 HYGROTHERMAL "MATERIAL PROPERTIES" OF THE SPORE

The diameter of a spore is of the order of ca. 3 μm [10]. Since the program WUFI was developed for wall assemblies, such small dimensions cannot be entered.

The model spore is therefore assumed to be of larger size (here 1 cm), and the hygrothermal parameters are adapted accordingly.

In the literature only the moisture retention curve of the spores of bacteria can be found [11]. These values are transferable to mould spores and will be used for our modeling. The top of Figure 7 shows the resulting moisture retention curve as a sorption isotherm. In future its measuring is planned.

The lowest RH (depending on temperature) at which complete germination occurs (see LIM in the left side of figure 5) can be used as starting point for the water content in the spore (according moisture retention curve in figure 7).

The permeability resp. the vapour diffusion resistance of the spore cannot be measured directly due to its dimensions. No corresponding informations can be found in literature. The vapour diffusion resistance depending on water content will be determined therefore iteratively using the results of laboratory experiments [3]. The diffusion resistance is varied until calculated and measured results are corresponding well for all three temperatures (see figure 8). The resulting diffusion equivalent air layer thickness is shown in bottom of figure 7.

8 INFLUENCE OF SUBSTRATE

According to the presumption the germination of spores is principally affected by thermal and hygric conditions only. Therefore it should be independent of the substrate. But normally the starting point of germination is defined by the first visible growth and not by the start of metabolism (compare figure 9). The germination is depending on the quality of the substrate according to these considerations. This influence of the substrate is taken into account by shifting the LIM upwards. This means, depending on the substrate, the demands on hygrothermal conditions for germination are increasing. Unfortunately, apart from the mentioned measurements of Erhorn and Gertis, no valuable informations can be found. For this reason the LIM for paper based vapour retarder and smart vapour retarder shown in figure 10 are estimated but plausible. They are used to get a suitable example for showing the possibilities of the new model. It was assumed that the paper based vapour retarder is a nearly optimal substrate for mould growth like wall paper, in contrary to polyamide foil. An enormous lack of research is obvious, especially in the range of the substrate depending growth of mould.

9 EXAMPLE „ROOF COVERED WITH METAL SHEETS“

The experiments on the roof covered with metal sheets caused the development of this model and are additionally serving as its first application. This gable roof has a pitch of 50° and the ridge is oriented in an east-west direction, so that one of the roof panes is facing north and the other is facing south. Fig. 11 (top) displays the basic design of the test sections. The interior view of the insulated roof in Fig. 11 (bottom) shows the three different variants.

The space between the rafters (rafter height 18 cm) had been completely filled with mineral wool (thermal conductivity ca. 0.04 W/mK), so that no air gap was left between the insulation and the rough boarding (30 mm thick). For rafters and boarding moist wood with a moisture content of at least 30 mass-% had been used. The investigated vapour retarders were a paper based one

with an s_d -value of ca. 3 meters, a polyethylene sheet with an s_d -value of 50 m and a moisture-adaptive polyamide sheet with an s_d -value between 0.1 m and 5 m, depending on the ambient humidity.

The courses of RH on the inner surfaces of the paper based retarder and the smart vapour retarder in this roof, calculated with the aid of WUFI for an observed period of 180 days, are shown in figure 12 (top). The surface temperatures were nearly independent from time at about 21 °C. These courses have served as boundary conditions for the calculation of the courses of the water content inside the spore in step 2.

Due to the high vapour diffusion of the spore wall the courses of the calculated moisture content in the spores are smoothed (compare figure 12 (bottom)) compared to the RH on the inner surface of the roof. On the paper based retarder the spore shows a distinctive higher water content in comparison with the smart vapour retarder and reaches more than 60% per Volume. Additionally the courses of the starting point of germination are implied for both materials. Since the surface temperature was nearly constant these courses show almost no change with time. It is evident, that the water content of the spore calculated for the paper based retarder lies for a long period on a much higher level than necessary for germination. After about 30 days the growth of mould starts, a result which is quite consistent with the observations on this roof. With the polyamide foil the moisture content exceeds this limit only for a very short period and therefore no risk of mould should be expected.

The influence of the the breather membrane for a roof covered with tiles is shown in figure 13 and compared to the results of the roof covered with metal sheets. The course for the metal roof (dotted line) shows the highest relative humidities. After the first 40 days a decreasing vapour diffusion resistance of the breather membrane leads to decreasing relative humidities at the paper based retarder (see figure 13, top). The influence of these boundary conditions on the water content of the spores are shown in figure 13, bottom.

While the course of the water content calculated for the metal roof lies highly above the water content necessary for germination over a period of about 100 days, a breather membrane with an equivalent air layer thickness of 0.1 m or less yields much better results. The water content lies slightly above the critical one for a period of about one month. Since for the experiments the wood of the rafters were wetted above normal initial water content and keeping in mind that paper based retarders have flame protection additives which are slightly biocide there should be no risk of mould. This corresponds well to practical experiences with paper based ratarders in roofs covered with tiles and having breather membranes with low diffusion resistances.

10 SUMMARY

Up to now the common methods to assess the risk of mould growth are based on steady boundary conditions. While in Germany only relative humidity is stated as decisive condition for mould growth, more and more measured Isopleths are used abroad. These isopleths state, depending on temperature, the relative humidity from which mould growth may occur. But all curves for growth are determined with steady state conditions, in spite of the non-steady state conditions in reality. This newly developed model, describing the hygrothermal behavior of the spore, allows for the first time to encounter the changing surface temperatures and RH's for the prediction of mould growth. Special research is still necessary in order to receive the required hygrothermal material properties of the spore, like moisture retention curve and vapour resistance of the spore wall. Even though the capability of the biohygrothermal model to assess the risk of mould growth can be demonstrated impressively with the chosen example. A new basis has been built up to describe non-steady biological processes in mould spores, up to the start of the metabolism at least.

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Table 1: Factors, their assessment and way of implementation within the biohygrothermal model.

