Prediction of mould fungus formation on the surface of and inside building components.

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Foreword from the Old Testament [8]

Cleansing from mildew

[33]The Lord said to Moses and Aaron: [34]"When you enter the land of Canaan, which I am giving you as your possession, and I put a spreading mildew in a house in that land, [35]the owner of the house must go and tell the priest: 'I have seen something that looks like mildew in my house.' [36]The priest is to order the house to be emptied before he goes in to examine the mildew, so that nothing in the house will be pronounced unclean. After this the priest is to go in and inspect the house. [37]He is to examine the mildew on the walls, and if it has greenish or reddish depressions that appear to be deeper than the surface of the wall, [38]the priest shall go out of the doorway of the house and close it up for seven days. [39]On the seventh day the priest shall return to inspect the house. If the mildew has spread on the walls, [40]he is to order that the contaminated stones be torn out and thrown into an unclean place outside the town. [41]He must have all the inside walls of the house scraped and the material that is scraped off dumped into an unclean place outside the town. [42]Then they are to take other stones to replace these and take new clay and plaster the house. [43]If the mildew reappears in the house after the stones have been torn out and the house scraped and plastered, [44]the priest is to go and examine it and, if the mildew has spread in the house, it is a destructive mildew; the house is unclean. [45]It must be torn down – its stones, timber and all the plaster – and taken out of the town to an unclean place. [46]Anyone who goes into the house while it is closed up will be unclean till evening. [47]Anyone who sleeps or eats in the house must wash his clothes. [48]But if the priest comes to examine it and the mildew has not spread after the house has been plastered, he shall pronounce the house clean, because the mildew is gone."

Glossary of terms

Aerobic/anaerobic
Biological processes taking place in the presence/absence of oxygen.

Allergy
Aggravated response by the immune system that deviates from the standard, defined by a pathogenic hypersensitivity; caused by contact of the organism with an allergen.

(Alternaria) sp.
The abbreviation sp. means that all species of the respective fungus genus are included.

Anamorph
Asexual fruiting bodies, imperfect stage.

Ascomycetes
Class of fungi that form spores in an ascidium (tubular organ), e.g. truffles.

Basidiomycetes
Mushrooms, class of higher fungi which is abundant in forms; often rich sporulation at special carriers (basidia) (e.g. agarics, boletes, lycoperdales, the closed fruiting bodies of which open only after the spore ripeness: e.g. puffballs).

Biocorrosion
Change of the structure and the stability of a building material through excretion of metabolic products that have a direct corrosive effect, through discolourations of biogenic pigments, through biogenic oxidation of structure-forming cations up to an enzymatical decomposition of the affected materials.

Biofouling

Occurrence of a microbial (mucous) coating on material surfaces, followed by chemical-physical effects such as changes in the diffusion behaviour.

Colony forming units (CFU)

Unit of measure for spore concentration per volume.

Conidia/Fungus spores

Asexually formed, characteristic reproduction organs (spores) of higher fungi.

Cytoplasm

The cytoplasm is the liquid basic substance inside the cell membrane. It contains various substances: ions, nutrients, enzymes etc. and is the place of numerous metabolic reactions and transport medium for many substances in the cell.

Deuteromycetes (Fungi imperfecti)

Imperfect fungi. Ascomycetes of which only anamorphic stages with conidia as reproductive cells are known, i.e. no complete course of development (e.g. fusarium species).

Fungus spore

Asexual reproduction unit.

Germ tube

Evagination developing from the spore, breaks through the spore septum.

Hazardous class

Division of the fungi into classes according to their hazard to health.

Hydrophilic
Water-loving or living in water.

Hypha
An individual filament of a fungus cormus.

Isopleths
Lines of equal spore germination times or equal growth.

Isopleth system
Germination time and growth rates in dependence on humidity and temperature.

Lethal
Leading to death (e.g. a certain amount of toxin).

LIM
Lowest Isopleth for Mould: temperature dependent lowest relative humidity under which no fungus activity (spore germination or mycelium growth) is expected; valid for all fungi of one hazardous class.

LIM_{Mat}
Lowest Isopleth for Mould for single substrate groups.

Mesophilic
Preferring the medium heat range.

Metabolism
Transformation of chemical substances in the organism into metabolic products.

Microbial Volatile Organic Compounds (MVOC)
Volatile organic compounds (alcohols, ketones, aldehydes, terpenes and aromatic compounds), formed by microorganisms.

Moisture storage function
Functional connection between applied relative humidity and the equilibrated moisture content existing in a porous building material; is used in the biohygrothermal model to characterize the moisture storage capacity of the inside of mould fungus spores.

Morphological
Concerning the external morph.

Mycelium
Totality of fungal hyphae.

Mycology
The branch of biology that deals with the study of fungi.

Mycoses
Parasitic infestation of the human body with fungi.

Mycotoxicoses
Intoxication caused by mould fungi.

Pathogenic
Morbific, nosogenetic.

Psychrophilic
Preferring the cold.

s_d value

Diffusion equivalent air layer thickness; used in the biohygrothermal model to describe the diffusion capacity of the spore septum of mould fungus spores.

Spore germination time

Period until the development of the germ tube becomes visible under the microscope.

Sporulation

Spore formation or dissemination of spores.

Substrate category

Division of the substrates (building materials, contamination) into different groups which special isopleth systems have been developed for.

Taxonomy

Classification of the living beings into a relationship system.

Time of Wetness (TOW)

Number of hours of high humidity per day, referring to 24 hours.

Water activity

Water which is freely disposable for the mould fungus, i.e. it is not chemically combined.

Xerophilic

Chersophilous, drought resistant.

Zygomycetes (phycomycetes/zygospore fungi)

Lower fungi (e.g. mould on bread).

List of symbols

Latin symbols

a,b	[-]	conversion coefficients
A_{Sp}	[m^2]	spore surface
a_w	[-]	water activity
$dH/d\vartheta$	[$J/(m^3K)$]	differential heat storage capacity of the moist building material
dM/dt	[-]	time-dependent mould index
d_{Sp}	[m]	spore diameter
D_{Spw}	[m]	spore septum thickness
$dw/d\varphi$	[kg/m^3]	differential moisture storage function of the building material
D_φ	[kg/(ms)]	liquid transport coefficient of the building material
f_R	[-]	non-dimensional temperature difference ratio
g_v	[$kg/(m^2s)$]	vapour diffusion flow density
g_w	[$kg/(m^2s)$]	liquid transport flow density
H	[J/m^3]	total enthalpy
$h_{i,e}$	[$W/(m^2 K)$]	heat transmission coefficient, inside and outside
h_v	[J/kg]	specific evaporation enthalpy of the water
$k_{1,2}$	[-]	correction factors in the Viitanen model
MI	[-]	mould index in the Viitanen model
p_{sat}	[Pa]	saturation vapour pressure
q	[W/m^2]	heat flow density
R_{si}	[$(m^2K)/W$]	inside heat transmission resistance
s_d value	[m]	diffusion equivalent air layer thickness
S_h	[W/m^3]	heat source or sink
S_W	[$kg/(m^3 s)$]	humidity source or sink
SQ	[-]	surface quality (0 = sawn after drying, 1 = chamber dried; in the Viitanen model)
t	[h]	time

t_m	[h]	duration until the mould index 1 is reached (in the Viitanen model)
t_v	[h]	duration until the first mycelium growth is perceptible with one's eyes (in the Viitanen model)
U	[W/(m² K)]	heat transition coefficient
V_{Sp}	[m^3]	spore volume
w	[kg/m³]	moisture content of building material
W	[-]	species of wood (0 = pinewood, 1 = whitewood; in the Viitanen model)
dW/dt	[mm/d]	mycelium growth rate

Greek symbols

δ_p	[kg/(msPa)]	water vapour permeability of the building material
ϑ	[°C]	temperature
ϑ_{Si}	[°C]	temperature of internal surface
ϑ_{Ai}	[°C]	temperature of indoor air
ϑ_{Ao}	[°C]	temperature of outside air
Θ	[-]	non-dimensional temperature difference ratio
λ	[W/(m K)]	heat conductivity of the building material
μ value	[-]	water vapour diffusion resistance coefficient of the dry building material
φ	[%]	relative air humidity or relative humidity
φ_{crit}	[%]	relative air humidity from which on mould fungus growth on wood samples is possible (in the Viitanen model)

Mathematical symbols

d	operator for complete differential
∂	operator for partial differential

Δ	difference operator
∇	vector operator

List of abbreviations

ATP	Adenosine Triphosphate
BRI	Building Related Illness
DIN	Deutsches Institut für Normung (German Institute for Standards)
DNA	Desoxyribonucleic acid
EN	European Standard (Europäische Norm)
ESP-r	Environmental Systems Performance research
EWT	Soil-Air Heat Exchanger (Erdreich/Luft-Wärmetauscher)
IBP	Fraunhofer Institute for Building Physics
CFU	Colony forming units
LGA	Landesgesundheitsamt (Regional Public Health Department)
LIM	Lowest Isopleth for Mould
LIM_{Mat}	Lowest Isopleth for Mould for substrate groups
MI	Mould Index
MVOC	Microbial Volatile Organic Compounds
M.-%	Mass percent
PE	Polyethylene
RNA	Ribonucleic acid
SBS	Sick Building Syndrome
TOW	Time of Wetness
vol.-%	Percent by volume
ETICS	Exterior Thermal Insulation Composite System
WHO	World Health Organisation
WSchV	Thermal Insulation Regulations (Wärmeschutzverordnung)
WUFI	Transient Heat and Moisture Transport (Wärme- und Feuchtetransport instationär) (calculation program)

Abstract

Life on earth would not be conceivable without fungi, bacteria and other microorganisms. These organisms are responsible for the fast decomposition of dead material, splitting it up into its components and thereby giving it a new access to a further life cycle. Therefore microorganisms as fungi and bacteria are important components of our ecosystem. In buildings, however, favourable growing conditions for mould fungi can also occur and cause fungus infestation. Despite the quality of house building having improved over the last decades, especially by measures aiming at the reduction of heat losses due to transmission and ventilation, the number of reports on building damages caused by microorganisms, especially by mould fungi is still increasing. The “Third Report on Building Damages” by the Federal Government of Germany in 1996 estimated the costs resulting from mould fungi damages to amount to more than 200 million Euro per year. Different causes, as for example the critical combination of the airtight construction method with insufficient ventilation of the building are given as reasons for the recent increasing occurance of mould fungi in dwellings. Whereas before the energy crisis in the 1970’s regulating the temperature was mainly operated by opening the windows, today, because of energy saving reasons, airing is not done as frequently. Especially the unintentional ventilation due to leakages was reduced considerably. As a result the air humidity in rooms rises. Thereby mould fungi do not only occur on the inside surface of external building components, but even inside construction parts.

The danger for the occupants of dwellings lies in the settling and spreading of pathogens (disease causing agents) through microorganisms. Therefore, consequent measures have to be taken to avoid health dangers that come from mould fungi on the surface of building components. For example, when selling a building in the USA proof has to be furnished guaranteeing that the dwelling is free of the mould fungus *Stachybotrys atra*. In comparison to health aspects, building damages caused by mould fungi – i.e. the

destructive effect the fungi have on building materials, like bio-corrosion or bio-fouling – only is of minor importance. For that reason the scientific paper on hand does not deal with building damages nor with legal problems ever occurring in this context.

In order to avoid the mould fungus formation in buildings, a strategy has to be set up that focuses on the growth conditions for mould fungi and also considers the complex transient processes of building physics. The application of biocides is always accompanied by additional health risks, especially when used indoors, and moreover can prevent the formation of mould fungus only over a limited period of time. Moreover, biocides often have a very selective effect, so that other fungi or microorganisms can spread instead. Besides a considerable limitation for the selection of biocides is to be expected within latest EU directives. A prerequisite for preventing mould fungus without the use of biocides is the knowledge of the boundary conditions under which fungus growth takes place. In reference to the boundary conditions for the growth of fungus it turns out that the decisive parameters of influence like temperature, humidity and substrate have to be available over a certain period of time simultaneously in order to enable the formation of mould fungi.

The presently common valuation methods for the growth of mould fungi do not, or only indirectly, take into account the transient boundary conditions. Whereas in German publications mainly the relative humidity is given as only criterion for mould fungus formation, the relative humidity in dependence on the temperature is seen as a cause by international experts. These characteristics usually do not allow any greater differentiation regarding the influence of the substrate, i.e. of the building material or the degree of contamination. Therefore, the main focus of this scientific paper on hand is to develop a planning instrument from the point of view of an engineer that aims at predicting the formation of mould fungus. This instrument is provided for being used by building physicists or consulting offices acting in the field of the building sector. This is also the reason for the deliberately chosen

simple approach employed in this interdisciplinary scientific paper. A biohygrothermal procedure was developed that makes it possible to predict mould fungus formation and is based on the comparison of the three already mentioned biological prerequisites for the growth of mould fungi and the transient growth conditions occurring in buildings. This procedure consists of two consecutive predictive models, i.e. the Isopleth model and the transient Biohygrothermal model. The Isopleth model makes it possible to determine the germination time of the spores and the mycelium growth on the basis of different isopleth systems that also regard the influence of the substrate for predicting the formation of the mould fungus. The isopleth system describes the hygrothermal prerequisites for the growth of the fungus. It consists of a boundary line that is dependent on the temperature and on the relative humidity regarding fungus activity, and of isolines that indicate spore germination time when spore germination is to be predicted, and stand for growth per time unit when the description of the mycelium growth is concerned.

Significant differences exist among the various fungus species. Therefore, when developing common isopleth systems only fungi were regarded that are dangerous to human health and also can be detected in buildings. Quantitative statements on the growth conditions temperature and humidity will be set up for these more than 150 species that fulfil both features, as far as they are given in literature. To further clarify the differentiation of the life phases of the mould fungi, the data for spore germination and mycelium growth will be given separately. In order to differentiate the mould fungi according to the health dangers they may cause, the so called hazardous classes will be defined as follows:

A. Fungus or its metabolic products are highly pathogen; they are not allowed to occur in used dwellings.

B. Fungus is pathogen when exposed over a long period and may cause allergic reactions.

C. Fungus is not dangerous to health, fungus formation however, may cause economic damage.

Classifying the fungi into three hazardous classes it occurs that the values of class C are only slightly different from that of class B. Therefore it is sufficient to differentiate within the Isopleth model only between the hazardous class A and a combined class B/C.

Within the Isopleth model the prerequisites for the growth of mould fungi in dependence of temperature and relative humidity are stated for the above mentioned hazardous classes at first for the optimal culture medium. The isopleth systems were developed for assessing the spore germination as well as the growth of the myceliums. They are based on measured biological data and also consider the growth conditions of all fungi of one hazardous class. The resulting lowest boundary lines of possible fungus activity are being called LIM (Lowest Isopleth for Mould).

In order to regard the influence of the substrate, that is the building materials or possible contamination, on the formation of mould fungus, isopleth systems for four categories of substrates were suggested that could be derived from experimental examinations. For this purpose four categories of substrates were determined and different building materials assigned:

Substrate category 0: Optimal culture medium

Substrate category I: Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, material for permanently elastic joints;

Substrate category II: Building materials with porous structure such as renderings, mineral building material, certain wood as

well as insulation material not covered by I;

Substrate category III: Building materials that are neither degradable nor contain any nutrients.

An individual isopleth system will only be set up for the categories 0, I and II, whereas in the building category 0 the isopleth systems for optimal culture media are applied. For the substrate category III no isopleth system is given since it can be assumed that formation of mould fungi is not possible without contamination. In case of considerable contamination, substrate category I always has to be assumed. The basic principle of the new method and of defining the building material categories is to assume a worst case scenario, therefore always being on the safe side in respect of preventing the formation of mould fungi. To what extent correcting the isopleth systems for individual building material categories towards increased relative humidity can still be done with a clear conscience, has to be proved by further measurements.

Altogether, the following four isopleth systems were developed for the spore germination and for the growth of the myceliums individually. Every one of the systems is valid for a whole group of mould fungi and takes into account, next to optimal culture media, also building material:

a) Isopleth systems for the hazardous class B/C (LIM B/C): systems referring to optimal culture medium. Therefore they provide the smallest prerequisites for the growth of fungi as far as relative humidity is concerned. They build up the limit for the growth of all species of fungi. This means that fungal growth for fungi of hazardous class A can also be excluded when the boundary conditions exclude the growth of fungi of hazardous class B/C.

b) Isopleth systems for the hazardous class A (LIM A): analogous to a), but only valid for all fungi of the hazardous class A.

c) Isopleth systems for the substrate category I (LIM_{Mat} I): valid for all mould fungi occurring in the building. In respect to the culture medium they do not refer to the optimal medium but to materials of category I.

d) Isopleth systems for the substrate category II (LIM_{Mat} II): analogous to c), but only valid for all materials belonging to the substrate category II.

For transient boundary conditions of temperature and relative humidity, either spore germination time or the mycelium growth can be determined with the help of these isopleth systems. The assessment of spore germination on the basis of the Isopleth model has the disadvantage that an interim drying out of the fungi spores cannot be taken into account in case of occurring transient microclimatic boundary conditions. Therefore in these cases, this process will more often predict the germination of spores than the Biohygrothermal model. In order to describe the mode of action for the fundamental means of influence on the germination of spores, i.e. the humidity available at certain temperatures, a new Biohygrothermal model was developed. This model makes it possible to calculate the moisture balance of a spore in dependence of the transient boundary conditions, thus even to consider interim drying out of the fungus spores.

The Biohygrothermal model for predicting the germination of the spores is based on the fundamental idea that a fungus spore has a certain osmotic potential because of the salts, sugar and further substances inherent in the spores. With the help of this osmotic potential spores can absorb water existing in the environment, i.e. in materials as well as in the air. This potential computationally is described by means of a moisture retention curve. A moisture retention curve for bacteria spores, found in literature, is used with slight modifications. The absorption of humidity through the spore septum is being described by a diffusion approach in the model. This simplification is justifiable because the humidity absorption always occurs isothermal, due to the small geometrical size of the mould fungus spore.

Furthermore the spore septum receives a humidity-dependent s_d value that is being iteratively adjusted by comparison of the calculated spore germination times with those given in the isopleth systems.

The Biohygrothermal model assumes that humidity absorption first takes place by means of diffusion, until a certain moisture content inside the spore is reached that is needed for starting the metabolism. From this point on the fungus can regulate its metabolism, if necessary independent of the surrounding conditions. Nevertheless, the substantial regulation mechanism still remains generally unknown and therefore cannot be described in an exemplary manner nor in terms of physics. However, this is not necessary since it is being assumed in the model that the critical moisture content that makes biological activity only possible, must not be passed. This critical moisture content is being fixed by the isopleth systems for the spore germination as follows. Depending on the temperature, the lowest relative humidity at which the spore germination takes place can be read off the respective LIM curves. With the help of the moisture storage function assumed for the inside spore, the corresponding critical moisture content can be calculated. Furthermore, the LIM curves in the isopleth systems of the appropriate categories of building materials have to be used when setting the critical moisture content.

In order to consider possible influences of the substrate, the s_d values of the spore septum were adjusted in that manner that the spore germination times measured in the Biohygrothermal model correspond with those taken from the isopleth systems in the building material categories I and II. By adjusting the s_d values of the spore septum as well as by slightly raising the moisture retention curve in the upper humidity range, a model spore can be stated that is valid for all of the three building material categories.

In order to get the transient conditions for temperature and relative humidity occurring in buildings, different possibilities will be presented. In case no measured values are on hand, modern hygrothermal calculation methods (i.e.

the program WUFI) can be used that take into account all important physical effects when calculating the hygrothermal conditions in one and two-dimensional structures. The assessment of the spore germination will be done directly for the microclimate on the surface. The hygrothermal conditions in 1 to 3 mm depth also should be referred to for the mycelium growth. This can also be done in a very simple manner with the help of the WUFI program. Three-dimensional structures can be assessed e.g. by using the appropriate calculation programs, like finite-difference-programs. The transient hygrothermal boundary conditions determined at the corresponding places on or within building components serve as input parameter for the Biohygrothermal model.

The biohygrothermal process is being validated by observation of plausibility, sensitivity analyses as well as the comparison with the results of laboratory experiments, experiments of outdoor testing sites and measurements in occupied dwellings. In all cases great correspondence between the results of the predictive models and the measurements and observations in practice is being observed. Since the material parameters for the Biohygrothermal model are in some aspects only adjusted or could only be assumed from experiments with spore-forming bacteria, they will have to be furthermore supported by specially selected biological experiments. Comparing the Biohygrothermal model with previously standard guidelines, preventive strategies and other predictive methods, it is shown that the Biohygrothermal model is by far exceeding the state of the art. Furthermore, the developed procedure is being employed in various typical examples. Based on these, conclusions for the prevention of mould fungi are being drawn.

1. Background and goal

Life on earth would not be conceivable without fungi, bacteria and other microorganisms. These organisms are responsible for the fast decomposition of dead material, splitting it up into its components and thereby giving it a new access to a further life cycle. Therefore, microorganisms as fungi and bacteria are important components of our ecosystem. Their properties are specifically used in some applications of process engineering, for example for exhaust air cleaning [27] by means of bio-filters or bio-washers as well as for sewage purification and the rehabilitation of loaded soil.

In buildings, however, favourable growing conditions for mould fungi can also occur and cause fungus infestation (e.g. [54, 98]). Despite the quality of house building having been improved over the last decades, especially by measures aiming at the reduction of heat losses due to transmission and ventilation, the number of reports on building damages caused by microorganisms, especially by mould fungi, is still increasing (e.g. [99]). The “Third Report on Building Damages” by the Federal Government of Germany in 1996 [26] estimated the costs resulting from mould fungi damages to amount to more than 200 million Euro per year. Different causes, as for example the critical combination of the airtight construction method with insufficient ventilation of the building are given as reasons for the recent increasing occurrence of mould fungi in dwellings. Whereas before the energy crisis in the seventies regulating the temperature was mainly operated by opening the windows, today, because of energy saving reasons, airing is not done as frequently. Especially the unintentional ventilation due to leakages was reduced considerably. As a result the air humidity in rooms rises. Thereby mould fungi do not only occur on the inside surface of external building components, but even inside construction parts (please see for example [70]).

The danger for the occupants of dwellings lies in the settling of pathogens

(disease causing agents) through microorganisms. Therefore, consequent measures have to be taken to avoid health dangers that come from mould fungi on the surface of building components. For example, when selling a building in the USA proof has to be furnished guaranteeing that the dwelling is free of the mould fungus *Stachybotrys atra*. In comparison to health aspects, building damages caused by mould fungi – i.e. the destructive effect the fungi have on building materials, like biocorrosion or biofouling [143] – only is of minor importance. For that reason the scientific paper on hand does not deal with building damages nor with legal problems ever occurring in this context (compare e.g. [56]).

In order to avoid the mould fungus formation in buildings, a strategy has to be set up that focuses on the growth conditions for mould fungi and also considers the complex transient processes of building physics. The application of biocides is always accompanied by additional health risks, especially when used indoors, and moreover can prevent the formation of mould fungus only over a limited period of time. Furthermore, biocides often have a very selective effect, so that other fungi or microorganisms can spread instead. Besides a considerable limitation for the selection of biocides is to be expected within latest EU directives. A prerequisite for preventing mould fungus without the use of biocides is the knowledge of the boundary conditions under which fungus growth takes place. Therefore, the aim of this paper on hand is to develop, validate and apply exemplary a new method that makes it possible to predict mould fungus formation, by comparing the growth conditions with the hygrothermal growth conditions in buildings. Figure 1 shows in this context a schematic diagram of the methodical procedure. The growth and spreading of mould fungi mainly depends on the climatic boundary conditions at the surfaces of construction parts and also inside these constructions. The decisive parameters are temperature, relative humidity and a corresponding substrate.

Based on the transient hygrothermal conditions known from measurements or calculations in building physics, and based on the material properties – in

their meaning as growth prerequisites – it is the aim of the new prediction method to deduce statements of what boundary conditions are needed by a fungus to grow and under which conditions there is no danger of fungus growth. Furthermore, the method should allow to make comparative, qualitative statements regarding in what way one can expect the growth of the fungus, i.e. the mycelium growth, to continue, in case of a spore germination, under different hygrothermal conditions.

Therefore, the main focus of this scientific paper on hand is to develop a planning instrument from the point of view of an engineer that aims at predicting the formation of mould fungus. This instrument is provided for being used by building physicists or consulting offices acting in the field of the building sector. This is also the reason for the deliberately chosen simple approach employed in this interdisciplinary scientific paper. The calculation program WUFI [76] as a modern hygrothermal calculation method allows to determine the transient courses of temperature and relative humidity at surfaces of building components as well as inside these parts for different geometries. WUFI has been validated well even experimentally by extensive investigations (e.g. [65] and [66]). Since the WUFI program was developed for hygrothermal calculations of building materials and components, biological data can only be used after having been processed adequately. That means that this scientific paper must combine the biological model part (hereinafter called Isopleth model) and the hygrothermal model part to a „biohygrothermal master model“.

2. Evaluation of literature

To reach the goal described above one first has to get a general idea of the current state of knowledge in the biology field of mould fungi, clarify the growth conditions and discuss the causes of their occurrence in buildings. After that, when evaluating the literature, the latest developments in hygrothermal calculation methods are explained and previous as well as

current standard guidelines and safety concepts regarding the formation of mould fungi are dealt with.

2.1 Mould fungi

In order to be able to prepare the growth conditions of mould fungi for the above mentioned prediction model, one has to analyze systematically the species that can be detected in buildings as well as possible dangers to human health resulting from that.

2.1.1 Overview

In contrast to algae and lichen, mould fungi do thrive also under unfavourable ambient conditions. Therefore, they are often called primary colonizer. To get an idea of the geometrical dimensions of fungal hyphae and spores in comparison with bacteria and cells of higher plants, please see Figure 2 showing the respective differences in size [116].

Definition of the mould fungus term

The colloquial German term „Schimmel“ (mould) goes back to the Old High German and has the same root as the German word „Schimmer“ (glimmer) [102]. Mould fungi are defined in the main by the following criteria [102]:

- mould fungi have a cotton wool type mycelium,
- they grow on solid culture media,
- they get nutrients by decomposing dead organic substances,
- reproduction takes place mainly asexually.

With that, however, an exact classification as defined by biology is not possible. Consequently, mould fungi can be found in the biological taxonomy in different classes. Classification into divisions, classes, orders etc. is done with regard to the morphological structure and on the basis of the teleomorph and anamorph (sexual and asexual reproduction) [40]. Figure 3 shows the presently customary fungi classification [125]. Mould fungi can be found in the following classes:

- zygomycetes

- ascomycetes and

- deuteromycetes (Fungi imperfecti).

Let's mention at this point an odd fact that often leads to mistakes, above all by experts who do not have any qualification in biology: Since the sexual reproduction of many species takes place under special ambient conditions only, the result is that one and the same fungus may be registered under two different names. For example, an existing fungus is called *Aspergillus repens* (class of deuteromycetes) when its anamorph occurs whereas the same fungus in its teleomorphic stage is known as *Eurotium repens* (class of ascomycetes).

Occurrence

The natural habitat of mould fungi are dead plants on the soil. So they can be found in composting plants, garbage and bio containers and near indoor plants. Therefore, it is no wonder that spores of mould fungi can be detected ubiquitously, that means at all places and in any season, although the measured spore concentrations of the outside air depend on seasonal and daily cycles [80, 135], as shown in investigations of the spore concentration in the outside air carried out for some North German places [139]. Hence, when measuring the indoor spore concentration (please see e.g. [101]), one

should also include the spore concentration of the outside air in the evaluation. The spore concentration is usually indicated in „colony forming units per volume“ (CFU/m³). Influence factors of the seasonal cycle as stated by Takahashi [129] are precipitation, mean monthly temperature and relative humidity, solar radiation, wind velocity and the barometric pressure. Therefore, it is no wonder that different authors make different statements concerning the maximum outer spore concentrations [87]. If, however, measurements in rooms show a spore concentration which is much higher than that in the outside air, there is in all probability a mould fungus growth in the dwelling, for example on indoor plant soil or even on building components, the cause for that.

2.1.2 Mould fungi in construction

This scientific paper on hand will deal only with mould fungi occurring in buildings. To infer the most important species in buildings that can be cultivated on standard media, from the more than 100,000 different species, essential passages in literature were evaluated in [55] and the results compiled. An overview of building materials that are often infested by mould fungi as well as the species involved are shown in Table A in the Appendix. Table 1 shows about 200 species occurring in buildings. This list contains those species that the various authors [12, 37, 39, 52, 81, 89, 97] and also the new draft of DIN 4108, part „Mould fungi“ [21], consider to be representative ones, that means they do occur in buildings quite often. It is surprising that only few species are mentioned by several authors in common. The reason for such discrepancies probably lies in the applied methods of collection, the different buildings, the humidities and temperatures within these buildings and finally also in the different geographical and seasonal boundary conditions. That’s the reason why it seems to be necessary to consider the growth conditions of all fungi mentioned in Table 1 in the prediction method, provided that corresponding data is existing.

2.1.3 Health hazard

It is a generally-known fact that fungi can cause diseases to human beings (e.g. [17, 59, 94]). As also indicated in Figure 1, it is necessary to assess the importance of various species with respect to health exactly so that suitable mould fungi are selected for the model development. For this purpose, it will be explained first of all which diseases are possibly to be expected and whether certain standard values for spore concentrations in rooms can be taken into account. Based on this, all fungi occurring in buildings will be simplistically divided into several hazardous classes.

Table 2 shows an overview of possible human diseases caused by mould fungi according to [32, 102, 113, 129]. On the whole there are three different fundamental kinds of diseases which are explained in the following:

Mycoses

A mycosis is the fungoid growth on a human host. In medicine, the name of the disease is made up of the fungus name and the ending -osis (from mycosis). The most widespread diseases are aspergilloses and penicillioses. Usually, mycoses do not represent a threat to human's life; but in case the patient has an immunodeficiency, they might become a serious danger. Let's mention at this point the so-called „Pharaohs' curse" when pulmonary mycoses took a fatal course. These are the organs that are infested preferably: skin, respiratory organs, eyes but also heart, liver, kidney and the digestive tract. Three causes are mentioned by Reiß [102]:

- Exposure at work: working with fungi-containing material, for example fungal elements in the dust of cereals, hay and straw, but also when treating mouldy wood.

- Accidental exposure: take-up of fungi-containing material through constructional defects, for example ventilation of dayrooms by mouldy air-conditioning systems, moisture in living quarters or through contaminated food, rubbish and dirt.

- Inconspicuous constant exposure: in the domestic environment, for example indoor plant soil or pets.

The most important mould fungus species causing mycoses are [102]: *Absidia sp., Aspergillus sp., Basidiobolus ranarum, Cephalosporium sp., Cladosporium sp., Fusarium sp., Mortierella sp., Mucor sp., Penicillium sp., Rhizopus sp., Scopulariopsis sp*. and *Verticillium sp.*

Mycotoxicoses

Mycotoxicoses are intoxications through toxic-active substances being produced by fungi by means of their metabolism. It is assumed that mould fungi produce such substances so as to assert themselves better against rival species. Toxins concerned here are aflatoxin and ochratoxin A, patulin, citrinin, citreoviridin, sterigmatocystin and mycophenol acid [102, 122]. These substances are mainly intaken by mouldy foodstuffs. But aflatoxins for example may get into the blood circulation also when inhaling contaminated dust and spores. Due to strict provisions concerning the handling of foodstuffs, acute intoxication signs have become rare in industrial states. More critical are here the chronic intoxication signs since the human body is not able to decompose and excrete these toxins. The most widespread chronic disease is the primary liver cancer (hepatocellular carcinoma). According to Reiß [102] about one million persons per year come down with that disease; one estimates that at least 200,000 persons per year all over the world die of it.

Toxic responses because of inhaling spores are described at high concentrations > 10^8 CFU/m³ and thus, they occur only at workplaces with

high loads of dust. *Stachybotrys* conidia having a high toxin content, show toxic influences on the immune system even from concentrations of 10 CFU/m³ on [124]. Mould fungi producing toxin are *Aspergillus sp., Penicillium sp., Fusarium sp., Cladosporium sp*. and *Stachybotrys sp.*

Allergies

Allergies are due to an excessive reaction of the immune system. The various allergy forms are divided into four types, depending on the immune reaction they cause [50, 87, 102]:

- Type 1 allergies caused by fungus allergens appear either as allergic rhinitis or as asthma. Allergic reactions, also allergies of the respiratory tract, proceed in two phases. The early phase sets in within minutes; the release of mediators (e.g. histamine from parent cells) is typical of this phase. 3 to 4 hours after inhaling the allergens, the late reaction takes place as a result of cell reactions to the mediators produced in the early phase.
- Type 2 allergies are reactions of antibodies and antigens on cell surfaces. This type of allergy is not caused by inhalation allergens but by oral intake, for example. Since inhalation allergens do not cause a type 2 reaction, this allergy type is not treated more detailed in this paper.
- Type 3 is caused by an immune complex formation between antigen and antibody. This happens approx. 4 to 6 hours after exposure; so it is a late reaction.
- Allergy type 4 is defined by a reaction of sensitised T-lymphocytes with an allergen. This takes place 24 to 48 hours after antigen contact, so a delayed reaction is typical of this type.

Mould fungi can cause inhalation allergies. It is not the mycelium which plays the decisive role but the spores. Many fungus spores have a size of only 2 to 5 µm and thus, they get into the bronchial tubes and can cause asthma.

Particles having a diameter of more than 10 µm are kept back by the mucous membrane of the nose and the pharynx and can cause allergic rhinitis. Typical allergic clinical characteristics that occur most frequently are the following:

- conjunctivitis,
- allergic coryza (rhinitis),
- inflammation of the respiratory tract (bronchitis),
- spell of breathlessness (bronchial asthma),
- skin eczema (atopic eczema, neurodermitis) and
- nettle rash (urticaria).

Sick Building Syndrome (SBS) and Building Related Illness (BRI)

Terms like SBS and BRI are mentioned more and more often in the context of mould fungi and therefore, they are explained here briefly. Sick Building Syndrome (SBS) and Building Related Illness (BRI) respectively are several nonspecific symptoms (e.g. mucosal irritations, smarting eyes, repeated common colds, but also fatigue and weakness of concentration) that arise when persons stay in certain buildings, without finding a clear cause. Factors of influence indicated are not only viruses, pollen, mites, nitrogen oxides, carbon monoxide, ozone, radon, emissions from building and facility materials and electromagnetic fields but also „Microbial Volatile Organic Compounds“ (MVOC) and fungus spores. The dangers caused by fungus spores are described above. McGrath [86] shows a connection between increased indoor concentrations of penicillium spores and SBS.

As the name already indicates, MVOC are volatile, organic compounds (alcohols, ketones, aldehydes, terpenes and aromatic compounds) that are formed among others also by fungi. Moisture and available food do influence the growth and with that also the production and composition of MVOC. One single MVOC is no sufficient criterion to prove microbial infestation at

building materials [62]. Nevertheless, high MVOC concentrations can be perceived also with the human nose. This makes itself felt by a musty, earthy smell which may indicate a mould fungus damage at an advanced stage.

Guidelines for admissible spore concentrations

In buildings, the transmission way “air” is the only one that plays a role with regard to the health hazard through fungi. Therefore, it is important to know what are the critical concentrations in rooms. However, there are no exact statements existing about which concentrations of fungoid aerosols (spores, mycelium containing dust, volatile microbial substances) do represent a hazard to health. Many recommendations for the assessment of fungus spore load indoors are based on values occurring in rooms that are free from fungus spores and not on data describing the influence on health. That is the reason why the instructions of legal directives do often differ widely from each other. An overview of these guidelines is given by Rao [97]. According to that, the recommendation by the World Health Organization (WHO) declares pathogenic and toxic fungus species not to be acceptable indoors. A concentration of ≤ 150 CFU/m³ is considered to be normal, if it is made up of a mixture of different fungus spores, and ≤ 500 CFU/m³, if they come from *Cladosporium* and other fungi usually occurring in the outside air [97]. As for the building practice, Senkpiel [123] states the experience value of 100 CFU/m³ over the outside air to be a good benchmark as an indicator of an intramural concentration.

As explained under 2.1.1, there are considerable fluctuations in spore concentrations in the outside air that may lead to changes also in living quarters, due to the air change in the building; thus, it is no longer noticeable in the end to what extent a mould fungus infestation in rooms contributes to an indoor concentration. Altogether, the conclusion has to be drawn that for the development of a model, hypotheses concerning an admissible spore concentration indoors are not suitable but that one has to assume that there must not be any fungus growth in buildings at all, if possible.

Classifying the fungi regarding their hazard to health

Table B in the Appendix lists some human pathogenic and allergenic mould fungi and the diseases caused by them [55]. To assess individual species regarding their hazard to health, the “Landesgesundheitsamt” (Regional Public Health Department) in Stuttgart [81] has made the following division which has not yet been published, though (group 1 to 3):

Group 1: Fungi of that group should not predominate indoors - long-term call for action.

Group 2: Fungi of that group should not repeatedly occur indoors - medium-term call for action.

Group 3: No fungi of that group must exist indoors - immediate call for action.

Table 1 shows the assignment of the single fungi to these 3 groups. Group 2 contains 15 fungi. 10 species are assigned to group 3, only few fungi are assigned to group 1.

2.1.4 Growth conditions

If the ambient conditions are optimal, like in a liquid complete medium for example, one can set an inherent law for the growth of mould fungi being divided into 6 successive phases:

A to B: initial growth-lag
B to C: acceleration phase
C to D: log-growth phase
D to E: delay phase

E to F: stationary phase
F to G: declining phase of growth.

Figure 4 shows the schematic diagram of this growth curve according to [102]; the number of germs is drawn logarithmically against the time. In the first phase, the initial growth-lag, the cells do increase, their metabolism is activated, but in the main the number of cells remains constant. The duration of this phase depends on the temperature and the humidity at the spores. After that the acceleration phase takes place which is followed by the log-growth phase. In that phase, the fungus confines itself to the reproduction of its vegetative units and the production of bio-mass. If the reproduction rate is falling due to unfavourable ambient conditions like lack of nutrients, the delay phase is reached. Finally, the stationary phase takes place with the number of germs being constant, because the new formation and the dying off of the cells is balanced. Since the existing nutrients become more and more scarce and since toxic metabolism products are created, the fungus culture will die off after the stationary phase at least in its centre. The fungus' life is endangered, and so it will sporulate in this phase, thus to ensure its survival.

In the following, all parameters are listed that influence the fungus metabolism directly. The limits between which the life and survival of mould fungi happens, will be shown. Table 3 gives an overview of the most important factors influencing the growth of microorganisms.

Temperature

Since a multitude of biochemical transformations are involved in the growth and development processes of an organism, one has to expect a dependence on temperature regarding the growth and development of microorganisms. As we know from mycology, fungi grow from 0 °C on at an optimal growth temperature of more than 30 °C. From various literature data [9, 123, 128] the conclusion can be drawn that mould fungi are able to grow within a temperature range of 0 °C to 50 °C. It has frequently been observed

that fungi are usually more tolerant towards cold than to heat stress [102]. The food industry makes good use of this discovery. Spores and myceliums are almost completely destroyed by heating the product for a short time up to 80 °C. Some spores of *Aspergillus sp.* and *Penicillium sp.*, however, do resist even these hostile conditions [140]. These non-cryophilic species do also keep their germinability up to -10°C [116]. Since the temperatures inside building constructions or at internal surfaces usually are between 0°C and 30°C, temperature will never have any lethal effect on mould fungi.

The bio-mass production changes, depending on the temperature. In Figure 5 one can notice a clear optimum of the growth rate drawn in dependence on temperature [39]. Accordingly, a change in temperature has an effect on the metabolism. Strasburger [128] says that a certain minimum temperature has to be exceeded in order to set off a growth process, i.e. the enzymatic activity of mould fungi. From that point on, with the temperature rising further, one can observe an acceleration of the growth rate. It slows down just before reaching the ideal range. When exceeding the optimum, impeding influences can be noticed which finally lead to a discontinuance of growth. Heat for example does restrict biosynthesis and growth very strongly and may stop it because proteins (enzymes) denature [16].

However, a small temperature difference of few kelvin can decide in many cases whether a special species does grow or not. A survey of the temperature range as well as the respective optimum of some representative fungi can be seen in Figure 6. One cannot only notice the large range but also the differences between the single fungi. According to Ayerst [4] one has to assume an uncertainty of ± 2 K as far as data is concerned which describes the dependence of the growth on temperature. Furthermore, various authors often make different statements regarding the temperature range for one and the same fungus. Table 4 contains the minimum, optimum and maximum growth conditions for spore germination and mycelium growth as far as temperature, relative humidity and pH value is concerned.

Humidity

The decisive criterion for the growth of microorganisms is the humidity available to the mould fungus, which can be taken by the fungus not only from the substrate but also from the air, either in the form of water or water vapour (e.g. [1]). This moisture content is described in biology often as water activity – „a_w value" – and is directly connected with the relative humidity in the building material or at the surface [9]:

$$\varphi = a_w \cdot 100 \qquad (1)$$

with:

φ	[%]	relative humidity
a_w	[-]	water activity

Hereinafter, the term relative humidity is used. Bieberstein [9] emphasizes that the formation of mould fungi can take place at humidity values that are still far away from the status of humidity saturation. It is not only the spore germination and the mycelium growth that strongly depend on the humidity available (besides temperature and nutrients) but also the mycotoxin production [84].

Already in 1949, Snow [127] proposed a rough classification of fungi for the growth parameter humidity: xerophilic fungi are those ones that are able to grow below a relative humidity of 85 %; mesophilic fungi need 85 %, hydrophilic fungi grow from 95 % on only. Since this division is already more than 50 years old, one has to correct the limits downwards by approx. 5 to 10 %, thus taken new investigations into account [5, 39]. Each single fungus species has its particular, characteristic humidity range that allows the species to live and that determines among others the growth intensity, as it can be seen from the values in Table 4.

From the data indicated in Table 4 one can draw the conclusion that the limit of humidity under which there is no mould fungoid growth occurring in buildings, is a relative humidity of approx. 70 %. Xerophilic fungi certainly need a relative humidity of only 65 %, but not all species occur in buildings [146]. With the degree of humidity increasing, the probability of mould fungus formation increases as well. At a relative humidity of 80 % the growth conditions are achieved for nearly all species of mould fungi. A higher humidity is a growth condition for only few species, the optimal range of which lies between 90 % and 96 %. Furthermore, one can assume that only few mould fungi can survive in water in liquid form [102].

Figure 7 represents the growth rate of different xerophilic fungi in dependence on the relative humidity at an optimal temperature according to [48]. Similar to the behaviour in dependence on the temperature, one can also notice clearly that the growth depends on the relative humidity.

Combination of temperature and humidity

The growth conditions temperature and humidity have been treated separately so far. But it has to be taken into account that the position of the minimum and optimum relative humidities may change at different temperatures. The minimum values can be reached only at optimum temperatures [116]. Overlapping of these two influences results in lines of equal growth (isopleths), when drawn in a diagram. The lowest curve represents those conditions under which there is no spore germination or growth detectable any more, as shown in Figure 8. The increase of the humidity need at temperatures beyond approx. 30 °C can be explained by the temperature dependence of the activity of enzymes involved in the metabolism. When germination times and growth rates respectively are indicated in dependence on humidity and temperature, one talks about isopleth systems. Figures 9 and 10 show such representations for example for *Aspergillus restrictus* (on the left) and *Aspergillus versicolor* (on the right) based on data determined by measurements [126].

Substrate

Besides humidity and temperature, the nutrient content of the substrate on which the fungus grows, is the most important influence factor for mould fungus formation. Most of the tests at hand concerning the temperature- and humidity-dependent fungus growth were carried out in the laboratory. The culture medium used here usually is a complete medium that is an optimal substrate for fungi. In buildings, however, there are smaller amounts of nutrients available to the fungus, compared with the complete medium, and the nutrients may be more undegradable, depending on the substrate (for example building material or contamination). On the other hand, even small amounts of organic additives in building materials (e.g. in mineral plaster) are enough to make microbiological growth possible.

Apart from some mineral nutrients and trace elements, carbonaceous and nitrogenous nutrients are of paramount importance. With the help of their enzymes, fungi can decompose substrates and transform them into utilizable matters [88]. Table C in the Appendix represents some substrate constituents that can be used by mould fungi as nutrients [14, 102], split up by the speed of degradability into quickly, moderately fast and slowly degradable substances or molecules. If there are not enough nutrients available, the growth decreases.

Gertis, Erhorn and Reiß [29, 37, 103] had carried out extensive measurements concerning the susceptibility of building materials to mould fungus infestation. Regarding the influence of the culture medium, these measurements proved that also contaminations by dust, fatty matters etc. for example, do influence the growth decisively. Further researches showed that the properties of the surface are the decisive factors [37] for the beginning of the mycelium growth, and that only with the mycelium getting into the building material (max. some millimeters) there is an influence also by the subsoil. This can be seen especially at coats of paint and wall papers and is

confirmed by [1]. That means that contaminations by dust, fingerprints and air pollution (kitchen, residues from taking showers, etc.) or human perspirations are sufficient for the formation of a layer, even on „sterile“ media, which is thin but relatively abundant in substrate and on which spore germination and beginning mycelium growth may take place, even though slightly delayed.

Block [11] indicates a growth rate in dependence on the relative humidities applied on different materials such as leather, cheese, wool, wood, cotton and glass wool and states that the minimum relative humidities from which on the fungus grows, are different with the used „fungus mixture“, depending on the material. For example, at a temperature of 30 °C mould fungi grow on leather from 76 %, on wood from 80 %, on wool generally from 85 % and on cotton and glass wool from 92 % upwards. This indicates that, taking the complete medium curve as basis, the respective temperature-dependent minimum relative humidities shift to higher humidities, depending on the substrate.

Kruppa, Veer and Rüden [63] investigated the behaviour of microorganisms on the building materials plaster board, sandlime brick and concrete. For this purpose, they colonized bacteria as well as mould fungi and yeasts on these materials under normal and extreme conditions. On this occasion they found out that at different temperature conditions from 10 °C to 30 °C fungi can grow on building materials within three days even at a relative humidity of 70 %. However, it is not a first infestation of mould fungi which is concerned here but a well-developed biofilm on the building materials that might have contained a sufficient amount of nutrients.

The influence of various building materials was investigated in detail by Ritschkoff [107], too. The results in Figure 11 show exemplary the mould index (method to describe the mould fungus growth; cf. 2.4) depending on the time in weeks for different building materials at a relative humidity of 97 % and temperatures of 15 °C (above) or 23 °C (below). Depending on the

material used, there are different exposure times to reach a special mould index. In most of the cases, the mould fungus germination at mineral building materials needs a slightly higher relative humidity and longer exposure periods in the corresponding laboratory climate, compared with building products made of wood. The reasons mentioned for that are the organic constituents in the wood. Though the investigations carried out by Ritschkoff yield results that seem to be contradictory in part. For example, the growth curve for cement products in Figure 11 at a relative humidity of 97 % and 23 °C (lower illustration) lies under the curve with the same humidity but with a temperature of only 15 °C (upper illustration). Grant [39] does also state minimum relative humidities from which on growth takes place for different materials like malt agar, wall paper, wood and glass. Each measurement was taken at 12 °C and 25 °C.

Establishing criteria to assess different nutrients on and within building products as a prerequisite for the growth of mould fungi is absolutely required, since otherwise all statements of fungoid growth would refer to complete media and a realistic prediction of a possible mould fungus growth in buildings would not be possible.

Time

Most of the tests to determine the germination time and the growth speed respectively were carried out under stationary conditions. This might be sufficient for some industrial sectors (e.g. preservation of foodstuffs). In the civil engineering field, temperature and relative humidity are subject to regular fluctuations. That is the reason why, from the view of building physics, it is necessary that one can state how long and how often which humidity state may act on a building component (e.g. an internal wall surface), before a mould fungus is formed. Therefore, Gertis, Erhorn and Reiß [37] investigated the effect of transient climatic conditions on the growth of mould fungi. Figure 12 shows that testing plant for mould fungus tests at building and surface materials. By this measurement equipment one

can vary the parameters atmospheric humidity, air temperature, air speed, surface humidity and temperature. 7 different plasters, 2 wall papers as well as 3 dispersion paints were tested. The surface temperature at the samples was 14 °C and 18.5 °C respectively. The time course of the air humidity fluctuations was investigated in the following combinations:

I	95 % for 24 h/d	
II	95 % for 6 h/d	and 60 % for 18 h/d
III	95 % for 3 h/d	and 60 % for 21 h/d
IV	95 % for 2 h/d	and 60 % for 22 h/d
V	95 % for 1 h/d	and 60 % for 23 h/d
VI	95 % for 0.5 h/d	and 60 % for 23.5 h/d

The growth intensity of the mould fungus was evaluated according to a 5-stage classification, the definition of which can be seen in Figure 13. Here the areas infested with mould fungus on the material surface were assessed with regard to the growth intensity by means of a microscope, without determining the respective individual fungus species. Figure 14 represents growth intensities on different materials determined by measurements. When looking at gypsum or plaster board with woodchip wall paper or various coats of paint for example, one can notice that after a period of 6 weeks at 18.5 °C and a humidity load of 95 % for 6 hours a day, mould fungus infestation occurs without as well as with heavy contamination. With the daily humidity load being reduced to 1 or 3 hours, fungus growth takes place only with existing contamination. The variants provided with fungicides do not show any fungoid growth.