Factor	Assessment	way of implementation within the biohygrothermal model.
Humidity	most relevant criterion for growth	moisture retention curve; diffusion kinetics
Temperature	strong influence	temperature dependend starting point; diffusion kinetics
Time	strong influence	non-steady course of the water content of the spore
Substrate	influence due to substrate and contamination	shift of the LIM
pH-Value	is influenced by the fungus itself; difficult to predict	not allowed for
Light	growth also without light	always assumed optimal
Oxygen	usually present	always assumed optimal
Spore dissemination	spores are ubiquitous	always assumed optimal
Roughness of the surface	increased contamination	as change in substrate
Biotic interactions	biotic interactions are unavoidable	not allowed for, since all species shall be avoided



Figure 1 Field testing area in Holzkirchen, Germany
Top: Photographic view of the whole area
Bottom: Photographic view of the building with roof made of metal sheets

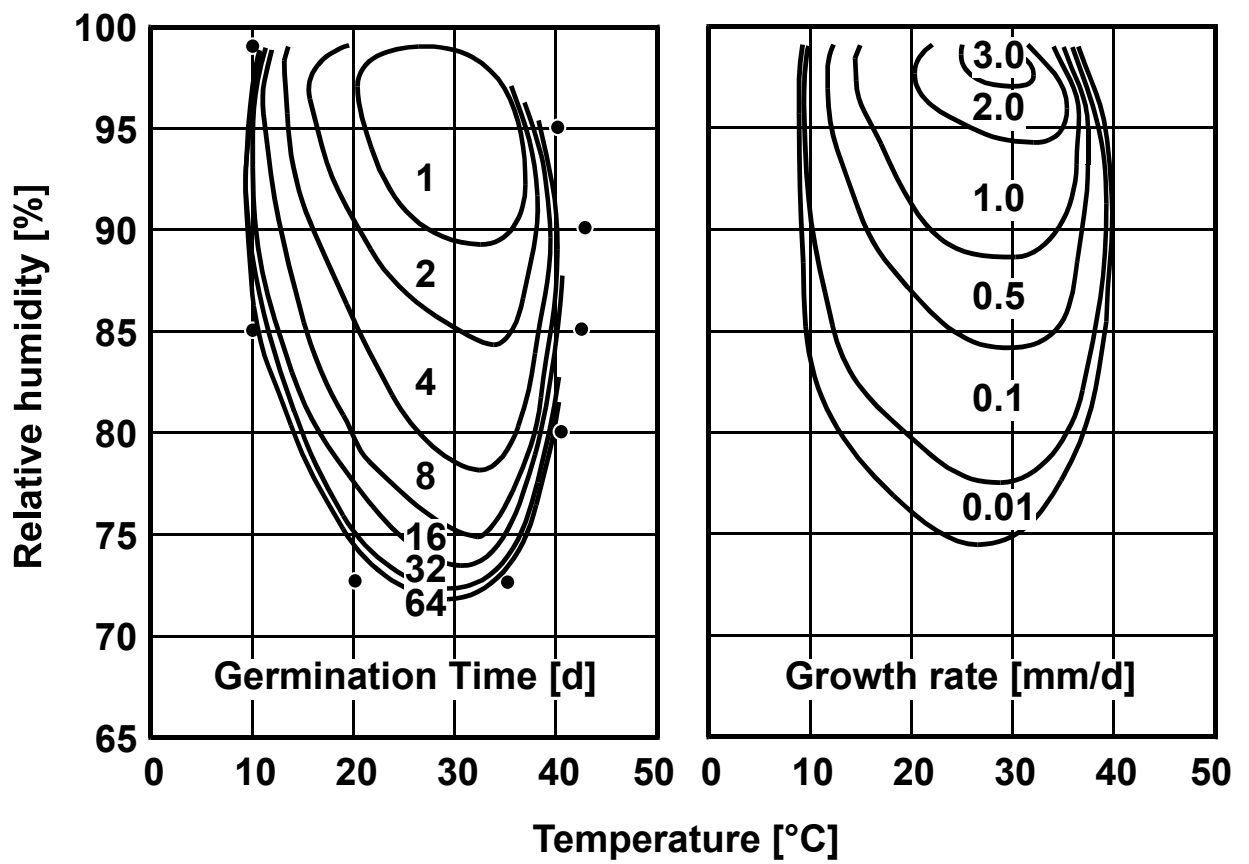
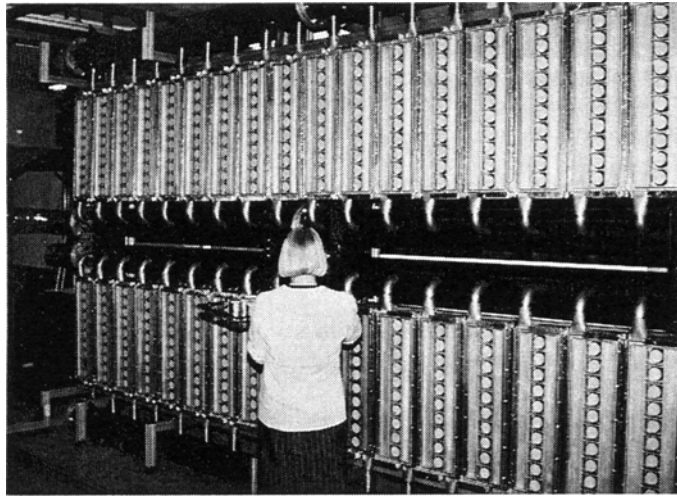


Figure 2 Isopleths for mould spores of *Aspergillus restrictus*.
 Left side: Isopleth for spore germination
 Right side: Isopleth for mycelium growth



Mold Growth

(surface temperature 14°C)

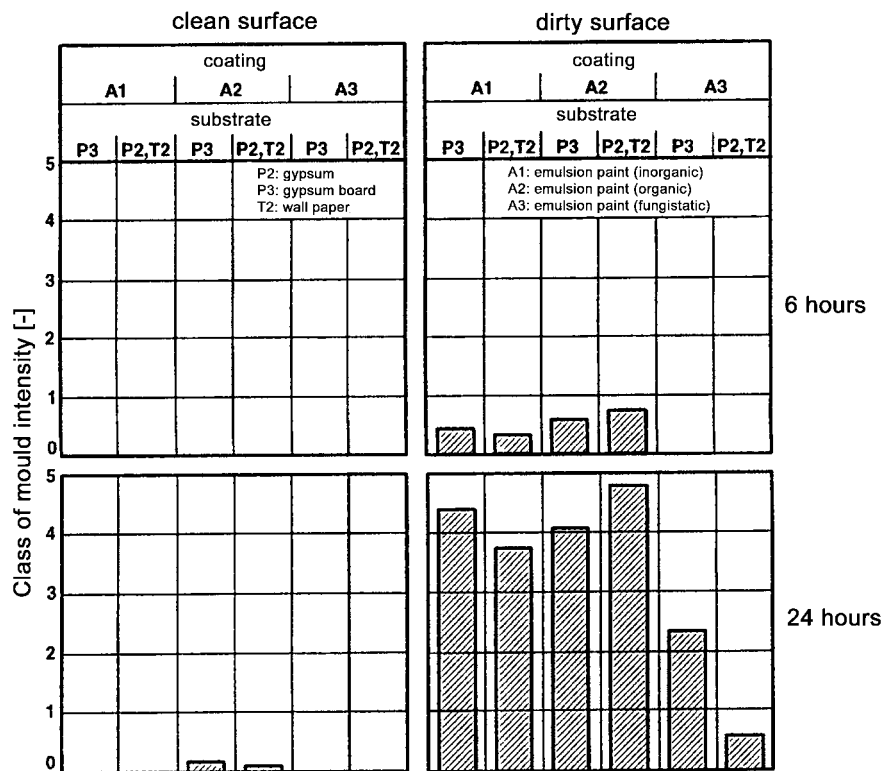


Figure 3 Investigations on mould growth at the surface of building materials
 Top: Photographic view of the experimental set-up
 Bottom: Resulting mould growth intensity on different paint coats with and without contamination

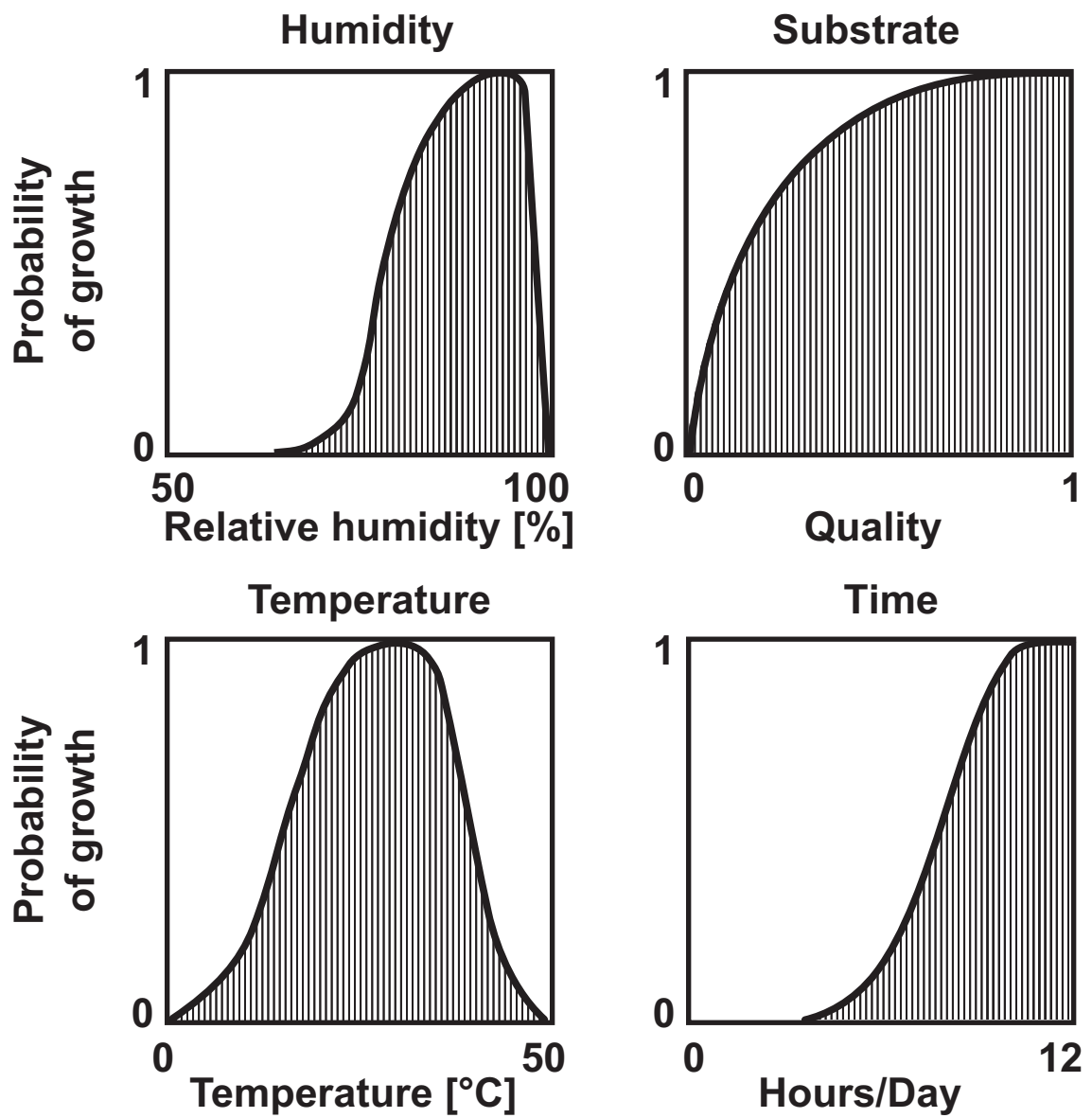


Figure 4 Schematic view of the most important factors humidity, temperature, substrate and time, which affect the probability of growth.