In comparison with the investigations carried out by Gertis [37], Table 5 contains a list of some literature data on the dependence of fungoid growth on time and special substrates. The individual data are explained in the following:

- In [147] Zöld states the number of daily hours when the mould fungus starts to grow at temperatures below 20 °C and relative humidities of more than 75 %. A range is regarded as safe, if, over a long period, the relative humidity of 75 % is not exceeded more than 8 to 12 hours per day, and if the limit of 75 % relative humidity is not exceeded more than 12 hours on 3 successive days. A state is described as critical when this limit is exceeded over a period of more than 12 hours on 5 successive days.

- Equal or a little smaller values for the daily time required for exceeding the relative humidity of 75 or 80 % are given by Cziesielski [15] and Richter [105]. But it is always emphasized that the stated condition for the relative humidity at the place of growth must last for 5 successive days.

- According to the TOW value definition (Time-of-wetness: hours of high humidity per time unit; see 2.4) by Adan [1], growth takes place, though delayed, if a relative humidity of at least 80 % is exceeded 4 hours a day.

The results of these investigations show that, depending on the hygrothermal boundary conditions and the material, different durations are necessary to enable mould fungi to grow. This implies that the calculation method to be developed for the prediction of mould fungus formation has not only to consider the influence of various substrates of building materials and contaminations but also transient boundary conditions.

Other factors of influence

Apart from the factors described above there are further ones influencing the growth of microorganisms such as pH value, salt content of the substrate, light, oxygen content, surface condition and biotic influences. In summary they may be assessed as follows:

pH value

For the assessment of the culture media quality, the pH value is another prerequisite for mould fungus growth. Figure 15 shows the range of this factor for different mould fungi, based on the data in Table 4. While the optimum growth range is at pH values between 5 and 7, pH values between 2 and 11 are tolerated in all by some single fungi [16]. Most of the species grow within a range of 3 and 9. Wall papers and coats of paint, for example, have a pH value between 5 (woodchip wall paper) and 8 (new color) [10]. On the other hand, there are various building materials like concrete for example that have pH values of more than 12; nevertheless, mould fungus growth even on these materials cannot be excluded, since only the pH value of the available culture medium is decisive. A sufficient amount of this culture medium does exist on nearly all component surfaces due to dust deposits. Furthermore, mould fungi are able to change the pH value of their direct environment in a way that it is favourable for their growth. This is done by activating the „proton pump“. The fungus releases various organic acids [16, 35] and with that, makes the extracellular space acid. For the mentioned reasons, the factor pH value is taken into consideration for the development of the model only indirectly by creating substrate groups.

Salt content of the substrate

The salt content of the substrate possibly has also an effect on the microbiological growth. However, there is no usable data about it currently existing in literature. This factor can therefore be considered in the following also only indirectly through various substrate groups.

Light

Mould fungi do not need light to grow [91]; this can be recognized by the fact that fungi grow also inside opaque building components. When excavating the Terra Cotta Warriors and Horses in China, Warscheid [142] found out that in some cases light even has an impeding effect. Therefore, it is not necessary to consider this factor as a growth condition.

Oxygen content

The oxygen content must be at least 0.14 to 0.25 % [55]. This concentration does exist on and in all building constructions. Below this value, some of the aerobic fungi may even change to fermentation [16, 87]. A sufficient oxygen content as a growth condition is therefore taken for granted.

Surface roughness

Microbial growth often occurs in zones where dust deposits do exist to a great extent. This is more often the case on materials with a high surface roughness or at places that are difficult to get to like corners and edges. But fungoid growth has been observed also on even surfaces. Therefore, it is of no use to quantify roughness as a growth condition. In connection with roughness, the porosity or the pore radius distribution of building materials is often indicated as factor of influence although its only effect lies in the possibility of storing moisture in the material. This effect is covered by the moisture storage function and is taken into account by means of the hygrothermal calculation methods presented under item 2.2.

Biotic influences

Biotics is the reciprocal influence of the fungi among each other and the competition with other microorganisms respectively. Since the essence of the prediction method is the prevention of a primary settlement of all fungi, biotic influences do not play any role.

2.1.5 Spore germination, mycelium growth and sporulation

The life cycle of a fungi colony can be divided into three phases, as illustrated in Figure 16. The first two stages of life (spore germination, mycelium growth) belong to the vegetative growth whereas the spore formation belongs to the reproductive phase.

Spore germination

Spores of mould fungi can be found more or less everywhere since they get to their place of activity with a mean settling velocity of only 0.1 cm/s [102] and through different transport ways like wind, humans and animals. Dissemination of spores is a perfect possibility of spreading genetic material. Depending on the fungus species, the spores can be unicellular or polycellular, can have different geometries and occur in different quantities. Most of the inside of the spores consists of cytoplasma, enriched with storage polymers, fats and carbohydrates. This viscous mixture having a moisture content of 10 to 20 M.-% (relating to the dry weight) [49] is surrounded by a permselective membrane and a more or less thick cell wall which is illustrated in the diagram of Figure 17. Most of the spores have a length of 2 to 20 µm and a density of 1.1 to 1.4 g/cm³ [102].

[7, 45, 83] mention moisture contents of 200 to 400 M.-% for the mycelium. As for the spores, only few data can be found in literature. [133] indicates for the fungus *Aspergillus fumigatus* moisture contents between 70 M-% or 52 M-% respectively for a 4- or 7-day old spore and 80 M-% at spore germination. Although it is not mentioned what ambient humidities were existing during this test, spores probably dry at first after sporulation, but then absorb humidity again for germination. The moisture content certainly depends on the specific nature of the fungus species and the age of the spores [133], but it can nevertheless be used as characteristic parameter when describing the germination. [49] as well points out that the spores increase their volume a little at germination and reach a moisture content of max. 60 to 80 M.-% (relating to the dry weight).

Since tests to determine the germination time of mould fungi are relatively time-consuming and since one cannot specify the beginning of growth exactly, detailed data are rare. Systematic investigations were carried out by Ayerst [4] and Smith [126] on complete media. The start of germination was defined by the development of the germ tube. For the purpose of perception,

the spores were projected onto a screen by an optical system similar to a slide projector. The germination times measured that way are shown in an isopleth system for spore germination in Figure 9 in dependence on temperature and relative humidity. The data found in literature concerning spore germination times of different fungi on optimum culture media (complete media) differ considerably from each other, as one can see in Figure 18. This can be explained by the fact that the test conditions are not standardized and different species are observed [146].

Mycelium growth

The mycelium growth of the fungus starts immediately after spore germination provided that the conditions are favourable. When indicating growth conditions, differences are made between the life stages spore germination and mycelium growth, as shown in Table 4. The humidity minimum values for spore germination are higher than those for vegetative growth, followed by sporulation [33, 84, 95, 96, 102, 108, 144]. This is quite useful since germination takes place only, if the fungus can continue to grow under these conditions (survival strategy).

For the description of the mycelium growth, one can find in literature data of growth rates in dependence on temperature and relative humidity, as illustrated in Figure 10 for 2 *Aspergilli*. Further isopleth systems of that kind describing the mycelium growth are outlined in the Appendix in Figures A to K. According to [63] mould fungi are able to survive, even if the temperature is considerably exceeded or if it falls below the reference value of this range over a longer period. That means that an existing contamination by microorganisms can be slowed down due to unfavourable growth conditions, or even stopped at best, but it cannot be destroyed. If the conditions are again favourable, growth starts again. That means that one should add the growth times or the progressing infested areas, when assessing the annual maximum mycelium growth at favourable growth conditions.

Sporulation

Sporulation (spore formation) serves for the further spreading of fungi tied to a habitat. Figure 19 shows a dense microbial growth of *Stachybotrys sp*. on a plaster board. The hyphae and the conidia can be seen clearly. When the growth conditions are sufficient, sporulation takes place after a certain stage of the mycelium growth. The mycelium does not die off after spore formation but continues to grow and forms spores again. If the living conditions get worse for further growth, spore formation increases. This is an important survival strategy by the fungi thus ensuring that a life cycle is not brought to an end without further spreading. That means that dissemination of the spores can happen relatively independent of the growth conditions. Since, moreover, spores are ubiquitous, the life stage of sporulation need not be considered, from the methodical view, for the development of a prediction method or prevention strategy concerning mould fungus formation.

2.1.6 The most important causes why mould fungi occur in buildings

Courts of law are often dealing with discussions on possible causes for mould fungus formation in buildings. Here is the question in the foreground whether the structural fabric, i.e. in the end the owner, or incorrect behaviour on the part of the user caused the fungus formation. Mould fungus formation can basically occur only, if all growth conditions described under item 2.1.4 are met with humidity being the most decisive factor. It is a well-known fact (among others [134]) that the causes for damages through humidity and mould fungi are above all the following:

- moisture production indoors,
- production of condensation water due to bad heat insulation, especially in the area of thermal bridges,
- insufficient heating,
- inadequate ventilation behaviour on the part of the occupants,

- leaks in the building wall
- penetration of driving rain
- as well as construction moisture.

In this connection it is no wonder that mould fungus formation does occur more often in old buildings than in new ones, above all, when new windows are installed but the facades are not redeveloped thermically. Due to the reduction of the infiltration air change caused by a higher tightness of the window joints, there are increased moisture loads in the rooms, since the airing behaviour of the occupants does not change in most of the cases. It was also found out that fungoid growth occurs more frequently in multiple dwelling units than in detached houses [30, 134]. To make a distinction between the single rooms, investigations in [28] and [100] are used. As shown in Table 6, bedrooms and children's rooms are by far affected most and moistureproof rooms like kitchens and bathrooms not that much.

Mould fungus formation occurs at building component surfaces as well as inside building components. It is often external walls obstructed by furniture for example, or building constructions with thermal bridges (above all windows) that are affected. In addition, constructions where humidity can accumulate within the building component (structures with trapped humidity or constructions that are vapour-proof on the outside) as well as building structures with interior insulation are endangered. Furthermore, infestation by mould fungi was detected also in technical systems. So, uninsulated cool pipelines may cause increased humidities in their environment or fungi grow inside the ducts of ventilation systems [91].

Building physical causes for mould fungi at component surfaces

Whether mould fungi occur on the room side of building structures depends on the existing surface temperature and humidity. These are on the other hand influenced by the special heat transition (described by the heat

transition coefficient), possible thermal bridges and the heat transmission resistances as well as the hygrothermal conditions existing in the room. Under stationary conditions, the surface temperature can be calculated as follows:

$$\vartheta_{Oi} = \vartheta_{Li} - U\, R_{si}\, (\vartheta_{Li} - \vartheta_{La}) \qquad (2)$$

ϑ_{Oi}	[°C]	Temperature of internal surface
ϑ_{Li}	[°C]	Temperature of indoor air
ϑ_{La}	[°C]	Temperature of outside air
U	[W/(m² K)]	Heat transition coefficient
R_{si}	[$(m^2$ K)/W]	Inside heat transmission resistance

Thermal bridges

Thermal bridges are characterized in winter by a surface temperature which is lower on room side than in the undisturbed area. The relative humidity increases at such places at constructional thermal bridges due to a locally limited increased U-value, in extreme cases up to the production of condensation water. This effect can be noticed also with geometric thermal bridges, as illustrated in Figure 20 by an external wall corner [60]. This figure indicates the internal surface temperatures existing at an outside air temperature of -15 °C in case of a post-beam construction with an U-value at the insulation of 0.5 W/(m² K) and of 1.0 W/(m² K) in the post area, and the resulting maximum admissible indoor air humdities. When these indoor air humidities are exceeded, at an assumed indoor air temperature of 20 °C, condensation water emerges. As it can be noticed, the lowest temperatures (marked by an arrow) at the wall surface do exist in the area of the geometric thermal bridge, i.e. in the room corner.

Increased heat transmission resistances

Furniture, curtains and the like are hardly a resistance for humidity. But due to the reduced convective and radiation-dependent heat transmission, the heat transmission resistances are increased and with that, also the relative humidities because of the temperatures getting lower. Figure 21 from [38] shows the surface temperatures of an outer corner with average thermal insulation and minimum thermal insulation respectively, in dependence on the distance from the outer corner. In one case, the corner is free (upper lines) and in the other case it is obstructed by furniture (bottom lines). On the right hand side one can see the relative indoor air humidity from which on condensation water may occur. Consequently, mould fungi can be found particularly behind cupboards and in corners, because they are able to grow already from a relative humidity of markedly under 100 %, depending on the temperature. To calculate the temperatures according to equation (2) the following heat transmission resistances are proposed in [110]:

Built-in cupboards:	R_{si} = 1.0 m²K/W
Free-standing cupboards:	R_{si} = 0.5 m²K/W und
Curtains:	R_{si} = 0.25 m²K/W.

Position of radiator

The position of the radiator in the room does influence the indoor temperatures, too. A difference of up to 8 K between air temperature and wall surface temperature can arise, as proved by a measurement carried out at the Fraunhofer Institute for Building Physics in [78]. Especially affected is the corner most distant from the radiator.

Moisture production in the room

The relative humidity arising at internal surfaces of external building components does not only depend on the temperature difference between indoor air and surface but above all on the moisture in the rooms. That humidity on the other hand mainly depends on the air change and the moisture production in the room. As shown in Table 7, the moisture production in buildings is strongly influenced by the occupants.

Ventilation

Airing the living quarters is the most effective method to remove humidity from the room [79]. The characteristic parameter for the effectiveness of the air change is the so-called number of air changes which indicates, referring to the space volume, the air quantity that is exchanged per hour and with that, replaced by outside air. The various bibliographical references do mainly refer to the hygienically determined air change (measure is the CO_2 concentration). The data demanded here differ widely from each other and lie within a range of 0.3 h^{-1} and 1.3 h^{-1}. [44] states air change values of 0.15 h^{-1} to 0.70 h^{-1} for the prevention of mould fungus growth. These values have to be met to remove the produced humidity from the room. In many cases, these values are not met, mostly where tight windows are concerned. Instructions on how to ventilate „correctly“ is given in [78]. One should ventilate above all after short moisture load peaks so as to avoid accumulating humidity absorption by sorptive internal surface materials.

Causes for mould fungi in building constructions

Apart from the mould fungus formation caused by the increased moisture at building component surfaces, there are other causes in the component inside leading to high material moisture and with that to microbial growth. The moisture rising from the soil or ground water belongs to that. Ground water penetrates from the soil into the building component, if the

construction work was faulty. The main reasons are damaged sealings, badly designed drain elements, incorrectly placed impermeable concrete or underlayers of gravel with a too small grain size underneath the base plate. Even an uninsulated foundation pedestal may lead in some cases to a cooling down of the base plate so that condensation water is coming up.

Rain penetrating through a damaged roof sealing or moisture from leaky pipelines as well as building moisture or condensation water can lead to increased moisture within building components, possibly getting into the structure and causing formation of mould fungi, depending on the climatic boundary conditions. A typical example is described in [77]. When examining a sheet metal roof that was vapour-proof at the outside, mould fungus was formed at the used vapour seal of paper foil as a result of summery reverse diffusion (see also item 5.3).

2.2 Hygrothermal calculation methods

For the prediction of mould fungus formation, the biological growth conditions (reference values) are compared with the hygrothermal conditions. Determination of these „actual values“ should take all influencing building physical processes into account. The modern hygrothermal calculation methods are well suitable for this purpose.

From the physical basics described by Künzel [76] for the heat and moisture transport, one can develop a closed differential equation system that allows to calculate the moisture behaviour of multilayered building components under natural climatic boundary conditions. The coupled equation systems and the numerical solution method forming the basis for the one- and two-dimensional data processing program WUFI (transient heat and moisture transport), are explained in brief. Afterwards, the required climate and material data and the corresponding boundary conditions will be dealt with.

2.2.1 Basics and software tool

Krus [64] gives an overview of the moisture transport phenomenons that may occur in porous mineral building materials, depending on the aggregate state. Some of the transport effects are less important under actual conditions at buildings and are therefore not considered. The following transport mechanisms, however, are essential for considerations in building physics:

- Vapour diffusion, based on the thermal proper motion of the molecules in gaseous aggregate state.
- Surface diffusion represents the liquid transport in the sorbate film of hygroscopic materials.
- Solution diffusion takes place only in non-porous materials such as organic polymers. The water is transported by the attachment and intercalation of water molecules into the polymeric macromolecules on the humid side. It is conducted by swelling processes.
- Capillary conduction is the transport of water in liquid form in capillary-porous building materials.

Derivation of transport equations

In [76] it is said that two independent driving potentials are required to calculate the non-isothermal moisture transport in porous materials. Simple and physically plausible transport coefficients result from the choice of the real moisture driving forces „vapour pressure" and „capillary pressure". By means of the Kelvin relation, the capillary pressure which is difficult to measure, can be converted into the relative humidity. The vapour pressure and the relative humidity are thus two generally known moisture transport potentials well-founded in physics and easy to measure.

For the heat as well as for the moisture, the conservation law does apply, i.e. the change of the enthalpy or of the moisture amount in a volume element is determined by the divergence of heat and moisture flows through the surface of this element and the heat and moisture sources or sinks. As for the heat, the following balance equation arises from the above with the heat sources or sinks resulting from phase changes:

$$\frac{\partial H}{\partial t} = -\nabla q + S_h \qquad (3)$$

H	[J/m³]	total enthalpy
q	[W/m²]	heat flow density
S_h	[W/m³]	heat source or sink

The moisture balance equation can be created by analogy with the balance equation for heat with the moisture sources and sinks usually not existing in structural designs:

$$\frac{\partial w}{\partial t} = -\nabla(g_w + g_v) + S_w \qquad (4)$$

w	[kg/m³]	moisture content of the building material
gw	[kg/(m² s)]	liquid transport flow density
gv	[kg/(m² s)]	vapour diffusion flow density
Sw	[kg/(m³ s)]	moisture source or sink

Resulting equation system

Due to the moisture dependence of the total enthalpy, the heat conductivity and the source term in equation (3) as well as due to the temperature and moisture dependence of the moisture flows in equation (4), the equations for the heat balance (3) and the moisture balance (4) are extremely non-linear

and coupled to each other. The result for the coupled heat and moisture transport is as follows:

$$\frac{dH}{d\vartheta}\,\frac{\partial\vartheta}{\partial t} = \nabla\left(\lambda\nabla\vartheta\right) + h_v\nabla\left(\delta_p\nabla(\varphi p_{sat})\right) \qquad (5)$$

$$\frac{dw}{d\varphi}\,\frac{\partial\varphi}{\partial t} = \nabla\left(D_\varphi\nabla\varphi + \delta_p\nabla(\varphi p_{sat})\right) \qquad (6)$$

$dH/d\vartheta$	[J/(m³K)]	differential heat storage capacity of the moist building material
$dw/d\varphi$	[kg/m³]	differential moisture storage function of the building material
λ	[W/(m K)]	heat conductivity of the moist building material
D_φ	[kg/(ms)]	liquid transport coefficient of the building material
δ_p	[kg/(msPa)]	water vapour permeability of the building material
h_v	[J/kg]	specific evaporation enthalpy of the water
p_{sat}	[Pa]	saturation vapour pressure
ϑ	[°C]	temperature
φ	[-]	relative humidity

The coupled equation system can be solved numerically by the WUFI program [76]. The moisture and temperature fields determined by means of the WUFI program serve as initial conditions for the further calculation with the biohygrothermal model.

2.2.2 Required input data

A list of data records required to calculate the heat and moisture behaviour of building products with the WUFI pogram is shown in Table 8. In the main, knowledge of the following data is necessary at first:

- The structure of the building component to be calculated and the numerical grid, the element quantities of which are adjusted to the layer structure and the local climatic influences to be expected.

- The thermal and hygric parameters and functions of the building materials involved in the structure; that is the bulk density, the porosity, the specific heat capacity, the moisture-dependent heat conductivity, the moisture-dependent water vapour diffusion resistance coefficient as well as, for hygroscopic capillary active materials, also the moisture storage function and the liquid transport functions for the suction process and the further distribution. The moisture storage function required for the calculations is made up of the sorption isotherm and the moisture retention curve and indicates in dependence on the relative humidity applied at the building material the moisture content of the same. The measurement of the sorption isotherm is regulated by the DIN 52 620 [24] (this is DIN EN ISO 12 571 [22] in future), but technically possible only up to a maximum relative air humidity of 95 %. The capillary water range beyond that is therefore covered by the pressure plate measurement [64]. The results of these two measurements are combined to a moisture storage function.

- The interior and exterior climatic boundary conditions as well as the presetting of the time steps which depends on the climate data and the required calculation accuracy. Exterior climate parameters are hourly mean values of temperature and relative air humidity as well as of solar radiation, normal and heavy rain and wind velocity. There are different, statistically evaluated annual courses of the climate available as typical courses for the exterior climate [72]. Figure 22 shows the climate data record used for the calculations [74]. For the interior climate, Künzel [73] evaluated measurements in numerous living quarters. Average moisture loads are defined from this for three cases of utilization: when the living space is used as office only (little load), when it is used as living quarters (normal load) and a high moisture load, for example in case of

overcrowded socially subsidized flats. If one calculates by means of these moisture loads the relative indoor air humidities arising in the course of a year, the result for these three cases of utilization are the sine-shaped courses shown in Figure 23. The lowest values are always in February and the highest ones in August.

- The transmission and symmetry conditions respectively at the component interfaces as well as the control parameters. Transmission conditions include the heat and moisture transmission coefficient, the degree of radiation absorption and also the rain factor. By means of the control parameters, the calculation accuracy, the form of the initial conditions and other calculation specific parameters are set.

2.3 Existing standard guidelines and technical directions

A large number of different „guidelines“ is existing in literature concerning the prevention of mould fungi inside and on building components (much more than 100 of such publications have been archived), most of them with the aim of informing the occupants on how to avoid mould fungus formation by giving advices about the correct ventilation or arrangement of furniture. Normative references can be found in the standard regulations for thermal and moisture insulation. However, there are no standards in Germany that deal especially with the problem of mould fungi, although there is a special DIN working group existing and another part for the DIN 4108 standard is under planning. Completed safety concepts particularly dealing with the microbial infestation have not yet been published either. The following paragraphs will give a brief assessment to what extent the single standards, decrees or technical regulations, usually referred to for energy saving and moisture insulation, are applicable regarding the prevention of mould fungus formation. Table 9 shows in this context a summary and assessment.

DIN 4108 – Thermal insulation in building construction

The DIN 4108 standard consists of several parts, with indications about mould fungus formation being mainly contained in 3 parts and in one part which is under planning. These parts are:

Part 2: Minimum thermal insulation

The new Part 2 of DIN 4108 [18] demands a certain minimum thermal insulation also for reasons of hygiene. In this context, this standard stipulates increased values for the thermal resistance (R-value), in contrast to the version of 1981. When complying with these minimum values of thermal insulation, damages caused by condensation water or mould fungus formation are generally avoided at indoor air temperatures and relative humdities that usually occur in dayrooms without air conditioning like living quarters and offices including domestic kitchens and bathrooms, with normal use and corresponding heating and airing. The growth condition for mould fungi assumed here is a relative humidity of 80 %. Problems occur, if furniture is arranged in front of external walls or if interconnecting doors stand open and inside air is exchanged between different dwelling zones. In such cases, mould fungi may grow although the minimum insulation values were met. To take the reduced heat transmission in such a case into account, there are already correction suggestions for the heat transmission coefficient existing in literature [31].

Part 3: Climate-dependent moisture insulation and Part 5: Calculation methods

The condensation water formation inside a building component that may occur due to the vapour pressure gradient and the diffusion resistances of the single component layers, can be assessed hygrically according to the graphical method developed by Glaser [20]. This quasi statical assessment method with its climatic „block boundary conditions“ has been proved successful for the assessment of the condensation water situation in standardized cases. The condensation water amount determined by means

of the Glaser method for the dew period has to be discharged again in the evaporation period. Furthermore, the total amount of condensation water must not exceed 1 kg/m² and 0.5 kg/m² respectively. The first figure is generally valid, the second one is valid, if condensation water occurs at separating surfaces with layers that are not capillary absorbent, whereby dripping or draining of the condensation water shall be avoided. One demand in case of condensation water production says: „The building materials (surfaces) getting into contact with the condensation water must not be damaged (corrosion/infestation by mould fungi)“ [19]. This indicates that thoughts of mould fungus formation have certainly been integrated; but one fundamental problem of that method is that the moisture situation is considered exclusively under stationary conditions and only within the typical cross section. Another disadvantage of DIN 4108 [19, 20] is the neglect of sorption and liquid transport effects. That is the reason why the Glaser method is not practical for constructions where these two effects are predominant [75], because all the simplifications do reflect the moisture balance inside the building component only insufficiently. Validated transient calculation methods (see item 2.2) are more suitable for a transient determination. These are therefore considered in the planned new version of DIN 4108 in Part 3, at least in form of references to effects and literature. Moreover, DIN 4108 Part 5 will be replaced in future by Part 3 and other standards.

Draft „Mould fungi“ for DIN 4108

Part of the new version of DIN 4108 [21] shall deal exclusively with the prevention of mould fungus formation, with the following thoughts being discussed:

- First of all, frequently occurring fungus species are listed. They are contained in Table 1.

- The moisture is stated as the essential prerequisite for mould fungus formation. One assumes here that mould fungus formation can take place at the component surface if there is a relative humidity of 80 % for at least 6 hours a day. The optimum for fungoid growth is indicated with a relative humidity between 90 % and 98 %. Reference is made also to xerophilic fungi that can grow from 65 % on.

- Regarding the nutrient requirements, it is indicated that mould fungi are undemanding and that a cursory contamination is enough to make them grow. The influence of the cursory contamination would even be higher than that of the subsoil substances. Thus, there is no distinction made between various building materials and surfaces.

- In addition to the above, measures are described which are necessary to ensure a sufficient ventilation of the rooms. Proposals are made of how to air the different kinds of rooms usefully. This item is not finished completely in the present version of the draft.

- Furthermore, examples of constructions are mentioned where mould fungi formation can be excluded.

All in all, the new draft of this DIN 4108 part can certainly be regarded as a relatively far-reaching concept of a standard concerning the prevention of mould fungi formation in Germany. However, with regard to the stated building physical and material technical requirements for the prevention of microbial settlement, the present draft version still does not seem to be sufficient yet.

Thermal bridge atlases

Issues of thermal insulation for thermal bridges are treated in so-called thermal bridge atlases. In [85], for example, values higher than 0.69 are

demanded for a non-dimensional temperature difference ratio Θ stated in equation (7):

$$\Theta = f_R = (\vartheta_{Oi} - \vartheta_{La}) / (\vartheta_{Li} - \vartheta_{La}) \quad (7)$$

with:

$\Theta = f_R$	[-]	non-dimensional temperature difference ratio
ϑ_{Oi}	[°C]	temperature internal surface
ϑ_{La}	[°C]	temperature outside air
ϑ_{Li}	[°C]	temperature indoor air

With that, condensation water production can be avoided also in the area of thermal bridges, if the room is used in a usual way. Nevertheless, [114] states that this does not absolutely apply for rooms with a high load of moisture like kitchen or bathroom, because one usually takes standardized climatic conditions in rooms as basis, i.e. a temperature of 20 °C and 50 % relative air humidity. Furthermore, it has to be considered also here that mould fungi do not need condensation water to grow. The new draft of DIN 4108 Part 2 states conditions also for mould fungus formation, as described above.

Heat insulation decree

Since the heat insulation decree [136] is always associated with microbial growth, it should be rectified here that the decree aims at the limitation of the maximum annual thermal heat demand as result of an energy balance [46]; therefore, it can certainly not be taken as basis for the assessment of the mould fungus problem.

DIN 68 800 (wood preservation)

To protect wooden parts against noxious animals and plants – insects and fungi – or against too high moisture, the DIN 68 800 standard stipulates demands on preventive structural and chemical wood preservation. These demands are binding for supporting structure; for non-load bearing elements they are just recommendations. According to DIN 68 800-2 [25], structural wood protection comprises all measures from the view of construction and building physics that shall avoid a detrimental change of the moisture content of wood pulp and timber materials and also the access of xylophagous insects to concealed wood. That means that moisture in wooden building components will be limited and thus, a chemical wood preservation can be avoided. The only quantifiable requirement stated here is the guarantee of a wood moisture below 20 M.-% (relating to the dry weight). If the wood installed has a moisture of more than 20 M-%, the surplus moisture must be removed within a period of 6 months. This assumption is based on the supposition that biological growth does not take place at wood moistures below 20 M.-%. Hence, this value represents a critical moisture from which on one has to expect microbiological growth. The approximate limit value for the building material wood can be regarded as a useful step towards material- dependent, hygric parameters for the prevention of mould fungi. Further references to data in standards, regulations and legal texts for the prevention of mould fungus formation on structural timber and predried lumber are mentioned in [58].

Further data

The draft of DIN EN ISO 13 788 [23] stipulates as a risk limit for the mould fungus infestation an enduring relative surface humidity of more than „...80 % over a longer period.“ Hints concerning critical temperatures and relative surface humidities for the prevention of mould fungi can be found in [52] and [134]. The values can be compared with those mentioned in the draft section „Mould fungi“ of DIN 4108 and are to be understood as estimating data,

particularly as there are no dependencies on materials indicated. Larger papers dealing with the growth conditions, the possibilities of avoiding mould fungus formation or the prediction of the same, have already been presented under item 2.1.4 or are treated under 2.4.

Safety concepts

The task of safety concepts is to avoid with a certain degree of probability potential damages that might be caused by improper construction or usage. Considering the safety is a usual thing in construction engineering, if there is a risk to life and limb (by a building collapse, for example). That is the reason why a multitude of safety concepts are existing in the field of statics and load-bearing structure. Such safety concepts are missing in the disciplines of building physics, especially with regard to energy, heat or moisture insulation and above all for the prevention of damages at buildings and of health hazards through mould fungi.

Cziesielski [15] is the only one who thought about safety concerning mould fungus formation. He demands a risk estimation of the minimum surface temperature, similar to the evidence of the suitability for use in construction engineering. A further development beyond proposed partial safety coefficients is not yet known, though. For that purpose, statistical distribution curves would have to be known for all single uncertainties. However, this does not seem to be the case as per the study of the literature in hand.

2.4 Existing models for predicting mould fungi

In order to assess the suitability of existing prediction models for mould fungi, it appears necessary to explain the respective underlying methodical concepts in brief and to discuss the advantages as well as disadvantages of the single methods. Table 10 gives an overview and a short assessment of the most important models.

Model of Time of Wetness (TOW)

Adan [1] describes the initial growth-lag, acceleration phase and log-growth phase (please see the growth curve in Figure 4) of mould fungi. For this, measurement results of fungus growth are described mathematically. At first, the influence of stationary conditions is recorded. To be able to assess transient courses of moisture on building components with regard to mould fungus formation, an evaluation based on the Time of Wetness is suggested. The TOW is the number of hours of high relative humidity (e.g. 80 %) per day, related to 24 hours. The assumption here is that mould fungus growth takes place, although with delay for a while, if a certain limit value is exceeded, which is indicated in hours per day with a relative humidity of more than 80 % for example.

Evaluation of the experiments shows that the fungus *Penicillium chrysogenum* grows only little on a plaster surface at a TOW of ≤ 0.5. In contrast to that, there is a strong influence at values higher than 0.5. The value of the relative humidity during the dry periods does not have any effect on the fungoid growth. The experiments carried out by Adan to find out what is the effect of quick changes in the relative humidity, proved that also the frequency is of nearly no influence on the fungoid growth.

The method by Adan described above is one of the first methods to take transient hygrothermal conditions for the prediction of fungoid growth into account. This method allows to describe mycelium growth in dependence on the TOW. In his paper, Adan states data for gypsum surfaces for this purpose. This data can be used to determine the substrate specific isopleths. Other authors carried out investigations on mould fungus formation on building components based on the TOW as well, as it is shown in Table 5. Indication of fungoid growth in dependence on the TOW is based on measured data and therefore, it cannot be used to predict a fungoid growth in dependence on any courses of temperature and humidity. Furthermore, one cannot derive any physical reasons for the fungi behaviour in

dependence on the TOW from the model described in [1]. This does especially apply to the effects occuring due to quick changes in the relative humidity.

Prediction on basis of the fuzzy logic

Figure 24 shows the qualitative assessment of the growth conditions for mould fungi in dependence on the factors of influence. In [91] it is assumed that the 3 growth conditions temperature, humidity and substrate must be given simultaneously for a certain time in order to enable mould fungus formation. The functional connections form the basis of a prognosis method for the assessment and prediction of mould fungus growth based on the fuzzy theory [2, 112]. This method has already been applied successfully to assess various outside building components as well as heating facilities with open air cycles. It is presented in [119] and explained in the following illustrated by the assessment of an internal wall surface. At first, the transient courses of temperature and humidity on the room side surfaces are calculated by means of hygrothermal calculation methods, based on the component characteristics and depending on the outside air temperature as well as the indoor climate. To combine temperature and humidity, which is required to assess the mould fungus growth, one can use the fuzzy logic. It takes into account the existing fuzziness at the indication of a humidity range which is favourable for fungoid growth. Here the transient function courses of the single influence factors are linked mathematically, as illustrated in Figure 25 for the combination of temperature and relative air humidity.

In the fuzzy logic, the function courses of the single variables are called „membership functions“. They represent the probability with which the special element (moisture, temperature) belongs to the „mould fungus growth“ set. According to that, the probability for fungoid growth at 0 °C is 0; at 10 °C the value is 0.25. The procedure for the relative humidity is analogous to that. That both conditions have to be fulfilled in case of a sufficient growth condition, is an AND operation in the fuzzy logic, i.e. a

minimum function. That means that the smaller membership or probability of both factors is taken into account. If, for example, the resulting membership value is 0.25 when assessing the temperature, and for the humidity it is 0.20, the latter is taken over as weaker growth condition (Figure 25). From that one determines the times of daily possible mould fungus growth and compares them with the data in literature about the influence of time on the growth (e.g. [37]). The time unit in question is usually one day, divided into 24 hours. For each hour one determines a probability from the boundary conditions (temperature and humidity), i.e. a membership value is stated. These hourly values are added for each day, i.e. one states the hours of optimum growth per day. Thus, a membership value of 0.2 for 10 hours means that a membership value of 1, i.e. optimum growth, would be there at 2 hours. Translating back the added, linked values of the membership functions is called „defuzzification“. The result is again a probability by which the quality, i.e. the growth intensity is expressed.

The fuzzy method meets the demand to yield a yes/no decision on the mould fungus infestation. There are many securities implied so that a negative statement (no infestation expected) will be correct in all probability. Therefore, the fuzzy method is well suitable to make statements on whether in cases of doubt further, more realistic investigations are necessary or whether an infestation can be excluded already at this stage of exploration. The determination of intensity in case of a positive statement, however, needs to be evaluated a little more critical. According to the model, just some hours of slight growth conditions are already enough to predict a growth intensity of 100 %, which does not always correspond to the real situation. One reason is that the influence of different building materials is not imaged in the model but that one assumes that the nutrients existing are always sufficient (even in case of contaminations).

Model by Clarke and Rowan

The name ESP-r (Environmental Systems Performance research) stands for the model by Clarke and Rowan, a climate technical space model developed at the University of Glasgow [13, 108]. For the purpose of predicting the mould fungus growth, the required surface temperatures and humidities at the building construction are determined and compared with the growth conditions of mould fungi in 6 classes, as illustrated in Figure 26. These classes represent different moisture limits of mould fungi, from highly xerophilic (chersophilous) up to highly hydrophilic (moisture-loving). Representatives for these classes are for example *Aspergillus repens* (highly xerophilic), *Aspergillus versicolor* (xerophilic), *Penicillium chrysogenum* (moderately xerophilic), *Cladosporium sphaerospermum* (moderately hydrophilic), *Ulocladium consortiale* (hydrophilic) and *Stachybotrys atra* (highly hydrophilic). To estimate the infestation by mould fungi, the calculated climate data is entered in Figure 26. Whenever an isopleth is exceeded, this is assessed as growth of the special fungi.

With the method proposed by Clarke and Rowan one can certainly determine the hygrothermal conditions at component surfaces from the view of building physics; but the disadvantage of estimating the mould fungus infestation is that aspects of time are not taken into consideration. Therefore, one does always assume fungus formation, whenever the isopleths shown in Figure 26 are exceeded. Division into some fungus classes is made with regard to the hygrothermal growth conditions, but not with regard to a possible health hazard or with regard to the dependence on the substrate. With that, one can use this model only as „worst case“ estimation with the lowest curve of those shown in Figure 26 being the basis for an ultimate total assessment.

Model by Viitanen, Ritschkoff and Hukka

The model by Viitanen [137, 138], Ritschkoff [107] and Hukka [51] for the description of mould fungus growth is based on laboratory tests on samples

made of different materials with the priority laid on whitewood and pinewood. To assess the mould fungus growth, Viitanen introduces a new term, the mould index, by which the fungoid growth is divided into 7 classes, according to Table 11.

Viitanen sets the following approximation equation for the maximum attainable mould index (MI) for wood in dependence on the moisture φ:

$$MI_{max} = 1 + 7\,(\varphi_{crit} - \varphi)/(\varphi_{crit}-100) - 2\,((\varphi_{crit} - \varphi)/(\varphi_{crit}-100))^2, \qquad (8)$$

with the critical relative humidity having to be calculated by the following formula:

$$\varphi_{crit} = -0.00267\,\vartheta^3 + 0.160\,\vartheta^2 - 3.13\,\vartheta + 100.0 \quad \text{if } \vartheta \le 20,$$
otherwise: 80 %. (9)

The mould index is described by Viitanen with the following equations:

$$dMI/dt = k_1\,k_2 \,/\, (7\,\exp(-0.69\,\ln\vartheta - 13.9\,\ln\varphi + 0.14\,W - 0.33\,SQ + 66.02)) \qquad (10)$$

$$k_1 = 2 \,/\, (t_v / t_m - 1) \quad \text{if } MI > 1, \text{ otherwise: } 1 \qquad (11)$$

$$k_2 = 1 - \exp\,[2.3\,(MI - MI_{max})] \qquad (12)$$

$$t_m = \exp(-0.68\,\ln\vartheta - 13.90\,\ln\varphi + 0.14\,W - 0.33\,SQ + 66.02) \qquad (13)$$

$$t_v = \exp(-0.74\,\ln\vartheta - 12.72\,\ln\varphi + 0.06\,W + 61.50) \qquad (14)$$

with:

MI	[-]	mould index
ϑ	[°C]	temperature
φ	[%]	relative humidity

φ_{crit}	[%]	relative air humidity from which on mould fungus growth on the wooden samples is possible
$k_{1,2}$	[-]	correction factors to adjust the model to transient conditions
t	[d]	time
t_m	[h]	duration until the mould index 1 is reached
t_v	[h]	duration until the first mycelium growth is perceptible with one's eyes
SQ	[-]	surface quality (0 = sawn after drying, 1 = chamber dried)
W	[-]	species of wood (0 = pinewood, 1 = whitewood)

Figure 27 shows arithmetical results on basis of these equation systems. The mould index for pinewood is indicated for example at a temperature of 20 °C and constant relative humidities in dependence on time. One can notice that there is only a certain maximum mould index, depending on humidity and temperature. Furthermore, the examinations in [51, 107, 137, 138] show that the temperature depending limit of the relative humidity, at which a mould index of 1 is only just achieved, is at approximately 80 %.

There were also tests on mould fungus growth carried out under changing climatic conditions. In this context, Figure 28 shows the influence of fast (hours; upper illustration) and slow fluctuations (days; bottom illustration) of the relative humidity on the time course of the mould index at an always constant temperature of 20 °C. One notices that, in contrast to constant conditions, i.e. a TOW of 1, lower TOW values require longer times to reach a respective mould index. From the point of view of quality, this does correspond to the results of Gertis [37] and is plausible.

The model of Viitanen, Ritschkoff and Hukka was developed especially for wood and is being extended for some building products. Systems of equations are offered to determine the development of the mould index arithmetically. Based on the relative humidity and the temperature, this

procedure allows to determine the temporal development of the fungoid growth. This method does function well for stationary hygrothermal boundary conditions. To estimate the influence by transient climatic boundary conditions – above all drying time intervals – on the mould fungus growth, an approximation formula is stated, but there is no physical model applied here [146]. There are only adaptations to measurement results made. However, the results on hand can be taken as basis for the generation of the substrate specific isopleth systems, as described in item 3.3.1.

3. New approaches for the prediction of mould fungus formation

Compared with other microorganisms, mould fungi do have a broad spectrum regarding the growth conditions (temperature and relative humidity) and therefore, they often play the role of primary colonizers. Furthermore, their myceliums may be the basic food for other microorganisms (such as mites), which may represent a further hazard to health and damage potential [106, 141]. To prevent microbial growth in buildings, it is therefore sufficient to concentrate upon mould fungi and to coordinate the prediction methods accordingly. At first, mould fungus species that are relevant to the model are defined in the following and divided into hazardous classes according to possible health hazards they may represent. After having analyzed and evaluated the factors influencing the mould fungus formation and after indication of the most important parameters, both parts of the prediction model, i.e. the isopleth model and the biohygrothermal model will be described.

3.1 Selection of mould fungi and their division into hazardous classes

When determining the growth conditions with respect to temperature and humidity, those mould fungi are to be considered that occur in buildings and that represent a hazard to health or are damage relevant. To select various species of mould fungi the data of which shall be used for the prediction

models, all fungi found in buildings (approx. 200 species) have been summarized in Table 1. In addition to that, this list indicates whether the single species are dangerous to health [55]. In the following, only those fungi will be considered that fulfill both criteria (dangerous to health or damage relevant and „detectable in buildings“).

Data about a possible health hazard to human beings and a usable division of mould fungi into hazardous classes cannot be found in literature. Therefore, a division into 3 different hazardous classes is made in agreement with Warscheid [142] and based on the still unpublished proposals by the Regional Public Health Department (LGA) Stuttgart [81]:

A. Fungus or its metabolic products are highly pathogen; they are not allowed to occur in used dwellings. Corresponds in most of the cases to the LGA weighting 3.

B. Fungus or its metabolic products are pathogen when exposed over a longer period in rooms or may cause allergic reactions.

C. Fungus is not dangerous to health, fungus formation however, may cause economic damage.

One can see from Table 1 that data is existing only for relatively few fungus species. Table 4 shows for these species the special data of minimum, optimum and maximum growth conditions regarding temperature, relative humidity and pH value. The values listed are sufficient to state for the 3 hazardous classes lower growth conditions for spore germination and mycelium growth. Classifying the fungi into 3 hazardous classes in Table 4, it is noticeable that the values of class C are only slightly different from that of class B. Therefore, it is sufficient to distinguish within the isopleth model only between the hazardous class A and a combined class B/C.

The uncertainties of the respective data records for one fungus are indicated with approx. 2 K or 2 % relative humidity [55]. When comparing the data for one special fungus in different pieces of literature, however, the differences are even bigger. Therefore, for reasons of safety, the summary of the growth conditions in Table 4 takes the great deviations of the literature data for each fungus species into account by using always the smallest minimum values and the biggest maximum values.

3.2 Factors of influence and assessment

A list of parameters that influence the growth of mould fungi is shown in Table 12. An evaluation of these parameters yields the result that temperature and humidity as well as the availability of nutrients in the substrate are the decisive factors influencing the fungoid growth. These three prerequisites for the growth must be existing simultaneously over a certain period. That is the reason why the time is one of the most important factors of influence and a transient consideration of mould fungus formation is therefore necessary.

The influence factors light, oxygen and spore flight are taken into account at the prediction by always assuming optimum conditions. Since fungi are growing also on even surfaces, the influence of surface roughness is not considered. As the model aims at the prevention of fungoid growth in general, it is not important whether a species is crowded out by another. Therefore, biotic influences are not taken into account.

As arising from the evaluation of literature, temperature and relative humidity do influence the growth conditions in different ways. These are:

- The growth conditions are different, depending on the fungus species. In the model, it is therefore always the lowest humidities that are taken as

basis for both hazardous classes A and B/C, in dependence on the temperature.

- Since the growth conditions are different also in the single life phases, separate evaluation curves are generated each for spore germination and mycelium growth. Sporulation is not considered in the model, because good and bad growth conditions make the fungus form spores in the same way.

- In order to consider the considerable influence of the substrate (availability of nutrients or salt content in the building material and in the contamination respectively, and the special pH value) on the fungoid growth, so-called „substrate categories“ are created.

3.3 New mathematical method

The following paragraphs describe the two models that are based on each other and used to predict mould fungus formation:

- Isopleth model: Determination of the spore germination times and the mycelium growth on the basis of so-called isopleth sytems that are valid for various hazardous classes and single substrate categories and with that, allow to consider the influence of the substrate when predicting mould fungus formation. An isopleth system describes the spore germination times or the mycelium growth to be expected in dependence on temperature and relative humidity.

- Biohygrothermal model: Calculation of the moisture balance (water absorption and discharge) of a spore by means of a transient biohygrothermal calculation method. With that method, one can determine which climatic boundary conditions allow spore germination. To adjust the physical parameters required for that and to consider the

influence of the substrate, one takes the isopleth systems as basis that were specified in the isopleth model for the individual substrate categories.

3.3.1 Isopleth model

The isopleth model shall allow a comparison of the hygrothermal conditions with the growth conditions for spore germination and mycelium growth. So-called isopleth systems are used for that purpose which describe the spore germination times and growth rates in dependence on temperature and relative humidity. However, complete isopleth systems are stated in literature only for some fungus species. Depending on the species, these systems differ considerably from each other and are valid only for complete medium as culture medium. If mould fungus formation on different substrates is to be predicted, it is therefore necessary to develop new types of isopleth systems. Such new systems must cover the growth conditions of the mould fungi occurring in buildings. Only singular measurements carried out for mould fungus formation on building materials are available here as basic data. To get a suitable prediction method, one has to evaluate the few measurement data available and create the isopleth systems by a process which shall be as simple as possible. To be always on the safe side when creating the model, first of all isopleth systems are developed that are valid for all fungus species of one hazardous class for optimal culture medium. All data that can be found in literature about the hygrothermal growth conditions are taken into consideration here. One can assume that these isopleths contain the lowest relative humidities necessary for fungoid growth for the total considered temperature range.

To generate isopleth systems for different substrates (e.g. building materials or contaminations) on the basis of the few data available in literature, it is assumed that the systems valid for optimal culture media do always consider the smallest humidities that are necessary to let the fungus grow, depending

on the temperature. Therefore, it seems to be useful to just shift them to a higher humidity, if less or a more unfavourable substrate is existing. Any other way of development that is more complicated would not be justifiable because of the bad data situation. Furthermore, the chosen shift allows to use the data record forms that are valid for optimal culture medium. The steps necessary to develop the single isopleth systems are summarized in Table 13 and are explained in the following. All in all, one distinguishes between 8 isopleth systems – resulting from two hazardous classes, two substrate categories, and each of them for spore germination and for mycelium growth – the respective lowest isoline of which is called LIM (Lowest Isopleth for Mould):

a) Hazardous class B/C (LIM B/C): These systems refer to biological complete media as culture media and therefore form the lower limit of all isopleth systems as far as the growth conditions are concerned, i.e. the lowest values for relative humidity. They are the growth limit for all mould fungi occurring in buildings. That means that, if the growth condition for class B/C is not met, mould fungus growth of hazardous class A is also excluded, because the relative humidity values existing for B/C are always lower than those for A, due to the existing data.

b) Hazardous class A (LIM A): Analogous to a), valid for all fungi of hazardous class A only.

c) Substrate category I (LIM_{Mat} I): Analogous to a), as for the culture medium, they do not refer to the complete medium but to materials of substrate category I mentioned in Table 14. Since investigations at building materials can be found in literature only for fungi of hazardous class B/C, it is presently not possible to generate a substrate-dependent isopleth system for hazardous class A. But the corresponding statement in a) is valid also here.

d) Substrate category II (LIM_{Mat} II): Analogous to c), only valid for all

materials belonging to the substrate category II.

Lowest Isopleth for Mould (LIM)

Item 3.2 described how to consider the various criteria when specifying the growth conditions temperature and relative humidity. So it becomes clear that, when determining the isopleth systems valid for all fungi, one first has to regard different species, since each species has its „own“ specific isopleths. To exclude spore germination or mycelium growth – also on complete medium –, one generates the lowest envelope for all minimum growth conditions of all mould fungi currently known and gets with that the so-called lowest isopleth for mould. When the humidity values are lower than that curve, there is no biological activity any more.

The specification of the LIM curves for the hazardous classes A and B/C is shown in Figure 29 for spore germination and in Figure 30 for mycelium growth. The single lines are based on the growth conditions summarized in Table 4 for various fungi. The temperature regarded here lies within a range from 0 °C to 30 °C only that is interesting from the view of building physics for indoor environments. The lowest line does always represent the limit of any fungus activity, i.e. with the hygrothermal conditions being more unfavourable, spore germination and mycelium growth can be excluded. The LIM means that on this line the spore germination time theoretically is infinitely big or the growth rate is 0 mm/d.