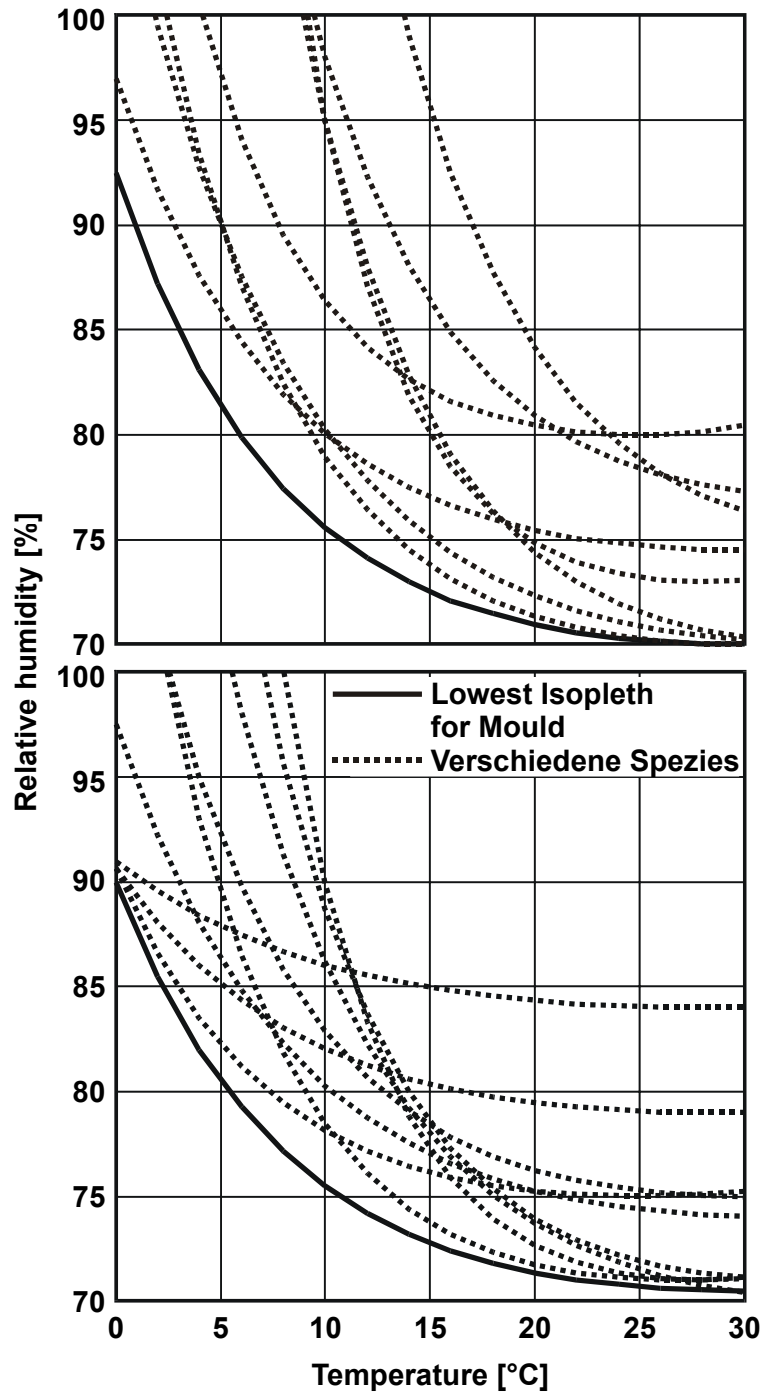
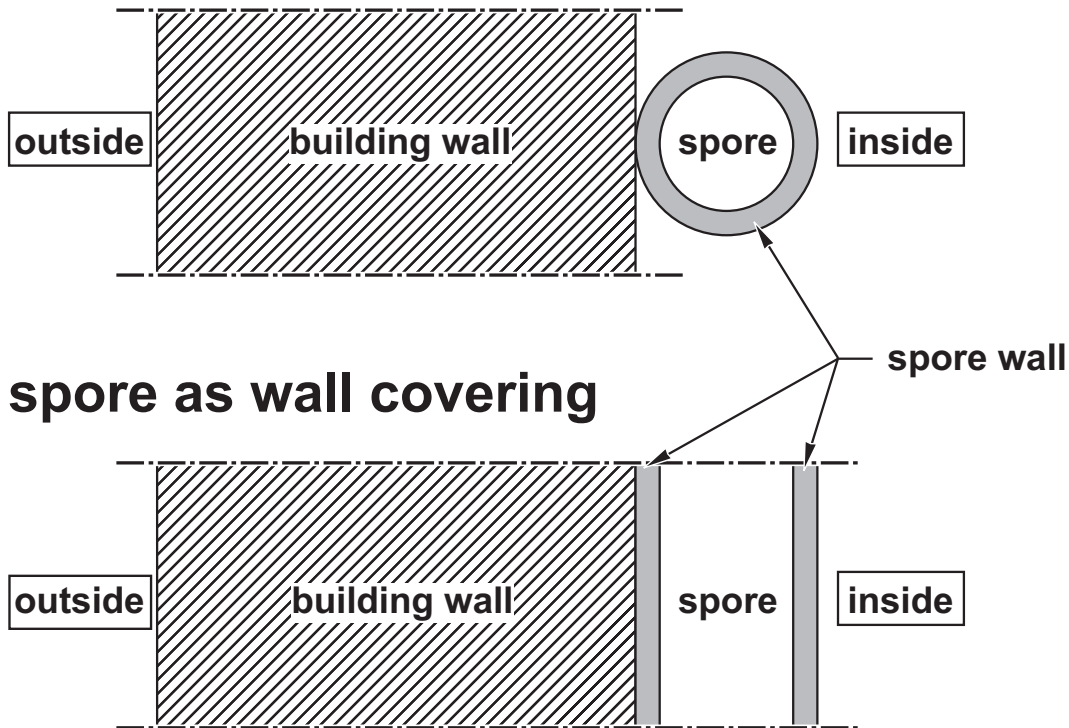