When specifying the LIM curves, uncertainties are included in a way that microbial activity below the LIM can be excluded for all species occurring in buildings for the special hazardous classes A and B/C, particularly since the culture medium which forms the basis for the specification of the isopleths (in most of the cases: complete medium) can be regarded as optimal. There are only slight differences in total, when comparing the LIM for spore germination with that of mycelium growth, but it can be noticed here that the LIM for spore germination is by a few % of relative humidity higher than the

LIM for mycelium growth, above all at lower temperatures. That means that in most of the cases spore germination takes place only, when a further growth is guaranteed.

To generate these envelope curves mathematically, one assumes that the LIM curve does correspond to a hyperbolic curve. This is also in accordance with the isopleths found in literature (see also Figures A to K in the Appendix, showing various isopleth systems). To determine the course of the envelope curve mathematically, one uses the semi-curve of a hyperbolic cosine function, lying to the left of the bottom peak value, for a range between 0 °C and 30 °C which is interesting from the view of building physics, in accordance with equation (15):

$$\varphi = a \cdot \cosh(\vartheta - \vartheta_{opt.}) + b \qquad (15)$$

with:

a, b	[-]	coefficients
φ	[-]	relative humidity
ϑ	[°C]	temperature
ϑ_{opt}	[°C]	optimum temperature for fungoid growth

The course of the curve is defined by the

- f_{LIM} (optimum temperature) = minimum relative humidity in the special temperature range
- f_{LIM} (minimum temperature) = optimum relative humidity in the special temperature range

as well as by the boundary condition

$df_{LIM}/d\vartheta$ (optimum temperature) = 0.

Isopleth systems for optimal culture medium

An isopleth system consists of the lower envelope curve (LIM), which depends on temperature and relative humidity, and a family of analogous isolines that parameterize the „spore germination times“, if spore germination is predicted, and the „growth per time unit“, if mycelium growth is described. In order to make the prediction of mould fungus formation as easy as possible, it is necessary to be able to specify isopleth systems that are valid for all fungi of one hazardous class. For this purpose, one has to carry out a multitude of methodical steps that are listed in Table 13. After generating the LIM curves, representative mould fungi are chosen at first. It is the fungus *Aspergillus versicolor* for the hazardous class A and the fungi *Aspergillus amstelodami, Aspergillus candidus, Aspergillus ruber* and *Wallemia sebi* for class B/C which have fungi-specific isopleths lying close to the course of the LIM curves, within the special temperature range that is interested from the view of building physics. Their isopleth systems shall be taken as basis for the development of isopleth systems for optimal culture medium that are valid for all fungi of one hazardous class. One distinguishes here between the two model systems for spore germination and for mycelium growth.

Isopleth systems for spore germination

If one knows about a complete isopleth system for spore germination, i.e. the spore germination times that depend on different temperatures and relative humidities, one can find out - by a comparison with the transient hygrothermal conditions occurring in the building - whether there are sufficiently long growth conditions for the spores to germinate. Spore germination times are those times that are required until the development of a germ tube as the first sign of mycelium growth is visible under the microscope. So the single isolines of the isopleth system illustrated in Figure 9 for example, specify the times required by the spores to germinate and become visible, under corresponding stationary hygrothermal

conditions. These indications are valid for optimal culture media because complete media are used in the underlying measurements.

In order to generate a complete isopleth system for spore germination that takes all fungi into consideration, the two LIM curves of the respective hazardous classes in Figure 31 are, based on measured isopleth systems of the representative fungi, shifted upwards until they touch the lines in the measured systems describing the different spore germination times at least at one position. This shall be explained by the following example: If for one of the representative fungus a spore germination time of 8 days was measured at 10 °C and 80 % relative humidity, the LIM curve describing this spore germination time, must be shifted until it crosses this point as isoline.

When repeating this procedure, a new isopleth system is generated which is valid for all fungi of one class. This is shown in Figure 31 above for the hazardous class A and below for class B/C. Maintaining the LIM curve form during its shift ensures that the spore germination times valid for different temperatures and relative humidities, do apply to all fungi. The representative fungi which were taken as basis are *Aspergillus versicolor* for class A and *Aspergillus amstelodami* for B. By comparing this system with isopleth systems of other fungi (see Figures A to K in the Appendix) it is guaranteed that the isopleth systems shown in Figure 31 do always contain the minimum spore germination times for single hygrothermal conditions.

Isopleth systems for mycelium growth

After germination the fungus starts to grow, if the hygrothermal conditions are sufficient. Growth can start again even after a period of unfavourable climatic conditions. In order to be able to predict the maximum growth to be expected, an isopleth system for mycelium growth has to be developed which is valid for all mould fungi. The growth velocities are stated in mm/d in dependence on temperature and relative humidity and are shown in the special isopleth systems in Figure 10 for 2 *Aspergilli*. The growth rates

usually indicated in mm/d or corresponding area occupancies (e.g. 70 % of a petri dish) can be used to evaluate the growth on building components only in the figurative sense in a way that the values are analyzed comparatively.

To generate isopleth systems for mycelium growth that are valid for all mould fungi, measured isopleth systems of representative fungi are used again. In contrast to the spore germination, there are measured systems for several fungi existing for the mycelium growth, as it can be seen in Figures A to K in the Appendix. Figure 30 shows for the mycelium growth one LIM curve each for both hazardous classes, which represents the lowest limit as far as the growth of all fungi of one hazardous class is concerned. Based on the special LIM, the single isolines are generated in a way that for each condition of temperature and relative humidity the highest growth rate of all fungi is selected and considered. A procedure is applied here which is analogous to that for the spore germination, i.e. the LIM curve is shifted upwards, with its form remaining the same, until it crosses, coming from below, the isoline for one special growth rate within the isopleth system measured for the representative fungus. This is controlled by means of the Figures A to K in the Appendix. Figure 32 shows the two isopleth systems for the hazardous classes A and B/C which are valid for optimal culture medium. These illustrations allow to determine the maximum growth rates for all fungi in dependence on hygrothermal boundary conditions. Of course it is also possible to take the respective isopleth systems for single fungi in the Appendix as basis to determine the mycelium growth.

Since there are not measured isopleth systems available for all fungi, a method is required by which one can generate such systems from the data found in literature. To determine the isolines in such isopleth systems, one can take the growth rates shown in Figures 5 and 7 for single fungi in dependence on temperature and relative humidity respectively. By means of these dependencies, the measured temperature- and humidity-dependent growth rates are projected onto the isopleth system; a schematic diagram of that is shown in Figure 33. In this example, a temperature of 28 °C and a

relative humidity of 97 % are regarded as optimal conditions for mould fungus growth. On the left-hand side of Figure 33 one can see the growth rate at an optimum temperature in dependence on the relative humidity. These values are calipered and drawn on the isothermal line at 28 °C in the isopleth system (on the bottom right of Figure 33). The assignment of the temperature-dependent growth rates at optimum relative humidity (on the top right of Figure 33) is entered on the line at optimum relative humidity (e.g. at 97 % on the bottom right of Figure 33). Connecting these 3 points of the same growth rate by means of a cosh function yields the corresponding isoline in the isopleth system for mycelium growth on the bottom right in Figure 33. Further isolines for mycelium growth are generated by analogy with that.

Isopleth systems for mould fungus formation on building products

Based on the isopleth systems generated up to now, one can make statements for spore germination or mycelium growth only for optimal culture media. If one wants to predict mould fungus formation on building products, a conversion is therefore necessary so as to take different substrates into account. For that purpose, isopleth systems have to be developed that are valid for special substrates and that are called in the following „substrate specific“ isopleth systems. As only few measurements of mould fungus formation on building products are available, is seems to be useful to define substrate categories and to generate isopleth systems for these groups. Division into groups is a usual process in construction supervision anyway, for example for heat conductivity classes. In contrast to considering single building materials, the indication of isopleth systems for substrate categories for the prediction of fungus formation with the isopleth model has the advantage that only a few curves have to be compared for the result interpretation. Furthermore, the creation of groups ensures that no accuracy is „pretended“, which would not be justifiable anyway for the evaluation of single substrates since only few measurement data is existing.

Definition of the substrate categories

Table 14 shows a definition of the substrate categories and the corresponding assignment of building materials. A separate isopleth system is generated only for those groups marked with 0, I and II; for the group 0, the systems represented in Figures 31 and 32 for optimal culture medium are valid. There is no isopleth system indicated for substrate group III, as it is assumed that mould fungi cannot grow on these materials without contamination. In case of a severe contamination, one should always take substrate category I as basis. Assigning a building material to a lower substrate category in dependence on the pH value is possible only, if it has been proved that the pH value is less than 2 or higher than 10 for a longer period, i.e. over several years (see Figure 15).

The methodical steps to be carried out when developing the substrate specific isopleth systems are explained in the following for spore germination and afterwards for the mycelium growth. A phenomenological approach is chosen here, that means, one acts on the observation that a mould fungus can germinate on optimal culture medium at certain hygrothermal conditions whereas on special substrates it needs higher humidities for germination [39]. That means that the moisture necessary for spore germination and mycelium growth does not only depend on the temperature but also on the substrate. Since the physiological connections responsible for that could not be cleared up completely yet [142], one acts simplistically on the assumption that the isopleth systems valid for the above mentioned substrate categories have to be above the respective isopleth systems for optimal culture medium. The isopleth systems for optimal culture medium (hazardous class B/C), shown in the lower parts of Figures 31 and 32, are shifted upwards to higher humidities by a certain value without changing their form. Apart from this parallel shift, an additional stretching or compression of these isopleth systems is conceivable as well, however, there are no indications existing in this context at the present state of knowledge so that a pure parallel shift of the total system appears to be useful for the time being. As literature data regarding mould fungus formation

on substrates is available in various forms, several possibilities of how to carry out the parallel shift are described in the following.

Substrate specific isopleth systems for spore germination

If the lower values for temperature and relative humidity for the germination of mould fungi on individual substrates are known, the LIM curves and the isopleth systems for optimal culture medium for the spore germination are shifted upwards. The two isopleth systems for spore germination for the substrate categories I and II as well as the related lowest growth limits, i.e. the LIM curves for mould fungus formation on building products (LIM_{Mat} I und LIM_{Mat} II) can be set that way.

The material-dependent growth conditions stated by Block in [11] allow to set the LIM_{Mat} curve for the substrate category I at one point. Thus, mould fungus starts to grow on leather, which belongs to substrate category I, at 30 °C and a relative humidity of 76 % after approx. 150 days. In [147] Zöld states that mould fungus growth starts on plaster board at temperatures of 20 °C and relative humidities of more than 75 %. Grant [39] ascertains further that, among others, the fungi *Aspergillus versicolor* as well as *Penicillium brevicompactum* and *Penicillium chrysogenum* can germinate on substrates of category I at 12 °C from a relative humidity of 83 %, at 25 °C from 79 % on. The minimum relative humidity for these species (LIM B/C) with an optimal culture medium is 74 %, in contrast to the minimum humidity of 70 % for the most xerophilic fungi of hazardous class B/C (compare Table 4). The LIM_{Mat} I should therefore be by approx. 4 % relative humidity under the relative humidities indicated by Block [11]. Considering this fact, the above indications allow to set the course of the LIM_{Mat} for the substrate category I in Figure 34 at the top. Taking a measurement uncertainty for the relative humidity of 2 % into account, the curve is specified for the LIM_{Mat} I on basis of the points 12 °C / 79 % relative humidity, 25 °C / 75 % and 30 °C / 76 %.

Furthermore, measurement results can be found in literature that describe longer spore germination times for single building materials at certain temperatures and relative humidities, in comparison with optimal culture medium. In order to generate substrate specific isopleth systems on the basis of this data, those isopleth systems for optimal culture medium (Figure 31) are shifted upwards as a whole until the spore germination times do correspond; one gets then the new isoline in the shifted isopleth system with the spore germination time, stated in literature for a mould fungus on a substrate for a certain temperature and relative humidity. A new LIM curve for this substrate ($LIM_{Mat\ I}$ or $LIM_{Mat\ II}$) is also created that way since the LIM for the hazardous class B/C is shifted as well.

To carry out this shift, one uses the substrate curves mentioned in [107]. Figure 11 shows the time-dependent mould index. Based on these measurement curves, one can read off the duration until the first biological activity is noticeable for always exactly one pair of relative humidity and temperature. It is not necessary here to achieve the mould index 1 (i.e. first visible mycelium growth), because germination must have been taken place before that. Since the available results are contradictory in part, one takes a mean value from the graphs in Figure 11 as basis for the shift of the isopleth systems, with always considering the shortest time that can be ascertained here. At a relative humidity of 97 % for example, one can read off more or less 1 day as the time for first biological activity on plaster board (substrate category I). With this method one can shift the isopleth system for optimal culture medium upwards until the spore germination times do correspond. The resulting isopleth system is identical with the results in Figure 34 at the top. However, for reasons of assurance, one should carry out further measurements of such substrate curves.

The shift can be carried out also on the basis of available transient TOW measurement results. With that one can specify the substrate specific isopleth systems. Here as well one should always use the results that are critical for fungoid growth. If, for example, Gertis ascertains in [37] that a

relative humidity of 95 % must be applied at a temperature of 18.5 °C at a plaster with dispersion paint, a plaster board or woodchip wall paper – each with contamination – for 6 weeks (i.e. 42 days), for 1 hour per day (TOW = 0.04) until first mould fungus growth is visible (see Figure 14 on the top right), this high moisture load is applied at the test items a little more than 1 day in total. If one considers on the other hand a possible interim drying out of the fungus spores, there is no contradiction to the isopleth system shown in Figure 34 at the top for substrate category I. Another reason to describe at this point the possibility of specifying substrate specific isolines by means of such time-dependent measurements is that the mould fungus test stand [37] offers good potentialities for further examinations. Moreover, according to Adan [1], a relative humidity of 80 % applied at plaster board for 12 hours per day at room temperature is sufficient to notice fungoid growth after a certain time. The data in [1] indicate that the spores begin to germinate after approx. 2 weeks at 20 °C and 80 % relative humidity. This is confirmed by the position of the special isoline in the isopleth system for substrate category I in Figure 34 at the top.

According to [11], growth takes place on wood (substrate category II) after 35 days at a temperature of 30 °C and a relative humidity of 80 %. From that one can fix the course of the corresponding LIM_{Mat} II (shown at the bottom of Figure 34), at least for one point. It is fixed for this temperature to 79 % relative humidity, since it is to be expected that, with a longer time of observation, germination can only just take place with the relative humidity being a little less than 80 %. All other results from biological experiments of fungus formation on building products that do not belong to substrate category I, are above that envelope curve (e.g. [11, 37, 39]). Further measurements would be reasonable to be safe about the specification of the isopleth system regarding the substrate category II. Since one can rather expect, however, a shift towards higher humidities, as it is also substantiated by the results of Ritschkoff [107] in Figure 11, it is useful to maintain the setting made for the isopleth system for substrate category II for the time being, until further data does exist.

Substrate specific isopleth systems for mycelium growth

To determine the resulting growth rates on special substrates which depend on temperature and relative humidity, one has to develop isopleth systems that are valid for the substrate categories I and II. However, since there is no usable data available in literature that allow to determine the isopleth systems for mycelium growth in dependence on the substrate, it is simplistically assumed that the LIM_{Mat} curves for spore germination and mycelium growth do correspond with good approximation. This assumption appears to be justified, if one considers the small difference between the LIM B/C curves for spore germination and mycelium growth. Thus, the isopleth system for mycelium growth for hazardous class B/C valid for optimal culture medium in Figure 32 bottom is shifted to higher humidities with the same vector as it was done for the isopleth systems for spore germination. Figure 35 shows the isopleth systems for mycelium growth for substrate category I (top illustration) and II (bottom illustration). With that one can determine by comparisons the growth that is to be expected for the single substrate categories in dependence on the hygrothermal conditions.

Assignment of the substrate categories to the hazardous classes

Figures 34 and 35 show the LIM_{Mat} curves of the substrate categories marked in Table 14 with I and II. The individual isopleth systems each refer to the hazardous class B/C. A differentiation regarding the hazardous classes A and B/C can be made only for the course of the LIM curve for optimal culture medium, since only here enough data is existing. As there are mixed cultures of various fungus species used for measurements on building materials, one cannot distinguish between single fungi and their allocation to the hazardous classes. Since fungi of hazardous class B/C have lower growth conditions, the LIM curves for B/C fungi are always determined with that, even if fungi of class A are existing in fungi mixtures.

In all, the chosen method of generating the substrate specific isopleth systems yields a prediction method the results of which are always on the

safe side. This is managed above all by shifting the isopleth systems valid for all fungi occurring in buildings for optimal culture medium (most rigorous requirements) with their form being maintained. Such shift is carried out on the basis of some existing measurement data by taking again the more critical values as basis. Applying these complete isopleths for different substrate categories for the prediction of mould fungus formation leads to useful results, as outlined later under item 5.

3.3.2 Transient biohygrothermal model

To prevent mould fungus formation in buildings, it is necessary to avoid spore germination. This means, however, that the effect of the most important influence factor on the germination of spores, that is the moisture available at certain temperatures, would have to be described in terms of quantity. For this purpose, a new type of a biohygrothermal model is developed that is able to calculate the moisture balance of a spore in dependence on transient boundary conditions. The transient biohygrothermal model is described in the following, emanating from a model idea and the given model assumptions. Furthermore, the parameters required for that and the determination of the same are dealt with.

Model idea

As shown by the curve in Figure 4, the growth of mould fungi passes through certain phases. Figure 36 represents in this connection schematically the substrate depending growth processes within the range of the initial growth-lag, the acceleration phase and the log-growth phase of mould fungi. The fungoid growth is drawn depending on time with complete medium and for the substrate categories I and II. One can see here the time when the metabolism of mould fungi starts and also the spore germination time influenced by the substrate which is defined by the first visible fungoid

growth, i.e. the development of the germ tube. The spore germination times represented in the isopleth systems describe exactly this point of time.

The model idea says that first of all the fungus spore absorbs in the initial growth-lag phase, if the hygrothermal ambient conditions are favourable, moisture by means of diffusion, independent of the culture medium, until a certain moisture content inside the spore (hereinafter called critical moisture content) is reached that is needed to start the metabolism (Figure 36). The further spore germination taking place from this point on during the acceleration phase does depend either on the nutrients inside the spore or on the nutrient or salt content of the substrate and the external pH value. Literature does not contain usable data regarding the conditions necessary to start metabolic activities. Before a first visible mould fungus growth takes place though, the spore is obviously influenced by the substrate, since the spore germination time on optimal culture medium differs significantly from that on substrates with only few nutrients (dashed lines in Figure 36). The so-called log-growth phase is the next stage. It serves to reproduce the vegetatives units and to produce bio-mass of the fungi. Now the growth can be indicated in mm/d, as shown in Figure 10. The slope of the curves (dW/dt) in Figure 36 depends again on the substrate.

As explained under item 2.1.5, the moisture content in the spore is decisive for the process of germination. In the model it is assumed that biological metabolic processes and the spore growth start only when the critical moisture content is reached (Figure 36). Until then the spore is regarded as non-physiologically active material the properties of which can be described with physical regularities and so the moisture transport through the spore septum by means of the Fick‘s law. Therefore, the biohygrothermal model assumes that water absorption takes place by means of pure diffusion until the metabolic processes start. After the metabolic activities have started, the fungus can regulate its metabolism on its own, if necessary independent of the surrounding conditions. The extensive regulation mechanism, however, is still unknown to a great extent and therefore cannot be described in terms

of physics. This is even not necessary since it has been assumed in the model that the critical moisture content that makes metabolic processes only possible, must not be exceeded at all.

The transient biohygrothermal method for predicting the germination of spores is based on the fundamental idea that a fungus spore has a certain osmotic potential because of the substances inherent in the spores. With the help of this osmotic potential spores can absorb water existing in the environment, i.e. in materials as well as in the air. This potential is described by means of a moisture storage function, the diffusion resistance of the spore septum by a moisture-dependent s_d value. Due to its geometrical size, the spore can be regarded isothermal; thus, also other transport processes (e.g. capillary absorption) can be described as diffusion by moisture-dependent s_d values. Apart from the climatic boundary conditions, it is the moisture storage function and the s_d value which are decisive for the humidity absorption.

Model assumptions

The biohygrothermal model can thus describe the development of the spore until the critical moisture content is reached. With the physiological activities beginning, the fungus can influence its nutrient and water balance on its own by various mechanisms. Since the present state of knowledge is not sufficient to model these procedures, the influence of the substrates shall be made possible by the following simplistic assumptions:

- The water absorption of the spores is calculated with the diffusion approach also after the metabolic processes have started.

- The critical moisture content is determined by means of the isopleths for spore germination as follows: depending on the temperature, the lowest relative humidity at which the spore germination takes place can be read off the respective LIM curves in the isopleths. With the help of the

moisture storage function valid for the spore inside, the corresponding critical moisture content can be calculated.

The period shown in Figure 36 between the beginning of metabolism and the first visible fungoid growth on optimal culture medium is taken into consideration by adjusting the s_d values of the spore septum in a way that the spore germination times calculated under stationary conditions by means of the biohygrothermal model correspond to those in the isopleths. In order to consider possible influences by the substrate, this adaptation is carried out by means of the LIM_{Mat} curves in the respective isopleths of the substrate categories 0, I and II.

Modeling of the mould fungus spores

For the calculation of the moisture content in a fungus spore by means of the biohygrothermal model it would be useful, if the transient hygrothermal processes in the model spore could be determined by well-known calculation methods. In order to make the calculation model simple, the fungus spore should be regarded as a „biological“ wall structure when being modeled. The procedure could be as follows.

In the upper part of Figure 37 one can see a quasi-real, enlarged spore. One can imagine this spore to be a ball having a spore septum. The real spore touches the building material, i.e. the hygrothermal boundary conditions at this surface do influence the hygric processes within the spore. However, due to its small size, the spore does certainly not influence the building physical boundary conditions in the area of the material surface. Therefore, it would not be useful to use an overall model, i.e. the component superstructure with the spore as lining, as it is shown in the centre of Figure 37. Such a calculation model with the spore as a layer in front of the building component would even lead to faulty results, since the spore would represent an additional high, unrealistic diffusion resistance. Therefore, the model spore is assumed to be independent of the wall, as shown at the bottom of

Figure 37. With that one can use any courses of temperature and humidity as climatic boundary conditions for the biohygrothermal model.

The calculations based on the biohygrothermal model are carried out by the WUFI [76] program. The geometric and material technical data of a spherical spore are converted into a one-dimensional structure (see Figure 37). The used geometrical parameters of the model spore in comparison with a natural spore are listed in Table 15.

Factors needed for the model are the spore dimensions (spore septum and spore inside), the permeability, that is to say the water vapour diffusion resistance of the spore septum, the moisture storage function of the spore and the moisture condition (critical moisture content), that describes the start of germination or the physiological processes. The thickness of a spore septum is indicated in [34] with approx. 500 nm. The diameter of the spore nucleus is assumed to be 2 µm. This is a total diameter of approx. 3 µm for a real spore. A diameter of $1.0 \cdot 10^{-2}$ m is assumed for the model spore. The moisture storage function given in literature [109] for bacteria spores can also be used to describe fungus spores [49]. But the units have to be converted, because the above mentioned moisture storage function is indicated in $g_{H20}/g_{bacteriaspore}$ and is needed, however, in vol.-% for the calculation with the WUFI program. This conversion can be executed by means of the bulk density of fungus spores that is within a range of 1.1 to 1.2 g/cm³, according to [45]. Therefore, a mean bulk density of 1.15 g/cm³ is assumed for fungus spores. The moisture storage function resulting from this is represented in Figure 38. It has been slightly modified in the range above 80 % relative humidity, i.e. it has been shifted upwards. This is necessary in order to get a model, along with the determination of the s_d value, by which the hygrothermal behaviour of the model spores can be calculated uniformly for all 3 substrate categories.

The water vapour diffusion resistance of a spore septum is needed for the WUFI calculations as moisture-dependent diffusion-equivalent air layer

thickness. It was not possible up to now to calculate this thickness directly, due to the small size of the spores. Therefore, the s_d value is adjusted for the model by reconversions on basis of the germination times in the isopleths for spore germination in hazardous class B/C (Figure 31 bottom) for the substrate categories I and II in Figure 34. By this reconversion, [146] the s_d values are adjusted, depending on moisture but under isothermal conditions, until the following two times do correspond:

- the time calculated by the biohygrothermal model, that is needed by a spore with an initital equilibrium moisture content corresponding to 50 % relative humidity, to reach the critical moisture content allowing it to germinate, and

- the spore germination time indicated in the isopleth system for different humidities.

The moisture-dependent s_d curve determined by that method is shown in Figure 39 for the range above a relative humidity of 70 %. This curve form corresponds to that of materials with solution diffusion; i.e. the s_d value becomes smaller at high relative humidities. By adjusting the s_d values of the spore septum a model of the spores can be given that is valid for all 3 substrate categories. To determine the critical moisture content inside the spore, one has to read off the relative humidity for the respective temperature from LIM B/C or LIM_{Mat} I or LIM_{Mat} II. By means of the moisture storage function one gets that way the corresponding moisture content which marks the beginning of metabolism activities.

3.4 Safety assumptions

When developing the two models, there are some points where no respective data can be found in literature or where physical modeling is not possible due to missing basic data. Assumptions are given here that are always „on

the safe side“ at the prediction. That means that mould fungus formation is predicted with the developed master model more likely than it would be in reality.

Another fundamental safety assumption is that light and oxygen are „existing in optimal quantities“. Furthermore, spores are supposed to be ubiquitous and one has used the smallest spore germination times per fungus that are known from literature. Since the spore germination times, for example, do considerably depend on the age of the spores or their adaptability, this approach appears to be reasonable. Biotic influences are not considered. Furthermore, the models take even those species into account that do occur in buildings only rarely. This is achieved by generating the LIM curves. To create the substrate specific isopleth systems, one uses the most unfavourable conditions that can be found in literature. For example, if there are different spore germination times for one and the same material with the boundary conditions being the same, one takes the smaller times. Classification of the different building materials is done in a way that they are always assigned to the more unfavourable substrate group. The combined effect of all these assumptions guarantees a safety concept by which predictions for mould fungus formation are always „on the safe side“.

4. Conversion into a calculation method

The following paragraphs will explain what is the structure of the method, what procedure shall be applied for the prediction and how the isopleth model and the transient biohygrothermal model do function computationally.

4.1 Method structure and procedure

The calculation method is based on a structure that connects the described models with each other. A diagram of the procedure is shown in Figure 40.

At first, the microclimatic boundary conditions required for the prediction of mould fungi formation are determined by the WUFI software tool or read in from external data sources. The definition of the substrate category is followed by an estimation, with the help of the respective isopleth systems for spore germination, whether the hygrothermal conditions occurring at a spore are sufficient for spore germination. In case fungus formation is indicated, a prognosis is made by means of the transient biohygrothermal model which can take a drying out of the spores into consideration and which indicates the periods that are critical from the hygrothermal view (e.g. thermal bridge effect due to a frost period in winter). If the biohygrothermal partial model does forecast fungus formation, too, one can carry out the calculation again with modified assumptions concerning material or construction. If spore germination cannot be excluded also then, one uses the isopleth model to evaluate to what extent mycelium growth takes place. Different constructions can be compared with each other here. Since the two models – isopleth model and biohygrothermal model – can be applied independent of each other, it appears to be useful to explain their mode of function as calculation method separately.

4.2 Transient hygrothermal growth conditions

Only simple initial data is needed for the biohygrothermal method for the prediction of mould fungus formation on and inside building components. On the one hand data about materials and a possible degree of contamination is required to allow the assignment to the substrate categories. On the other hand the calculation method requires transient courses of temperature and relative humidity at those positions of the building construction where mould fungus growth is expected to be possible. There are mainly 3 ways to do so:

1. Data records are read in from measurements at existing superstructures of building components.

2. Data from transient thermal calculations can be applied, carried out for example with building calculation programs like SUNCODE [92] or three-dimensional finite-difference programs [130]. It has to be paid attention here, though, that influences by the sorption or building moisture are not considered (see item 2.2). But when applying three-dimensional calculation programs, one can image complicated structures like wall-ceiling connections, room corners or window constructions.

3. By the hygrothermal calculation program WUFI, one- or two-dimensional structures can be modeled and any climatic boundary conditions can be read in. The interior climate is indicated on the basis of existing data records.

For more complex building constructions it appears to be useful to apply the possibilities 2 and 3 iteratively so that, for example, influences by thermal bridges are determined with three-dimensional heat calculation programs and that these results are read into the WUFI program as boundary conditions for temperature. However, for most of the cases, one- or two-dimensional calculations are sufficient. For a useful evaluation of the building construction, the time resolution of the climatic boundary conditions must be that exact that the significant transient hygrothermal conditions are recorded sufficiently fine so that short high humidities are not „averaged away“. Usually it is enough when hourly mean values are available (see item 5.6).

Spores meeting with a humid surface where they start to germinate, do not have any contact to the inside of the underground material at first. Therefore, it is sufficient to consider the hygrothermal conditions at the component surfaces, if one wants to assess the spore germination. In contrast to that, when determining the mycelium growth rates, it is not sufficient to consider only the conditions at the surface; here it is rather necessary to take also the hygrothermal conditions up to approx. 3 mm within the component into account. This does justice to the fact that mould fungi grow from a certain

growth phase on into the inside of the material and can thus use moisture also from the deeper component layers.

4.3 Functionality of the isopleth model

To be in a position to compare the biological growth conditions with the calculated hygrothermal conditions, one has to compare, on basis of the isopleth model, the calculated transient courses of temperature and relative humidity in the building component surface with the spore germination time and mycelium growth data in the respective isopleth systems. Isopleth systems are available for this purpose, as shown in Figures 31, 32, 34 and 35, for the hazardous classes A and B/C respectively on optimal culture medium as well as for the substrate categories I and II. The growth conditions characterized by the time courses of temperature and relative humidity, serve as input parameters. These microclimatic boundary conditions are entered into the isopleth systems as hourly values. The computer allows to carry out the evaluations on basis of the isopleth model automatically. For this, the single isopleth systems are described on basis of the equation (15). By analogy with that, the single isolines are recorded. The areas between the isolines are interpolated. If the growth conditions are above the respective LIM curve for a certain duration, mould fungus activity may take place, depending on the hazardous class and substrate category. The following paragraphs explain in detail this mode of function of the isopleth model for the evaluation of spore germination and mycelium growth.

Spore germination

Spore germination is possible whenever a certain temperature and relative humidity lasts for a certain time. The time durations are defined by the isolines in the isopleth models and stated for single substrate categories. With that one can state, depending on the material, whether there is the possibility of spore germination at respective stationary hygrothermal growth conditions. Usually, the temperature and humidity conditions that do exist are

transient, though. To record and evaluate by means of the isopleth model even these courses, that are taken from examinations in building physics, the time contributions made by single hygrothermal conditions to spore germination are summed up on basis of the respective isopleth systems for spore germination. That means, it is indicated by means of the single isolines (e.g. 4 days), what is the contribution of an hourly value lying for example on this isoline, to spore germination, i.e.1 / (4 days · 24 hours) = 0.01. These values are added and entered as time course. If the sum value reaches 1, it is assumed that spore germination is achieved and that the fungus begins to grow. With that, one gets a simple evaluation possibility; it can be indicated whether spore germination takes place within a certain period. In Figure 41 at the bottom one can see the results determined that way for the internal wall surface in the wall centre, in the room corner and behind the furniture at the external wall. A fast spore germination can be noticed only behind the furniture. In the room corner, spore germination occurs after a considerably longer time only. This example of use is dealt with in detail under item 5.4.

The assessment of spore germination on the basis of the isopleth model has the disadvantage that an interim drying out of the fungi spores cannot be taken into account in case the occurring microclimatic boundary conditions are transient. In such cases, this process will therefore predict the germination of spores more often than the biohygrothermal model.

Mycelium growth

Analogous to the above, it is possible to state the maximum intensity of the fungoid growth with the help of the substrate specific isopleth systems for mycelium growth. The mycelium growth can be determined by analogy with that on basis of the respective isopleth systems. Here, the single hourly values for temperature and relative humidity are evaluated. For example, the position of an hourly value in the isopleth system in the range of 6 mm growth per day means that the fungus grows by 6 mm per 24 hours, i.e. by 0.25 mm

in the period in question. A sum value is created also here which is represented as course in the upper graph of Figure 41. One can notice that the fungus grows considerably faster behind the furniture than in the corner, for example.

The indication in mm/d comes from biological examinations where a Petri dish with complete medium is inoculated with fungus spores in the centre and a circular growth appears. So one can interpret 1 mm/d can in a way that the diameter of a fungoid growth increases by 1 mm per day. Since, however, it is usually an unknown number of fungus spores that germinate and grow on a wall surface, the statements of a mycelium growth after a certain time are to be regarded only from the point of view of quality. Therefore, Figure 41 shows an „equivalent“ mycelium growth. Nevertheless, comparisons can be made between different substrates or climatic boundary conditions. An initial phase for mycelium growth after a longer standstill of fungus activity due to unfavourable growth conditions is not taken into consideration so that always the more critical case is covered.

4.4 Functionality of the biohygrothermal model

The first step is to determine the transient temperature and humidity courses as boundary conditions by means of measurements or mathematical methods. After that, the actual calculations are carried out with the biohygrothermal model. By reading in any climate data, the influence of building physical factors on the transient moisture and temperature behaviour of building components and component surfaces can easily be considered at the prediction of mould fungus formation.

Figure 42 shows a flow chart on the mode of function of the biohygrothermal model. First of all, the courses of temperature and relative humidity as microclimatic boundary conditions are read in for the biohygrothermal calculation of the model spore. With the help of the spore modeling entered into the WUFI program, the moisture content in the model spore is

determined in dependence of the microclimatic boundary conditions. The moisture content is compared with the critical moisture content from which on spore germination takes place, as it is represented in Figure 43 for the case of a mould fungus formation on the vapour seal in a vapour-proof gable roof. If the moisture content in the model spore exceeds the limit value, spore germination begins and the calculation can be carried out again, if required, with modified material data, superstructures or climatic boundary conditions.

5. Validation of the developed method

A thorough validation is absolutely necessary in order to check the developed method. First, the plausibility is considered. Afterwards, the calculation results of the biohygrothermal model are compared with laboratory and outdoor experiments and measurements in used dwellings. An experimental verification of the isopleth model to assess spore germination and mycelium growth is carried out additionally. A comparison with other prediction methods for mould fungus formation and with data found in literature as well as a sensitivity analysis do complete the validation process.

5.1 Plausibility considerations

In the course of the plausibility checks one takes familiar mould fungi occurring „in daily life“ as basis and verifies whether they can be explained by means of the isopleth model. Table 16 shows a summary of such plausibility considerations and the comparison with the curves in the isopleth model.

When determining the possibility of mould fungus formation for free-standing objects in a room and outside of buildings by using a typical annual course

of the climatic conditions and when comparing the results with that of the isopleths, there is no microbial activity noticeable with regard to living quarters for the substrate categories I and II. However, when assuming an optimal culture medium, mould fungi do occur on basis of the isopleth model which does also correspond with the experiences in daily life. For these comparisons, the results of temperature and relative humidity measurements in several dwellings outlined in [73] are used as basis. Here, the highest relative humidities in dwellings in the third quarter (July, August and September) at a temperature of 20 °C are 70 % or a little higher. When the culture medium is optimal, (Figure 31), these climatic conditions are sufficient to let spores germinate; with the substrate categories I and II (Figure 34) there is no germination, though.

In the annual course, the daily mean values of the outside air temperature and the relative humidity [67] in the months August to November are above the LIM for optimal culture medium (Figure 31). The values in autumn even exceed the LIM_{Mat} of substrate category I (Figure 34 at the top), which indicates that non-preserved wood, for example, may become mouldy in some cases. Plasters that belong to substrate category II, may not show any infestation by fungi, according to the specification of the LIM_{Mat} curve in Figure 34 bottom. Such predictions do also correspond with observations made in reality.

When recalculating a possible mould fungus formation on food (LIM for optimal culture medium) or on the synthetic material of the refrigerator (substrate category II), supposing climatic conditions in a refrigerator, a fungus formation can be observed in the first case, but none in the second. This does again correspond to the daily experiences. A temperature of 10 °C and a relative humidity of 80 % in the freezing compartments were assumed. This is equivalent to a temperature of 20°C and a relative humidity of little less than 50 % in living quarters.

Those cases that are interesting from the view of building physics, that is fungus formation behind cupboards, in room corners or at thermal bridges, were also checked by the developed model. Table 17 contains measurements of temperatures and relative humidity indoors and at the surfaces carried out in a climatic chamber. Mould fungus formation could be detected at some measurement places. When taking the measured hygrothermal data as boundary conditions for the isopleth model and assigning the wall materials to the substrate categories, the prediction is identical with the observations regarding fungus formation (right column in Table 17). Results of further calculations concerning a possible mould fungus formation at wall surfaces with different interior climatic boundary conditions are explained under item 7.1.

5.2 Laboratory tests

Biological laboratory tests are taken as basis to validate the biohygrothermal model. First of all, the spore germination times measured with the biohygrothermal model are compared with the measured data from literature that are represented in the isopleth systems. Furthermore, test results determined in the test stand for mould fungi at the Fraunhofer Institute for Building Physics are used as basis for comparison.

The biohygrothermal model is based on the fundamental idea that a fungus spore can absorb water vapour existing in the environment due to its own osmotic potential. For modeling purposes, the fungus inside is described by means of the moisture storage function and the spore septum by a moisture-dependent s_d value. Humidity absorption must proceed faster at high temperatures than at low ones because the water vapour partial pressure is the driving potential for diffusion processes and there are bigger water vapour partial pressure differences between the spore surroundings and the spore inside at higher temperatures than at low ones during germination. To recalculate this, the s_d values for the fungus species *Aspergillus restrictus*

were adapted in [146]. This adaptation was made for 24 °C by comparing the spore germination times for different relative humidities, indicated for this temperature in the isopleth system measured by Smith [126] (Figure 9), with the calculation results and adapting the s_d values step-by-step. When determining the spore germination times by means of the biohygrothermal model, they are expected to become longer for lower temperatures (for example 20°C and 15°C). A comparison with the spore germination times indicated in the above mentioned isopleth system for 20 °C and 15 °C is shown in Figure 44. The concurrence is good. The deviation is only 0.6 hours, for example, at a temperature of 20 °C and a relative humidity of 80 % with a spore germination time of approx. 8 days; thus, the deviation is less than 1 %. This indicates that the assumptions given in the model reflect the biohygrothermal processes actually existing within a spore very well.

In the test stand shown in Figure 12 for tests concerning mould fungi at building and surface materials, the parameters air humidity, air temperature, air speed, surface moisture and surface temperature can be modified. Therefore, the results yielded in that test stand [37] are well suitable for the experimental verification of the biohygrothermal model. In one test series, a relative humidity of 95 % at 18.5 °C and 60 % and 26.1 °C are applied to the samples alternately for a certain daily duration. If one calculates by means of the biohygrothermal model the courses of the moisture contents in the model spore, for the case of a severe contamination (Figure 14 on the right) with an assumed humidity period of 95 % lasting 1, 3 or 6 hours a day, one notices a building up of the spore moisture, as shown in Figure 45. Depending on how long the high humidity (95 %) lasts a day, one gets different moisture contents. When using the LIM for optimal culture medium to determine the critical moisture content, which is plausible since the „severe contamination“ is produced by an easily degradable organic substance, fungus is already formed with a humidity of 95 % lasting only 1 hour per day. This does well correspond to the indications on the right-hand side of Figure 14 [37]. Mould fungus formation can be observed always when the high humidity lasts for 3 hours and above all, if it lasts for 6 hours a day.

With the culture medium being more unfavourable (substrate category I or II), the relative humidity of 95 % must last at least 3, rather 6 hours per day to start fungoid growth (Figure 14 on the left). As explained in [37], germination is slowed down at 14 °C, in contrast to the tests carried out with a surface temperature of 18.5 °C. This is proved by the biohygrothermal calculations as well. Above all, the critical moisture content is at a temperature of 14 °C just under 30 vol.-% and with that, it is bigger than for 18.5 °C. At this temperature, the critical moisture content is 25 vol.-% for substrate category II, as represented in Figure 45. The shown hatched strip illustrates the temperature change between 18.5 °C (upper value) and 26.1 °C (lower value). All in all, one can notice a good correspondence between the predictions from biohygrothermal calculations and the measurements carried out in the test stand for mould fungi.

In [15] Cziesielski says that a relative humidity of 80 % at the building component surfaces has to be exceeded for 6 hours per day over at least 5 days in order to make mould fungi grow. If one recalculates these conditions with the biohygrothermal model, fungus formation does really begin after approximately 5 days, at an assumed temperature of 20 °C and a humidity alternation of 60 % for 18 hours and 90 % for 6 hours. If a relative humidity of 60 % for 16 hours is assumed, 80 % humidity for 6 hours per day are not sufficient for spore germination. With an air humidity of 85 % for 8 hours per day, fungus formation starts after approx. 20 days only. With the relative humidity being constant at 80 % the spore germination time is 12 days, as one can see in Figure 34 at the top. It is always the substrate category I that is assumed here. Altogether, the statement by [15], which is a little generalizing, can be confirmed and even elaborated with the results of the new model.

5.3 Outdoor tests

To validate the biohygrothermal model by means of outdoor experiments, one uses measurements of the drying out behaviour of unvented gable roofs

that are vapour-proof outside, stated in [77], where one variant proved mould fungus formation inside the building component structure [70]. Figure 46 at the top shows a photograph of the test building. At roofs with sheet metal covering, moisture actually cannot get to the outside, due to the high outer vapour diffusion resistance of such roofs. Because of the high solar radiation on the southern side and with that, higher temperatures in the area of the sheet covering, the so-called „reverse diffusion“ takes place from time to time. That means that moisture drifts from the outside to the inside in the direction of the temperature gradient. With diffusion-open vapour seals, a roof dries out mainly in warm summer months towards the inside, i.e. towards the room. That is the reason why there is a temporary increased moisture load at the vapour seals. Detailed investigations of that were carried out.

The test fields of the gable roof consist of a sheet covering on a planking, insulation of mineral wool and various vapour seal foils (Figure 46 bottom). The s_d value of the paper foil is 3 m, that of the moisture-adaptive plastic foil varies between 0.4 m at high summery humidity (80 % relative humidity) and 4 m at approx. 30 % relative humidity in winter, depending on the climatic boundary conditions. To simulate a high initial moisture content in the measurement, the wood was moistened before installation and determined regularly during measurements. The test variants and hygrothermal influences as well as the interpretation of the same are discussed in [77]. The building physical tests proved that the lowest wood humidities were determined when using the plastic foil [71]. Carrying out the test with the paper foil, it was found out at the end of the test that there was not only a musty smell but also mouldy spots, i.e. an extensive mould fungus formation took place in the roof structure. By means of the WUFI calculation program, the courses of the temperature and relative humidity on the room side surfaces of the paper foil and the plastic vapour seal were recalculated for an observation period of 180 days (Figure 43 at the top). This data is the basis for the biohygrothermal model. The results are shown in Figure 43 bottom. The two relatively constant curves represent the critical moisture

contents in the model spore. When these values are exceeded, one has to expect mould fungus formation. The course shown as a dashed line applies to the vapour seal of paper foil, the solid line for the used plastic foil. The curve of the critical moisture content for plastic (belonging to substrate category II) lies above the curve for the paper foil which belongs to substrate category I. The moisture contents in the spores existing on the vapour seals, that have been calculated with the biohygrothermal model, are to be compared with the critical moisture contents. The calculation shows that the moisture contents on the paper foil are considerably higher than those on the plastic foil. Furthermore, one notices that the moisture content of the spore on the paper foil lies above the critical moisture content for a relatively long time. Consequently, one has to expect mould fungus formation after approx. 60 days, which does correspond well to the observations during the outdoor measurements [121]. At the plastic foil, the critical moisture content is exceeded only for a short time; an extensive mould fungus growth is therefore not to be expected. This was not observed either, particularly since the growth conditions of plastic are even more unfavourable than it is described by the LIM for substrate category II.

5.4 Measurements in used objects

The new developed prediction models shall be verified by means of some selected examples of mould fungus formation in used buildings. For this purpose, a typical microbial infestation in 2 different rooms as well as at the outside facade is referred to. For several years, redevelopments of old buildings are carried out with the aim to make improvements with respect to energy. Damages by mould fungi could then be observed again and again in the uninsulated dwellings [28, 29, 31]. In some objects, the thermal and hygric situation at wall structures with mould infestation was measured; they can be used to verify the prediction model.

In one case mould fungus infestation could be observed on the plastic-coated furniture surface installed towards the external wall. The mean temperature in the room was 20 °C and the relative humidity 57 %. At the mouldy place, 14 °C and 84 % relative humidity were measured during a lasting cold winter period with an outside air temperature of 0 °C on average. When comparing these climatic boundary conditions with the isopleth system valid for overlaid plywood of substrate category II (Figure 34 bottom), it turns out that the fungus could grow on the plate at the place towards the external wall because the germination time for that is only 16 days approximately. Climatic conditions that do not allow any germination can be found, however, already some centimeters away from the wall. Undisturbed by the cold wall, the temperature on the tabletop is approx. 20 °C. A relative humidity of at least 80 % would have to exist to allow mould fungus formation at this temperature.

The second case of mould fungus infestation occurred behind a built-in cupboard in the bedroom of a dwelling in the 1st upper floor at the northeastern external wall of a house built in 1955 and redeveloped in 1993/94 [104]. The heat flows through the external wall, the internal and external surface temperature and air temperature were measured during a cold period over a longer time and evaluated [115]. The relative humidity in the bedroom was measured as well. The special data records are on hand and are referred to when checking the isopleth model. At the external wall points the mean values of that measurement is a surface temperature of 12.0 °C and a relative humidity of 69 % in the middle of the wall and 9.2 °C and 83 % relative humidity in the external wall corners. If one compares these average hygrothermal conditions (which are typical for winter) with the isopleths for plaster (substrate category II) in Figure 34 at the bottom, one finds out that in the middle of the wall no fungus formation is to be expected. There was no fungus formation observed either at the places not concealed by the furniture in the bedroom in the tested object which is also confirmed by the model. In contrast to that, the LIM_{Mat} II curve for 9.2 °C in the external wall corner is at approx. 85 %, thus only just above the measured value of the

relative humidity. Applying a heat transmission resistance of 1 m² K/W for built-in cupboards according to [110], one determines a surface temperature of 7.3 °C on the plaster behind the cupboard and a mean relative humidity of 94 %. According to the isopleths for substrate category II in Figure 34 bottom, these hygrothermal conditions need to last for only one week to cause fungoid growth; this does also correspond to the observation in the case described. The transient boundary conditions available in 10-minutes values were evaluated by means of the isopleths for spore germination and mycelium growth with the transient method. As it is shown in Figure 41, the climatic boundary conditions in the middle of the wall are not sufficient to cause spore germination. In the room corner, however, spore germination took place due to good growth conditions lasting a short time, but the mycelium growth here is not worth mentioning. The situation behind the furniture is different. An extensive fungal infestation is predicted there. Using the biohygrothermal prediction model, one gets analogous results. The room corner is the only place, where no spore germination is predicted with the biohygrothermal calculations – in contrast to the results achieved with the isopleth model. The reason for that is that the biohygrothermal model considers a drying out of the spores, caused by temporary lower humidities.

At the outside facades of a housing area finished from summer to autumn, a biological growth was visible after a short time. As described in [68], one could notice a flat-spread mould fungus infestation above all in the area of the window lintel (distinct discolouration). The window lintels were insulated with mineral wool and not with polystyrene rigid foam, like the rest of the wall area. On the wall surface in the middle of the wall one can mainly notice circular patterns of infestation. Drilling core samples were taken at these points. It turned out that the insulant plates of polystyrene rigid foam were not mounted with flush joints but that there is a gap of approx. three millimetres between them. This gap goes through up to the concrete underneath it. The circular infestation by fungi roughly appears in the area where four insulant plates do cross. In this case, a humidifying mechanism becomes active that was already analyzed and documented in connection with the risk of

damages due to frost („diffusion humidification" [69]). Such diffusion humidification has directly to do with the high water vapour permeability of the mineral wool insulation and the air gap between the insulant plates respectively. Since with a moist brickwork or concrete, the moisture transport from the room to the outside does take place permanently in the cold season and not only temporarily like in case of nighttime condensation production or due to precipitation, it is comprehensible that the biological growth appeared relatively early. To investigate the moisture balance in the area of the window lintels and of the air gap between the insulant plates further, since it is a decisive factor for the assessment of mould fungus formation, two-dimensional hygrothermal calculations are carried out with the WUFI program. Here the following wall structure is assumed (from the inside to the outside):

Wall material:	150 mm concrete
Insulating material:	160 mm polystyrene in the middle of the wall and 160 mm mineral wool in the window lintel
Plaster:	5 mm synthetic resin plaster or, for comparison 10 mm mineral plaster.

A 3 mm thick air gap between the polystyrene plates is assumed. The calculation is based on the material parameters from the WUFI database. A normal room side moisture load is assumed. The exterior climate used is the test reference year available in hourly mean values for the location [53]. The calculated wall is aligned northwards, since this wall dries out most slowly due to the low solar radiation. Starting on 1st of October, calculations over a period of one year are carried out. To keep the turnaround time within sensible bounds, one calculates with daily mean values. Such values are suitable because in the present case neither driving rain nor direct solar radiation are of importance. An initial moisture content of 15 vol.-% for concrete and of 10 vol.-% for plaster is assumed.

Figure 47 shows for the first year the course of temperature (above) and the relative humidity in the exterior plaster (middle) at the position of the plate joint (dashed line) and the window lintel (dotted line) in comparison to the plaster in the undisturbed area, that is the middle of the wall (dot-dash line). Except the period from mid-November to mid-January, the courses do considerably differ from each other in the two different positions. Whereas the relative humidity at the plaster (substrate category II) in the middle of the wall is reduced from this time on due to the increasing outside air temperatures and with that plaster temperatures (top illustration), it stays at the plate joint at approx. 90 % until mid-July. Within the window lintel area there are even higher humidities in the plaster, compared with the air gaps [68]. When taking these climate data as boundary conditions for the calculations with the biohygrothermal model, one can see in Figure 47 at the bottom that the moisture contents in the model spores existing on the plaster are also approximately the same in the period from mid-November to mid-January, but that there are lower values in the middle of the wall at other times. The great fluctuations in the course of the critical moisture content can be explained by the great temperature changes at an outside facade. The maximum values of the critical moisture contents at temperatures of approx. 0 °C do correspond to the „free water saturation“ of the spore and are at approx. 92 vol.-%, irrespective of the temperature.

The moisture content in the spores in the middle of the wall is always below the critical moisture content, except the initial values in the first two weeks after completion. That means that no fungoid growth should occur in the middle of the wall; this does also correspond to the observations at the object and to the experiences from practice. The case is different for the plasters in the window lintel region and at the air gaps at the plate joints. In the window lintel area, the critical moisture content is exceeded in the first six weeks after completion and from April on. As it could be observed also at the object, an extensive fungoid growth occurs already in spring. The critical moisture content at the plate joint is not exceeded that much which leads to a slightly smaller infestation.

Figure 48 represents the values determined on basis of the isopleths for substrate category II for spore germination and mycelium growth in addition to the results of the biohygrothermal model. In order to eliminate the influence of the high construction moisture in the late autumn, one evaluates only the period January to June. To assess the mycelium growth, the climatic boundary conditions at the plaster surface as well as in a building component depth of approx. 2 mm are applied. It turned out that the climatic boundary conditions in the middle of the wall are not sufficient for spore germination. In the area of the window lintel and the plate joint, however, an extensive fungal infestation is predicted. This does correspond to the statements of the biohygrothermal model and to the actual observations at the building.

5.5 Comparison with data from literature

The validation process does also include a comparison of the isopleth system and biohygrothermal model results with the data found in literature on measured spore germination times and with calculation results of other prediction methods. To test the isopleth model, the used evaluation curves (LIM A, LIM B/C and LIM_{Mat}) are compared with the respective data in literature. As one can see in Figure 49 at the top, the LIM for spore germination and mycelium growth respectively for hazardous class B/C is always below all other isolines. While Hens [47] and Clarke [13] use curves the course of which is more or less equal and that lie in a temperature range of more than 15 °C above the LIM, the curve measured by Smith [126] in that range for the mould fungus *Aspergillus restrictus* is close to the LIM B/C. The reason for this is that all fungus species occurring in buildings and being dangerous to health and also the fungus activity on optimal culture medium were considered for the generation of the separate LIM curve. The LIM A is above the LIM B/C. Comparable literature does not exist about it since no-one has defined hazardous classes yet.

A comparison of literature data mostly referring to building materials, with the LIM_{Mat} of substrate categories I and II, is shown in Figure 49 at the bottom. One can see that the proposed curve of substrate category I is the lower envelope curve for all temperatures. From 20 °C on, this LIM_{Mat} is a bit lower than the data from literature. The cause for that is the upward shift of the LIM B/C for optimal culture medium to define the LIM_{Mat} curves. With that, the low growth conditions at optimum temperatures (between 25 °C and 30 °C) known from the biological measurements are covered as well; thus, the real situation is imaged better than by assuming a constant relative humidity of 80 % above approx. 15 °C, as proposed by Viitanen [137]. The data for the substrate category II form the upper envelope curve. Altogether, one notices that the own method allows to proceed more differentiated when determining the spore germination times and the mycelium growth. Above all, application cases where a fruitful substrate is involved, can also be considered.

When comparing the spore germination times from the biohygrothermal model under consideration of substrate category II with those times determined with the Viitanen [137] model, the two models do differ from each other which is shown in Figure 50. The spore germination times determined with the biohygrothermal model are below those values calculated according to Viitanen. This can be explained by the influence of different building materials and the pretreatment of the same. Thus, pre-dried wood for example, must first absorb humidity during measurements on mould fungus formation whereas fungi germinate faster on wood with an actual moisture content. Furthermore, the spore germination times might be different, depending on the wood species and the sample material. Since the biohygrothermal method is always based on the more critical assumptions, the spore germination times determined with that are shorter than the data found in literature.

Viitanen uses only few mould fungi for his examinations, whereas the biohygrothermal method is based on the unfavourable growth conditions of all fungi occurring in buildings. Thus, the spore germination times of the fungi used by Viitanen (e.g. *Aspergillus versicolor*, *Aspergillus niger*, *Penicillium sp*.) for a relative humidity of 80 % are for example 8 days on optimal substrate, while the lowest value applied in the own method is 2 days (please see in this context Table D in the Appendix). This is the main reason for the differences in Figure 50.

If one compares additionally the spore germination times determined by the biohygrothermal method with the data stated by Hens [47] or Block [11], which are shown in Figure 50 as well, it can be found out that the times calculated by the biohygrothermal model are certainly on the safe side, but do not deviate much from this literature data. The lowest relative humidities from which on fungus activity for materials of both substrate groups begins [39], result in values for high spore germination times. These do also correspond well with the results of the biohygrothermal method.

5.6 Sensitivity analysis

In order to check possible fluctuations and uncertainties that may occur during biohygrothermal calculations, various sensitivity analyses are carried out. The following parameters do basically influence the fluctuation margins for spore germination times possibly arising when calculating with the biohygrothermal model:

- The substrate category taken as basis to determine the critical moisture content,

- the moisture storage function to describe the osmotic potential inside the model spore,

- the iteratively determined moisture-dependent s_d value to describe the diffusion resistances of the spore septum,

- the initial value of the relative humidity in the surroundings of the model spores that is taken as basis for the calculation of the spore germination times under stationary conditions,

- the calculation time step used for the biohygrothermal calculation with the WUFI program.

The effect of the substrate category, assumed for the determination of the critical moisture content, on the spore germination times can be read from the isopleth systems shown in Figures 31 and 34 for optimal culture medium and the substrate categories I and II respectively, because modeling in the biohygrothermal model was adapted to this data. For the case of a mould fungus formation on a vapour seal in a vapour-proof gable roof described under item 5.3, one can see the position of the critical moisture contents for the two substrate categories in Figure 43 bottom.

In the course of the spore modeling, the s_d value was adapted after having determined the moisture storage function. Adaptation was carried out by reconversions on basis of the germination times for the hazardous class B/C (Figure 31 bottom) as well as the substrate categories I and II in Figure 34. In general, one could have varied also the moisture storage function by keeping the s_d value curve, since these two parameters do influence each other. As there are, however, no data for s_d values existing in literature, but certainly for the moisture storage function, the first mentioned possibility was chosen. Therefore, the sensitivity analysis includes only changes of the s_d value. Here the total s_d value curve is varied by $\pm$ 20 % (variant plan see Table 18). A lower value leads to a faster humidity absorption by the spore and with that to shorter spore germination times. As shown in Figure 51 at the top, the result for the spore germination times under stationary ambient conditions is a relatively slight scattering of the different s_d values used. This

illustration represents the spore germination times in dependence on the relative humidity applied at the spore for the three substrate groups.

On the other hand, the initial moisture content in the model spore has a much greater influence on the germination time, above all at the substrate category 0 and smaller humidities. When the initial moisture is reduced, the time until germination starts is increased. Via the moisture storage function, the initial moisture is clearly connected with the ambient humidity the spores are exposed to at the beginning of the measurements and spore germination time calculations. Since usually no values are indicated for laboratory examinations, a great variation is made, i.e. ambient humidities of between 30 % and 65 % relative humidity are compared with each other. As shown on Figure 51 bottom, relatively big variances are noticeable at the substrate category 0. The main reasons for that are the different quantities of moisture to be absorbed by the model spore when varying the initial moisture content so that it is able to germinate. This moisture quantity is calculated from the difference between the moisture content required for germination and the initital moisture content. The difference for the standard case with an initial condition of 50 % relative humidity shall be defined in the following as reference value (corresponds to 100 %). Regarding the substrate category 0, this difference is 270 % with an initial moisture of 30 % relative humidity, i.e. the spore must absorb 2.7 times the moisture, compared with the standard case. With an initial condition of 65 % relative humidity, this difference would be 37 %. The smaller variance for the substrate category II results from the smaller deviations as against the standard case with 165 % for the initial moisture of 30 % and 76 % for the initial moisture of 65 %. This makes the relations shown in Figure 51 understandable. One notices that, when determining the s_d values by iterative recalculation of the germination times in the isopleths, other s_d values would arise when choosing different initial humidities. Since, though, modeling was adjusted to the spore germination times in the isopleth systems, the confidence accuracy of the biohygrothermal model is not restricted. Certainly, the question arises what influence do the s_d values have on the moisture contents existing in the

model spore at transient ambient climate. In that context, Figure 52 shows the course of the moisture content in a model spore with variation of the s_d value by ± 20 %. A time section from Figure 43 below (mould fungus formation on a vapour seal in a vapour-proof gable roof) was used. As it can be seen, the uppermost and lowest ends in the course of the moisture content are cut off, when the s_d value is higher (Figure 52). But this is restricted only to some tenth vol.-% and does therefore not influence the prediction of a possible mould fungus formation significantly.

In order to estimate the influence of the calculation time step used with the WUFI program system, the building up of the spore moisture in the mould fungus test stand (cf. Figure 45) is calculated with a different calculation time step at a relative humidity of 95 % increased for 3 hours per day, compared with 60 %, and represented in Figure 53 with high resolution. One can see that there is no significant difference in the spore moisture content between the calculation time steps of 0.2 hours and 0.1 hours so that a time step of 0.2 hours can be regarded as sufficient in that case. Applying a time step of one hour, the moisture content is slightly below that. This is due to the extreme fluctuations of the relative humidity between 60 % and 95 % within a few minutes in the test stand. As further calculations showed, a calculation time step of one hour is sufficient. With high temperature or humidity fluctuations, a further sophistication of the time step may be taken into account.

6. Assessment of the developed method

6.1 New approaches and functional features

The current standard methods to assess mould fungus formation usually take stationary boundary conditions into account. Whereas in most of the cases in Germany only the relative humidity is indicated as criterion, isopleth systems are used as basis for the assessment more frequently by international

experts. Relative humidities are stated here, depending on the temperature. If these humidities are exceeded, mould fungus formation may take place. However, there are neither isopleth systems for different substrate groups nor for the assessment of the health hazard caused by mould fungi available yet. This was done in the present isopleth model which, moreover, contains a differentiation of spore germination and the mycelium growth. That allows in a relatively easy way to determine the probability of a spore germination and to quantify the mycelium growth that is existing or to be expected.

There are only few prediction models published up to now that allow a consideration of transient boundary conditions – and if yes, only indirectly. So for example, the influence of temporarily occurring dry periods on the spore germination cannot be determined with those models. In contrast to that, the developed model takes the occurring transient growth conditions into account. With that, it is possible for the first time to estimate the moisture content of mould fungus spores in dependence on the transient hygrothermal boundary conditions and to state whether fungus spores become active, that is to say whether fungoid growth starts. The moisture storage function inside the spore required for the biohygrothermal model could be adopted from examinations of bacteria spores. The moisture-dependent s_d value describing the moisture passage through the spore septum, was specified in a way that the determined spore germination times correspond under stationary conditions with those spore germination times valid in the isopleths for the hazardous class B/C and for the substrate categories I and II. The influence of the substrate was taken into account by making the critical moisture content in the fungus spores, from which on spore germination takes place, depend on the isopleths for the different substrate categories. This allows to cover even the substrate influence in the biohygrothermal model.

An iterative procedure is proposed in the paper on hand, enabling to combine both models (isopleth model and biohygrothermal model), thus allowing to predict, after the spore germination has been estimated, the

following mycelium growth in dependence on transient growth conditions. Basic principle of the new method is to always assume the most unfavourable case, that means to be always on the safe side with the prediction from the health care point of view. Whether for example a correction of the isopleth systems for the single substrate categories towards a higher humidity appears to be too „sharp“ or justifiable after all, would have to be confirmed by further measurements. A comparison with previously existing standard guidelines for mould fungus formation and corresponding prediction models shows that the method described in this paper surpasses the present state of knowledge by far and deepens the understanding for the formation of mould fungi considerably. Furthermore, there is a good concurrence yielded in the validation.

6.2 Model restrictions

To estimate objectively the functionality and prediction reliability of the present method, the methodical simplifications shall be analyzed critically as well:

- Influence factors such as pH value, salt content, light, oxygen content, surface quality and biogenic factors are not considered in the models, but it is assumed that they do not impede germination and growth. That simplification has the consequence that the determined spore germination times may be lower or the growth rates may be higher than they are under real conditions. That means for the actual application that the results gained with the new method imply a „preventive“ aspect.
- Differences in the osmotic potential of various substrates are not considered in the isopleth model in concrete terms but generalized by the definition of substrate groups. The same does apply to possible influences of deposits or contaminations on the building component surface. By this simplification, the calculated growth rates and spore germination times can be predicted only for different groups, but not for each single material. If the assignment of a material to a special

substrate category is uncertain, one should choose that group which is, from the preventive point of view, more critical for mould fungus formation.

- For the prediction of the spore germination, the substrates (building material and possible contamination) are not considered directly at the biohygrothermal calculations, since the processes inside the spore taking place after the metabolism activity has started, cannot be described mathematically and thus they cannot be modeled either. In order to include nevertheless the influence of different materials, the critical moisture content is considered in the model on basis of the various LIM_{Mat} curves existing for the various substrate categories. Also here it is recommended to use the more critical substrate group for mould fungus formation, if there is any doubt.

- The moisture storage function used for mould fungus spores is a curve which was measured for bacteria and slightly modified. Since there are no measured values existing for mould fungus spores, the moisture- and temperature-dependent diffusion resistances of the spore septa were determined by recalculation. Adaptation was made by means of the isopleths for the substrate categories 0, I and II. The confidence accuracy of the developed model is not restricted by that, because the calculated values do correspond under stationary conditions with the data in the isopleth model. Under transient conditions there are only marginal uncertainties resulting from the s_d value adjustment, as also proved by the sensitivity analysis carried out under item 5.6.

6.3 Further investigations required

Altogether, there is a need for further investigations comprising measurements with the aim of a further sophistication and an extension of the two model approaches.

Isopleth model

Isopleth systems for the hazardous classes A and B/C can presently be indicated only for optimal culture medium, since only for that medium enough data is available. It is not possible to differentiate the hazardous classes within the substrate groups, as for the isopleth specification measured data had to be used that are based on examinations with mixed cultures of different fungus species and that do not allow any distinction between single species or hazardous classes. For a further development of the model, it would be eligible to investigate the mould fungus growth of species of one single hazardous class. A more differentiated specification of the substrate specific isopleths valid for all mould fungus species can be executed only by further systematical measurements of the spore germination times and growth rates of the fungus mycelium for different substrates. This should be carried out for stationary as well as for transient hygrothermal boundary conditions.

Another aim should be the quantitative investigation of the influence of contaminations on building component surfaces, in dependence on various influence factors like surface roughness and cleaning intervals. It is of interest to what extent deposits and contaminations on surfaces do influence the assignment of materials to the proposed substrate groups. Recording the influence of the pH value or the salt content on the positions of the isolines in the isopleth systems could be helpful for the model, if for example the effect of anti-mould coatings increasing the pH value shall be included [124]. For that, systematical investigations on the time course of pH values on different surfaces are necessary, in dependence on the transient hygrothermal indoor air conditions and anti-mould agents influencing the surface. Furthermore, it appears to be useful to investigate further the connection between the constituents of building products and growth rates. When fitting out the building materials calculatedly with special constituents, mould fungus growth could be prevented.

Transient biohygrothermal model

Up to now, this model is based on a pure phenomenological consideration. The spore germination times depend not only on temperature and relative humidity but also on the substrate. In order to take this into account, the LIM curves indicated in the isopleth systems are used for the determination of the critical moisture content that marks the spore germination for different substrate categories. For a detailed clarification of the growth curves, one has to record the initial conditions for the metabolism. To find out the exact time of germination of a spore under certain humidity and temperature conditions, one could take the increase of metabolic activity inside the spore as basis (e.g. through a respiratory measurement, ATP or molecular biological RNA content measurement) that takes place before the germ tube becomes visible. The advantage would be that the influence of different substances on the metabolic activity of individual mould fungi could be investigated.

The exact determination of the moisture storage function of spores in dependence on the nutrients contained in the spores would be necessary to carry out biohygrothermal calculations separately for various mould fungus species. The moisture storage function and the moisture contents of fungus spores can be determined by recording the weight of a certain quantity of fungus spores in dependence on the air humidity applied at these spores; the s_d value for the humidity absorption by different fungus spores could be derived from the time course of the weight gain at the above mentioned measurements. Furthermore, biochemical data of the fungus spore composition, i.e. the osmotic properties of special „compatible solutes“ and storage substances in the spores, do represent a material reference factor for the moisture storage function. In addition, the moisture- and temperature-dependent diffusion resistances of the spore septa should be exactly determined by measurements for single mould fungi. With that, the assumptions made in the model could be confirmed on the one hand. On the

other hand, a possibility could be created of stating differences in the moisture balance of single species.

An extension of the biohygrothermal model to record also the time-dependent influence of substrate-related osmotic potentials, conditional on the salt contents of the substrate itself or by anthropogenic contaminations on the substrate surface, would be useful. In addition, it must be checked to what extent the germination processes of other microorganisms, of bacteria or xylophagous fungi for example, can be described with the selected approach.

All in all, a „mould fungus catalog“ might be useful for the practitioner, containing building constructions and boundary conditions recommended for the prevention of mould fungus growth at different interior climates. The combination of the biohygrothermal model and a hygric space model to directly record the influence of different ventilation strategies should be aimed at. Mastering a space model with various ventilation strategies is essential for practical measures to prevent mould fungi. Based on that, a sophisticated safety concept for the prediction of mould fungus formation should be created.

7. Examples of application

The application of the developed method shall now be demonstrated exemplary by means of various building constructions. Selection of the building products to be tested is based on the typical problem cases described under item 2.1.6. Table 19 contains a summary of the chosen calculation examples. It includes data of the building constructions and the parameters from building physics taken into consideration. These examples shall show how to proceed methodically when determining the required hygrothermal climatic boundary conditions and indicate the essential building physical phenomenons. The discussion of the results and the

assessment of possible risks caused by mould fungi leads to an overall assessment of the constructions or systems.

7.1 Internal wall surfaces

The risk of mould fungus formation shall be assessed at the internal surface of a monolithic, northwards oriented external wall of brickwork, with inside lime-cement plaster, of an old building, described in [65]. Different heat conductivities of the 36.5 cm thick wall as well as different moisture loads according to Figure 23 are applied as climatic boundary conditions in the dwelling. Table 20 contains the most important test parameters as well as the result of the mould fungus assessment for the cases A to G mentioned there. As the exterior climate one uses measured climate data records as hourly mean values, as shown in Figure 22 for a representative year in the decade mean values and decade sums respectively [74]. All material data are taken from the WUFI database. For the 7 cases mentioned in Table 20, the arising microclimatic boundary conditions at the plaster surface have been determined by the WUFI program under consideration of the different interior climates. By means of the biohygrothermal model the moisture contents in the model spores were calculated each for substrate category II, that includes plaster, and compared with the critical moisture contents (Figures 54 and 55).

In cases A and B the insulating level is varied for a mean moisture load. The heat conductivities assumed for the calculations are in dry condition 0.2 W/(m K) in case A and 0.6 W/(m K) in case B. As noticeable in Figure 54 (dashed lines), there is no mould fungus in the wall centre at a heat transition coefficient of the brickwork of 0.6 W/(m² K) in case A and 1.3 W/(m² K) in case B. The moisture contents in the spores are above the critical moisture contents. This could be expected since the relative humidity at the wall is only 62 % in summer and only 43 % in winter with a good insulation (case A), and with a reduced insulation value (case B) it increases to only max. 69 %, as proved by the calculation.

A piece of furniture standing in front of the wall impedes the convective airflow in the area of the plaster surface behind it. In terms of building physics this can be described with a reduced heat transmission coefficient. Therefore, one has assumed in the cases C and D a value of 2 W/(m² K) for free-standing cupboards, according to the proposal of Cziesielski [110]. Mould fungus growth does occur only with a heat transmission coefficient of the brickwork of 0.6 W/(m K) in case D. As represented in Figure 54, the moisture content in the spore (dashed thin line) lies considerably above the critical moisture content (solid thin line) already at the end of October. Critical conditions arise above all in the two cold periods, December and February, of the climate data record used. In contrast to that, fungoid growth can be avoided with a better insulation (case C). In case E, the WUFI calculations are based on a high moisture load according to Figure 23. One can notice that there is no mould fungus, due to the good insulation. In the cases A to C and E, the moisture contents in the spores certainly differ slightly, but for reasons of clarity only one line is shown in Figure 54. The same does apply to the critical moisture content.

To estimate in addition the effects by a redevelopment of a building, one assumes in case F that new windows are installed with maintaining the previous insulation level at the external walls. The new tight windows cause an increased moisture load in the rooms which is considered by taking a high moisture load as calculation basis. No fungus growth can be observed in the wall centre (not shown in Figure 55). But when applying a reduced inner heat transmission coefficient of 4 W/(m²K), for plaster areas behind curtains for example, as shown in Figure 55 at the top, microbial activity takes place in case F. The influence of a piece of furniture at a badly insulated external wall at a low moisture load is assessed in case G. As represented in Figure 55 bottom, critical conditions arise here only in December with mould fungus growth. In February, having a reduced moisture load in the room, no increased moisture content is reached in the spores any more.

To sum up the results one may say that a good insulation is the most important measure to prevent mould fungus formation. The second measure that should be guaranteed is a sufficient ventilation, above all at low outside air temperatures, and moving the cupboards away from the external walls; the latter is to be done only for badly insulated building constructions (in old buildings, for example).

7.2 Thermal bridge at windows

Thermal bridges at windows are areas where mould fungi occur often. First of all, the temperature distribution (Figure 56) and the heat flows are calculated by a three-dimensional finite-difference method [130] with the help of the characteristic data of the building component by using the inner and outer heat transmission coefficient according to DIN 4108. From that calculation one gets the position of the lowest inner surface temperature. It exists in the area of the glass edge bond. Here one can find permanently elastic materials and often depositions or slight contaminations. One calculates therefore with substrate category II to assess mould fungus formation. Depending on the outside air temperature, one can indicate in the stationary case the room side surface temperature at the glass edge bond. Figure 57 shows the respective curve for an indoor air temperature of 20 °C. Taking the example of a window made of plastic, the heat storage capacity and the sorption capacity shall be ignored, i.e. the temperature and the relative humidity are calculated only in dependence on the exterior and interior climatic boundary conditions. For different moisture loads in dwellings [73], it can thus be ascertained at what atmospheric conditions mould fungus formation can be expected. The data record used for the exterior climate is the typical year shown in Figure 22.

Figure 58 shows the biohygrothermally calculated moisture contents in the model spores at normal and low moisture load. The comparison with the drawn critical moisture content demonstrates that mould fungi do grow in

both cases in late summer and in autumn, under consideration of the substrate category II, since there is not only a relatively high inside air humidity but also lower outside air temperatures in this season. The cool June in the used climate data record is to be evaluated critically as well. In the actual winter, the low indoor moisture load becomes apparent. Altogether, the conclusion can be drawn from this example that the dwelling needs to be ventilated well above all in autumn. Furthermore, one can assume that cleaning the windows frequently leads to more unfavourable growth conditions for mould fungi at windows. The spores can certainly germinate but an extensive fungus growth is restricted due to the nutrient content in the substrate.

7.3 Unvented gable roofs

In the last two to three years, damages by fungi appeared in some roof structures already in the construction phase or shortly after completion, partly to a great extent [145]. That usually led to unpleasant discussions since accusations are made first that the material supplied is technically insufficient or defective already on delivery. But in most of the cases the real reasons for such fungus formation are constructional boundary conditions or insufficient building physical planning. One example of such a mould fungus formation inside a roof construction, caused by building moisture already existing and transported further through diffusion processes, is the unvented gable roof already dealt with in 5.3 [77]. By means of the biohygrothermal model it shall be determined what are the effects of different outer diffusion resistances of such a roof construction on microbial activity. Apart from the virtually vapour-proof sheet metal roof, one considers also gable roofs with outer vapour diffusion resistances of 1 cm, 10 cm and 100 cm. Temperature and humidity courses in the vapour seal region are calculated with the WUFI program over a period of 2 years. For the transient calculations an indoor climate is applied that corresponds to an average moisture load (see Figure 23), as per [73], and the exterior climate data records according to Figure 22 are used.

The humidity courses turning up at the vapour seal over the first half year are demonstrated in Figure 59 at the top. The moisture contents in the model spores and the comparison with the respective critical moisture contents is shown in Figure 59 bottom. It can be noticed that, in comparison with the nearly vapour-proof sheet metal roof, the moisture contents in the spores are falling with the outer vapour diffusion resistances getting lower. Nevertheless, the critical moisture content is exceeded in all cases, considering substrate category I (paper foil). With a diffusion resistance of 1 cm or 10 cm, the limit is overstepped approx. 40 days only. In such cases, a mould fungus infestation is often not observed in reality, either because it is not detected or otherwise the provision with biocides was sufficiently effective in the first year. In the second test year, a mould fungus formation is not expected any more since the building moisture has dried out at all variants.

7.4 ETICS facade

To find out after what period of time the hygrothermal conditions at the plastered exterior thermal insulation composite systems (ETICS) facade of a housing area [68] described in 5.4, do no longer allow fungoid growth, one uses the biohygrothermal model to determine how drying out of building moisture influences the microbial activity. For that purpose, the temperature and moisture courses on the plaster in the wall centre as well as in the window lintel region and at the plate joint are calculated by the WUFI program over a period of 10 years, starting in October (building construction). The test reference year is covered several times.
The calculation results are shown in Figure 47 at the bottom for the first year. It is only the wall centre that remains free from growth. In the second year, the moisture in the window lintel region dries out towards the end of summer so that also here fungoid growth need not be expected (Figure 60 at the top). The plaster drawn over the plate joint requires about 8 years for the same drying out process, as demonstrated in Figure 60 at the bottom. From these

results the conclusion can be drawn that there are no biohygrothermally critical conditions arising on the facade after one year at the latest, except at damaged systems. That means that a biocide, if required, may be put down so as to be effective for the first year only. To see it in perspective it must be emphasized that these calculations do not consider the influence of long-wave radiation which may, with exterior thermal insulation composite systems, lead to nightly hypothermia and possibly to microbial growth. That influence should be investigated later.

7.5 Ventilation systems with open air cycles

The risk of mould fungus formation in ventilation systems is well-known [93]. In the following two application examples possible fungoid growth shall be assessed. In both systems air is conducted through ducts and then supplied to the room for heating or cooling purposes.

Hybrid heating systems

In order to reduce the need for thermal heat in buildings, systems were developed that use hollow spaces of building components for the transport and the component masses for the storage of solar energy [41, 43, 57, 61]. For reasons of energy it is advantageous to charge and discharge part of these mass-loaded components through open air cycles [90]. When the exterior and interior climatic conditions are unfavourable, condensation water may accumulate and with that, microbial growth can occur inside the components of such hybrid heating systems [6, 36]. From the view of hygiene, the suitability for use is restricted and the need for maintenance is increased. With the help of component characteristic data and operating states, representative climate data records were determined in [82] und [91] at differently designed hybrid heating systems with air cycles. These data records can be used for the assessment of mould fungus formation by the biohygrothermal model. Figure 61 shows the vertical section through the selected construction. Such external wall superstructures may, when oriented

southwards, store solar energy effectively and supply it to the interior with a delay of 4 to 12 hours, depending on the building material and the wall thickness. With a gap between the glass pane and the brickwork being ventilated, a better utilization of the solar energy may be achieved. Due to the solar radiation, the air in the outer air cycle is warmed up at the heated absorber sheet and can supply the stored energy to the hollow brick wall, i.e. „charge“ the wall. The inner air duct leads through an air gap behind an inner leaf of plaster board mounted on the wall. An additional heating element is located in the lower area. The external wall is discharged as soon as a convection in the gap is initiated. In case of long lasting cold weather periods and at nights, the high transmission heat losses have a negative effect [42]; mould fungus formation in the inner air duct (open discharge cycle) cannot be excluded.

In [91] the construction shown in Figure 61 was investigated by calculations. First of all, the temperature distribution under stationary boundary conditions is determined by means of a three-dimensional finite-difference method [130], with the lowest temperature arising in the vertical centre of the collector. This can be explained by the fact that the glass top represents thermically the position of lowest insulation. When entering the temperature distribution depending on the building component height, one gets the curves shown in Figure 62 for the construction type in Figure 61 at an outside air temperature of 0 °C and an inside air temperature of 20 °C for different variants demonstrated in Figure 62. The illustration on the left-hand side describes the outer air duct side. Since a mould fungus formation is expected mainly in the discharge cycle, it is the distribution along the component edge of the inner air duct which is decisive (on the right-hand side in the figure). There is a noticeable influence of the horizontal ducts of the outer ring system (in Figure 61 in the region of the lower opening flap). In the standard case of a storage wall with a thickness of 8 cm, the temperature of 16 °C in the wall centre falls in that area by more than 2 K. Compared with the insulated wall centre, the cause is here the higher heat conductivity of the air in the horizontal flow duct. That way, one can define the position of the

lowest surface temperature. The operating state „standstill“ is the most unfavourable case, since with flowing air the surface temperature would increase against the standstill state [91]. At first, a typical three-day period in autumn is taken from the test reference year [53] for the transient calculations and the lowest surface temperature in the inner air duct is calculated for it, dependent on time (Figure 63 on the left-hand side). Afterwards, the relative air humidity at the place of the lowest temperature in the inner air duct (see Figure 62 on the right) is calculated and represented in Figure 63 on the bottom left. It depends only on the hygrothermal state of the inside air, which is assumed with a temperature of 20 °C and a relative humidity of 50 %. A calculation for the winter analogous to the above is shown on the right-hand side in Figure 63. The results are used as climatic boundary condition for the biohygrothermal model by stringing the three-day climate records together, thus calculating a period of 6 weeks. In addition to the standard case (inner climate with constant 20 °C and 50 % relative humidity), the indoor air humidity is varied by also calculating with a relative humidity of 65 % (high moisture load) for autumn and with 40 % (normal moisture load) in winter. For the prediction of mould fungus growth a nutritious substrate is assumed as a result of dust deposit, since the system is operated without any filter. Furthermore, the inner leaf of plaster board belongs to substrate category I.

Figure 64 shows the calculated moisture contents in the spores as well as the comparison with the critical moisture contents (solid lines) for autumn (top illustration) and for winter (bottom illustration). One can notice that spore germination takes place in autumn after approx. 3 weeks only at a high indoor humidity of 65 %. At 50 % and at 60 % (not shown in the figure) the duct remains free from mould fungi. In winter, however, fungi may grow quickly under these conditions. Microbial growth is not to be expected only, if the indoor humidity is less than 40 %. In [91] it is additionally investigated whether a replacement of the 8 cm thick storage wall with a 36 cm thick wall will increase the lowest temperature in the system in a way that no mould fungi do grow any more. In autumn, the lowest surface temperature is

increased here by approx. 1 K, as shown on the right-hand side of Figure 62, and the relative humidity does never exceed the critical values, even if there is a high moisture load; thus, mould fungus formation can be excluded. A similar result is achieved with an insulation of 12 cm (see also Figure 62, right-hand side). In winter, however, the growth conditions are met in the standard case (50 % indoor relative humidity) even if the brickwork is 36 cm thick. If one assumes that the building constructional possibilities are exhausted with that, the problem of mould fungus formation must be solved then by installing special systems. A heater located in the building component would be ideal for that which would serve more or less as „mould fungus controller“ and would have been connected whenever the relative air humidity exceeds the temperature-dependent moisture value indicated in the LIM_{Mat} curve for substrate category I at the most unfavourable position.

Soil-air heat exchanger

The heating energy demand arising at well-insulated buildings above all through ventilation heat losses, can be reduced by pre-heating the outside air supplied to the building by means of a soil-air heat exchanger (EWT) as described in [117]. Such systems can be used in summer also to cool buildings. The outside air is sucked in, guided through the tube system installed in the ground and then supplied to the building, often directly without intermediate connected heat exchanger. Since cooling down the air, which is mostly humid in summer – regarded absolutely –, leads always to an increase of the relative humidity in the duct, the risk of mould fungus formation in such ducts shall be assessed, based on the results summarized in [118]. A distribution of the fungus spores through the soil-air heat exchanger as open ventilation system would represent a danger to health. Basis is a 40 m long EWT installed in a depth of 2 m made of a plastic or clay pipe with a pipe diameter of 10 cm. The measurements and calculations of an EWT carried out in [118] prove clearly that above all in cases of high outside air temperatures where such a system is applied, an underrun of the dew point temperature in the duct cannot be avoided. Thus, condensation

water is generated certainly only on few days per year and drains off due to the inclined installation of the pipes. And the EWT dries out again after it is disconnected. However, if one converts the absolute humidity of approx.11 g/m³ on a typical day in July [67] into an average temperature of approx. 10 °C in the ground in a depth of 2 m, then the relative humidity in the duct is still above 90 %. When comparing these climatic boundary conditions with the isopleths represented in Figure 34 at the bottom for the substrate category II, it can easily be seen that the microbial growth in the EWT is to be expected in case of a clay pipe (substrate group II) after approx. 4 days. That could be avoided by using a plastic pipe belonging to substrate group III, but only if there is no contamination in the EWT tube. Therefore, the use of a filter insert and frequent cleaning are absolutely required for a hygienic, perfect operation in summer.

8. Conclusions

The distinctive features of the new prediction method as against the previous standard methods to estimate the risk of mould fungus formation are a repeated experimental validation and an elaborated indication of growth conditions. In the isopleth model, the spore germination times and growth rates can be specified for three different substrate categories in dependence on temperature and relative humidity. These indications refer to all fungus species occurring in buildings, as it is known according to the current state of knowledge, with always the lowest spore germination times and the highest growth rates being considered. That allows to determine the minimum time needed by mould fungi to germinate, for different building materials and degrees of contamination. One just has to know the hygrothermal boundary conditions. After germination has begun, it can be predicted what is the maximum mycelium growth to be expected.

As for optimal culture media, separate isopleth systems allow to predict mould fungus formation for various hazardous classes. For this purpose, the

health hazard caused by fungi was divided into three classes which the growth conditions for each single species are assigned to. That allows not only to predict the mould fungus formation for all fungi of one class or group but also respective individual assessments.

In the case of stationary climatic boundary conditions, mould fungus formation can be excluded according to the isopleth model, if the hygrothermal growth conditions indicated in the isopleth systems for spore germination are not exceeded, depending on the substrate. Basis is here the course of the respective LIM, that describes the lowest limit of fungus activity, in the range of 0 °C and 30 °C which is an interesting range from the view of building physics. It turns out that at high temperatures a lower relative humidity is sufficient to let mould fungi grow, whereas at high humidities even lower temperatures might be critical. With that, elaborated indications are available for the first time that allow to state the relative humidities needed by a mould fungus to grow for different substrate groups, in dependence on the temperature. For an optimal culture medium for example, at a temperature of 15 °C, a relative humidity of approx. 73 % is sufficient for hazardous class B/C and 77 % for fungi dangerous to health (hazardous class A) and for the substrate groups I and II 77 % and 82 % respectively; the latter values do apply to all mould fungi occurring in buildings. It turns out for some species that an increase of the indoor air temperature – often indicated as a measure to prevent fungus formation – may result in a higher risk of mould fungus formation. Increasing the indoor air temperature and with that the surface temperature by additional heating, the relative humidity in the room and at the surfaces is certainly reduced; but at the same time the relative humidity needed by fungi to grow is reduced at higher temperatures.

As it was proved by the examples of application under item 7, improving the thermal insulation level is an optimum measure to reduce the risk of mould fungus formation at internal surfaces of external building components. Figure 65 represents a nomogram on basis of the respective LIM_{Mat} curves to determine the maximum admissible indoor air humidity at which there is

no mould fungus growth at the internal surface of an external building component any more, in dependence on the arising internal surface temperature (bottom illustrations) for the two substrate categories I and II. The internal surface temperature on the other hand can be read off for different stationary outside air temperatures (top illustrations) for an indoor air temperature of 16 °C (illustrations on the left) and 20 °C (illustrations on the right), in dependence on the heat transition coefficient. When assessing thermal bridges, one can either directly take the internal surface temperature determined at the thermal bridge position as basis or set simplistically a fictitious heat transition coefficient for the thermal bridge region.

To assess building constructions at any climatic boundary conditions, the transient courses of temperature and relative humidity can be calculated as input parameters for the biohygrothermal model by means of the hygrothermal calculation program WUFI at interesting places in the building construction where fungoid growth is expected. With that, it is possible for the first time to assess the effect of short humidity peaks, caused by taking a shower or cooking for example, on a possible mould fungus formation, depending on the construction (e.g. sorptive plasters); because with the biohygrothermal calculations the effect that transient humidity courses have on the humidification and dehumidification of mould fungus spores can be determined directly. As it could be seen from the consideration of the building up of the model spore moisture, high peaks of 95 % relative humidity for example lasting one hour per day are first of all not critical. However, if they last more than three hours a day, one has to expect fungus formation within a few weeks, above all at materials belonging to substrate group I.

Since the material parameters that serve as basis for the hygrothermal calculations as well as the practically occurring climatic boundary conditions are generally subject to fluctuations, it is recommended to validate the calculation results in measurements by taking samples in order to get quantitatively reliable statements. Apart from the climate input parameters,

the accuracy of the biohygrothermal calculation results depends only on the parameters of the model spores, i.e. on the moisture storage function and the s_d value. But the specification of the same is relatively simple, because they do influence the results only slightly. Different spore germination times arise, however, with different substrate categories by means of which the critical moisture contents are set. For reasons of safety it is therefore recommended for biohygrothermal calculations to always choose that group which is more favourable for fungoid growth (i.e. the more critical group), if the assignment of building materials to a substrate group is not clear.

9. Summary

Mould fungal infestation, particularly at internal surfaces of external building components, but also at other places on and within components recently got into the news. The elimination or prevention is not only accompanied by considerable redevelopment costs. Mould fungi may also represent a hazard to the health of the occupants. That gives rise to insecurity. It is certainly possible to reduce or avoid mould fungus formation indoors for some time by biocides or similar agents. Though a hazard to health through these products cannot be ruled out. Therefore, to avoid mould fungus formation in buildings, one has to develop a prevention strategy that is based on the growth conditions for mould fungi and that considers the complex transient processes of building physics.

It turned out that the three most important growth conditions „temperature, humidity and substrate“ must be existing simultaneously over a certain period of time to enable fungoid growth. The currently usual methods for the assessment of mould fungus formation do not, or only indirectly, consider the transient boundary conditions. Publications mentioned the relative humidity as the only criterion for a while. Meanwhile, there are also indications in literature about the dependence of the relative humidity on the temperature when mould fungus formation may take place in case is exceeded. However,

these characteristics usually do not allow any greater differentiation regarding the influence of substrate, building material or contamination. Therefore, the main focus of this scientific paper on hand was the development of a biohygrothermal method allowing the prediction of mould fungus formation based on all three mentioned biological growth conditions for mould fungi at transient boundary conditions. The new procedure comprises two prediction models that are based on each other: the isopleth model and the transient biohygrothermal model.

The isopleth model makes it possible to determine the germination times of the spores and the mycelium growth on the basis of isopleth systems with also considering the influence of the substrate for the prediction of mould fungus formation. An isopleth system describes the hygrothermal growth conditions of a fungus and consists of a temperature- and humidity-dependent curve system, the so-called „isopleths“ that represent spore germination times when spore germination is to be predicted, and growth per time unit when the description of the mycelium growth is concerned.

Significant differences exist among the various fungus species, as far as the growth conditions are concerned. Therefore, when developing common isopleth systems only those fungi were taken into account that occur in buildings and that are dangerous to human health or damage the construction. Quantitative statements on the growth conditions temperature and humidity are set up for the approx. 200 species that fulfill both features. To make further distinctions between the life phases of the mould fungi, the data for spore germination and mycelium growth are given separately. In order to differentiate the mould fungi according to the health hazard they may represent, the so-called „hazardous classes“ are defined as follows:

A. Fungus or its metabolic products are highly pathogenic; they are not allowed to occur in used dwellings.

B. Fungus or its metabolic products are pathogenic when exposed in rooms over a long period or they may cause allergic reactions.

C. Fungus is not dangerous to health, fungus formation however, may cause economic damage.

Classifying the fungi into three hazardous classes it turns out that the values of class C are only slightly different from that of class B. Therefore, it is sufficient to differentiate within the isopleth model only between the hazardous class A and a combined class B/C. The isopleth systems are based on measured biological data and consider the growth conditions of all fungi of one hazardous class. The resulting lowest limits of possible fungus activity have been called LIM (Lowest Isopleth for Mould).

The prerequisites for the growth of mould fungi in dependence on temperature and relative humidity are stated for the above mentioned hazardous classes at first for the optimal culture medium. In order to regard the influence of the substrate, that is the building materials or possible contamination, on the formation of mould fungus, isopleth systems for two categories of substrates are suggested (envelope curve LIM_{Mat}) that could be derived from experimental examinations. For this purpose four categories of substrates were defined and different building materials assigned:

Substrate category 0: Optimal culture medium

Substrate category I: Biologically utilizable substrates like wall paper, plaster board, building materials made of biologically degradable raw materials, material for permanently elastic joints;

Substrate category II: Building materials with porous structure such as plasters, mineral building material, certain wood as well as insulating material not covered by I;

Substrate category III: Building materials that are neither degradable nor contain any nutrients.

An individual isopleth system is set up only for the categories 0, I and II; in the category 0, the isopleths for optimal culture media are applied. For the substrate category III no isopleth system is given since it can be assumed that formation of mould fungi is not possible without contamination. In case of considerable contamination, substrate category I should always be taken as basis. The basic principle of the new method and of defining the building material categories is to assume a worst case scenario, i.e. always being on the safe side in respect of preventing the formation of mould fungi.

Altogether, eight isopleth systems were developed for the spore germination and for the mycelium growth individually. Each of the systems is valid for a whole group of mould fungi and considers not only optimal culture media but also different substrates:

a) Isopleth systems for the hazardous class B/C (LIM B/C). Systems referring to biological complete media as substrate and therefore they provide the smallest prerequisites for the growth of fungi as far as relative humidity is concerned. They form the growth limit for all fungus species occurring in buildings. This means that, when the boundary conditions do not allow the growth of fungi of hazardous class B/C, growth of fungi of hazardous class A can be excluded as well.

b) Isopleth systems for the hazardous class A (LIM A). Analogous to a), but only valid for all fungi of the hazardous class A.

c) Isopleth systems for the substrate category I ($LIM_{Mat\ I}$). Valid for all mould fungi occurring in buildings. They do not refer to the complete medium but to materials belonging to category I.

d) Isopleth systems for the substrate category II (LIM_{Mat} II). Analogous to c), but only valid for all materials belonging to the substrate category II.

For transient boundary conditions of temperature and relative humidity, either spore germination time or the mycelium growth can be determined with the help of these isopleth systems. The assessment of spore germination on the basis of the isopleth model has the disadvantage that an interim drying out of the fungus spores in case of occurring transient microclimatic boundary conditions cannot be taken into account. Therefore, this process will predict the germination of spores more often than the biohygrothermal model.

To describe the mode of action of the fundamental factor of influence on the germination of spores, i.e. the humidity available at certain temperatures, a new biohygrothermal model was developed. This model makes it possible to calculate the moisture balance of a spore in dependence of the transient boundary conditions, thus even to consider interim drying out of the fungus spores. The biohygrothermal model for predicting the germination of the spores is based on the fundamental idea that a fungus spore has a certain osmotic potential because of the substances inherent in the spores. With the help of this osmotic potential spores can absorb water existing in the environment. This potential is mathematically described by means of a moisture storage function. The absorption of moisture through the spore septum is calculated by a diffusion approach in the model. This simplification is justified because the humidity absorption always takes place isothermally, due to the small geometrical size of the mould fungus spore. Furthermore, the spore septum gets a moisture-dependent s_d value that is iteratively adjusted by comparing the calculated spore germination times with those given in the isopleth systems. If a certain moisture content is reached inside the spore that allows to start metabolic activity, the fungus can regulate its metabolism on its own, independent of the ambient conditions. Nevertheless, the complicated regulation mechanism still remains generally unknown and therefore cannot be described in an

exemplary manner. However, this is not necessary because the critical moisture content that makes biological activity only possible, must not be passed. This limit moisture content is fixed by means of the isopleth systems for spore germination where, depending on the temperature, the lowest relative humidity at which spore germination takes place can be read off the respective LIM curves. With the help of the moisture storage function assumed for the spore inside, the moisture content occurring in the spore can be calculated and compared with the critical moisture content.

In order to consider possible influences of the substrate, the s_d values of the spore septum were adjusted in a way that the spore germination times measured in the biohygrothermal model under stationary conditions correspond to those in the isopleth systems of the substrate categories I and II. By adjusting the s_d values of the spore septum a model spore can be defined that is valid for all three substrate categories. Furthermore, the LIM curves in the isopleth systems of the appropriate substrate categories have to be used when specifying the substrate-dependent critical moisture contents.

One can gain the transient conditions for temperature and relative humidity occurring in buildings by means of the WUFI program for one and two-dimensional structures. The spore germination is assessed based on the microclimate on the surface. To assess the mycelium growth, the hygrothermal conditions in a depth of 1 to 3 mm are referred to as well. This can be done again with the help of the WUFI program very easily. The transient hygrothermal boundary conditions determined at the corresponding places on or within building components serve as input parameter for the biohygrothermal model.

The biohygrothermal process is validated by plausibility considerations, sensitivity analyses as well as by the comparison with the results of laboratory experiments, outdoor tests and measurements in occupied dwellings. It turned out in all cases that the results of the prediction models

do greatly correspond with the measurements and observations in practice. Since the material parameters for the biohygrothermal model are adjusted in some aspects or could only be taken over from experiments with spore-forming bacteria, they will have to be supported further by specially selected biological experiments.

Comparing the biohygrothermal model with previous standard guidelines, preventive strategies and other predictive methods, it is shown that the biohygrothermal model is by far exceeding the present state of knowledge. The arithmetical prediction of mould fungus formation allows the treatment of questions that could not be answered up to now, neither with simple estimations nor by measurements with reasonable effort. For example, it was not possible up to now to determine experimentally the hygrothermal behaviour of redeveloped external wall constructions and to assess the danger of a recurring microbial settlement after the redevelopment. With the biohygrothermal method, parameter studies in order to choose the suitable construction are relatively easy now. Apart from that, the assessment of internal construction parts is completely unproblematic as well. It is exactly these simple and very reasonable features that let one expect a wide use of the new method for the prediction of mould fungus formation when planning building projects or redevelopment measures.

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Table 1 Compilation of fungi occurring in building. This list contains those fungi which different authors and also the new draft of DIN 4108, part Mould Fungi, consider to be representative ones for occurring in buildings. Furthermore, the fungi are classified concerning health danger and the availability of data is added too.