Figure 5 Development of the Lowest Isopleths for Mould from Isopleths of different species.
 Top: Spore germination
 Bottom: Mycelium growth

real model (spore highly enlarged)



model spore

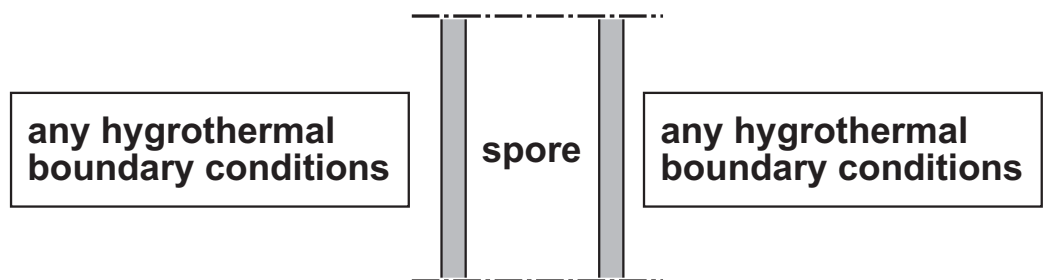


Figure 6 Development of the biohygrothermal model
Top: Wall with a mould spore (highly enlarged) on the inner surface
Middle: Spore treated as „biological layer“. This yields to a nonrealistic additional diffusion resistance for the building wall.
Bottom: Separate consideration of the biological layer. The inner surface temperature and humidity of the building wall serve as boundary conditions on both sides of the spore (biological layer).

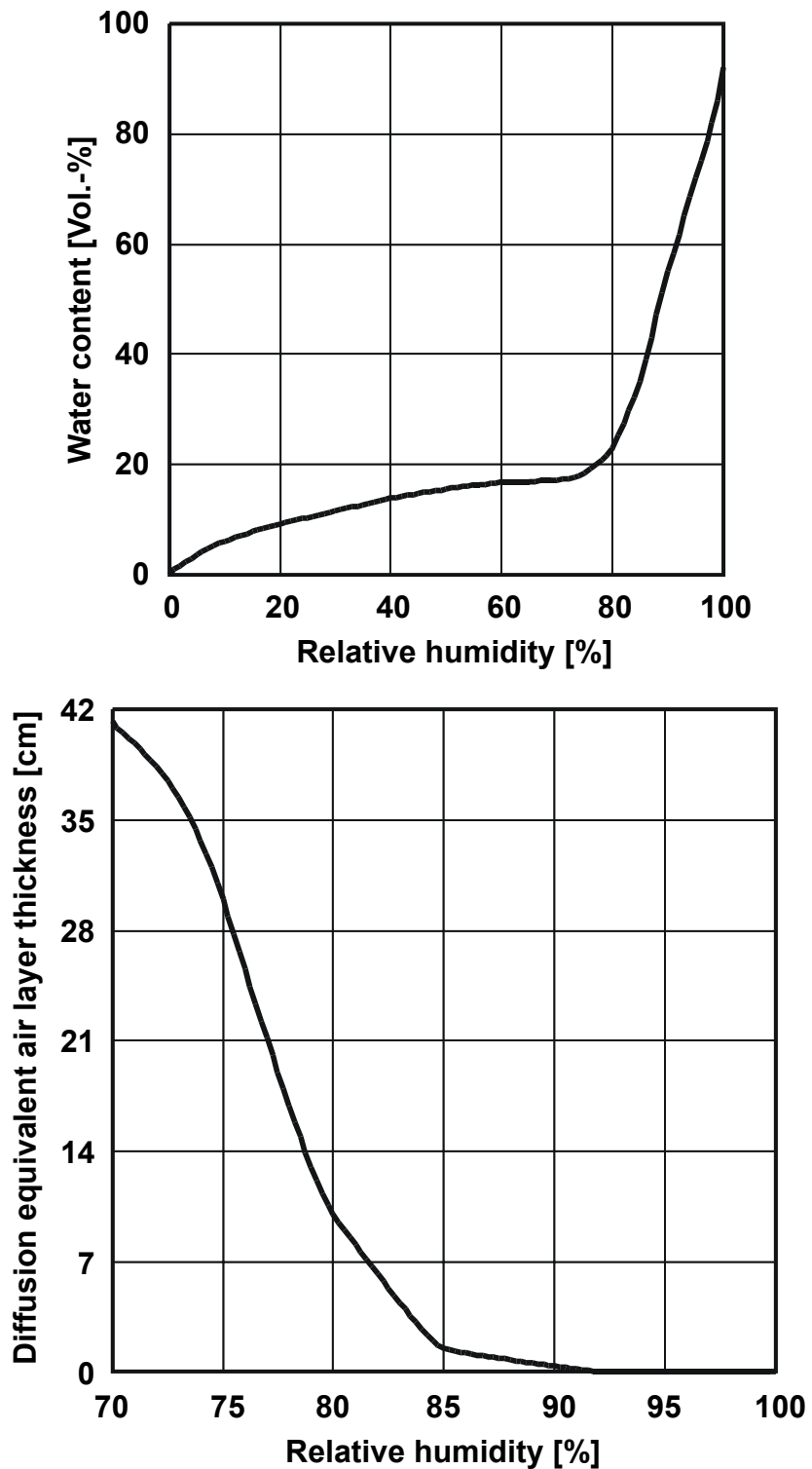


Figure 7 Hygrothermal „material properties“ of the mould spore
 Top: Moisture retention curve
 Bottom: Diffusion equivalent air layer thickness of the spore wall.

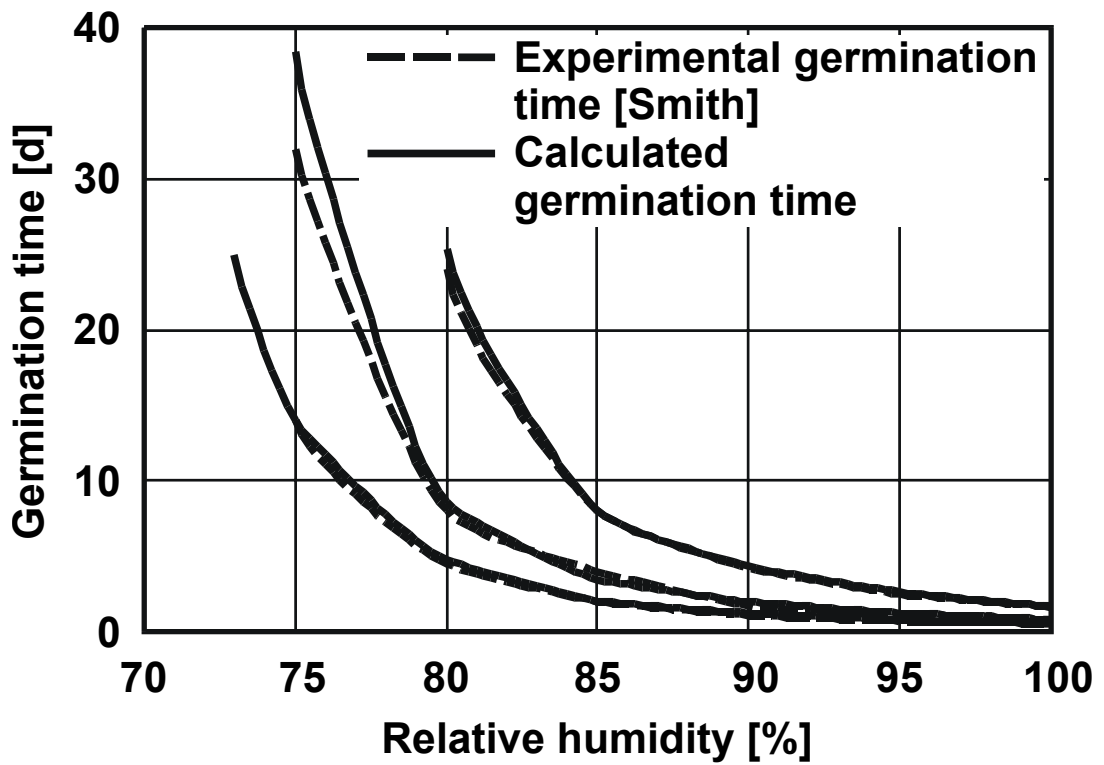


Figure 8 Comparison of the experimental germination times to the results calculated with the biohygrothermal model. For all temperatures a good correspondance is reached.

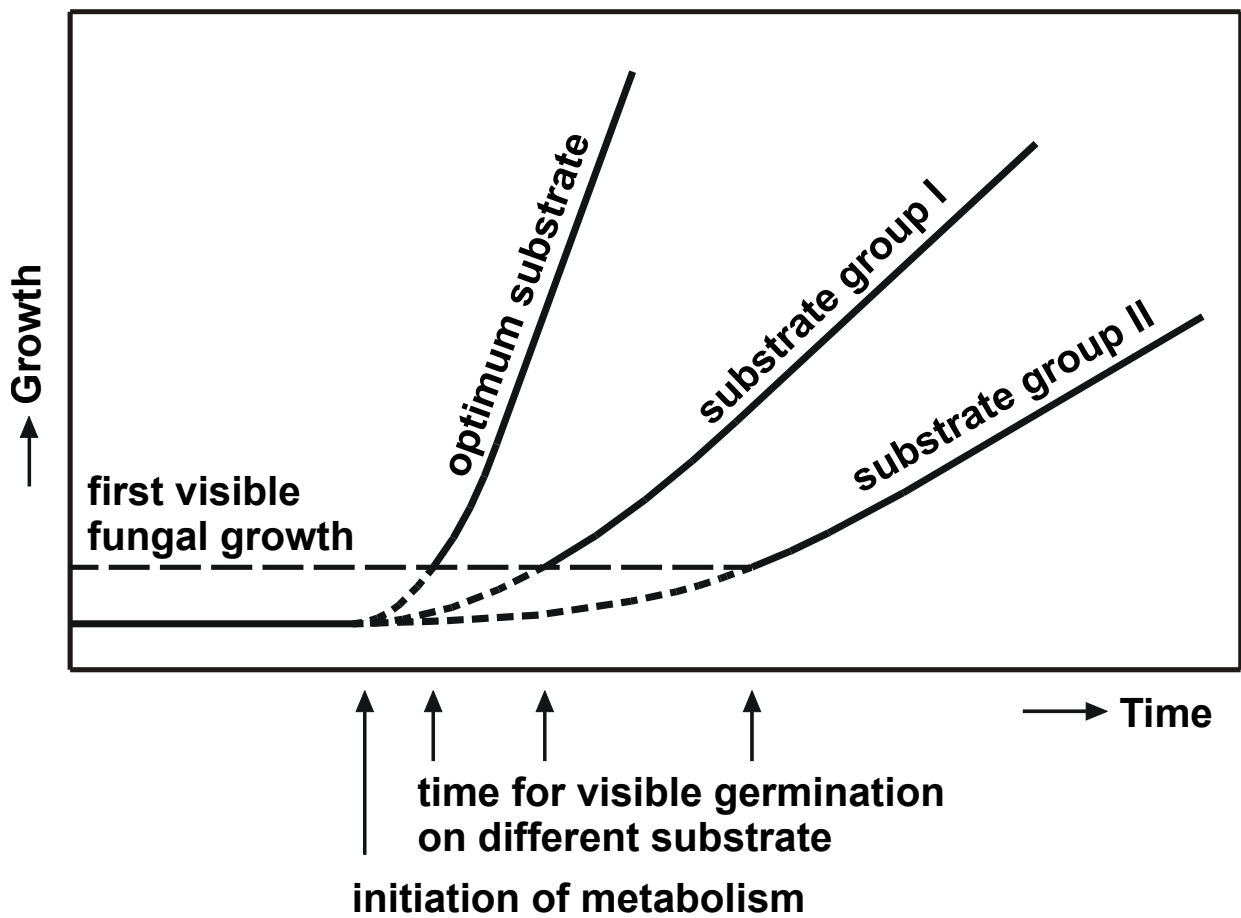


Figure 9 First visible fungal growth, which is defined as starting point for germination, on different substrates. In contrast to the start of metabolism a dependency on the substrate is given.