Species of fungi	found in buildings [55] 1)	representative in buildings								health danger [55] 2)	specificated by [81] 3)	danger classes 4)	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Absidia sp.	■					■				■		B		
Absidia corymbifera	■									■		B		
Absidia glauca	■											C		
Acremonium sp.	■		■	■	■			■		■	2	B		
Acr. cephalosporium	■			■						■		B		
Acr. furcatum	■											C		
Acr. obclavatum	■											C		
Acr. strictum	■											C		
Acrostalagmus sp.	■											C		
Alternaria sp.	■	■	■	■	■		■	■		■	2	B		■
Alternaria alternata	■			■	■		■			■		B		■
Alternaria tenuis	■	■							■	■		B		
Aspergillus sp.	■	■	■	■	■	■	■	■	■	■		B	■	■
Asp. amstelodami	■	■							■	■		B	■	■
Asp. brevicompactum									■	■		-		
Asp. candidus	■									■		B	■	■
Asp. carbonarius	■											C		
Asp. chevalieri												-	■	■
Asp. clavatus										■		-	■	■
Asp. echinulatus												-		
Asp. fischeri	■											C		
Asp. flaviceps	■											C		
Asp. flavus	■		■							■	3	A	■	■
Asp. fumigatus	■	■	■		■					■	3	A	■	■

Continuation of table 1

Species of fungi	found in buildings [55] [1]	representative in buildings								health danger [55] [2]	specificated by [81] [3]	danger classes [4]	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Asp. glaucus	■											C		
Asp. halophilus	■											C		
Asp. mangini												-		
Asp. nidulans	■		■							■	3	A	■	■
Asp. niger	■	■	■		■				■	■	2	A	■	■
Asp. ochraceus	■	■								■		B		
Asp. parasiticus	■									■		B		
Asp. penicilloides	■		■							■	3	A		■
Asp. repens							■					-	■	■
Asp. restrictus	■	■	■							■	2	B		■
Asp. ruber	■	■							■	■		B	■	■
Asp. sydowii	■											C		
Asp. tamarii	■											C		
Asp. terreus	■									■	2	B	■	■
Asp. ustus	■	■	■							■		B		
Asp. versicolor	■	■	■				■		■	■	2	A	■	■
Asp. wentii	■			■								C		
Aureobasidium sp.	■	■	■	■	■		■	■	■	■		C		
Aureobasidium pullulans	■	■	■	■	■		■		■	■	2	B		
Bipolaris sorokiniana	■									■		B		
Botrytis sp.	■	■	■		■					■				■
Botrytis cinera	■	■	■							■	1	B		■
Canadia albicans										■		B		■
Cephalosporium sp.	■									■		B		
Chaetomium sp.	■		■	■	■					■	3	A		
Chaetomium globosum	■			■								C		
Chrysonilia sp.	■			■						■		B		
Chrysosporium fastidium	■											C		
Cladosporium sp.	■	■			■	■	■	■	■	■		-		■
Cla. herbariorum							■					-		
Cla. herbarum	■	■			■		■			■		B		

Continuation of table 1

Species of fungi	found in buildings [55] [1]	representative in buildings								health danger [55] [2]	specificated by [81] [3]	Danger classes [4]	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Cla. cladosporioides	■	■			■		■		■	■		B		■
Cla. macrocarpum	■											C		
Cla. resinae	■											C		
Cla. sphaerosperum.	■						■					C		
Cla. tenuissimum	■											C		
Cla. trichoides										■		B		
Cryptococcus sp.								■				-		
Cryptostroma corticale	■											C		
Cunnighamella elegans										■		B		
Curvullaria sp.	■				■			■		■		-		
Curvullaria geniculata										■		B		
Curvullaria lunata	■									■		B		
Emericella nidulans	■											C		
Epioccum sp.	■		■		■					■		C		
Epioccum nigrum	■		■							■	2	B		
Epioccum purpurascens	■											C		
Eurotium sp.	■		■	■						■		-		
Eurotium herbariorum	■		■	■						■	2	B		
Exophiala dermatitidis	■											C		
Exophiala jeanselmei	■											C		
Exophila spinefera	■											C		
Fusarium sp.	■		■		■		■	■		■	3	A		
Fus. culmorum	■									■		B		
Fus. graminearum										■		-		
Fus. moniliforme							■			■		-		
Fus. oxysporum	■									■		B		
Fus. solani	■									■		B		
Fus. sporotrichoides										■		-		
Fus. verticillioides	■									■		B		
Geomyces sp.	■			■			■					C		
Geomyces pannorum							■					-		

Continuation of table 1

Species of fungi	found in buildings [55] [1]	representative in buildings								health danger [55] [2]	specificated by [81] [3]	danger classes [4]	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Geotrichum sp.	■				■							C		
Geotrichum candidum					■									
Gliocladium sp.					■									
Gliocladium fimbriatum												-		
Gliocladium roseum	■											C		
Gliomastix murorum			■									-		
Gymnoascus sp.	■											C		
Helminthosporium					■									
Herbarum						■						-		
Hefepilze			■	■						■	1	B		
Hormodendrum sp.	■											C		
Memnoniella echinata										■		-		
Monilia sp.	■				■							C		
Monocillium sp.	■			■								C		
Monocillium				■								-		
Mortierella sp.	■											C		
Mort. niveo-luteum										■				
Mucor sp.	■		■		■	■	■			■	3	A		
Mucor flavus	■											C		
Mucor plumbeus	■						■			■		B		■
Mucor pusillus										■		B		■
Mucor racernosus	■											C		
Mucor rouxii	■											C		
Myrothecium varrucaria	■											C		
Neurospora sitophila												-		■
Nigrospora					■									
Oospora					■									
Oidiodendron sp.	■			■								C		
Oidiodendron				■								-		
Paecilomyces sp.	■		■	■	■					■		B		
Paecilomyces lilachinus	■			■								C		

Continuation of table 1

Species of fungi	found in buildings [55] [1]	representative in buildings								health danger [55] [2]	specificated by [81] [3]	danger classes [4]	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Paecilomyces variotii	■		■		■					■	3	A		
Papulaspora sp.	■											C		
Penicillium sp.	■	■	■	■	■	■	■	■	■	■		B		■
Pen. aethiopum										■		-		
Pen. aurantiogriseum	■									■		B		
Pen. bervicompactum	■	■	■	■	■		■			■	2	B		■
Pen. chrysogenum	■	■	■	■			■		■	■	2	B		■
Pen. citreonigrum	■		■									C		
Pen. citrinum	■									■		C		
Pen. commune										■		-		
Pen. corylophilum	■											C		
Pen. cyclopium	■				■					■		B		
Pen. decumbens	■											C		
Pen. echinulatum	■											C		
Pen. expansum	■	■	■							■	2	B		■
Pen. frequentans / glabrum	■	■							■	■		-		
Pen. funiculosum	■				■							C		
Pen. glabrum	■		■							■		B		
Pen. griseofulvum	■											C		
Pen. italicum												-		■
Pen. janthinellum	■											C		
Pen. lapidosum	■	■										-		
Pen. myczynskii	■											C		
Pen. nigricans							■					-		
Pen. notatum	■									■		B		
Pen. olivinoviride	■											C		
Pen. oxalicum	■											C		
Pen. purpurogenum	■	■										C		
Pen. rubrum	■											C		
Pen. simplicissimum	■											C		
Pen. spinulosum	■			■			■			■		B		

Continuation of table 1

Species of fungi	found in buildings [55] [1]	representative in buildings								health danger [55] [2]	specificated by [81] [3]	danger classes [4]	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Pen. verrucosum	■			■						■		B		
Pen. viridicatum										■		-		
Pen. vulpium										■		-		
Phialophora heteromorpha	■									■		B		
Phoma sp.	■				■		■					C		
Phoma herbarum							■					-		
Phoma leveillei	■											C		
Phoma putaminum	■											C		
Phoma violaceae	■											C		
Rhinocladiella sp.	■											C		
Rhizopus sp.	■		■		■					■	3	A		■
Rhizopus arrhizus										■		-		
Rhizopus oryzae										■		B		
Rhizopus stolonifer	■											C		■
Rhodotorula sp. (Hefe)	■							■		■	1	B		
Scopulariopsis sp.	■			■	■					■		B		■
Scop. brevicausalis	■			■	■					■		B		■
Scop. brumptii	■									■		B		
Scop. fusca	■									■		B		
Scytalidium circinatum	■											C		
Scytalidium lignicola	■											C		
Sistotrema brinkmannii							■					-		
Sphaeropsidales				■								-		
Sporobolomyces roseus	■											C		
Sporotrichum sp.	■											C		
Sporthrix sp.	■	■		■								C		
Stachybortrys sp.	■		■	■	■		■			■		B	■	■
Stachybotrys atra	■		■				■			■	3	A	■	■
Stemphylium sp.	■				■							C		
steriles Mycel				■								-		
Torula					■									

Continuation of table 1

Species of fungi	found in buildings [55] [1]	representative in buildings								health danger [55] [2]	specificated by [81] [3]	danger classes [4]	Data available	
		Gertis [37]	LGA [81]	Nielsen [89]	Annex [52]	Carl [12]	Grant [39]	Rao [97]	DIN 4108 [21]				Spore germination	Mycelium growth
Trichoderma sp.	■		■	■	■							C		■
Trichoderma harzianum	■									■	2	B		
Trichoderma lignorum	■									■		B		
Trichoderma viride	■		■	■						■	2	B		■
Trichothecium sp.	■		■		■					■				■
Trichothecium roseum	■		■							■	2	C		■
Tritirachium	■		■	■								C		
Ulocladium sp.	■			■	■		■					C		
Ulocladium atrum	■											C		
Ulocladium chartarum				■			■					-		
Ulocladium consortiale				■	■		■					-		
Ustilago sp.										■		B		
Verticillium sp.	■				■					■		B		
Wallemia sebi	■		■	■				■		■	1	C		■
Xeromyces sp.	■											C		

1) Shown are all fungi which are found in the appraised literature and found in buildings (according to [55]).
2) Shown are all harmful fungi mentioned in the appraised literature (according to [55]).
3) The shown classification of the LGA [81] of fungi concerning health risk, means in detail:
   1: Fungi of this group should not dominate in the interior - long-term action is needed.
   2: Fungi of this group should not predominate - medium-term is needed.
   3: Fungi of this group should not appear in the interior - instant action is needed.
4) Meaning of the danger classes:
   A. Fungi is toxicologic and should not appear in housing spaces (corresponds with LGA-classification).
   B. The fungi is harmful when exposed to it for a longer time, meaning allergical reactions, pathgenous.
   C. The fungi is not harmful, but causes economic damages.

Table 2 Survey of possible human diseases caused by mould fungi according to [32, 102, 113, 129].

Term	Description	Types	Infested organs / diseases	Examples of mould fungi involved
mycoses[1)]	fungus growth at or in a human host	epidermal mycoses [2)]	skin	Aspergillus fumigatus Penicillium spinulosum
		endo- and system mycoses [3)]	inner organs, e.g.: heart, liver, kidney	Aspergillus niger Absidia sp., Mucor, sp.
mycotoxicoses	intoxication by mycotoxins	aflatoxicoses	e.g. hepatitis primary liver cancer	Aspergillus flavus Penicillium parasiticus
		penicillium mycotoxicoses	endemic nephropathy cardiac beriberi	Penicillium verrucosum Penicillium citreoviride
		fusarium mycotoxicoses	e.g.: cancer alimentary toxic aleukia	Fusarium sporotrichioides Fusarium poae
		alternaria mycotoxicoses	onyalai	tenuazon acid and salts from Phoma sorghina
		stachybotryo toxicosis	no data	Stachybotrys atra
mycogen allergies	contact of fungal elements with humid mucous membranes	bronchial asthma		various phycomycetes
		allergic alveolitis	lung	aspergillus species penicillium species

1) Further mycoses are known, for example muco-, zygo-, phaeohypho- and otomycoses.
2) One distinguishes here between aspergilloses and penicillioses.
3) One distinguishes here between aspergilloses and phycomycoses.

Table 3 Decisive influence factors for the germination and growth of mould fungi, with indication of the minimum and maximum growth range.

Influence factor	Parameter	Unit	Growth range		Remarks
			minimum	maximum	
temperature	temperature at the component surface	°C	-8	60	depends on the fungus species and the life phase (spore germination or mycelium growth)
humidity	relative humidity at the component surface	%	70[1)]	100	
substrate	nutrients and salt content	-	-	-	nutrients may be found also in dust deposits
environment	pH value of surface	-	2	11	[2)]
time	e.g. hours per day	h/d	1	-	depending on temperature and humidity
atmosphere	oxygen content	%	0.25		always existing

1) There are mould fungi known (Xeromyces) that grow on cookies even from a relative humidity of 45 % on.
2) The pH value does also depend on the relative humidity and the temperature and is influenced by the fungus.

Table 4 Specification of minimum, optimum as well as maximum growth conditions for individual fungi concerning temperature, relative humidity and pH-value, with reference to spore germination as well as mycelium growth for different danger classes.

Species of fungi	Danger classes	Growth conditions												
		Temperature [°C]						Relative humidity [%]				pH-value [-]		
		Spore germination			Mycelium growth			Spore ger.		Mycelium gr				
		min.	opt.	max.	min.	opt.	max.	min.	opt.	min.	opt.	min.	opt.	max.
Asp. flavus	A	10	30	45	6	40	45	80	100	78	98	2,5	7,5	>10
Asp. fumigatus	A	10	40	50	10	43	57	80	97	82	97	3	6,5	8
Asp. nidulans	A	10	37	50	6	40	48	75	95	78	97			
Asp. niger	A	10	35	50	6	37	47	77	98	76	98	1,5		9,8
Asp. penicillioides	A				5	25	37							
Asp. versicolor	A	8	30	42	4	30	40	74	91	75	95			
Stachybotrys atra	A	5	25	40	2	23	37	85	97	89	98			
Gefährdungsklasse A	A	5	33	50	2	40	57	74	96	75	97	2	7	10
Absidia corymbifera	B					35	45					3		8
Absidia glauca	B				-8	30	43			70				
Alternaria alternata	B	3	35	37	-2	30	32	84		85	98	<2,7	5,4	>8
Asp. amstelodami	B	5	35	43	7	33	42	70	90	71	100			
Asp. candidus	B	10	35	45	3	32	57	70	95	74	90	2,1		7,7
Asp. ochraceus	B					32				77	95	3	6,5	10
Asp. parasiticus	B				10	37				82		2	6,5	10,5
Asp. restrictus	B	10	28		10	28		73	95	71	90			
Asp. ruber	B	5	30	42	4	27	38	70	90	71	93			
Asp. terreus	B	14	40	50	11	40	47	75	99	77	97			
Aureobasidium pullulans	B				2	25	35			88				
Botrytis cinera	B				-3	21	36			93				
Cla. cladosporioides	B				-5	28	32	85		84	96	3,1		7,7
Eurotium herbariorum	B					30	40	73		75	96			
Fusarium culmorum	B	3	25	37	0	25	31	87		90				
Fusarium oxysporum	B				5	30	37			90		2		9
Fusarium solani	B									90				
Mucor plumbeus	B				4	25	35	93		93	98		7	
Pen. brevicompactum	B	5	25	32	-2	25	30	78		75	96			
Pen. chrysogenum	B				-4	28	38	78		79	98			
Pen. cyclopium	B	5	25	33	2	25	37	80	97	80	98	2		10
Pen. expansum	B	<0			-3	26	35	82		82	95			
Scopulariopsis brevicausalis	B				5	30	37			85	94		9,5	
Trichoderma viride	B				0	28	37				99			
Gefährdungsklasse B	B	3	31	50	-8	29	57	70	94	70	96	2	7	11
Chaetomium globosum	C					35								
Chrysosporium fastidium	C							69	93	72	92			
Cla. sphaerosperum	C					25				81,5				
Paecilomyces lilachinus	C					35	60	84		84				
Pen. citrinum	C							84		80		2	5,5	10
Rhizopus stolonifer	C	1,5	28	33	10	26	37	84		92	98			<6,8
Trichothecium roseum	C	5			15	25	35	90		86	96			
Ulocladium sp.	C									89				
Wallemia sebi	C		30		5	30	40	69		70				
Gefährdungsklasse C	C	2	29	33	5	29	60	69		70	95	2		10

Table 5 List containing some data of how long the relative humidity and temperature must last per day until spore germination and first visible mycelium growth takes place, with indication of the corresponding place in literature.

Minimal rel. humidity [%] [1]	Temperature data [°C]	Duration [h/d] [2]		Remarks	Literature
		daily [h/d]	days [d] [3]		
75	[4]	[4]	3	various materials	[63]
	[4]	12	5		[105]
80					[147]
		6			[15]
		12	every day	plaster board	[1]
95	14	< 24	6 weeks	plasters and coats of paint without contamination	[37]
	18.5	6			
	14	< 24		plaster with slight contamination	
		6		dispersion paint, plaster board and woodchip wall paper with contamination	
	18.5	1			

1) This humidity and temperature condition respectively is sufficient for growth.
2) This daily time unit is sufficient for growth.
3) Number of successive days with the mentioned conditions.
4) No data indicated.

Table 6 Frequency of mould fungi occurrence in different rooms according to [134].

Room	Frequency in %		
	acc. to [100]	acc. to [28]	average
Bedroom	40	42	41
Children's room	30	21	26
Living room	11	22	16
Bathroom	13	2	8
Kitchen	4	11	8
Others (corridor for example)	2	2	2

Table 7 Survey of moisture emission in rooms at a room temperature of 20°C.

Source of moisture		Moisture emission per hour [g/h]
human, little activity		30 – 40
drying clothes (4.5 kgs drum)	spin-dried	50 – 200
	dripping wet	100 – 500
indoor plants (violet, for example)		5 – 10
potted plants (fern, for example)		7 – 15
middle-sized rubber plant		10 – 20
free water surface (aquarium, for example)		approx. 40 [1)]

1) per square meter.

Table 8 List of the data required to calculate the heat and moisture behaviour of building components with the WUFI program.

Input parameters	Required data records or data
geometry	structure of the building component to be calculated
	numerical grid
thermal and hygric material parameters and functions	bulk density and porosity
	specific heat capacity
	moisture dependent heat conductivity
	water vapour diffusion resistance coefficient
	moisture storage function, if applicable
	directional liquid transport functions for the suction process and the further distribution, if applicable
climate parameters	temperature
	relative humidity
	short-wave radiation (outside only)
	precipitation onto the component surface (outside only)
transmission and symmetry conditions	heat and moisture transmission coefficient
	degree of radiation absorption
	rain factor (outside only)
control parameters	time steps
	calculation accuracy
	form of initial conditions (e.g. start time)
	other calculation specific parameters

Table 9 Survey and assessment of the existing specifications in German standards, decrees and directives that refer to the prevention of mould fungus infestation.

Standard	Methodical approach	Aim	Critical assessment	Applicability[1)]
existing DIN 4108 [19, 20]	Part 2: minimum thermal insulation	prevention of surface condensation water	stationary method	not applicable
	Parts 3 and 5: Glaser method	assessment of condensation water in the typical cross section	mould fungi do also grow without condensation water	
Draft DIN 4108 [2)]]	indication of critical humidities	prevention of mould fungi		only approximately applicable
Thermal bridge atlases (e.g.])	cataloging of thermal bridges	prevention of surface condensation water in the area of thermal bridges		to record the surface temperature at thermal bridges
Heat insulation decree [3)]]	energy balance	registration of the annual thermal heat demand	no reference to mould fungi [4)]	not applicable
DIN 68 800]	limitation of wood moisture	prevention of microbial growth	reasonable approach	assessment of the isopleths for wooden products
Annex 14 [52]	indication of temperature and humidity	prevention of mould fungi	no dependence on substrate	only approximately applicable

1) Applicability with regard to the prediction of mould fungus infestation.
2) New draft of DIN 4108, Part „Mould fungi“.
3) Applies by analogy with EN 832.
4) The Heat Insulation Decree (WSchV) is discussed here as it is often associated with mould fungus formation.

Table 10 Survey and assessment of the existing models for the prediction of mould fungi and their applicability for bio-hygrothermal calculations.

Model	Methodical approach	Assessment	Applicability
Time of Wetness]	indication of a limit value for the relative humidity in hours per day	influence of temperature is not considered	to determine substrate specific isopleths
Fuzzy Logic [91]	mathematical combination of the growth conditions temperature and relative humidity	dependence on the substrate is not considered	suitable as worst case estimation
Model by Clarke and Rowan [13, 108]	isopleths for various fungus classes are indicated	dependence on the substrate is not considered no statements concerning time	
Model by Viitanen and Hukka [137, 138]	mould index is determined time-dependent by a formula which is derived from experiments	applies presently only for wooden products spore germination is consid-ered in general only	to determine substrate specific isopleths

Table 11 Mould index in dependence on the area covered in % and characteristic features.

Mould Index	Area covered in [%]	Characteristic feature
0	0	no growth
1	≤ 1	little growth, visible only under the microscope
2	≤ 10	moderate growth, visible only under the microscope
3	≤ 30	visually visible growth
4	≤ 70	
5	> 70	
6	100	

Table 12 Survey and assessment of the factors influencing the mould fungus growth and their consideration in the prediction models.

<table>
<tr><th rowspan="2">Factor of influence</th><th rowspan="2">Assessment</th><th colspan="2">Consideration of the factors in the</th></tr>
<tr><th>Isopleth model</th><th>Transient model (biohygrothermal model)</th></tr>
<tr><td>humidity</td><td>most important growth condition</td><td rowspan="2">combination of temperature and relative humidity by means of isopleths</td><td>diffusion kinetics, i.e.:
moisture storage function
s_d value of the spore septum</td></tr>
<tr><td>temperature</td><td rowspan="2">strong influence</td><td rowspan="2">transient course of the moisture contents in the spores</td></tr>
<tr><td>time</td><td>time data contained in the isopleths</td></tr>
<tr><td>availability of nutrients</td><td rowspan="3">influence through material and contamination</td><td>substrate categories</td><td rowspan="3">indirect consideration by using the substrate categories to determine the critical moisture content</td></tr>
<tr><td>salt content</td><td rowspan="2">contained indirectly in the substrate categories</td></tr>
<tr><td>pH value</td><td>is changed by the fungus itself</td></tr>
<tr><td>light</td><td>growth possible even without light</td><td colspan="2" rowspan="3">not considered in the model;
is always regarded as sufficiently existing</td></tr>
<tr><td>oxygen</td><td>always existing</td></tr>
<tr><td>spore dissemination</td><td>spores are ubiquitous</td></tr>
<tr><td>surface roughness</td><td>only slight influences</td><td colspan="2">contained through the substrate categories</td></tr>
<tr><td>biotics</td><td>influences existing</td><td colspan="2">consideration by LIM</td></tr>
</table>

Table 13 Necessary steps to generate stationary isopleth systems for the prediction of mould fungus growth

<table>
<tr><td>Step</td><td colspan="2">Spore germination</td><td colspan="2">Mycelium growth</td></tr>
<tr><td>1</td><td colspan="4">determination of LIM curves under consideration of the respective fungi for the hazardous classes A, B/C</td></tr>
<tr><td>2</td><td colspan="4">specification of representative mould fungi by comparing the LIM with the isopleths of the single fungus</td></tr>
<tr><td rowspan="4">3</td><td colspan="4">isopleth systems for optimum substrates with the isolines meaning:</td></tr>
<tr><td colspan="2">spore germination times</td><td colspan="2">growth per time unit</td></tr>
<tr><td>representative fungus</td><td>for all mould fungi on basis of the LIM B/C</td><td>representative fungus</td><td>for all mould fungi on basis of the LIM B/C</td></tr>
<tr><td>Aspergillus versicolor</td><td>determination of isolines (spore germination times) by parallel shift of the LIM B/C</td><td>Aspergillus amstelodami</td><td>determination of isolines (mycelium growth) by parallel shift of the LIM B/C</td></tr>
<tr><td>4</td><td colspan="4">generation of substrate specific isopleth systems</td></tr>
</table>

Table 14 Assignment of different materials to substrate categories.

Data of the component layers close to the surface			Assignment to substrate group, depending on degree of contamination [2]	
Substrate category [1]		Typical representatives	none	severe
0	optimal culture medium	biological complete media	0	0
I	bio-utilizable substrates [3]	wall papers, plaster board, building products of easily degradable raw materials, material for permanently elastic joints	I	I
II	substrates with porous structure	plasters, mineral building materials, some woods, insulants not belonging to group I	II	I
III	inert substrates [4]	metals, foils, glass, tiles	III	I

1) Depending on the degree of contamination, the classification into the substrate group may change.
2) The degree of contamination is divided into not contaminated („none“) and severely contaminated („severe“).
3) These substrates can either have bio-utilizable deposits or they are decomposed.
4) These substrates can neither be decomposed nor do they contain nutrients.

Table 15 List of the geometric parameters of the model spore required for the biohygrothermal model compared with the natural spore.

Criterion	Unit	Natural spore	Model spore
diameter d_{Sp}	m	$3.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-2}$
septum thickness d_{Spw}	m	$5.0 \cdot 10^{-7}$	$1.0 \cdot 10^{-3}$
volume V_{Sp}	m^3	$1.4 \cdot 10^{-17}$	$1.0 \cdot 10^{-2}$
surface A_{Sp}	m^2	$2.8 \cdot 10^{-11}$	2.0
ratio: volume/surface	m	$5.0 \cdot 10^{-7}$	$5.0 \cdot 10^{-3}$

Table 16 Survey of the different plausibility tests to verify the isopleth model.

Object of inspection	Assessment carried out	Expected result	Correspon-dence
free-standing objects in the room and outdoors	comparing the annual course of the interior and exterior climate data with the isopleths	mould fungus growth only in case of severe contamina-tions	yes
foodstuffs in refrigerators	comparing the inner climate of the fridge with the isopleths	mould fungus growth	yes
room corner or thermal bridge	comparing a typical annual course of the respective climate data with the isopleths	mould fungus growth	yes
typical cross section (component centre)		no mould fungus growth	yes

Table 17 List of data for the validation of the ispoleth model by means of observations in a climatic chamber. The hygrothermal data of a detected mould fungus infestation in 2 climatic chambers of the Fraunhofer Institute for Building Physics are compared with the mould fungus prediction according to the isopleth model.

Places of measurement	Substrate category	Room		Wall surface		Mould fungus growth	
		temperature [°C]	relative humidity [%]	tempera-ture [°C]	relative humidity [%]	observed	calculated with isopleth model
A1	I	23.0	80	17.5	100	yes	yes
A2				19.0		yes	yes
A3	II			23.0	80	partially	1)
B1	I	20.0	65	16.0	84	yes	yes
B2				17.3	77	no	no
B3				17.7	75	no	no

1) This value is exactly on the boundary line (LIM_{Mat} II for substrate category II).

Table 18 Variation parameters of the sensitivity analysis to verify the transient biohygrothermal model.

Criterion	Description of variations
critical moisture content	using the LIM curves in the isopleth systems of various substrate groups
diffusion resistance of the spore septum	variation of the s_d value by ± 20 %
initial moisture content in the spore	ambient humidities between 30 % and 65 % relative humidity
calculation time steps	time steps used: 0.1; 0.2 and 1 hours

Table 19 List of the data applied in the examples of application and references to literature.

Item	Constructions	Material	Geometric position [1)]	Effects [2)]	Literature
7.1	monolithic external wall	plastered brickwork	internal surface of an external wall in the wall centre and behind a cupboard	insulating level heat transmis-sion interior climate	[65]
7.2	window frame	plastic with contamination	thermal bridge at the edge bond	thermal bridge	[120] [130]
7.3	unvented gable roofs	vapour seals (paper foil)	at the vapour seal in unvented steep roofs with different outer vapour diffusion resis-tances	drying out of building moisture	[77] [121]
7.4	ETICS facade	plaster	wall centre as well as plate joints	exterior climate	[68]
7.5	ventilation sys-tems	plastic or clay	in the tube system of a hybrid heating sys-tem or a soil-air heat exchanger	operating states	[91] [117]

1) Geometric position in the building construction where the hygrothermal parameters are evaluated and with that, the danger of mould fungus formation is assessed.
2) Analysis to what extent certain building physical effects or the choice of boundary conditions do influence the probabil-ity of mould fungus formation.

Table 20 Case variants to assess a possible mould fungus formation at a plastered monolithic external wall made of brickwork.

Case	Heat conductivity of the brickwork [1]	Moisture load in the room [2]	Situation	Heat transmission coefficient	Mould fungus formation
	W/(m K)	% rel. humidity		W/(m² K)	
A	0.2	medium (50 ± 10)	free wall	8	no
B	0.6				
C	0.2		cupboard	2	
D	0.6				yes
E	0.2	high (55 ± 5)	free wall	8	no
F	0.6		curtain	4	yes
G		low (45 ± 15)	cupboard	2	

1) Heat conductivity in a dry state.
2) The data in brackets describes the mean value and the fluctuation of the relative humidity in the course of one year (Figure 23).

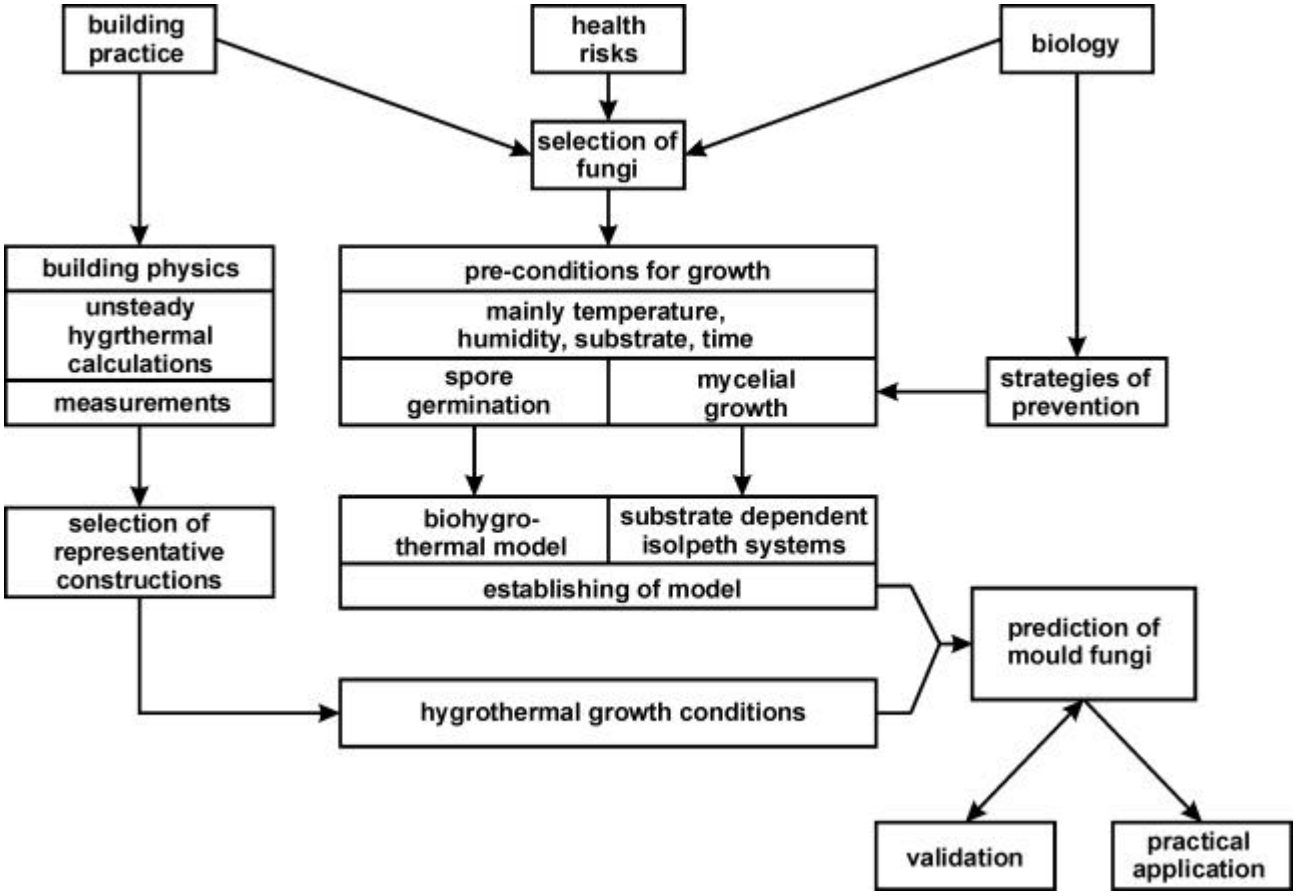


Fig. 1 Schematic diagram of the methodical procedure when developing the biohygrothermal method.

The method shall be limited to those fungi causing damages at buildings or that are dangerous to health. In the isopleth submodel, the spore germination and the mycelium growth are determined, based on substrate specific isopleth systems and in dependence on the hygrothermal boundary conditions. The biohygrothermal submodel describes the behaviour of the fungus spores until germination, on the basis of a physical modelling of the mould fungus spores. The validation of the prediction models is followed by the application of the model in practice.

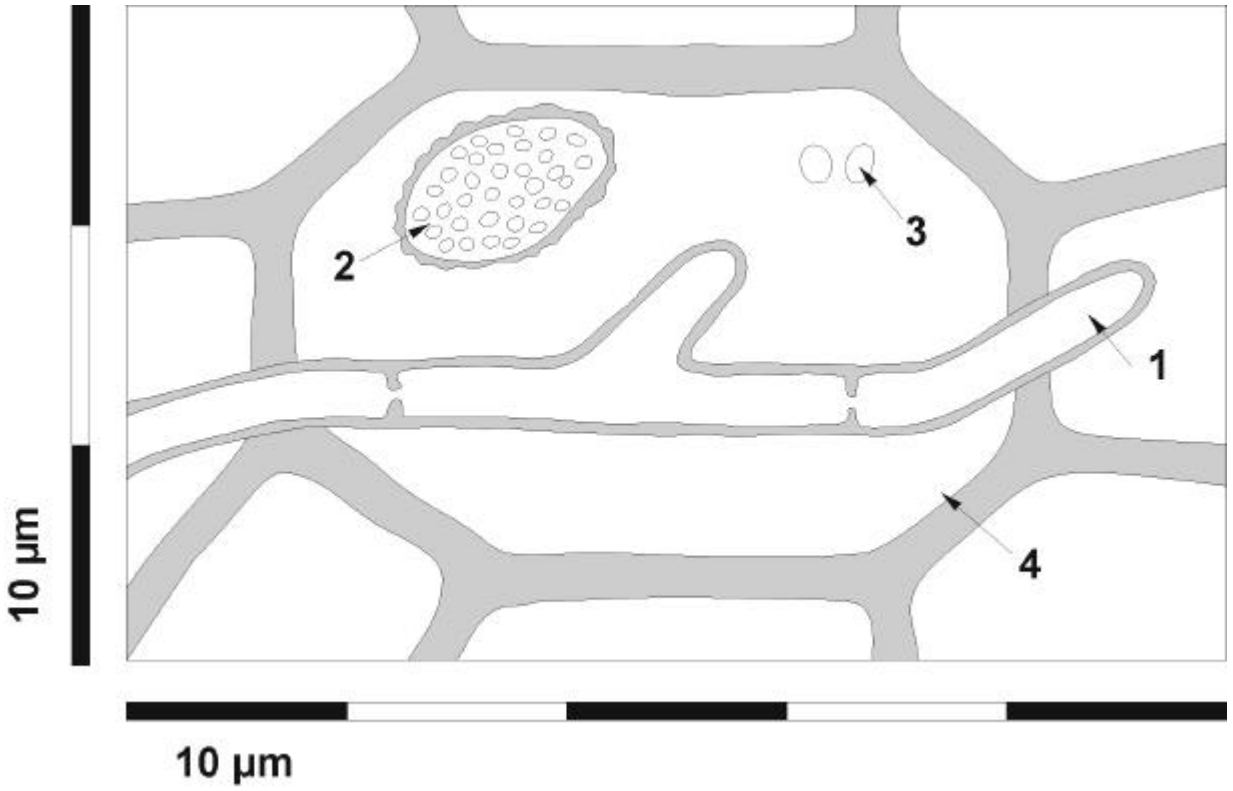


Fig. 2 Schematic diagram of the size of a fungal hypha (1), a fungus spore (2), bacteria (3) and a cell of a higher plant (4), according to [116].

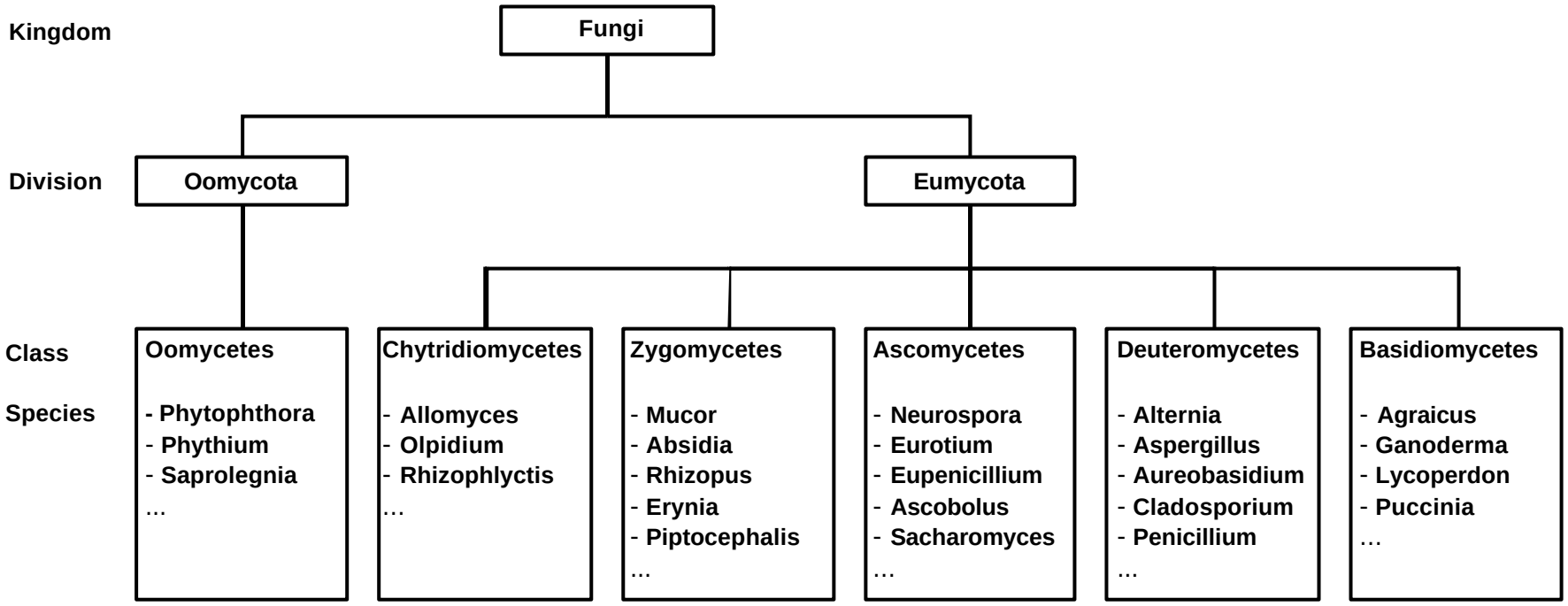


Fig. 3 Schematic overview of how to divide the fungi kingdom into the divisions Oomycota (cell walls made of cellulose) and Eumycota (cell walls mainly of chitin) according to Sitte [125].

Oomycota consist of one class only, that is the Oomycetes. Eumycota can be divided into five classes. The 3 classes Zygomycetes, Ascomycetes and Deuteromycetes (Fungi imperfecti) contain so-called mould fungi.

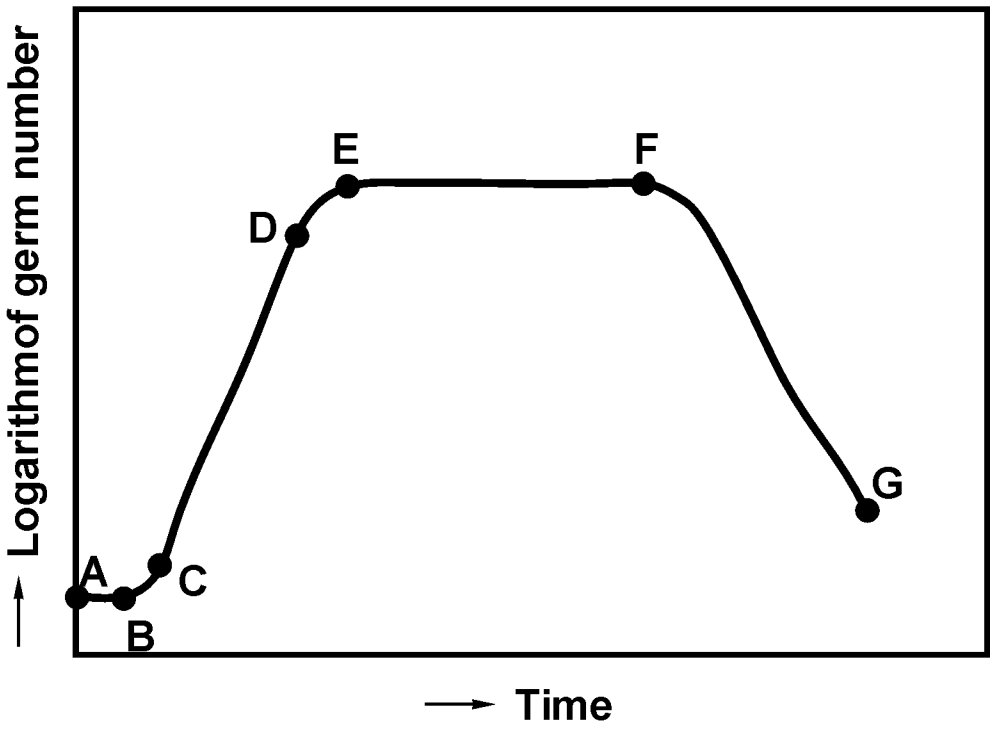


Fig. 4 Schematic diagram of the growth curve of a mould fungus culture according to Reiß [102]:

A to B: initial growth-lag

B to C: acceleration phase

C to D: log-growth phase

D to E: delay phase

E to F: stationary phase

F to G: declining phase of growth

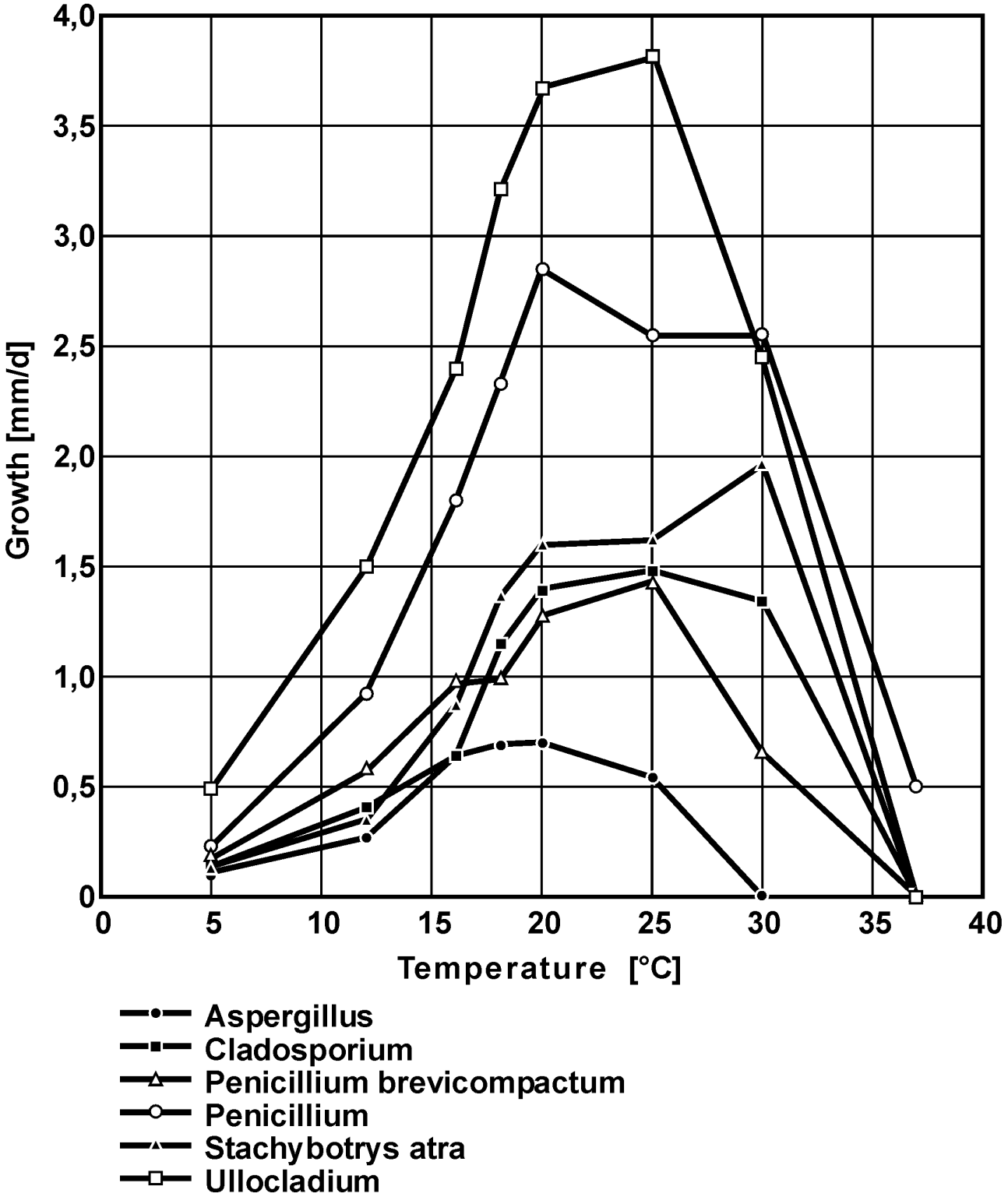


Fig. 5 Growth rates of various mould fungi in dependence of the temperature according to Grant [39].

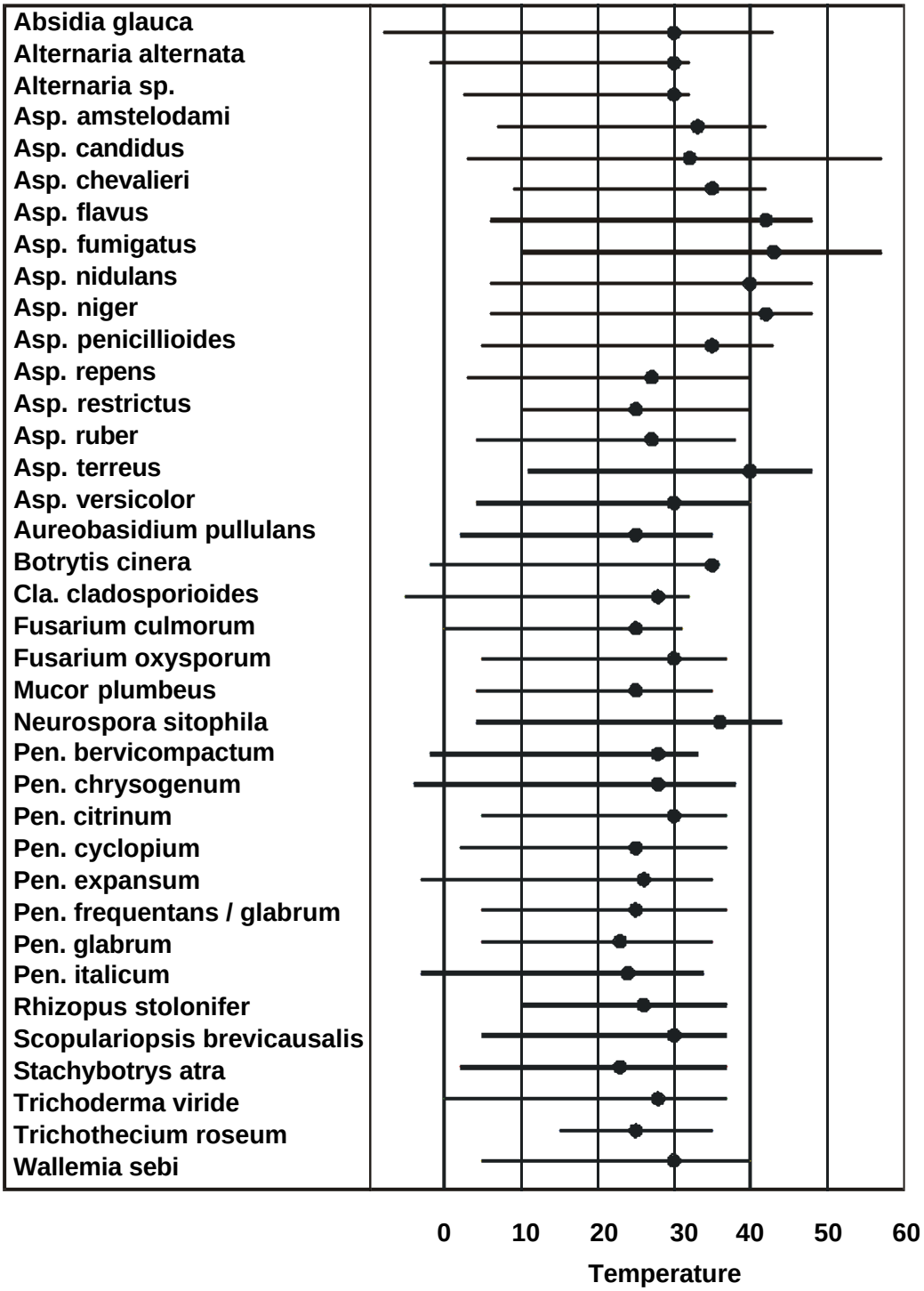


Fig 6 Schematic diagram of the temperature range for the occurrence of various mould fungi. The optimum values are marked by points. Here is the meaning of the abbreviations:
Asp.: *Aspergillus*
Cla.: *Cladosporium*
Pen.: *Penicillium*
sp.: species.