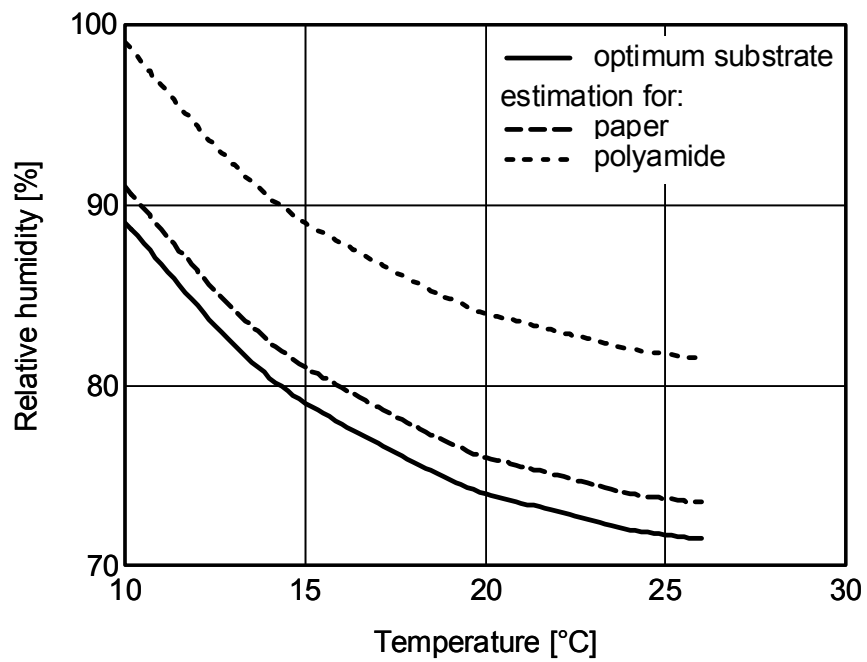


Figure 10 Change of the Lowest Isopleth for Mould (LIM) for different substrates.
 For paper as an almost optimal substrate the LIM is shifted only slightly in contrast to that of polyamide foil.

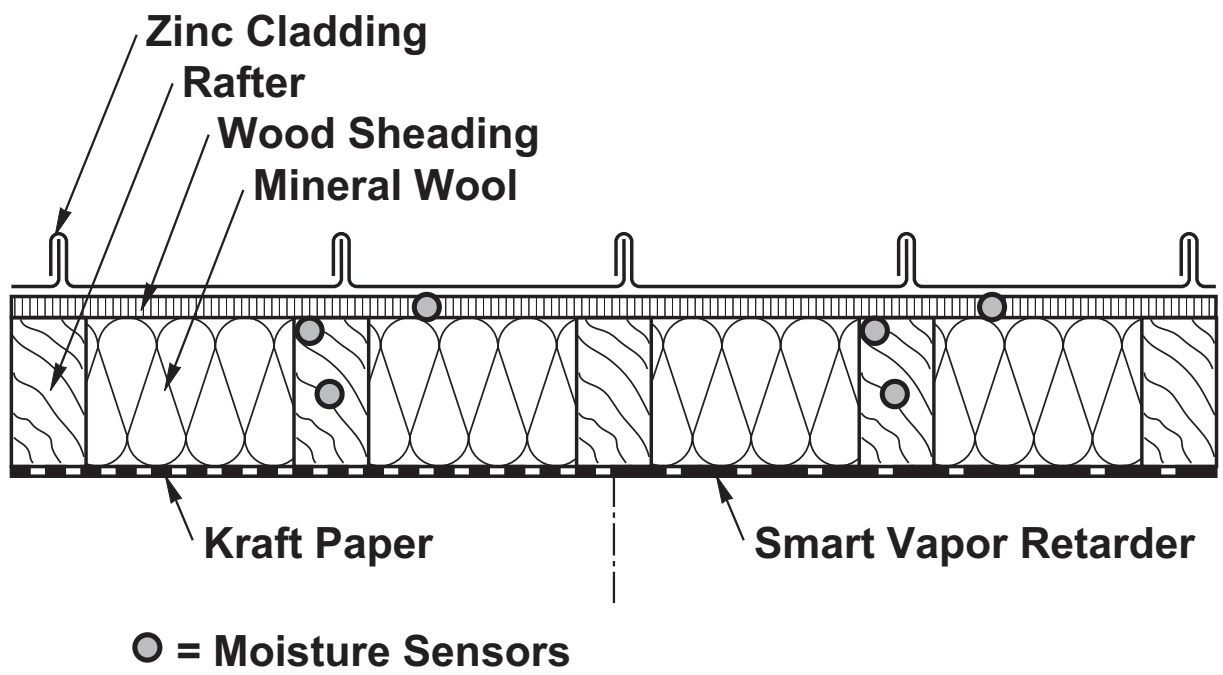


Figure 11 The tested roof covered with metal sheets.
 Top: Basic design of the test sections.
 Bottom: Photographical view of the interior