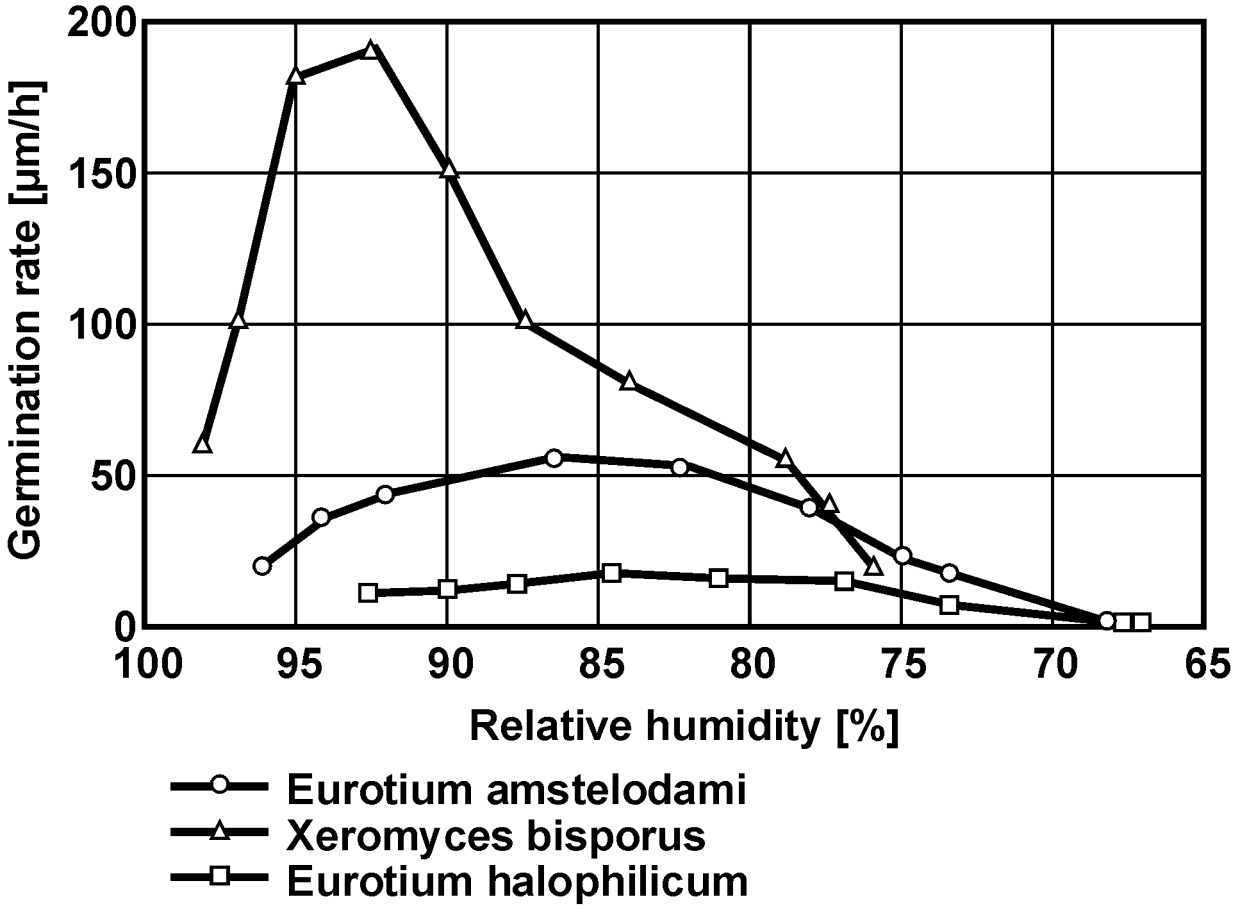


Fig. 7 Growth rates of three xerophilic fungi depending on the relative humidity on a culture medium of glucose and fructose at 25 °C according to Hocking [48].

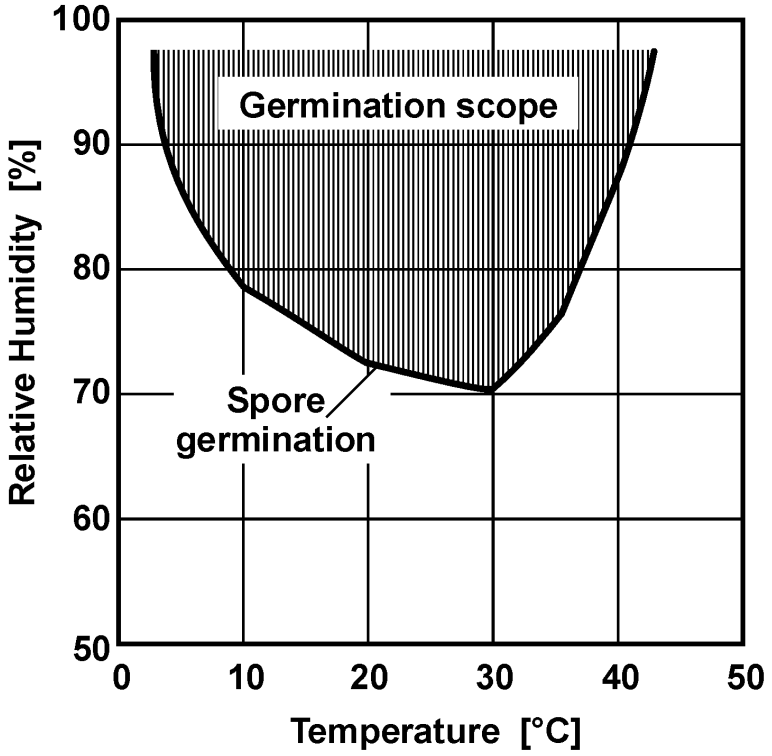


Fig. 8 Schematic diagram of the growth range for mould fungi depending on temperature and relative humidity; serving as a preparation for the determination of growth isopleths.

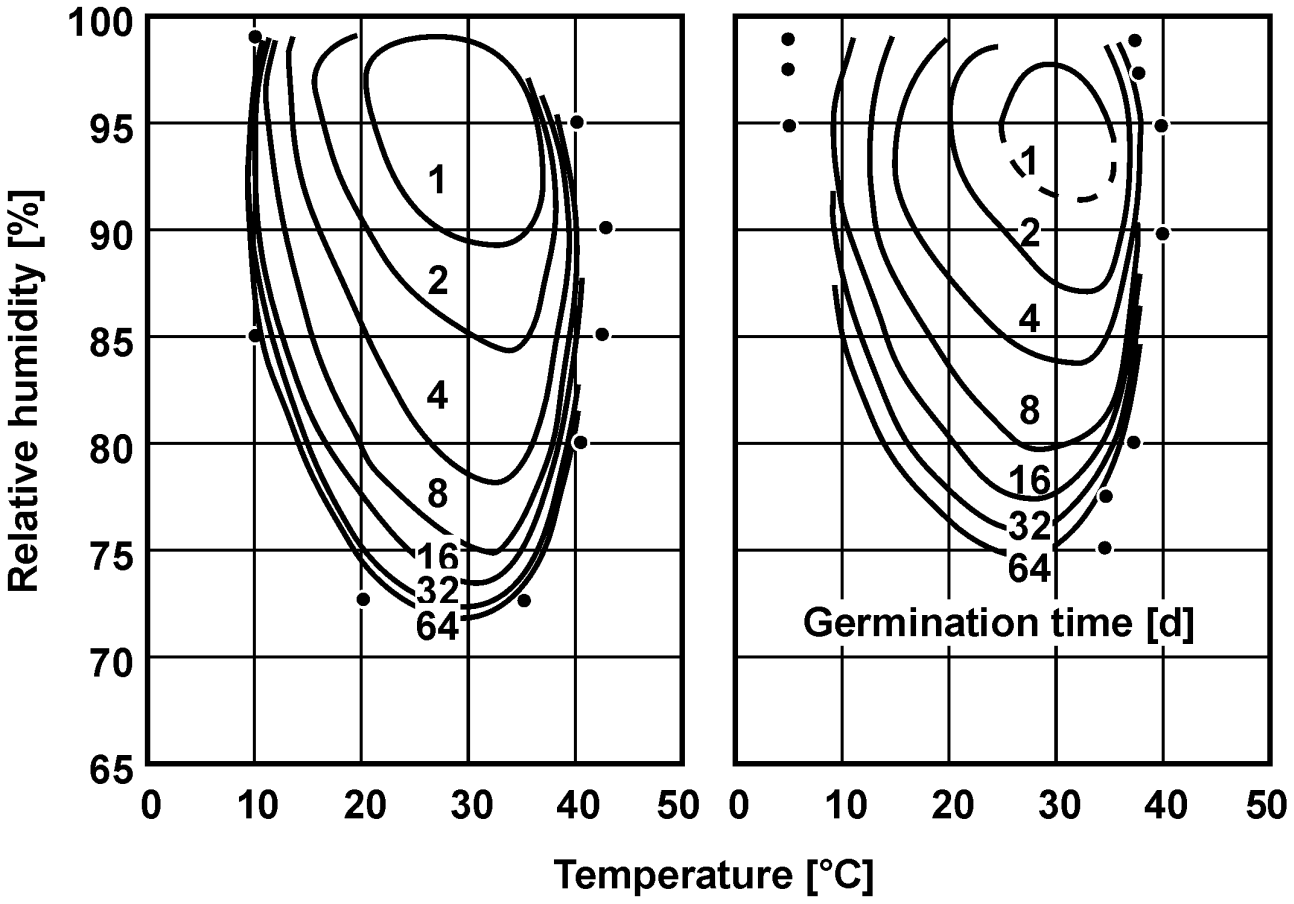


Fig. 9 Isopleth systems for spore germination of the mould fungi *Aspergillus restrictus* (on the left) and *Aspergillus versicolor* (on the right) according to Smith [126].

The isolines indicate, in dependence on temperature and relative humidity, the germination times in days (entered numerical values). The points mark conditions under which no germination took yet place after 95 days.

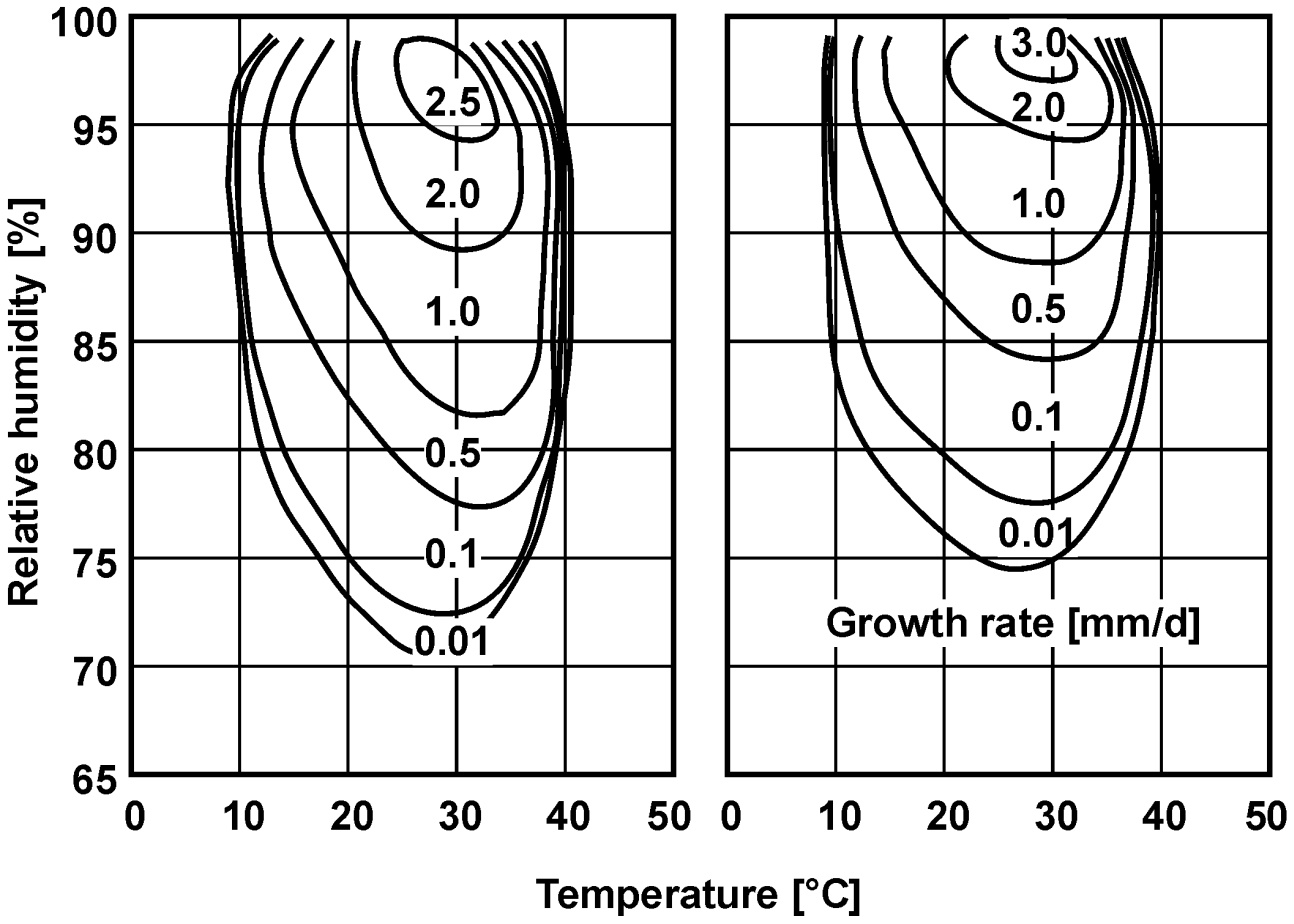


Fig. 10 Isopleth systems for mycelium growth of the mould fungi *Aspergillus restrictus* (on the left) and *Aspergillus versicolor* (on the right) in dependence on temperature and relative humidity according to Smith [126]. The numbers at the isolines represent the growth rates in mm/d.

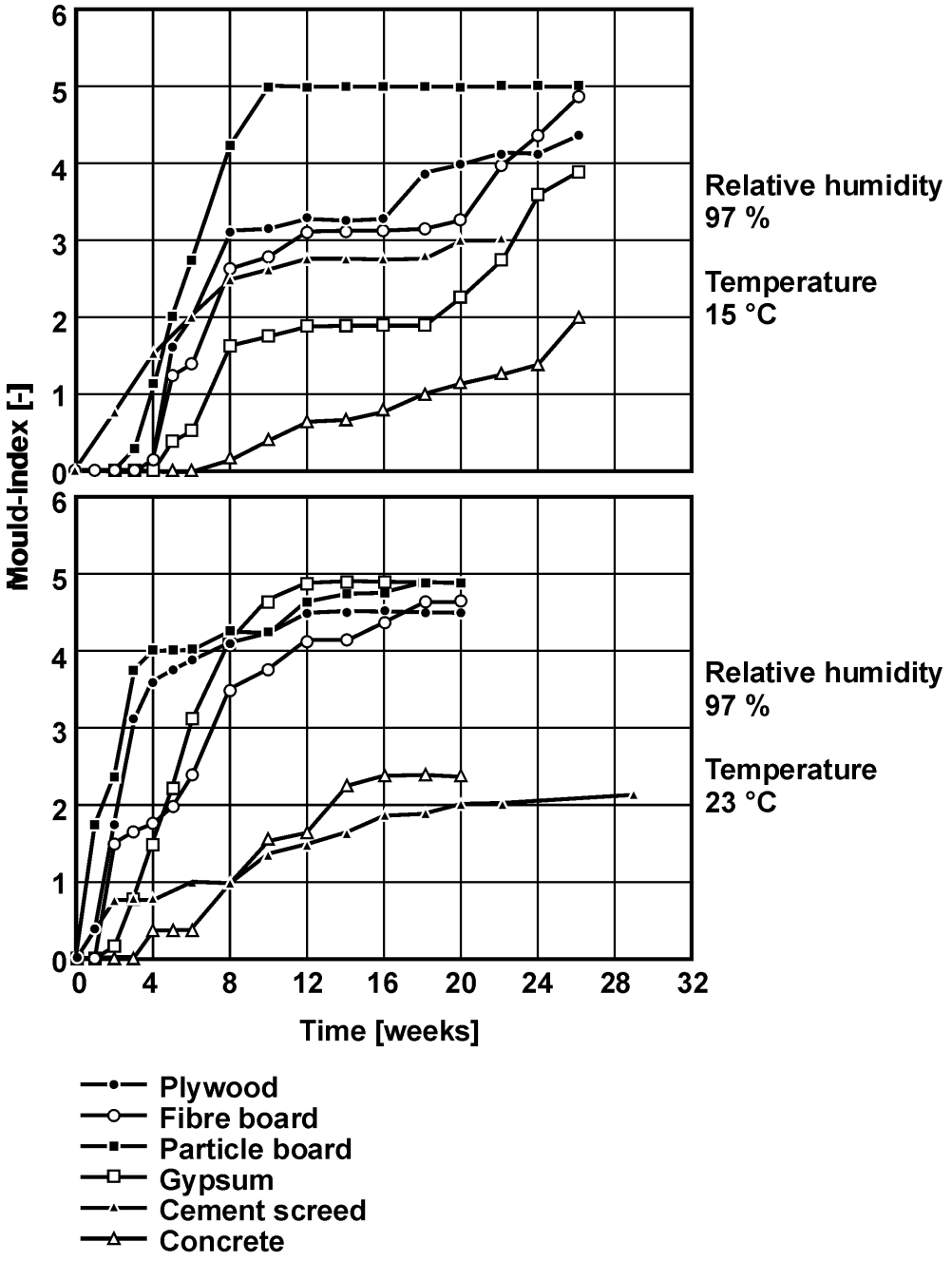


Fig. 11 Time course of the measured mould index in dependence on temperature for different building materials.

Above: Temperature: 15 °C.

Below: Temperature: 23 °C.

One can see the mould index determined in measurements for wooden and for mineral building materials at a relative humidity of 97 % and different temperatures according to Ritschkoff [107]. The mould index is explained in Table 11.

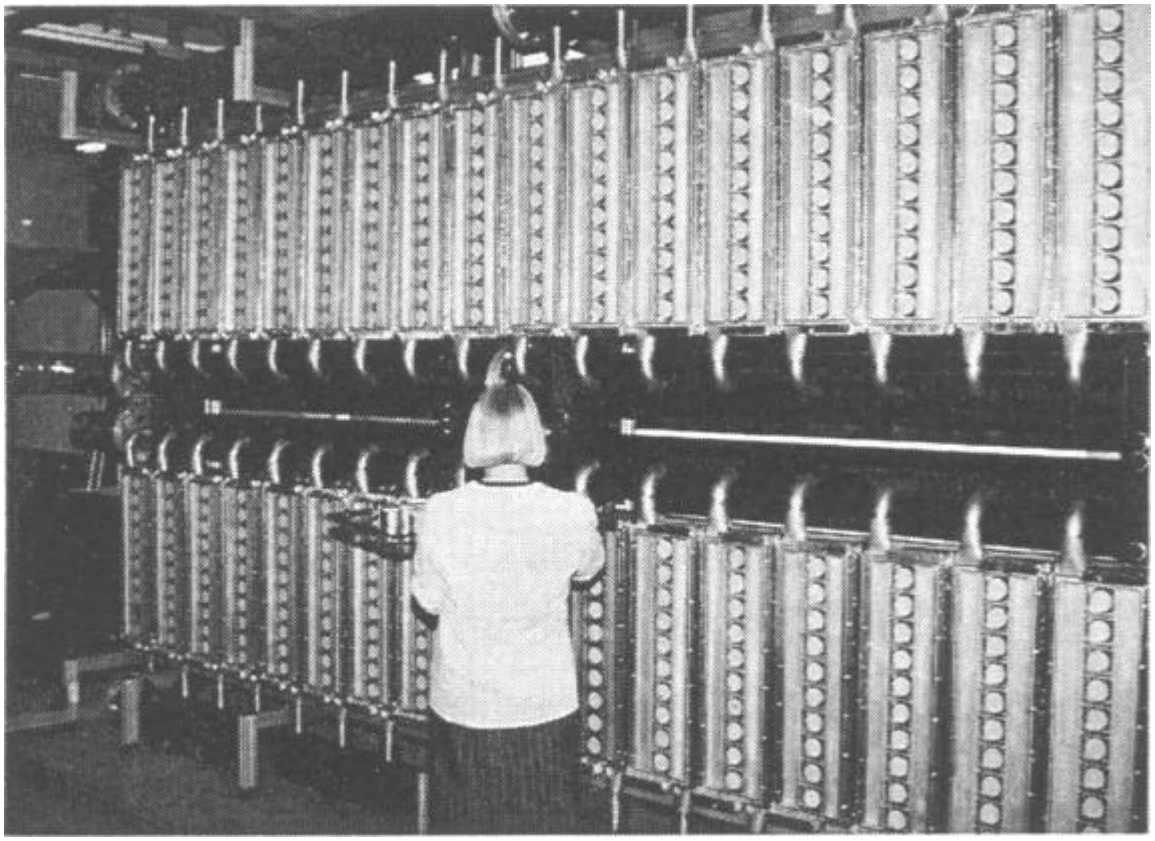


Fig. 12 Photograph of the mould fungus test stand at the Fraunhofer Institute for Building Physics.

This system for mould fungus tests on building and surface materials allows to vary the air humidity, air temperature, air speed, surface humidity and surface temperature.

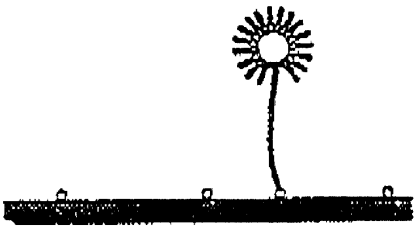
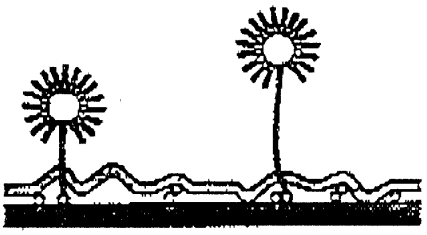
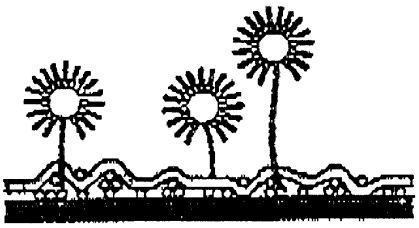
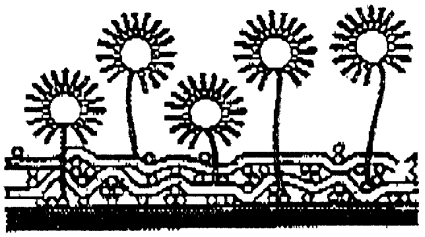
Class	Features	Pictograph
0	no growth detectable	
1	growth visible only under the microscope	
2	growth visible with the naked eye	
3	noticeable growth	
4	strong growth	
5	total overgrowth	

Fig. 13 Definition of the growth intensity classes that form the basis for the evaluation of the test results in [37].

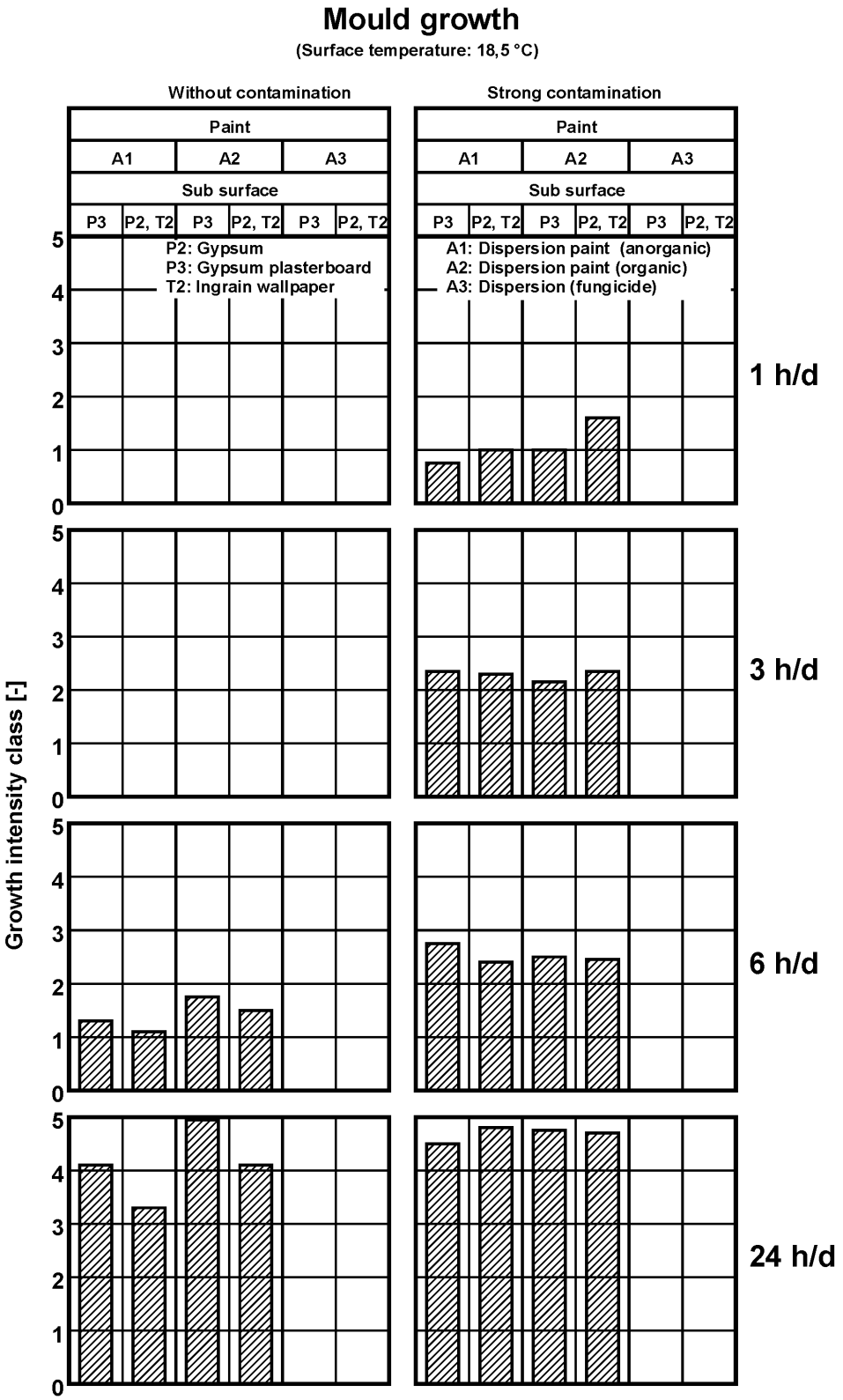


Fig. 14 Growth intensity of mould fungi on different coats of paint with and without contamination at a certain surface temperature and different times of action after a testing period of 6 weeks according to Gertis [37].

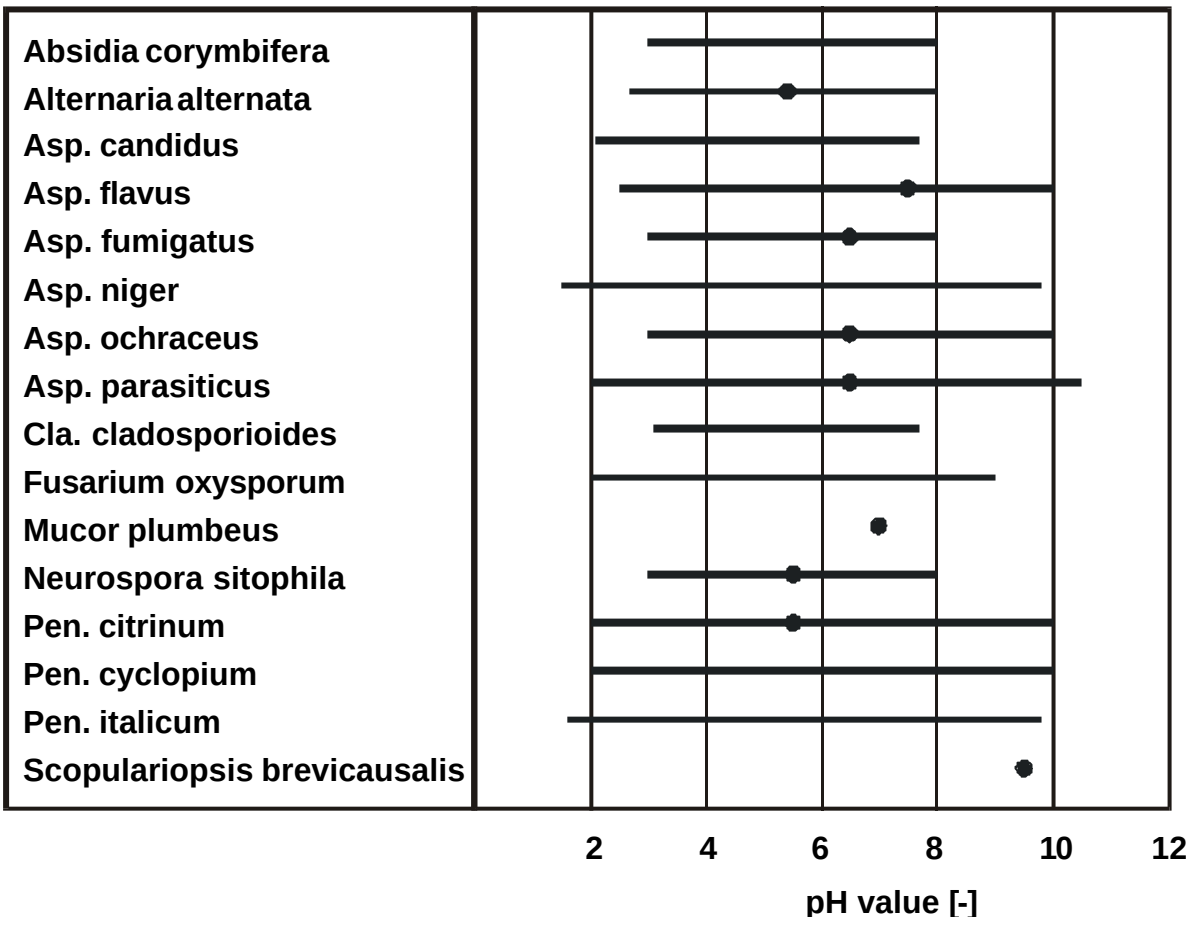


Fig. 15 Schematic diagram of the pH value range for mould fungi at colonized material surfaces according to the evaluation of literature in Table 4 for representative mould fungi. The optimum values are marked by points.

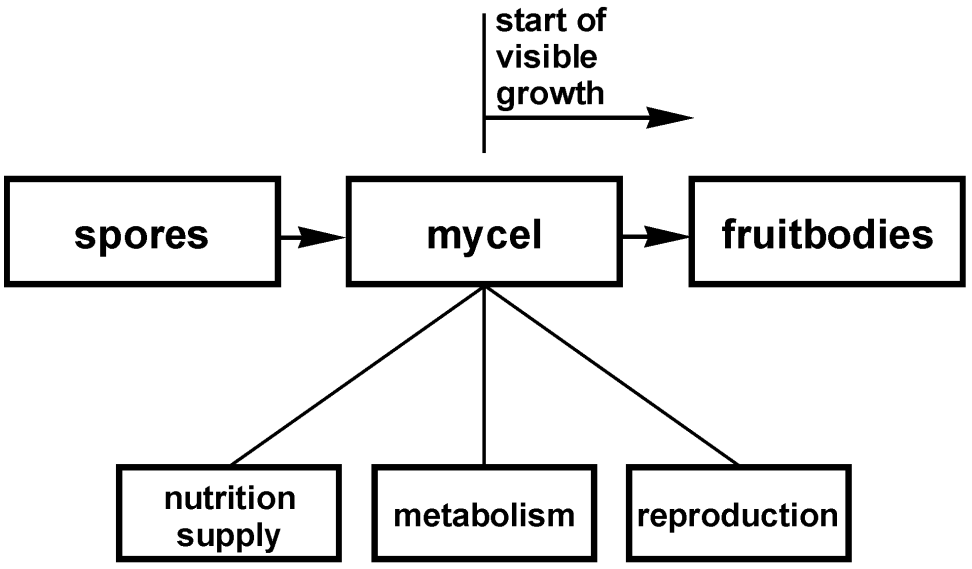


Fig. 16 Schematic diagram showing the sequence of fungoid growth.

When the climatic conditions are sufficient, the spore germinates. A mycelium is produced where the food intake, the metabolic processes and the reproduction take place. The result of the reproduction is the formation of new spores (sporulation) in the fruiting bodies.

Fig. 17 Schematic diagram of a biological membrane according to [111].

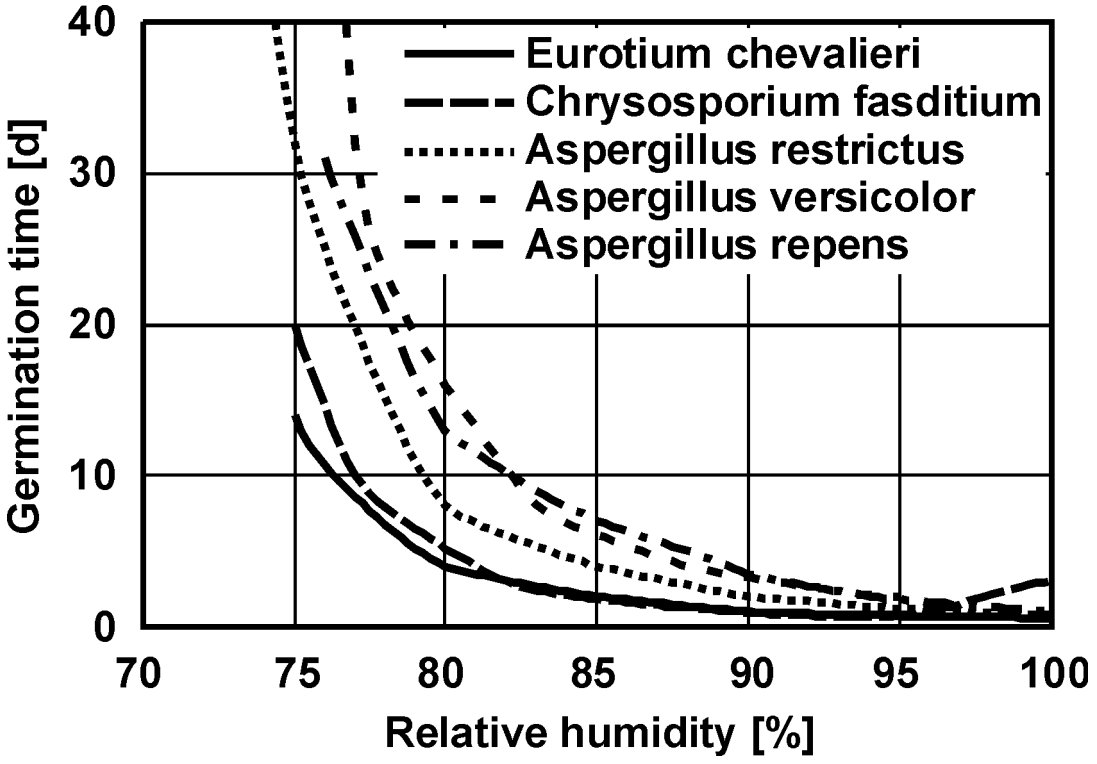


Fig. 18 Spore germination times of various mould fungi, depending on the relative humidity.

The times vary, depending on the experimental setup, the species used and the temperature applied.

Aspergillus repens, on gelatin at 20 °C; data according to Snow [127]
Eurotium chevalieri, on complete medium at 25 °C; data according to Pitt [96]
Chrysosporium fasditum, on complete medium at 25 °C; data according to Pitt [96]
Aspergillus restrictus, on complete medium at 20 °C; data according to Smith [126]
Aspergillus versicolor, on complete medium at 20 °C; data according to Smith [126].

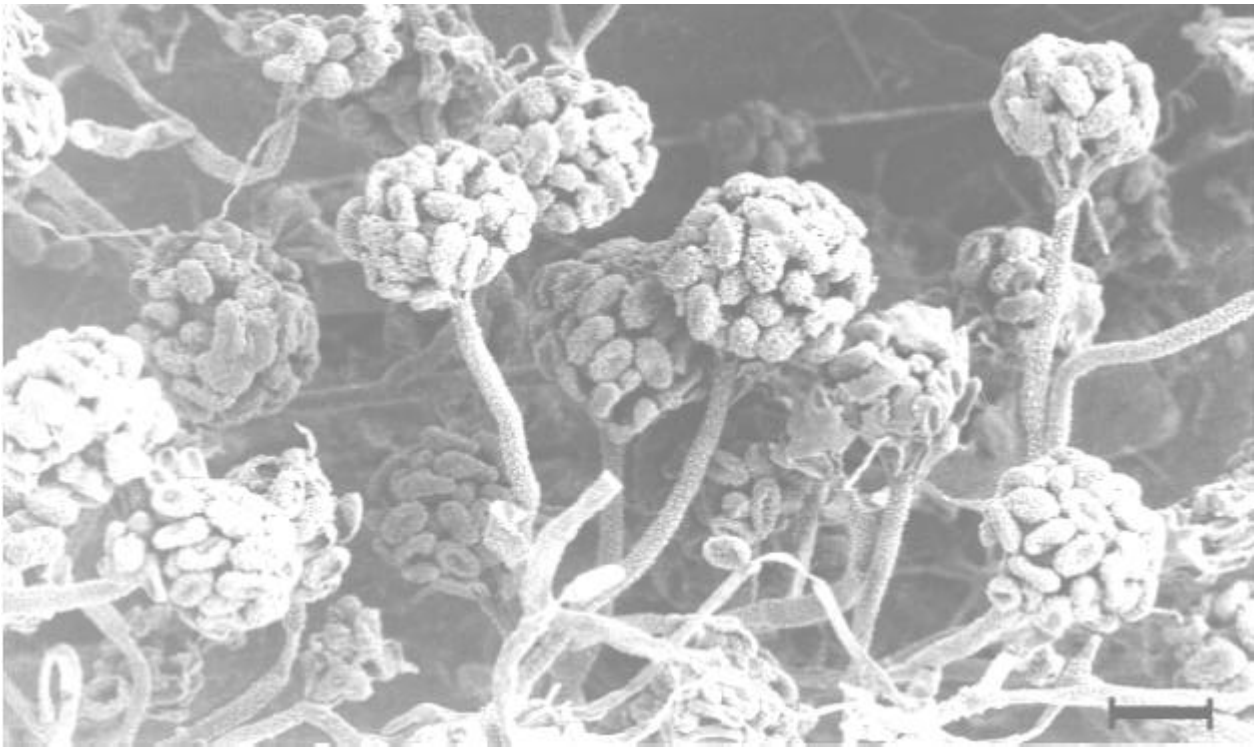


Fig. 19 Dense growth of myceliums and conidio spores of *Stachybotrys* on a plaster board according to Anderson [3]. The black bar shown on the bottom right corresponds to 10 µm.

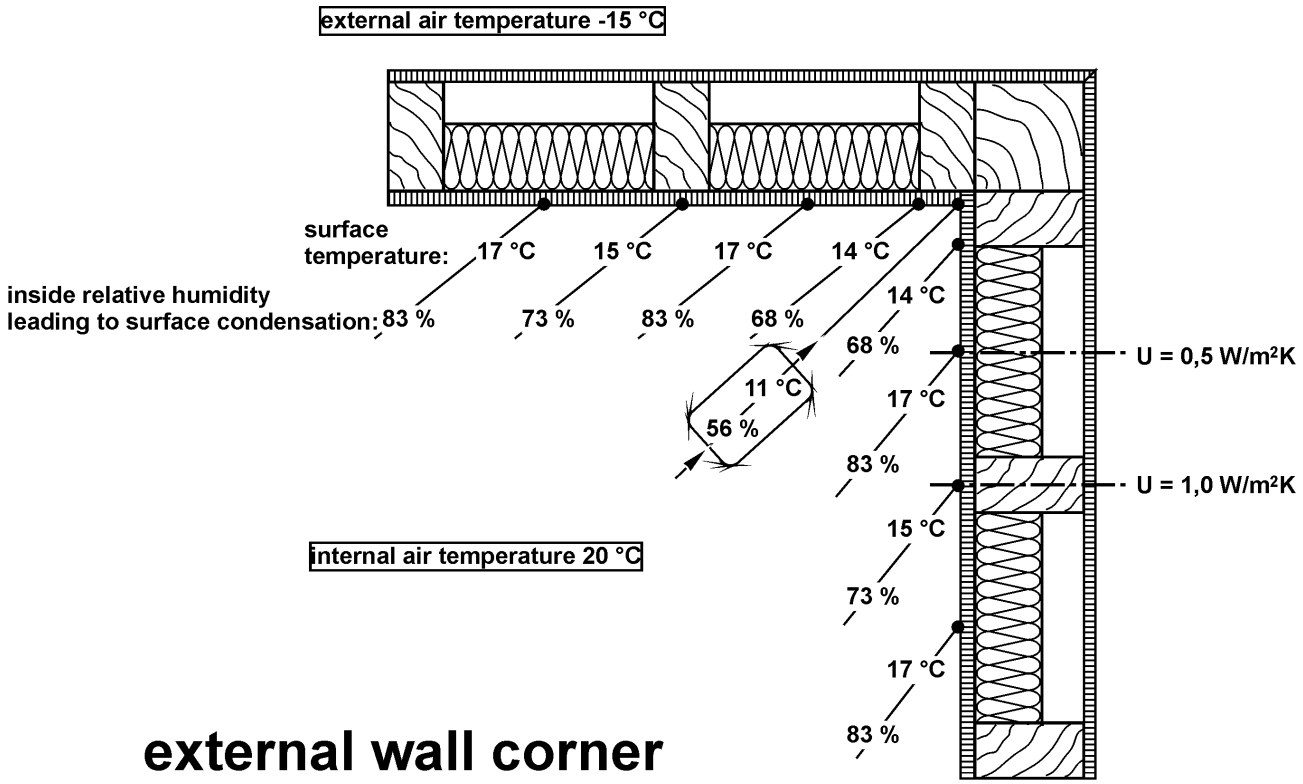


Fig. 20 Representation of the thermal bridge effect in an external wall corner according to [60].

The illustration shows the internal surface temperatures arising in case of a post-beam construction with a heat transition coefficient of insulation of 0.5 W/(m² K) and of 1.0 W/(m² K) in the post region at an outside air temperature of -15 °C. Furthermore, it is shown what resulting maximum indoor air humidities are admissible without condensation water being produced at an indoor air temperature of 20 °C. In the area of the geometric thermal bridge, i.e. in the corner, one can notice the lowest temperatures at the wall surface (marked with an arrow).

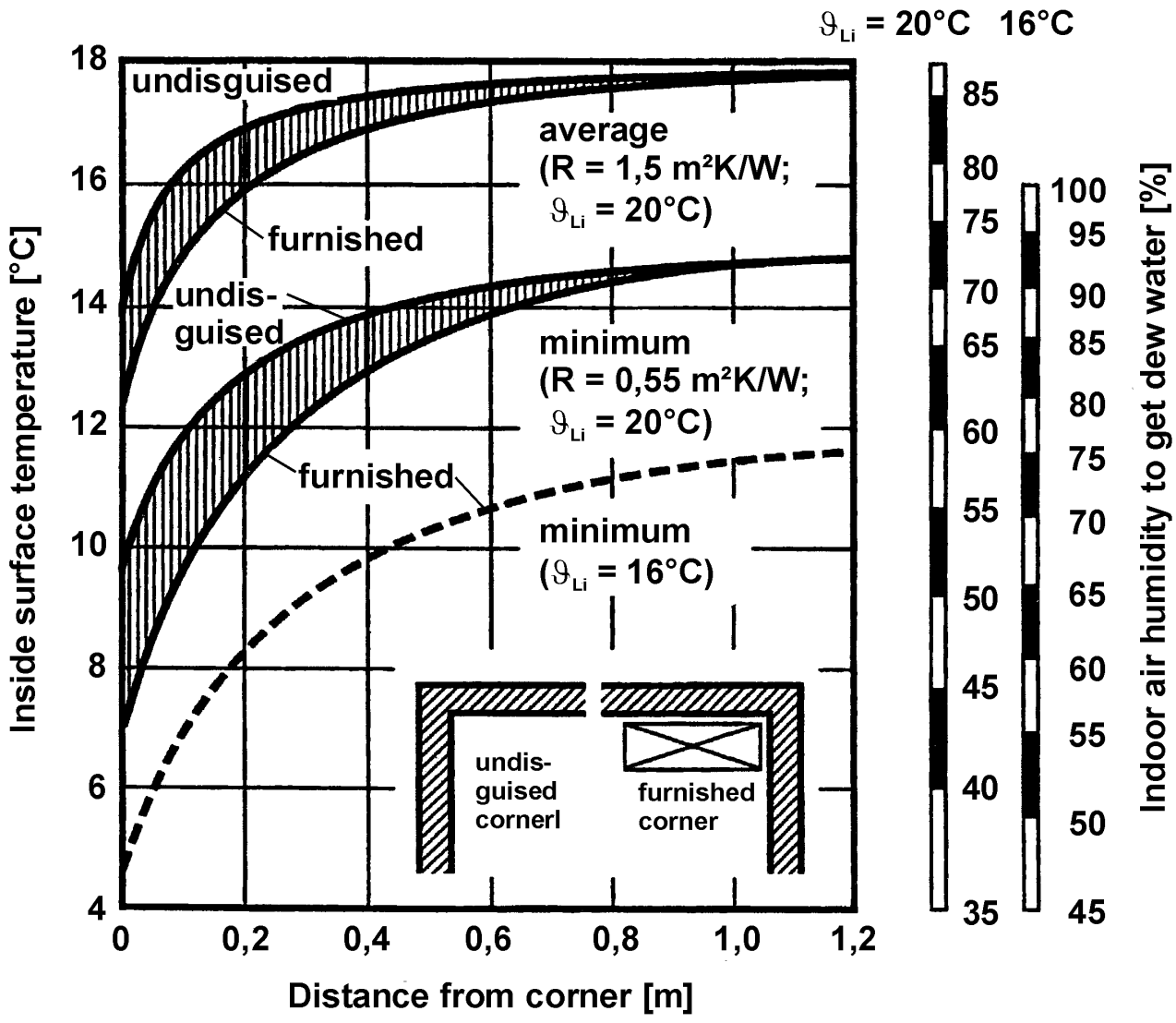


Fig. 21 Internal surface temperature of an external wall corner with average and with minimum thermal insulation in dependence on the distance from the external corner according to Gertis [38].

In one case the corner is free, in the other case it is obstructed by furniture. On the right one can see the relative indoor air humidity at which condensation water may arise.

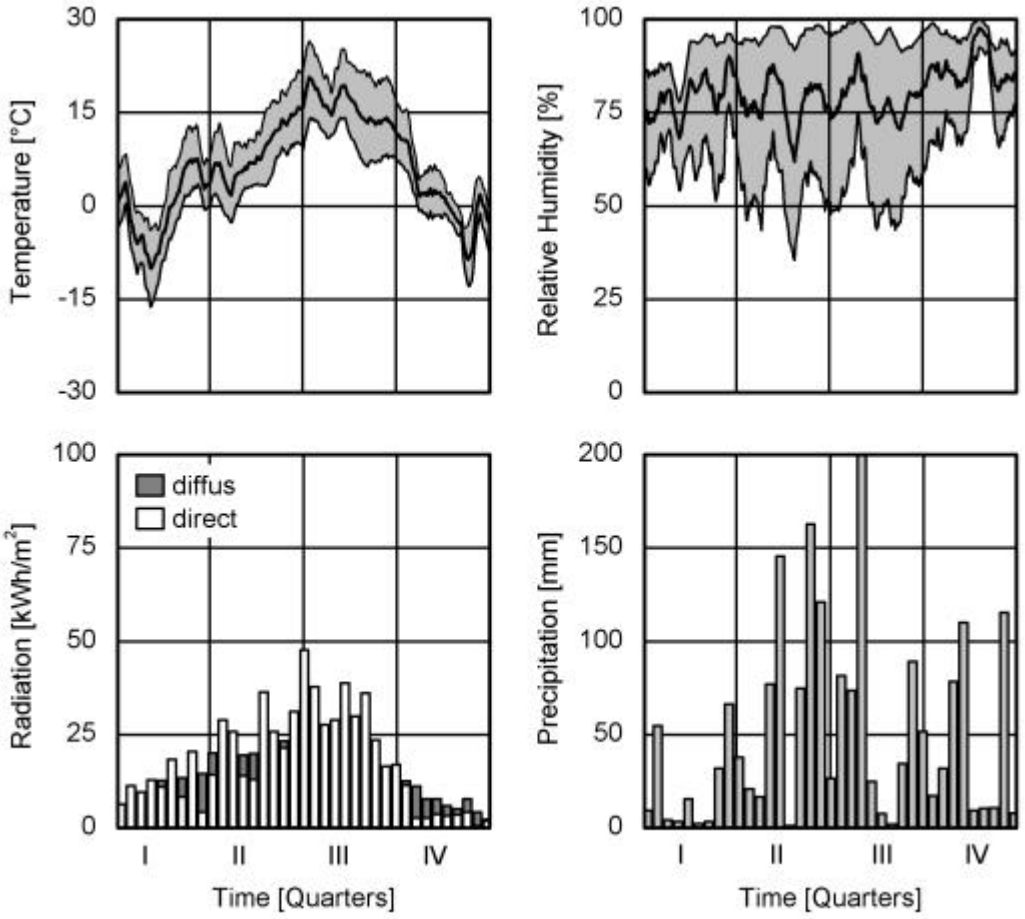


Fig. 22 Climatic boundary conditions based on measured hourly mean values of a typical year (location: Holzkirchen) according to [74].

The outside air temperature and humidity are represented as moving decade average with indication of the daily fluctuation range; the short-wave radiation and the precipitation are shown as decade sums.

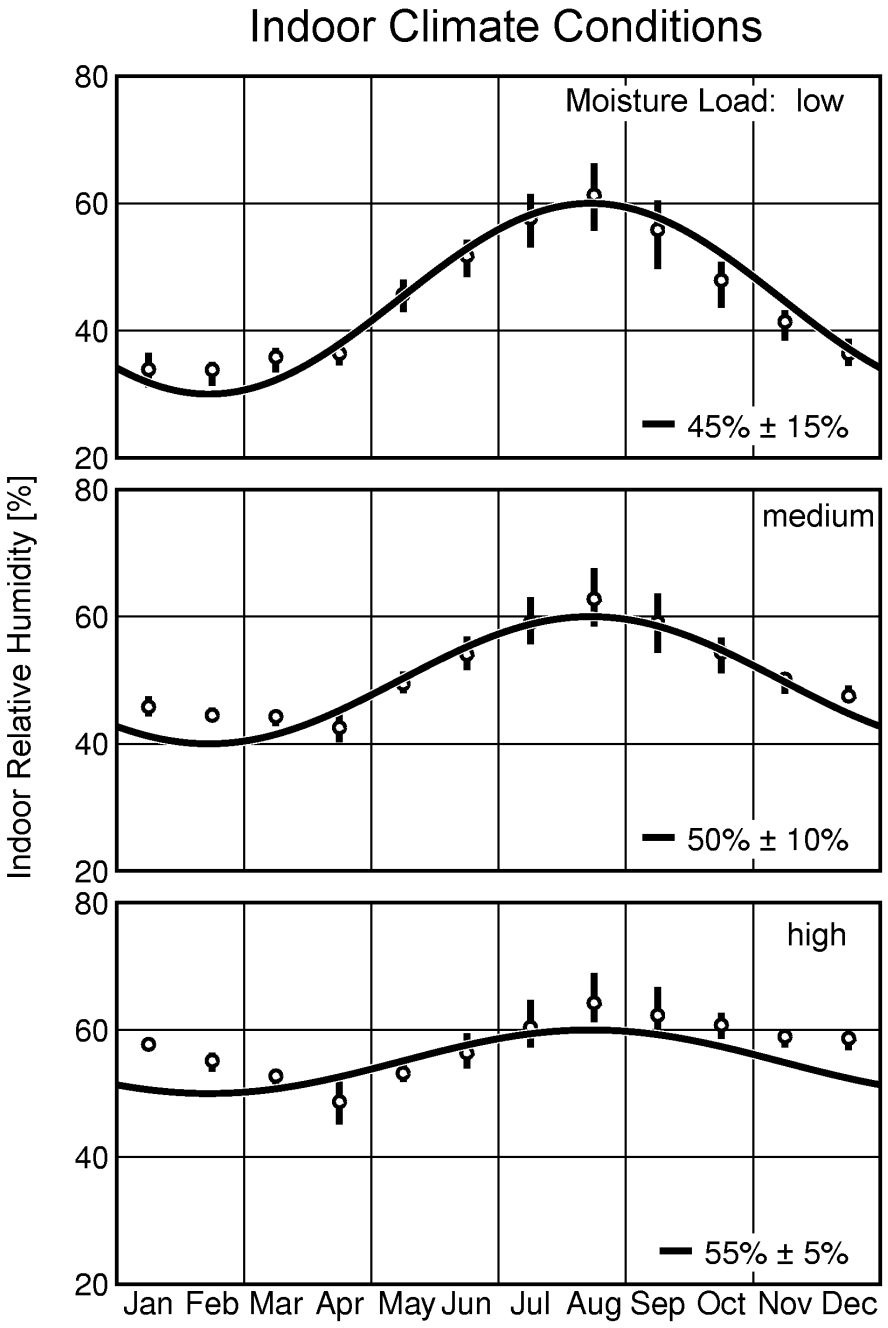


Fig. 23 Measured and approximated courses of the relative air humidity in the indoor air for 3 different humidity loads according to [73].

The drawn measuring points and bars represent the mean values and scatterings determined by the measurements. In addition, the illustration shows the annual mean value of the relative humidity as well as its annual fluctuation for the sine approximation.

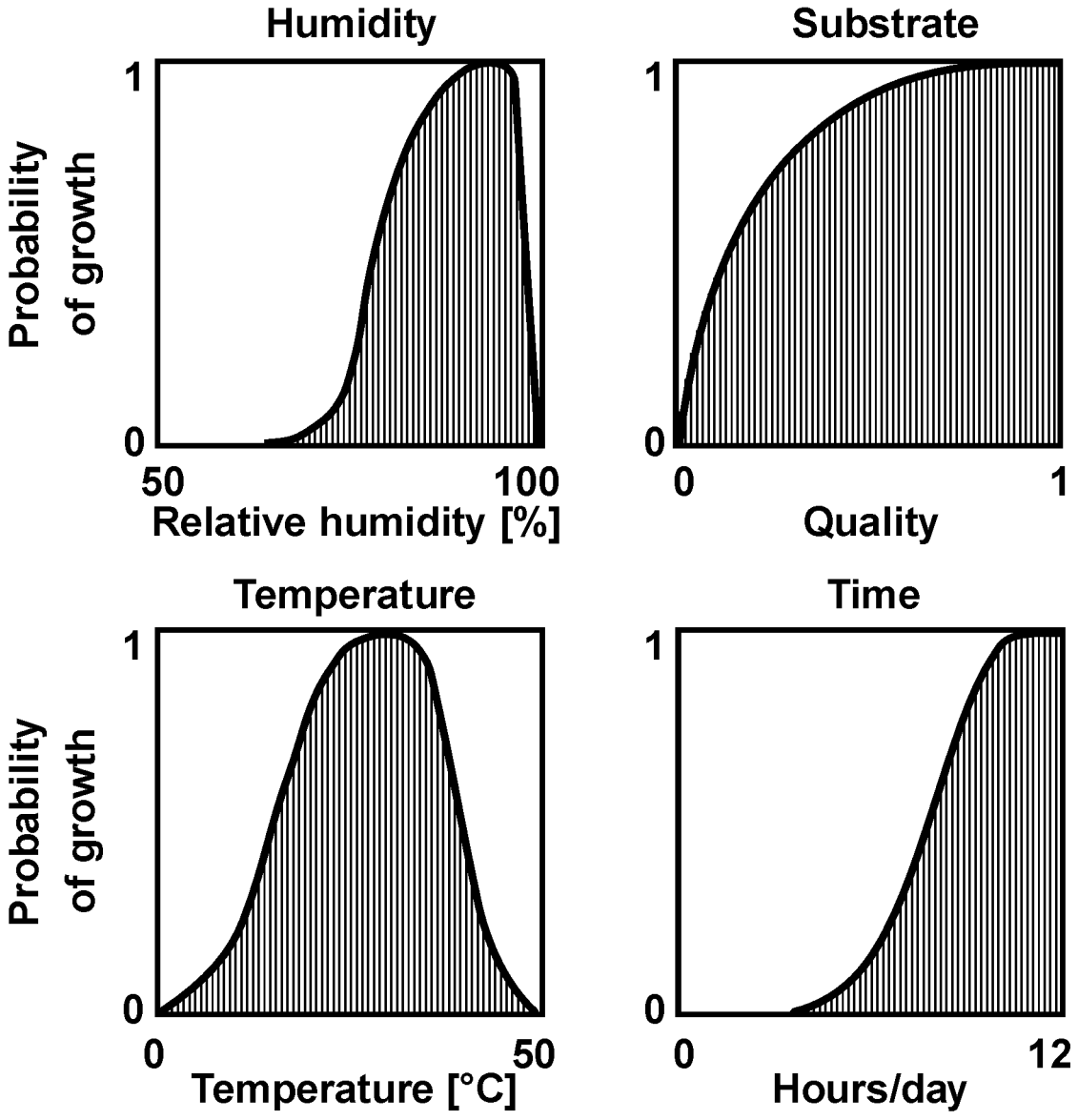


Fig. 24 Qualitative assessment of the growth conditions for mould fungi in dependence on various influence factors according to [91].

Growth probability:
0: no growth
1: optimal growth.

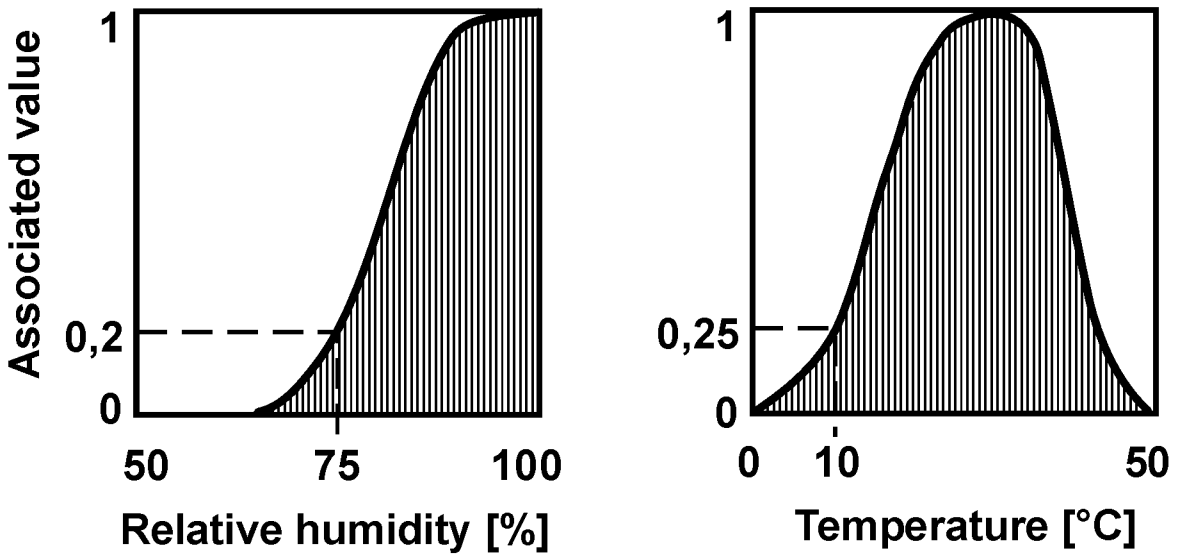


Fig. 25 Schematic diagram of the membership values of the influence factors temperature and relative humidity according to [91].

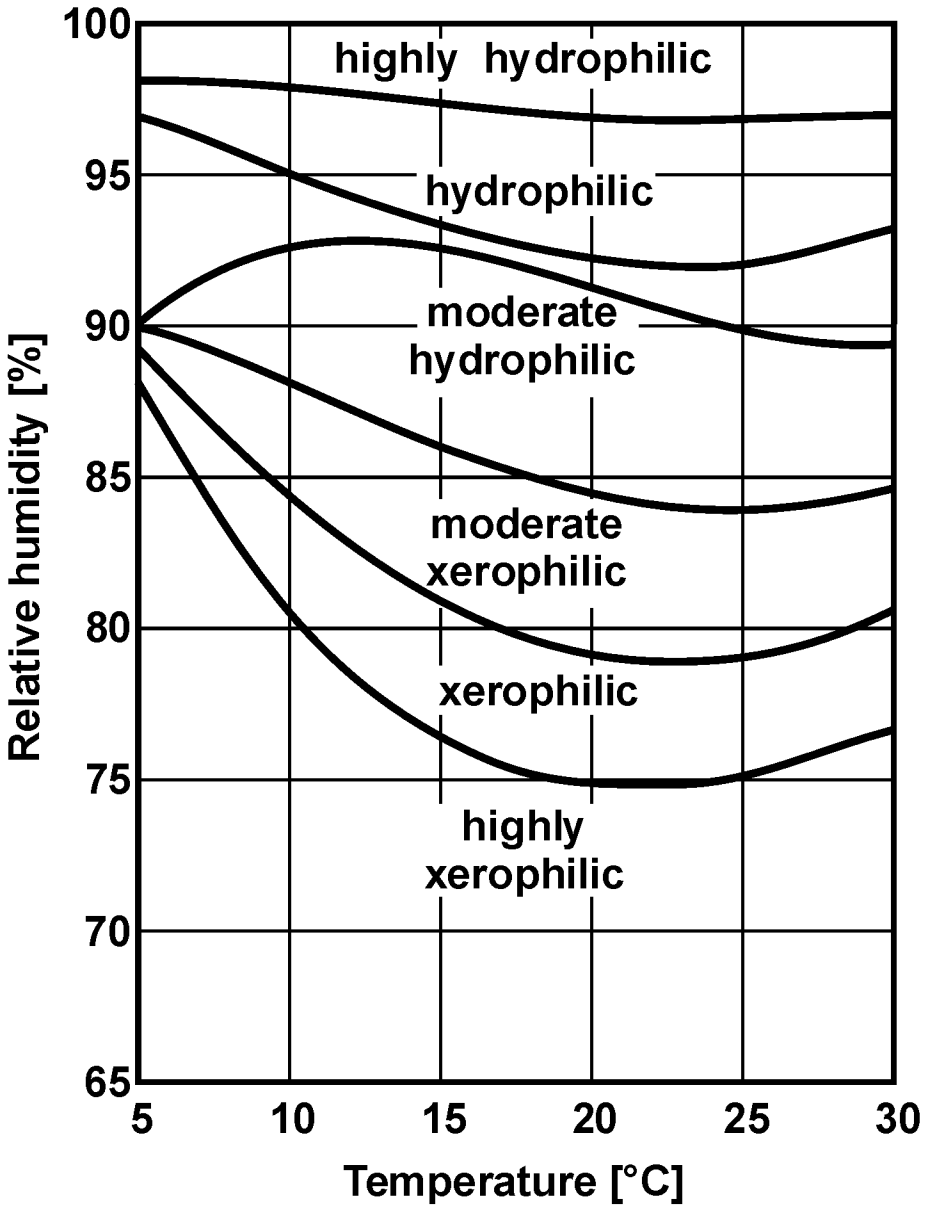


Fig. 26 Representation of the lower envelope curves of the respective growth range (isopleths) for different mould fungus categories, in dependence on temperature and relative humidity according to Clarke [13].

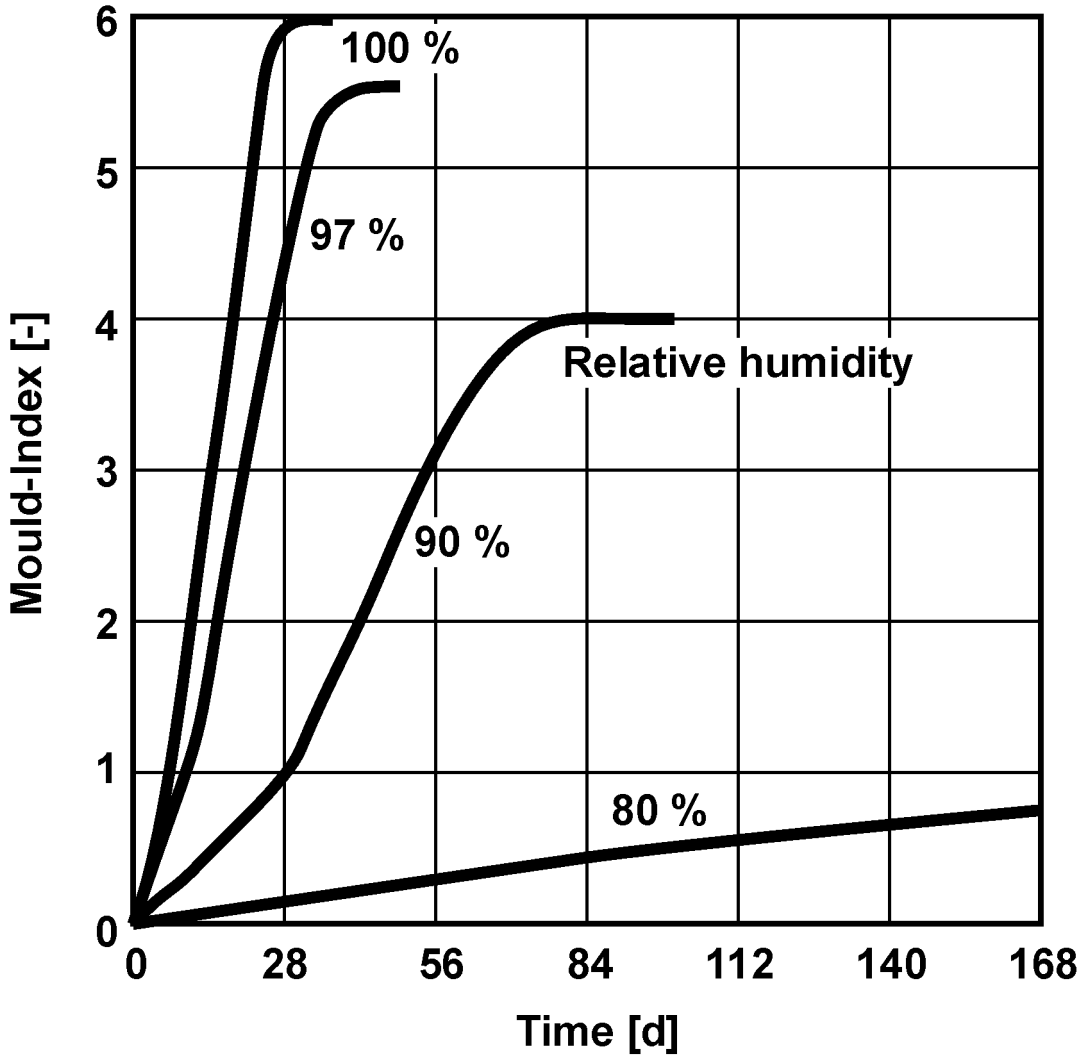


Fig. 27 Time course of the calculated mould index in dependence on the relative humidity.

This figure shows the mould index for pinewood at 20 °C according to Viitanen [138]. The mould index is explained in Table 11.

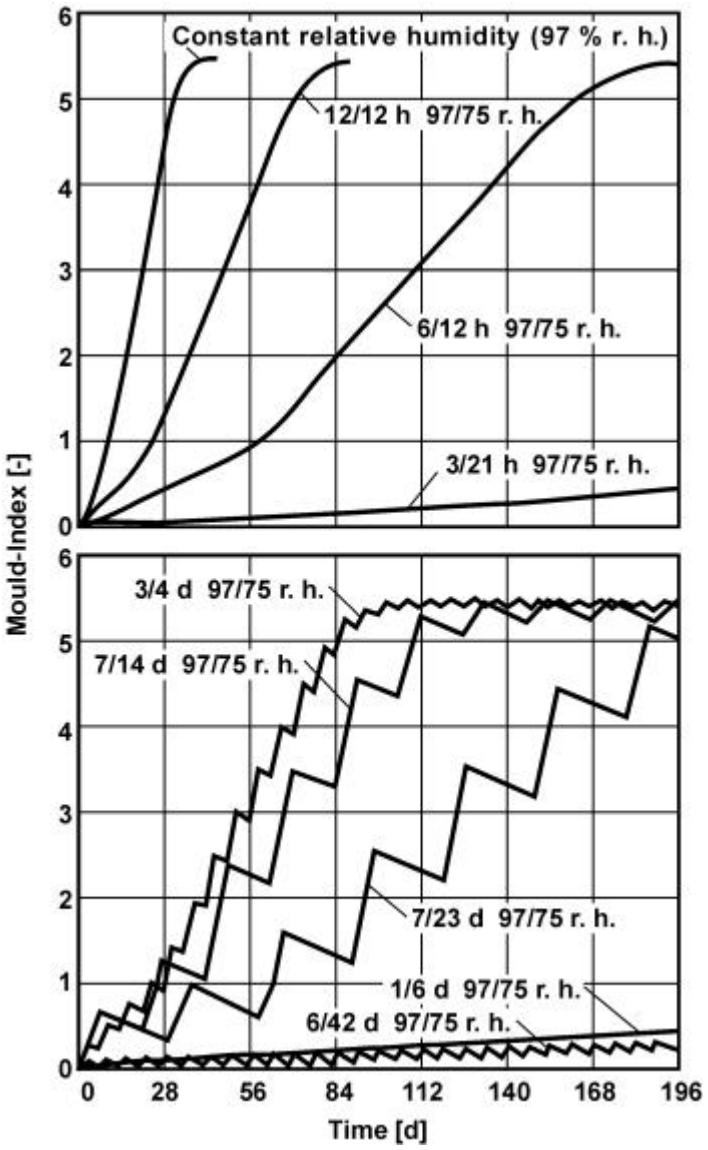


Fig. 28 Time course of the calculated mould index in dependence on various climatic boundary conditions.

Above: Fast changes (hours).

Below: Slow changes (days).

This figure shows the mould index for pinewood at 20 °C and fluctuating climatic boundary conditions according to Ritschkoff [107]. The numbers at the curves represent the climatic boundary conditions. The mould index is explained in Table 11.

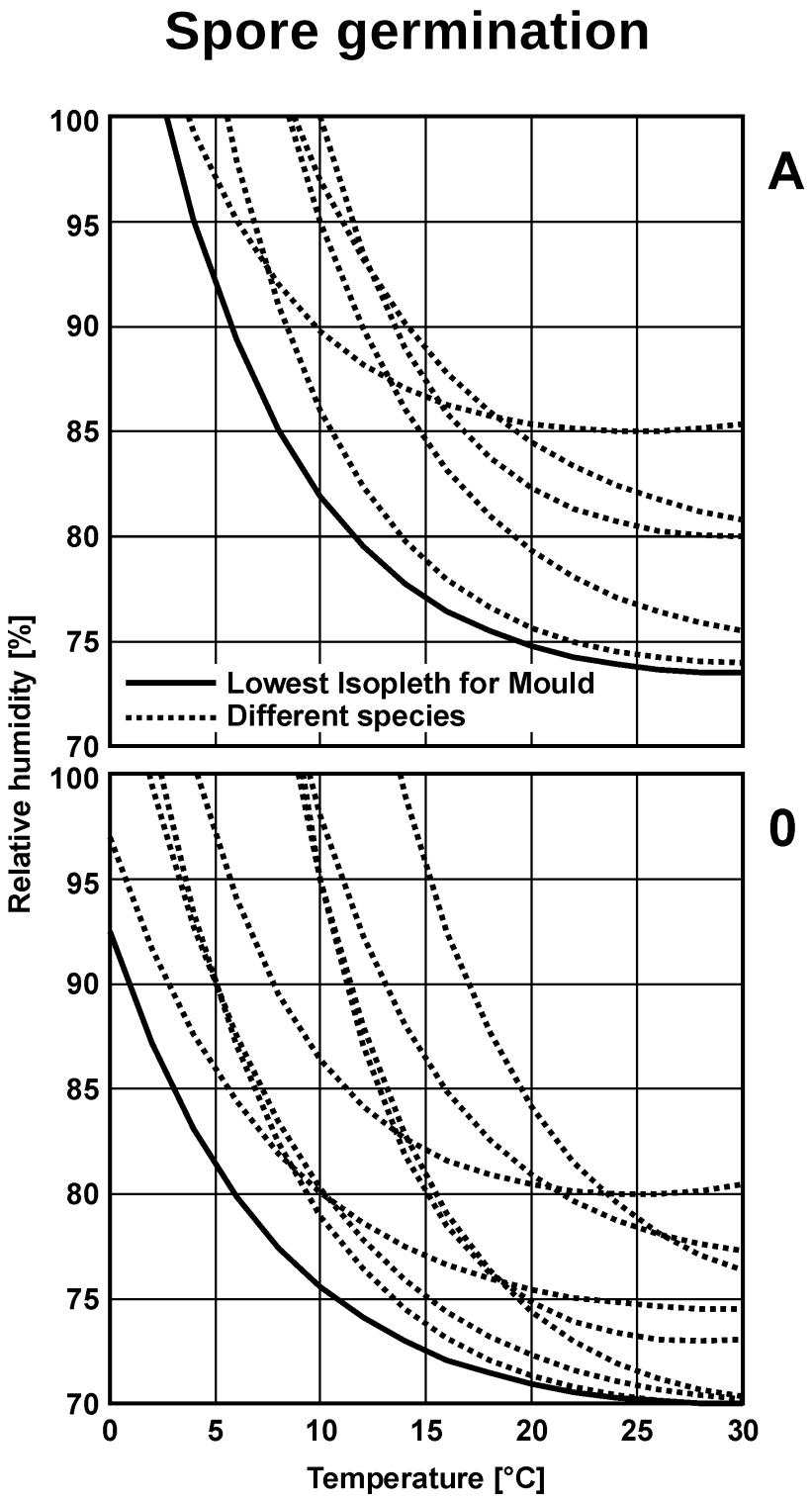


Fig. 29 Isopleths for spore germination of various fungus species considered in the model (see Table 4) and the Lowest Isopleth for Mould (LIM) resulting from that.

The top illustration applies to fungi of hazardous class A, the bottom illustration to class B/C.

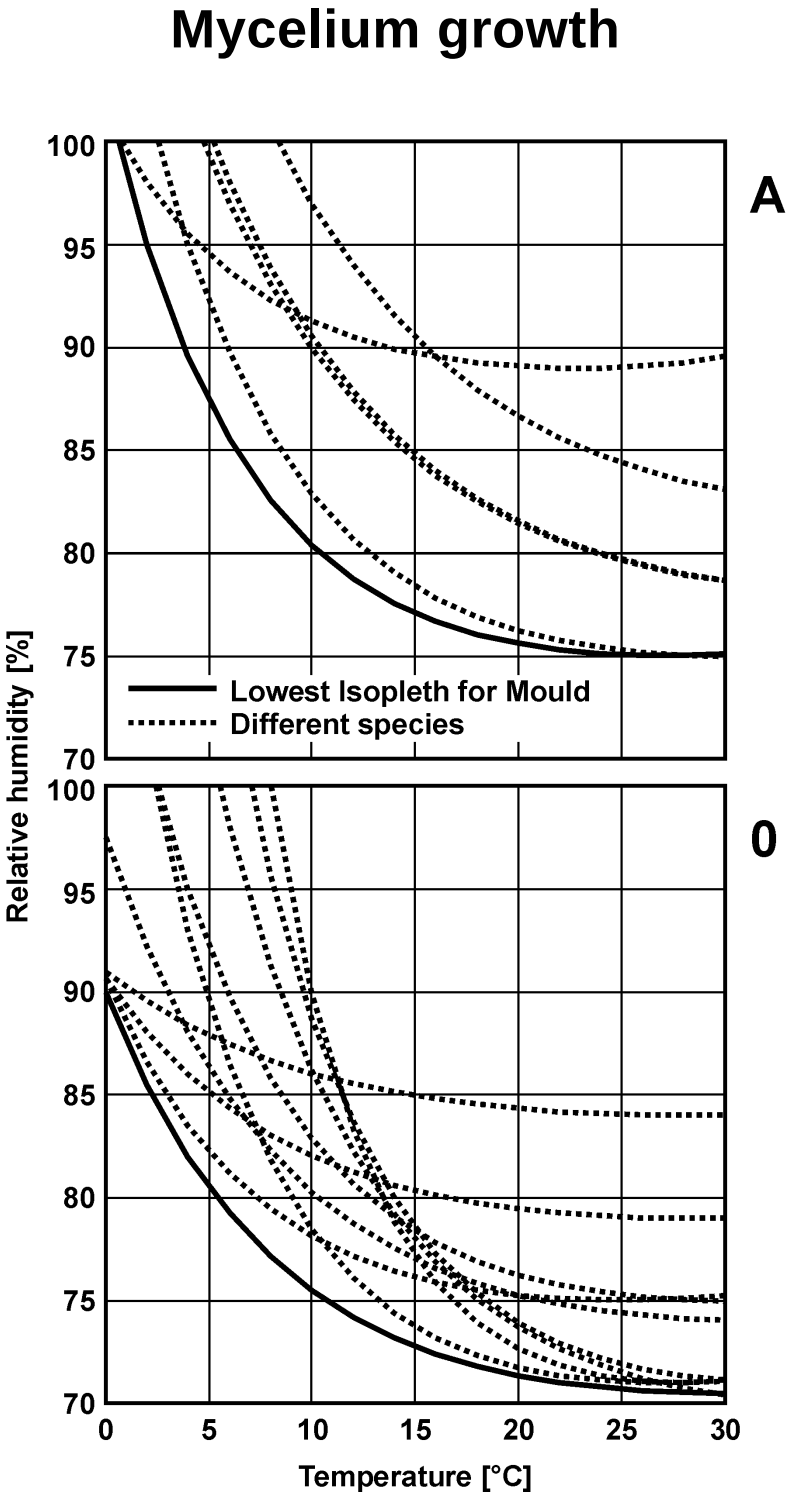


Fig. 30 Isopleths for mycelium growth of various fungus species considered in the model (see Table 4) and the Lowest Isopleth for Mould (LIM) resulting from that.

The top illustration applies to fungi of hazardous class A, the bottom illustration to class B/C.

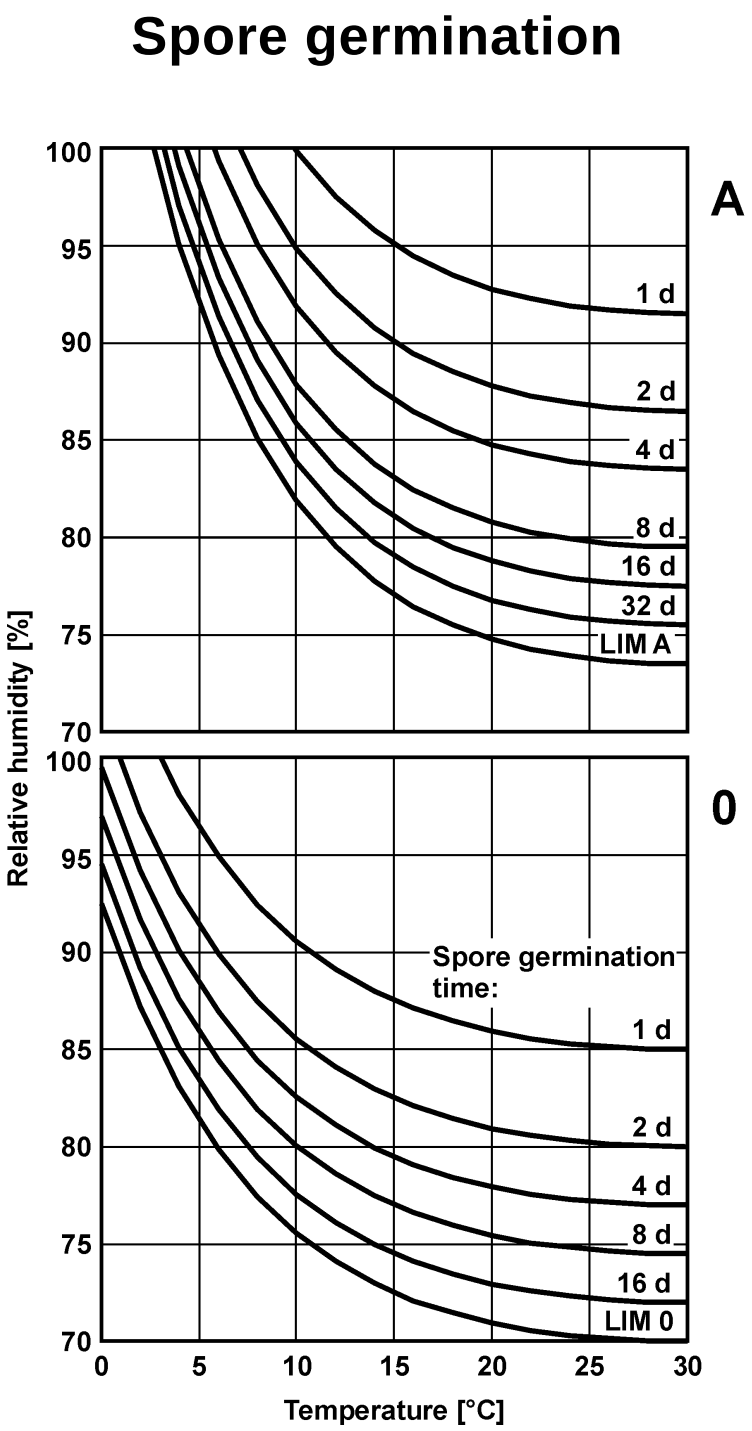


Fig. 31 Generalized isopleth system for spore germination, valid for all fungi of hazardous class A (above) and B/C (below).

The position of the Lowest Isopleth for Mould (LIM) is taken over from Figure 29 and represents the lowest limit of the biological activity in a hazardous class. The number of days indicated marks the duration after which first germinations take place.

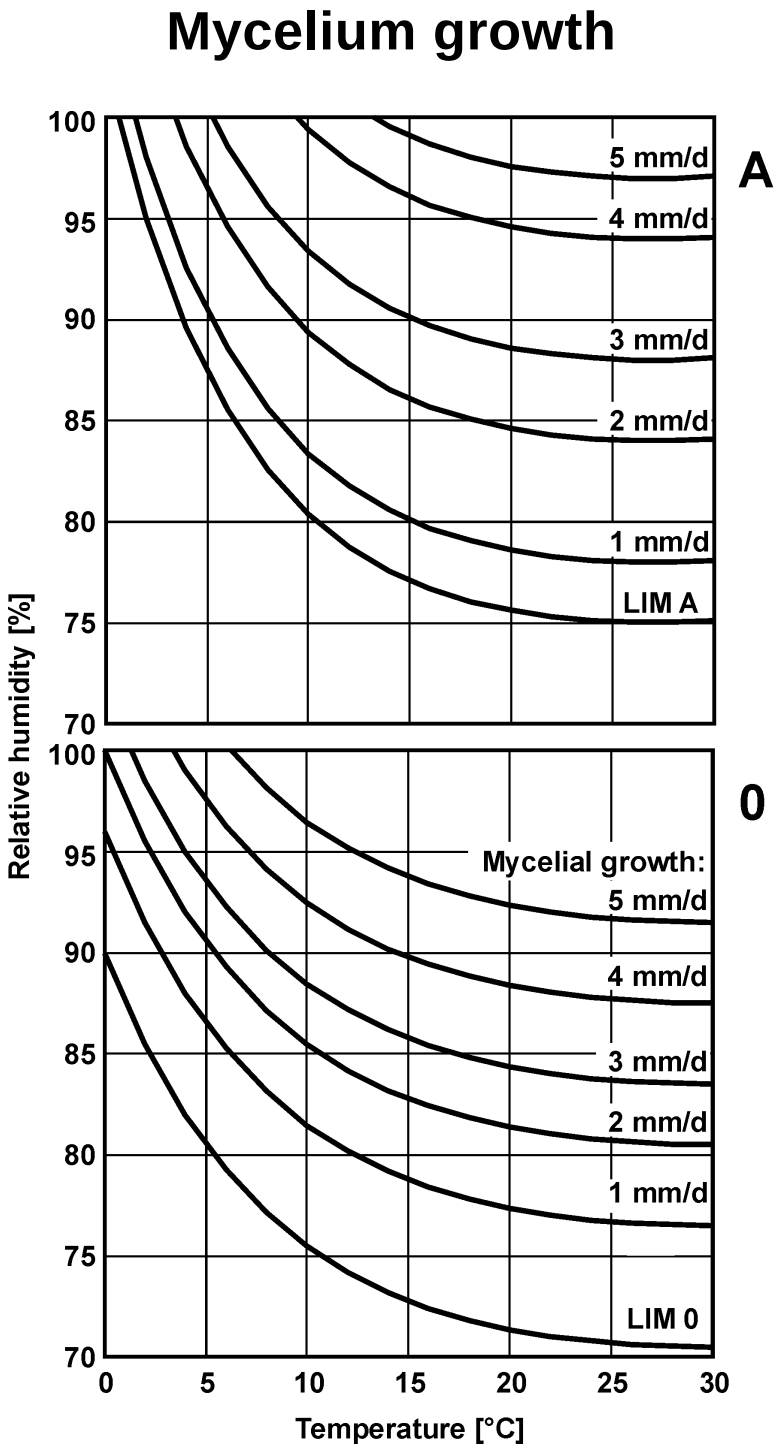


Fig. 32 Generalized isopleth system for mycelium growth, valid for all fungi of hazardous class A (above) and B/C (below).

The position of the Lowest Isopleth for Mould (LIM) is taken over from Figure 30 and represents the lowest limit of the biological activity in a hazardous class. The indicated number in mm/d marks the growth to be expected.

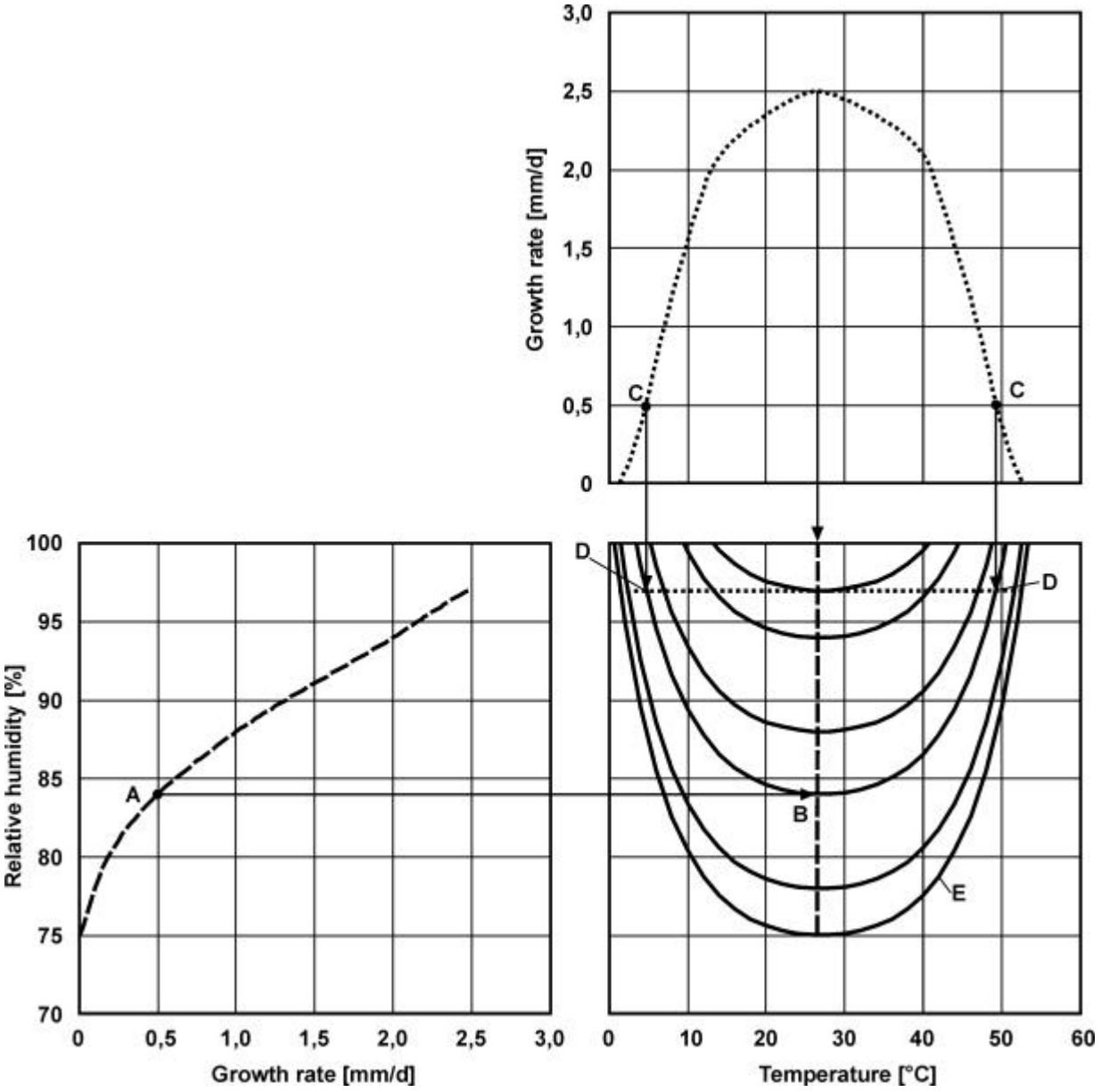


Fig. 33 Schematic diagram of how to generate the isopleths by projecting the measured temperature- and humidity-dependent growth rates (cf. Figures 5 and 7) onto an isopleth system for mycelium growth.

How to use the nomogram:

A: The growth depending on the relative humidity is read off.
B: This value is entered at the temperature which is optimal for growth.
C: The growth depending on the temperature is read off.
D: These values are entered at the relative humidity which is optimal for growth.
E: Connecting these 3 points (B, D) by means of the cosh function defined according to Gl. (15), one gets the isopleth for the growth rates.

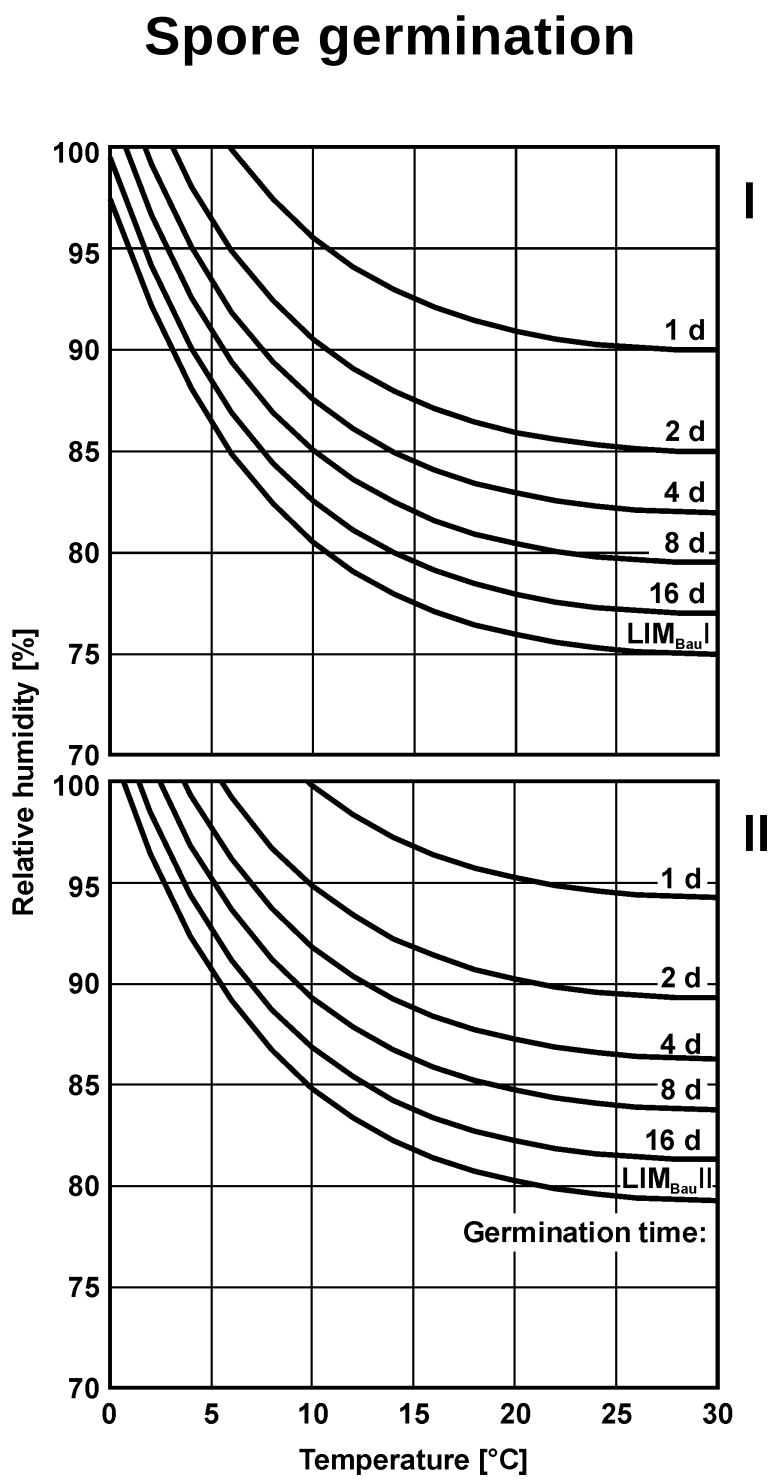


Fig. 34 Generalized isopleth system for spore germination, valid for all fungi of substrate category I (above) and II (below).

The indications in days are spore germination times. Below the LIM_{Mat}, there is no biological activity expected on building materials belonging to the respective group.

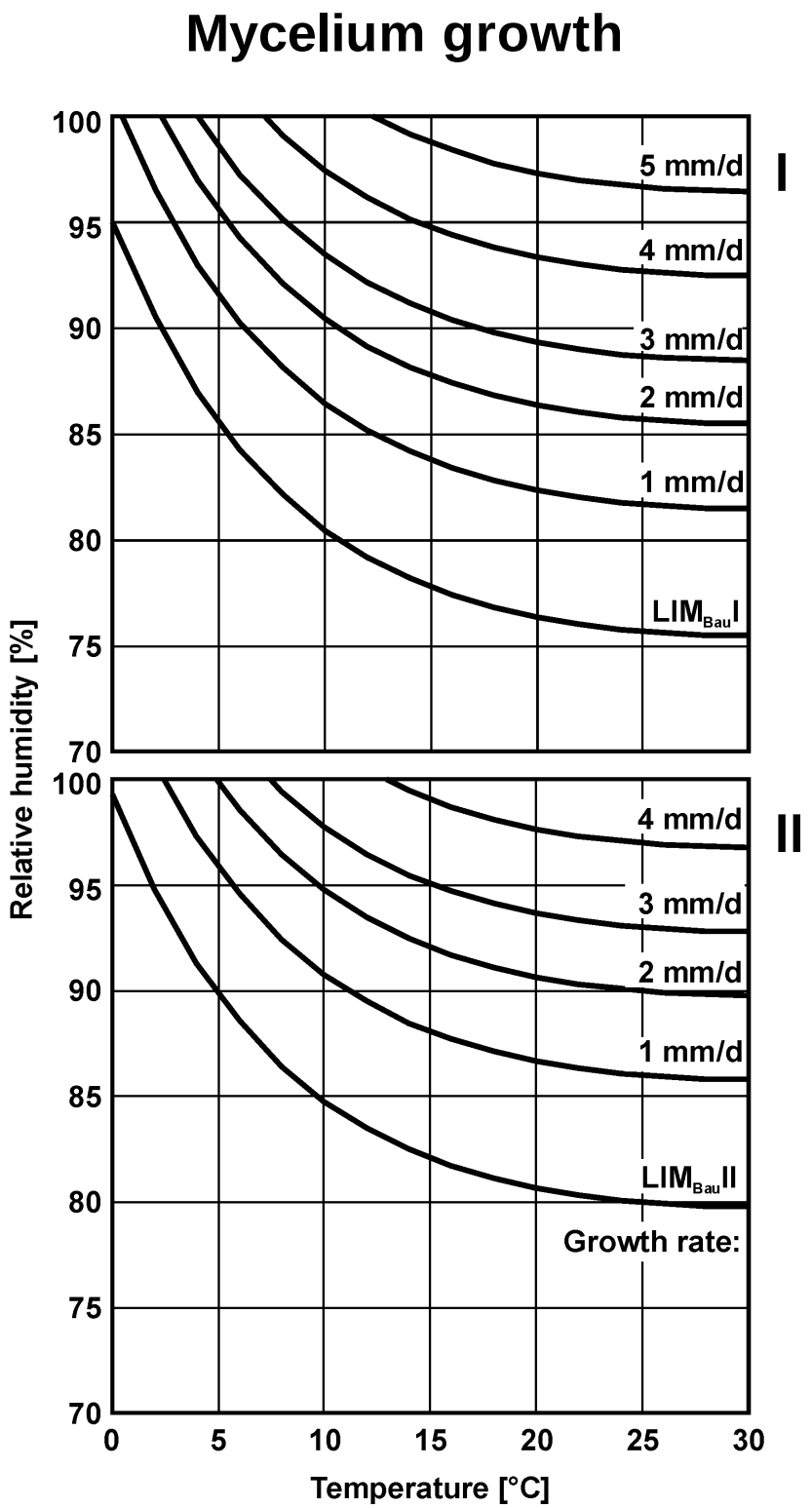


Fig. 35 Generalized isopleth system for mycelium growth, valid for all fungi of substrate category I (above) and II (below).

The indications in mm/d mean mycelium growth. Below the LIM_{Mat}, there is no biological activity expected on building materials belonging to the respective group.