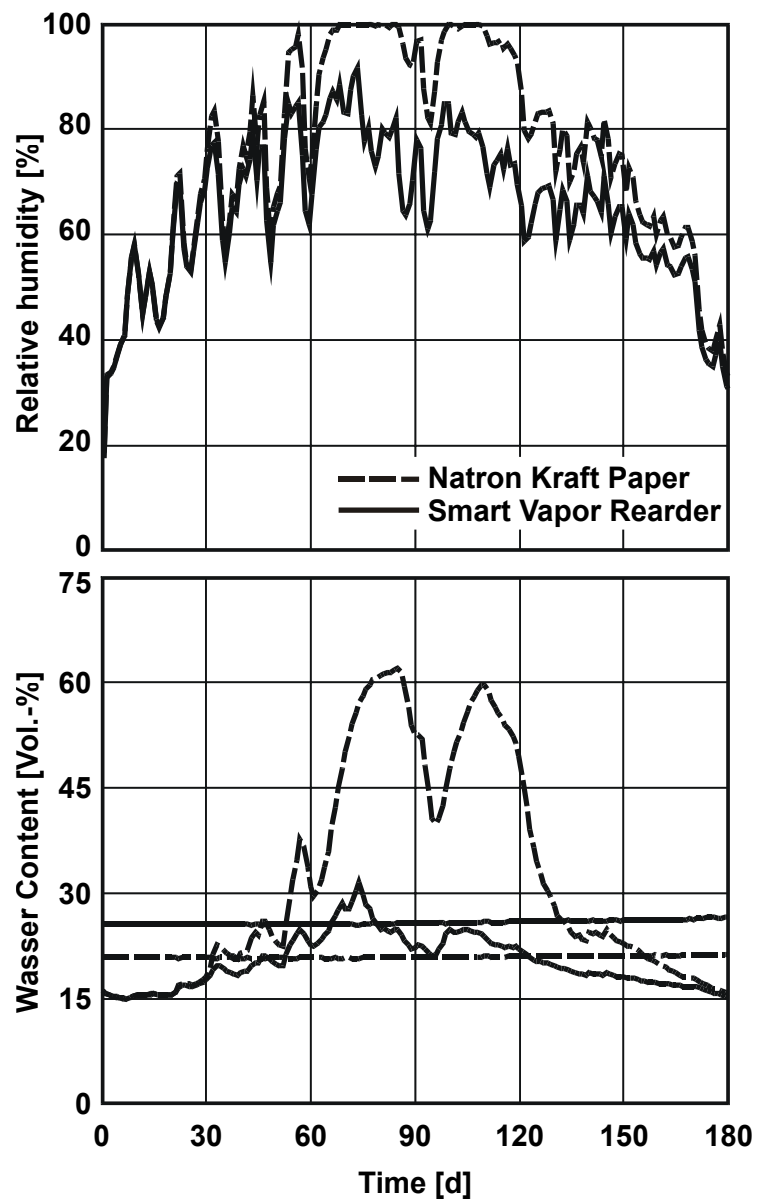


Figure 12 Calculated results for the vapour retarders inside the roof.
 Top: Courses of the relative humidities on paper based vapour retarder and smart vapour retarder. This courses serves as boundary conditions for the calculation of the moisture balance of the spore.
 Bottom: Courses of the water content inside the spores on paper based vapour retarder and smart vapour retarder. The courses of the starting point for germination are implied for both materials (horizontal lines).

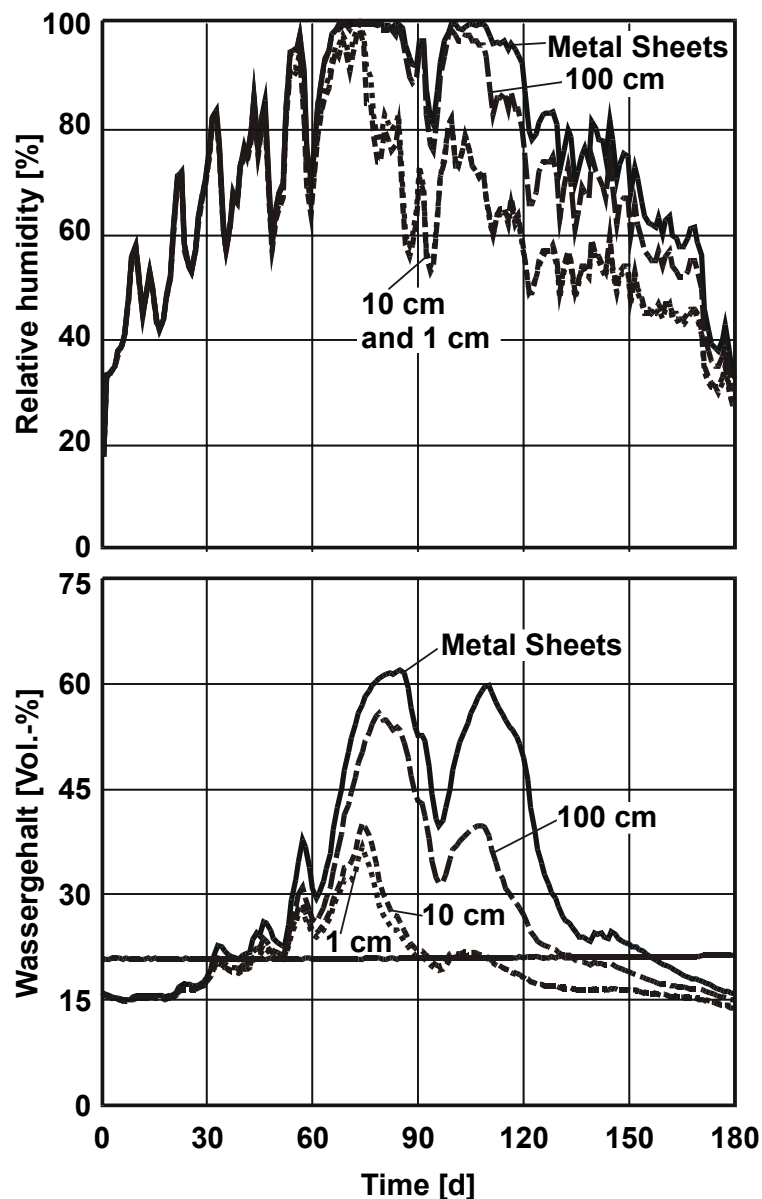


Figure 13 Calculated results for the vapour retarders inside the roof. Top: Courses of the relative humidities on paper based vapour retarder for breather membranes with different equivalent air layer thicknesses and comparison with results for a metal roof. This courses serves as boundary conditions for the calculation of the moisture balance of the spore. Bottom: Courses of the water content inside the spores on paper based vapour retarder using the boundary conditions shown above. The courses of the starting point for germination is implied (horizontal line).