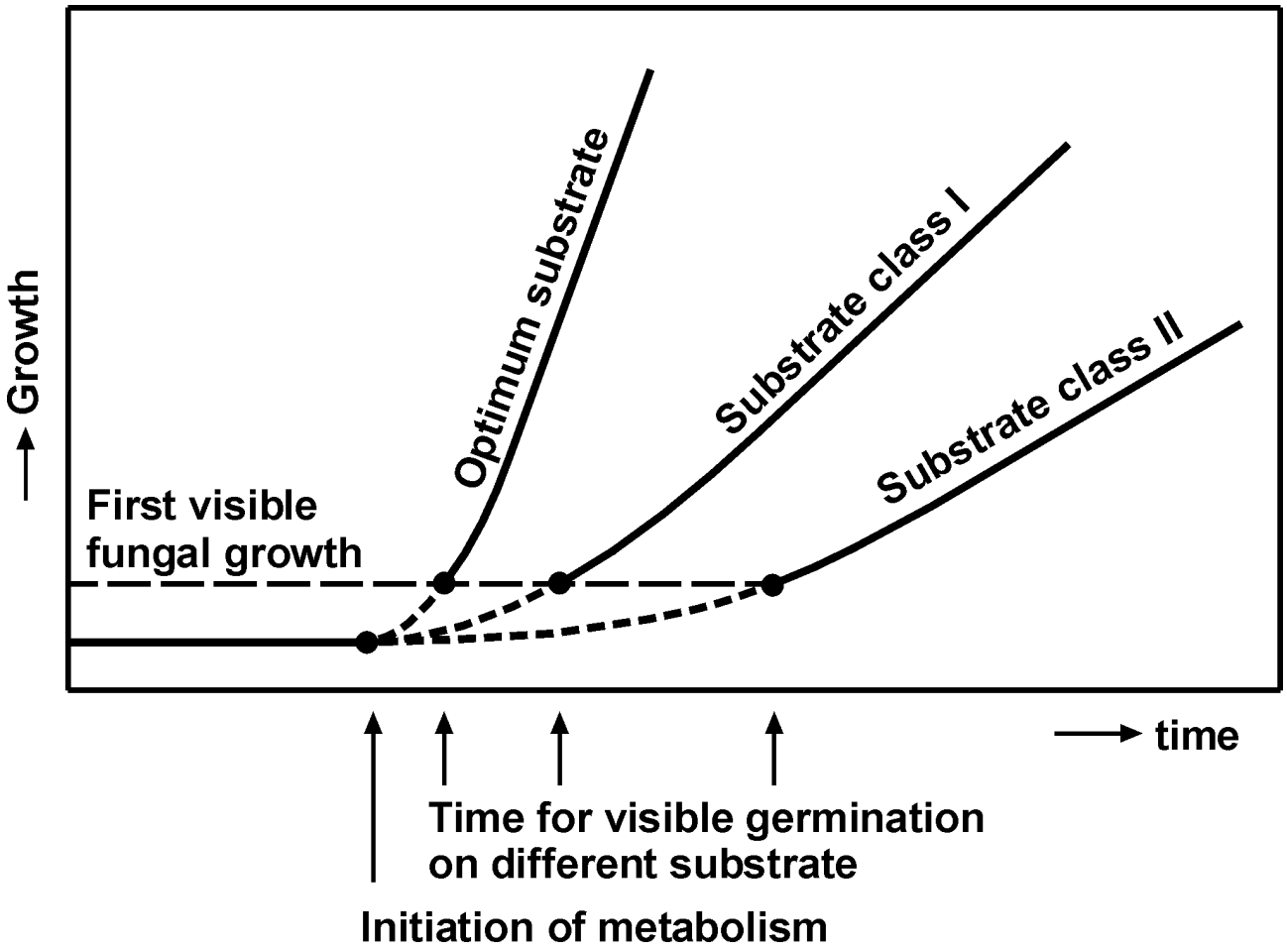


Fig. 36 Schematic diagram of the model idea for the substrate-dependent growth processes in the range of the initial growth-lag, the acceleration phase and the log-growth phase (cf. Figure 4) of mould fungi.

The figure shows the fungoid growth in dependence of time with an optimal culture medium and for the substrate groups I and II. In addition, one can see the time of metabolism start by mould fungi and the spore germination time influenced by the substrate, which is generally defined by the first visible mould fungus growth.

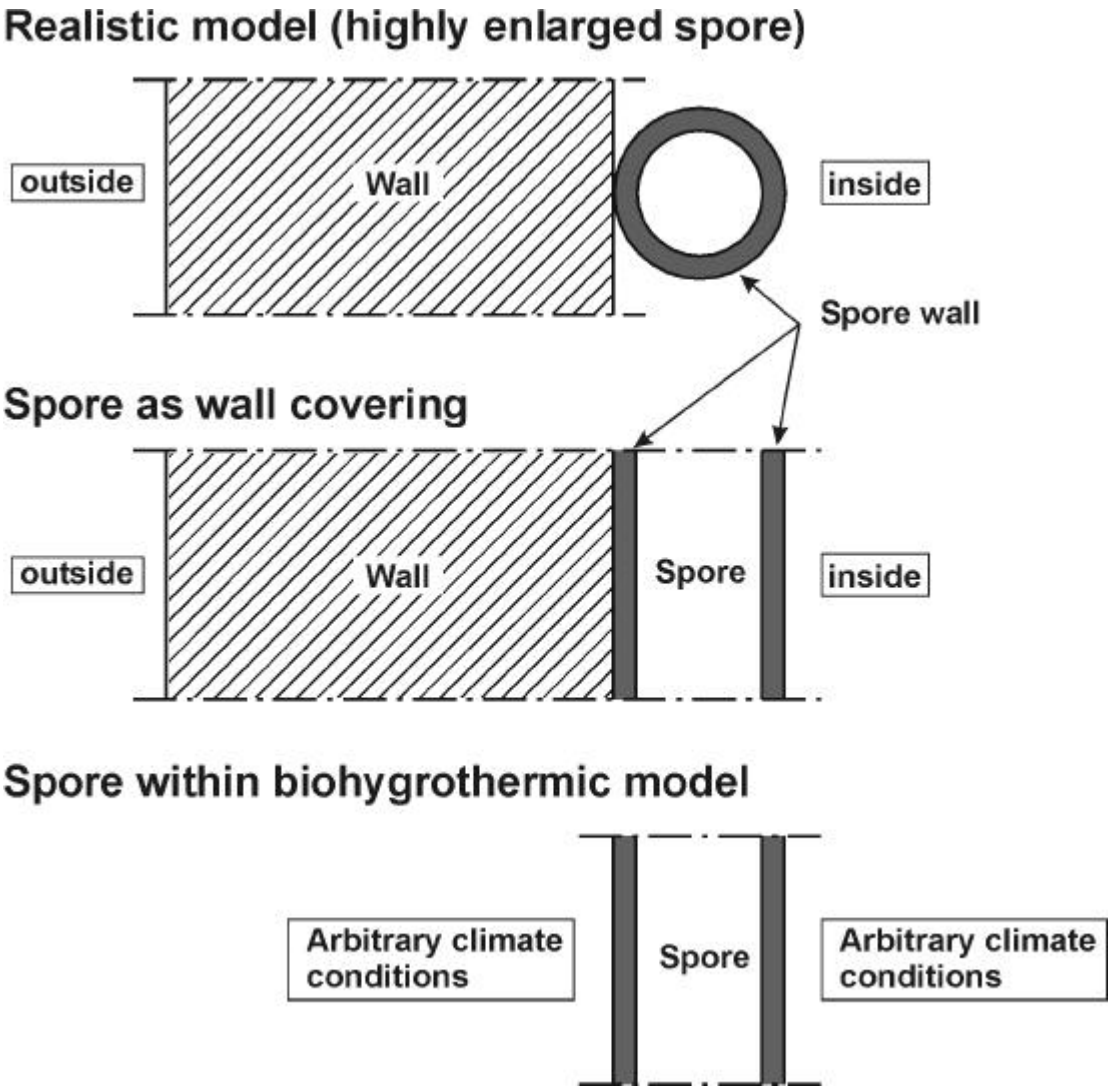


Fig. 37 Schematic comparable view of a spore on a wall (above), a spore as wall covering (middle) and a model spore (below).

The ratio between spore diameter and wall thickness (30 cm) is approx. 1:100,000. The real spore touches the building material, i.e. the hygrothermal boundary conditions at this surface do influence the hygric processes inside the spore. However, due to its small size, the spore has no effect on the building physical boundary conditions in the area of the material surface. Therefore, one does not use a master model, as per the component structure with the spore as wall covering (middle), but a „model spore“ (below) that is independent of the wall. With that, any courses of temperature and relative humidity can be considered as climatic boundary conditions for the biohygrothermal calculations.

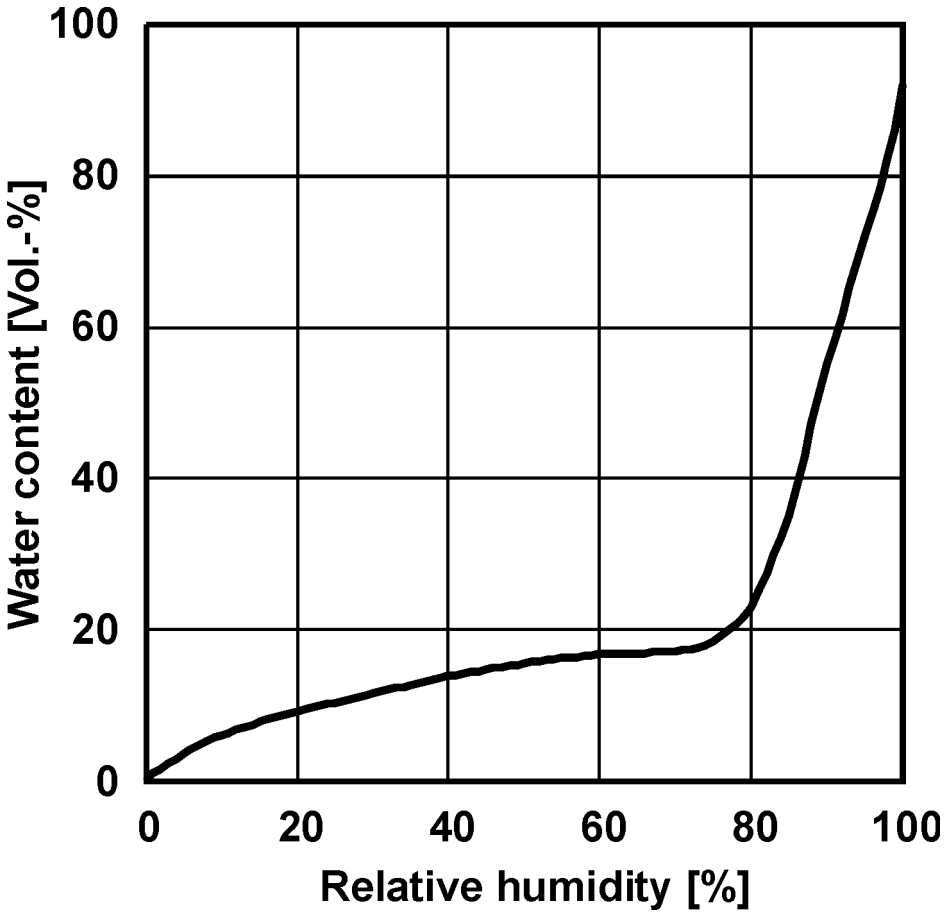


Fig. 38 Moisture storage function to describe a model spore.

The moisture storage function taken from measurements of bacteria spores according to Rubel [109] is converted for mould fungus spores and slightly modified.

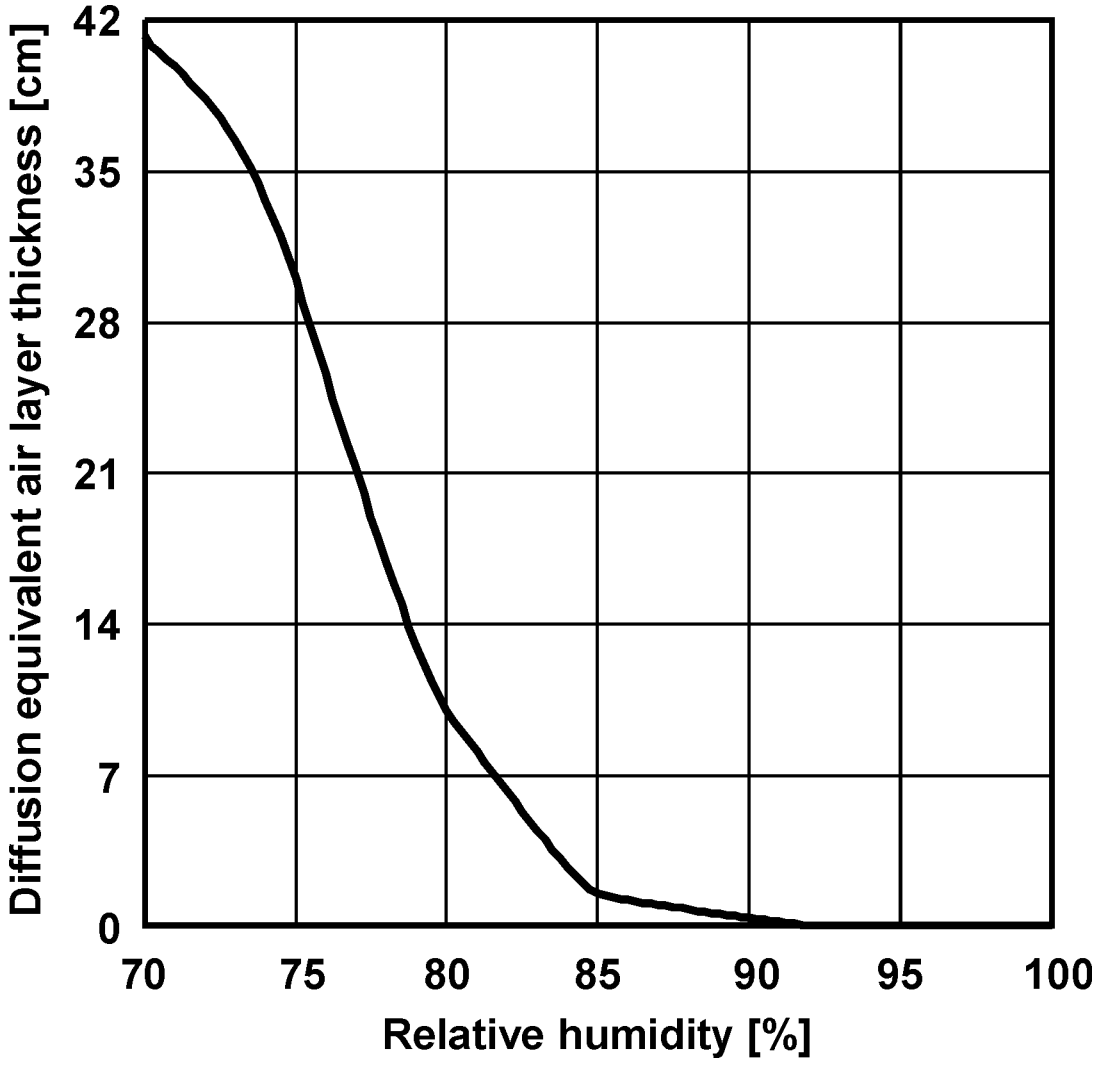


Fig. 39 Diffusion equivalent air layer thickness (s_d value) of a model spore as it is applied for the spore septum used in the biohygrothermal model, converted to the special scales (see Table 15).

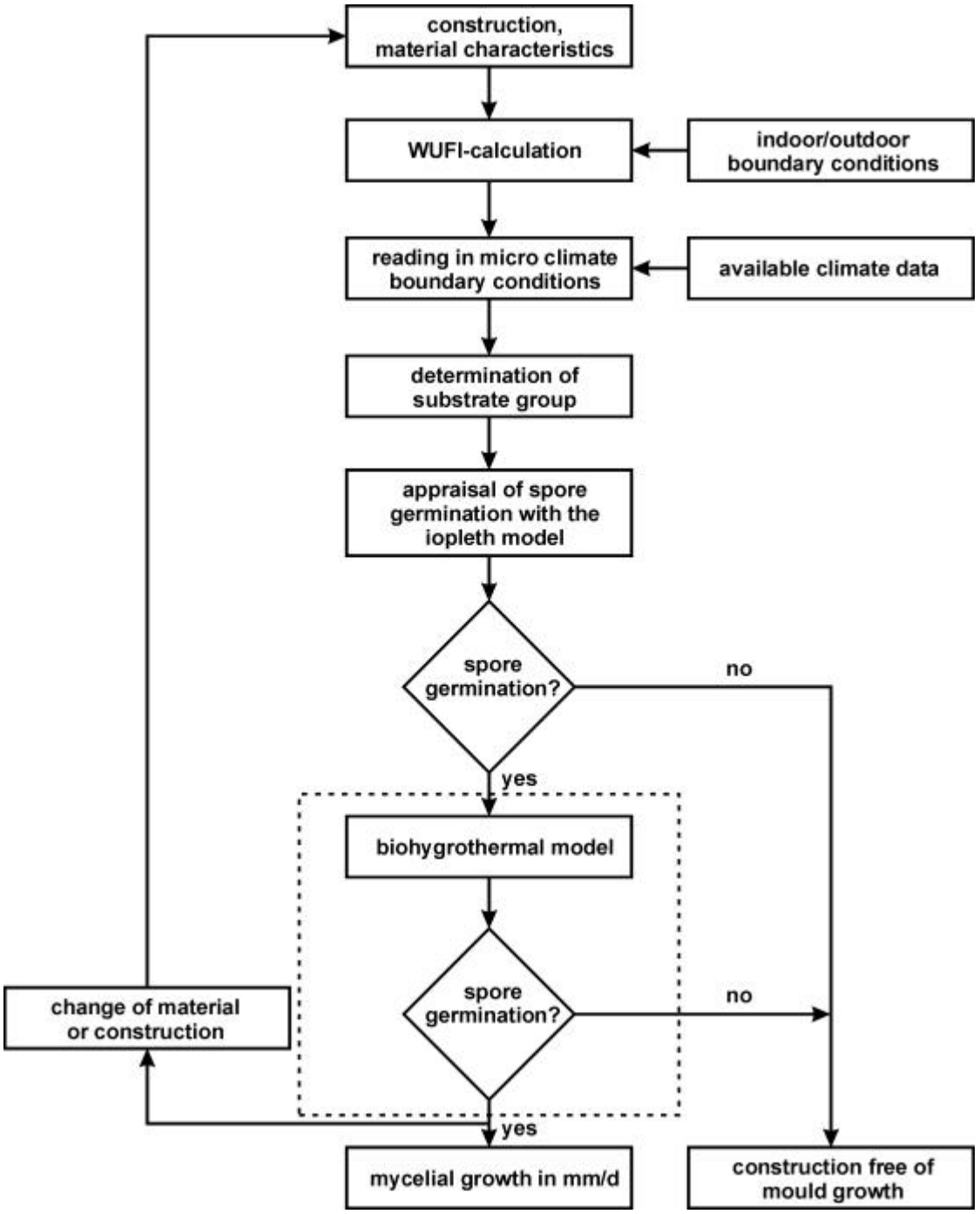


Fig. 40 Flow chart showing the procedure of how to predict mould fungus formation by means of the isopleth model and the biohygrothermal model.

The box with the dashed border refers to the procedure at the biohygrothermal calculations and is explained in detail in Figure 42.

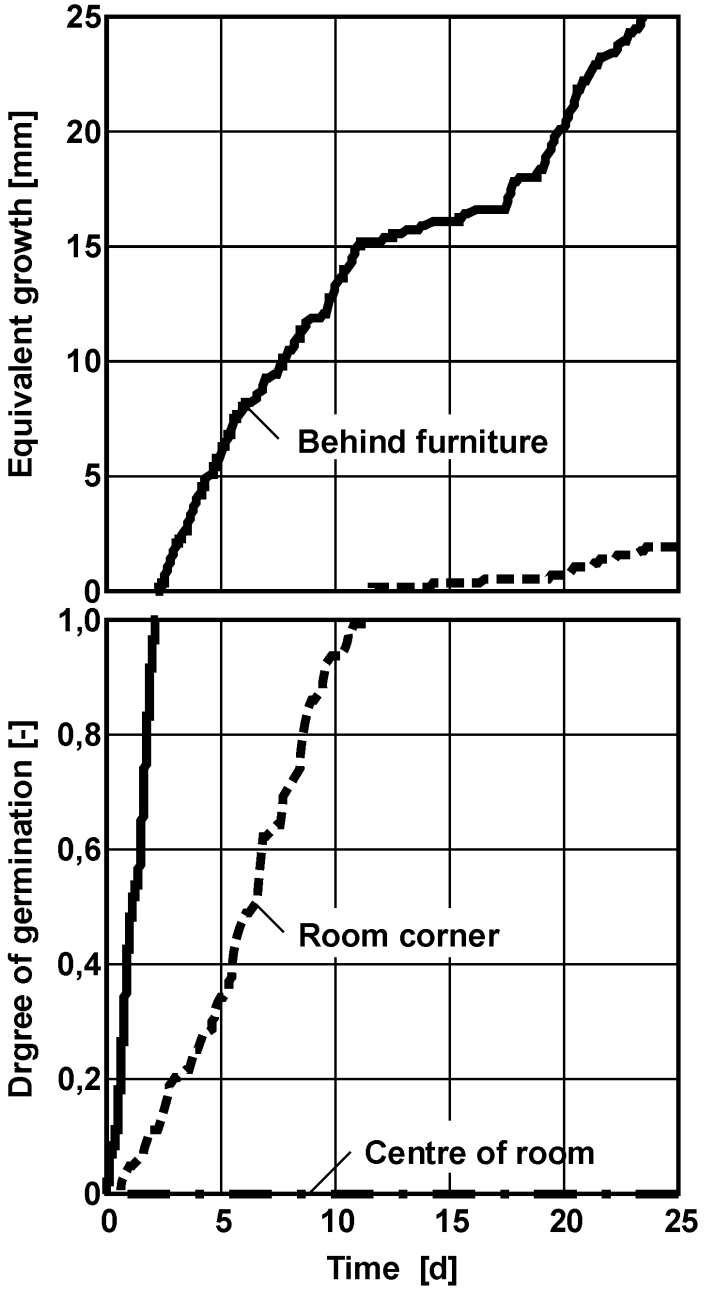


Fig. 41 Time course of spore germination and growth according to the isopleth model for 3 different places (wall centre, corner and behind the furniture).

Above: equivalent mycelium growth in mm.

Below: degree of germination.

Data applied:
Substrate group II as per Figure 34 bottom and 35 bottom.

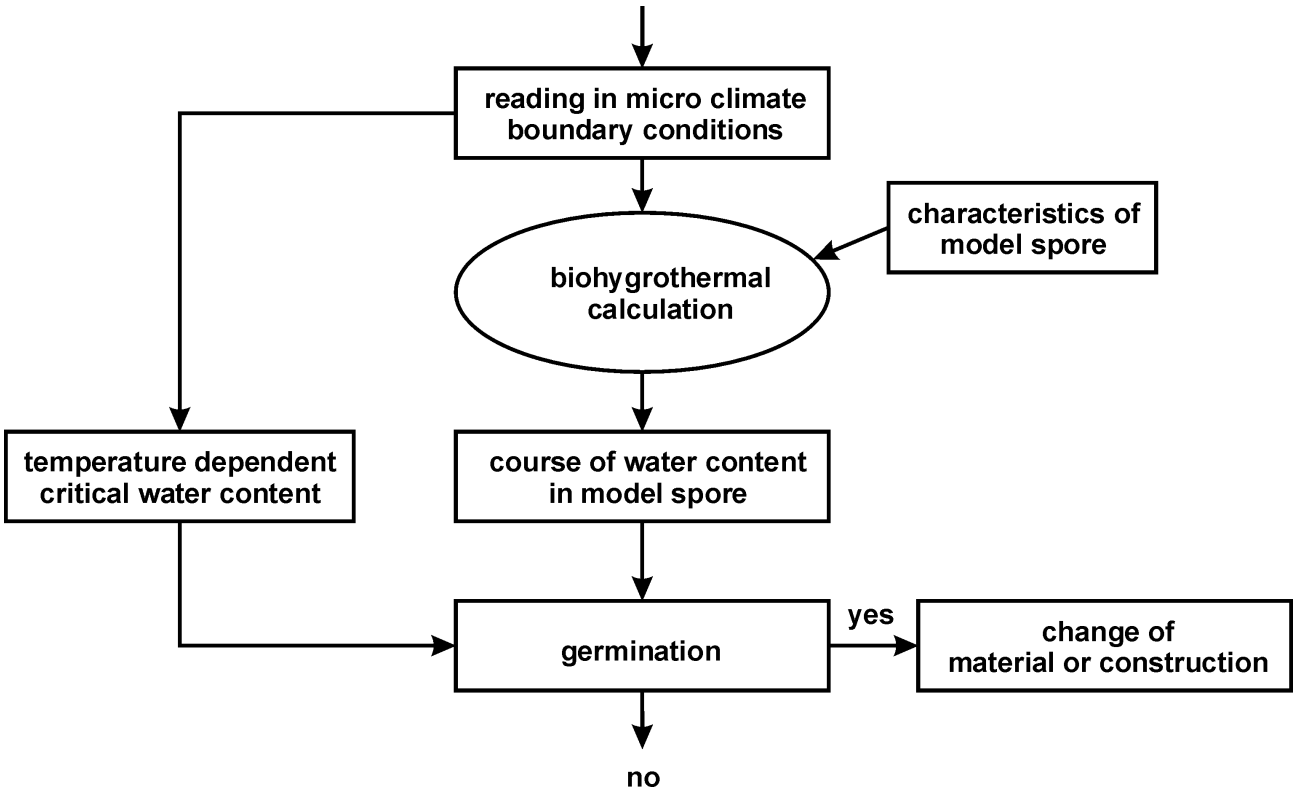


Fig. 42 Flow chart showing the procedure of how to predict mould fungus formation by means of biohygrothermal calculations.

First of all, the climatic boundary conditions and the material data of the model spore are read into the WUFI calculation program and the course of the moisture content in the spore is calculated biohygrothermally. Whether germination is to be expected is determined by comparing the moisture content inside the spore with the temperature-dependent critical moisture content.

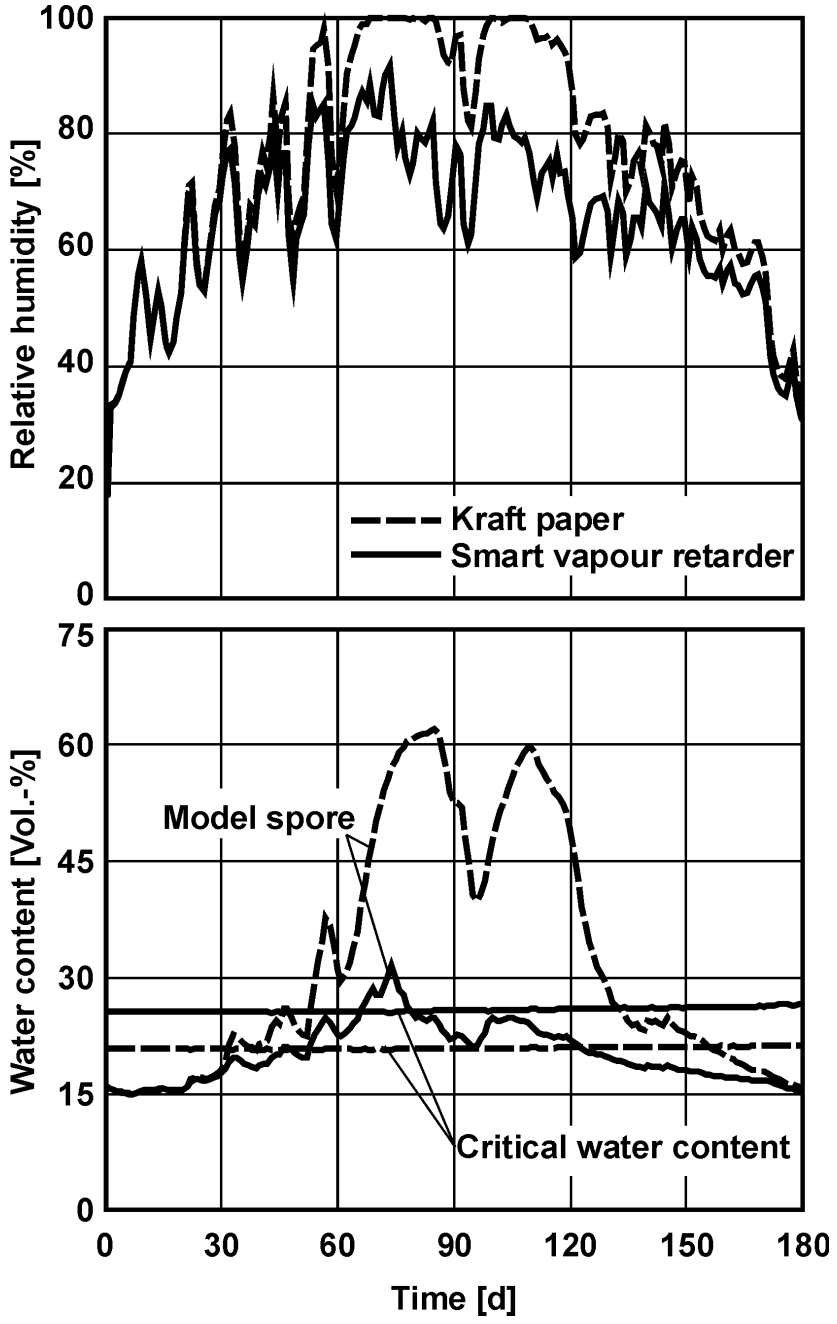


Fig. 43 Time courses of the relative humidities at the vapour seals of paper foil and plastic foil (upper illustration) determined with the WUFI calculation program and the moisture content in the spores existing on the vapour seals (bottom illustration).

The bottom diagram does additionally show the critical moisture contents from which on germination takes place.

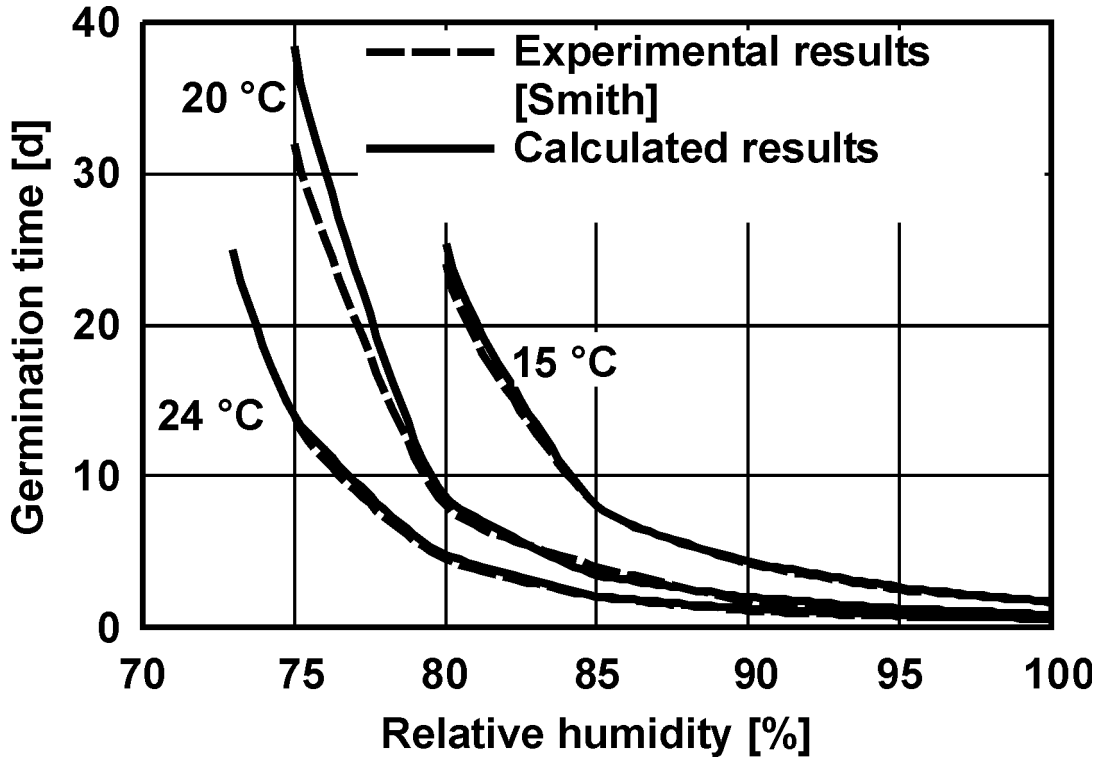


Fig. 44 Comparison between the spore germination time, in dependence on the relative humidity and temperature, stated by Smith [126] and the results of biohygrothermal calculations for the mould fungus *Aspergillus restrictus*.

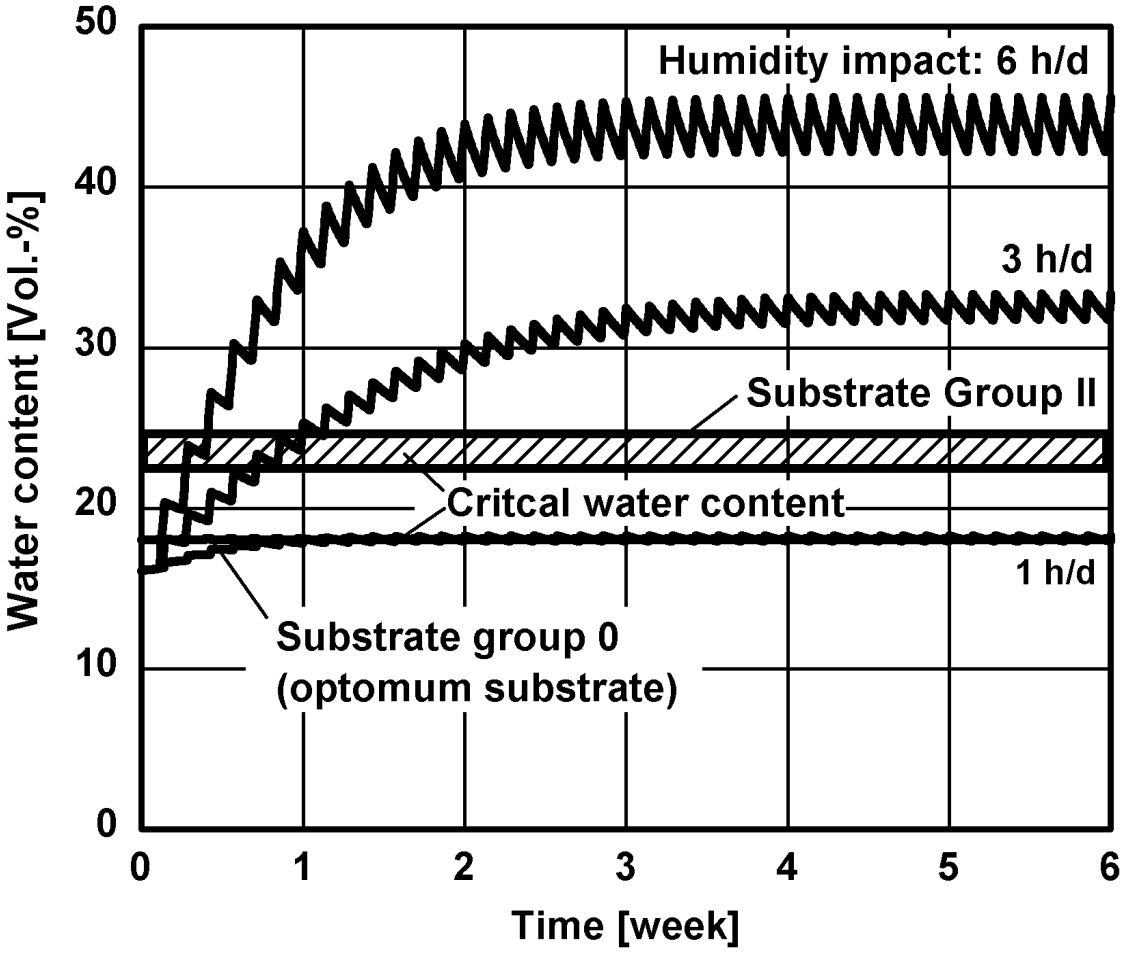


Fig. 45 Time courses of the moisture contents calculated with the biohygrothermal model in the spores existing in the mould fungus test stand [37], with different times of humidity influence per day and indication of the critical moisture contents.

Data applied:

Boundary conditions (as in the test stand [37]):

- relative humidity: 95 %
- temperature: 18,5 °C
- time of influence per day: 1 h, 3 h, 6 h (varies)
- other time: 60 % relative humidity and 26.1 °C.

Critical moisture content from which on germination takes place:

- substrate categories 0 and II
- hatched area: marks the critical moisture content arising in the test stand in the temperature range between 18.5 °C (upper value) and 26.1 °C (lower value).

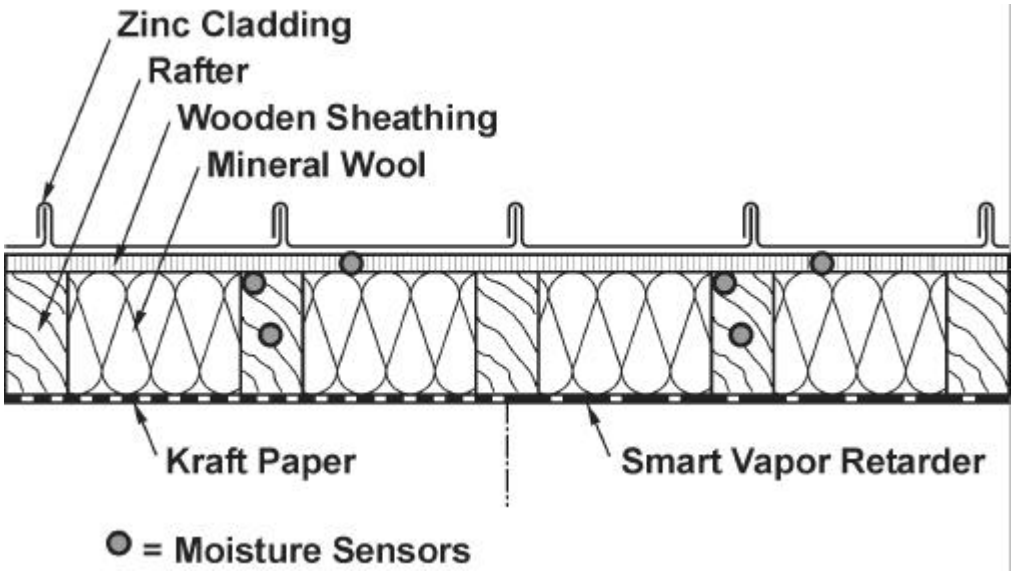


Fig. 46 Data concerning the gable roof tests according to [70].

Above: Photograph of the test building with the gable roof.

Below: Schematic cross section of the tested roof construction with the material and the measured points of wood moisture indicated.

Applied s_d values:
Paper foil: 3 m
Plastic foil: variable (0.4 m in summer; 4 m in winter).

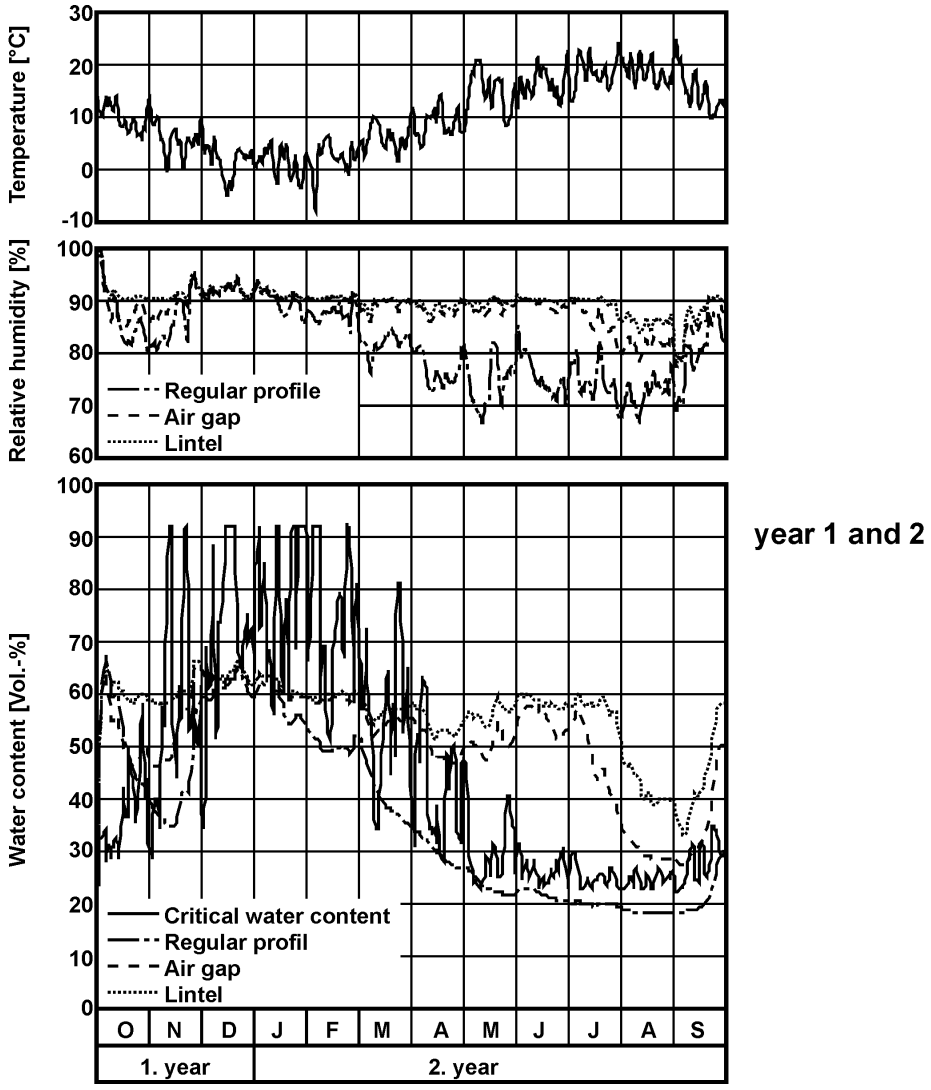


Fig. 47 Calculated time courses of temperature (above) and relative humidity (middle) and of the moisture content in the spore (below) at various positions of the exterior plaster of an external wall.

Applied data and boundary conditions:
climate data: according to data record [53]
wall structure: ETICS on concrete as wall material
tested positions:
- undisturbed area: no mould fungus formation
- plate joint (ETICS): mould fungus formation
- window lintel: mould fungus formation.

The bottom illustration does also show the course of the critical moisture content; it applies to all positions on the wall and indicates from which value on spore germination takes place.

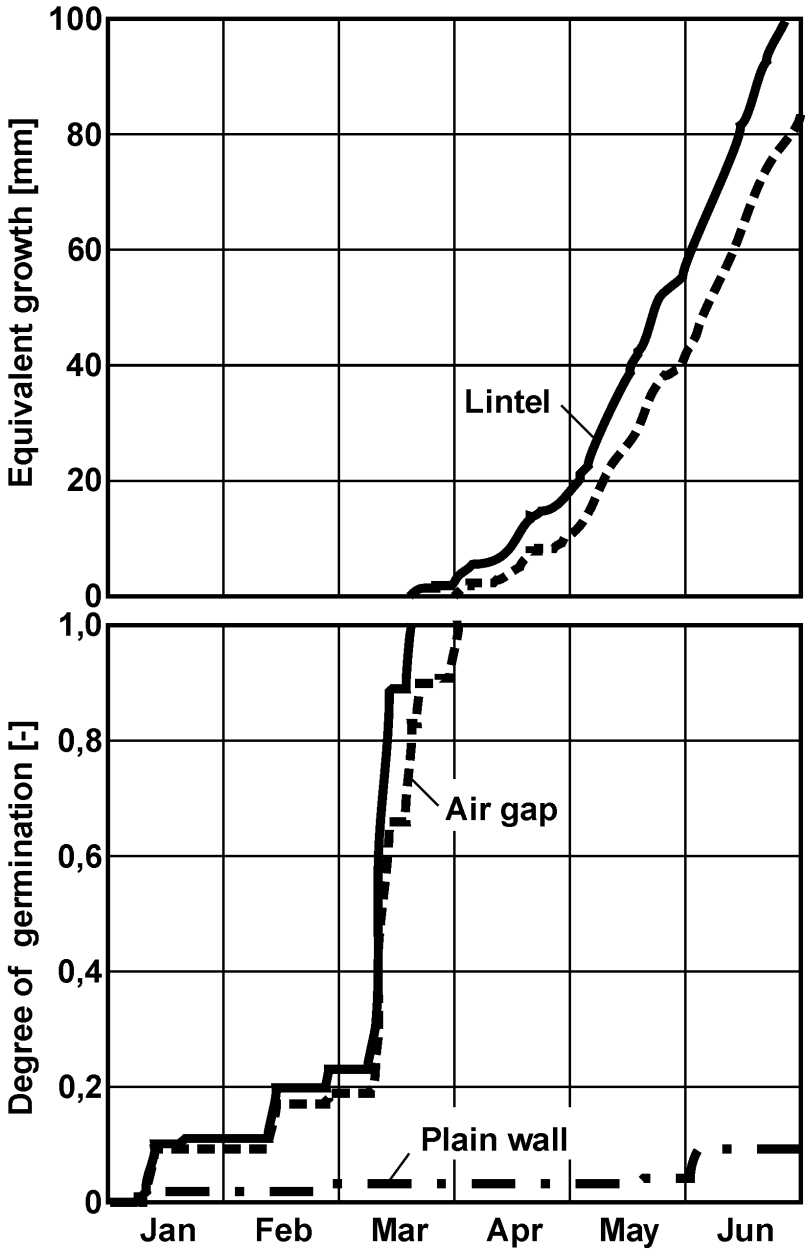


Fig. 48 Time course of spore germination and growth according to the isopleth model for 3 different positions (wall centre, plate joint and window lintel).

Above: equivalent mycelium growth in mm.

Below: degree of germination.

Data applied:
substrate category II acc. to Figure 34 bottom and 35 bottom.

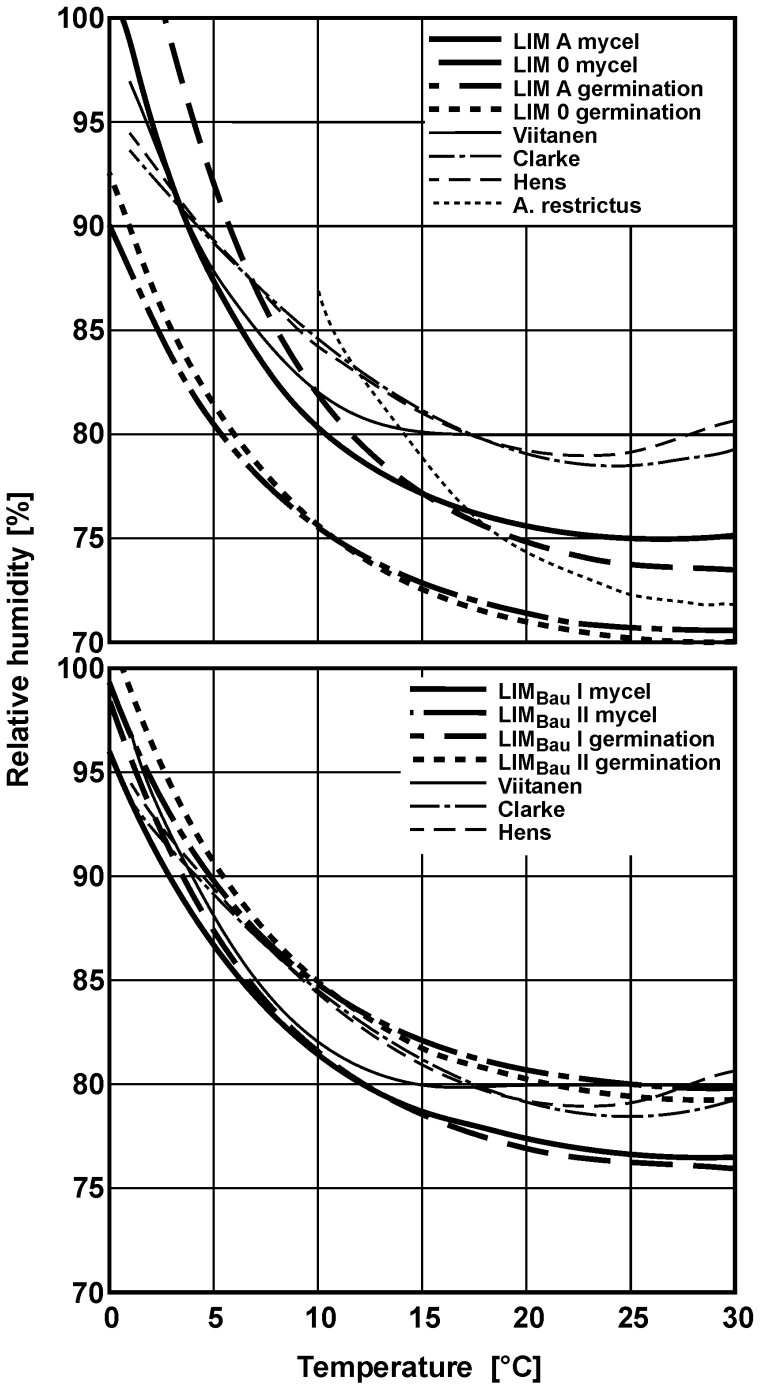


Fig. 49 Minimum growth conditions (LIM curves) in dependence on temperature and relative humidity as applied in the isopleth system, compared with the isopleths of Viitanen ([137, 138]), Clarke [13] and Hens [47] found in literature and the mould fungus *Aspergillus restrictus* according to Smith [126].

Above: hazardous classes A and B/C.
Below: substrate categories I and II.

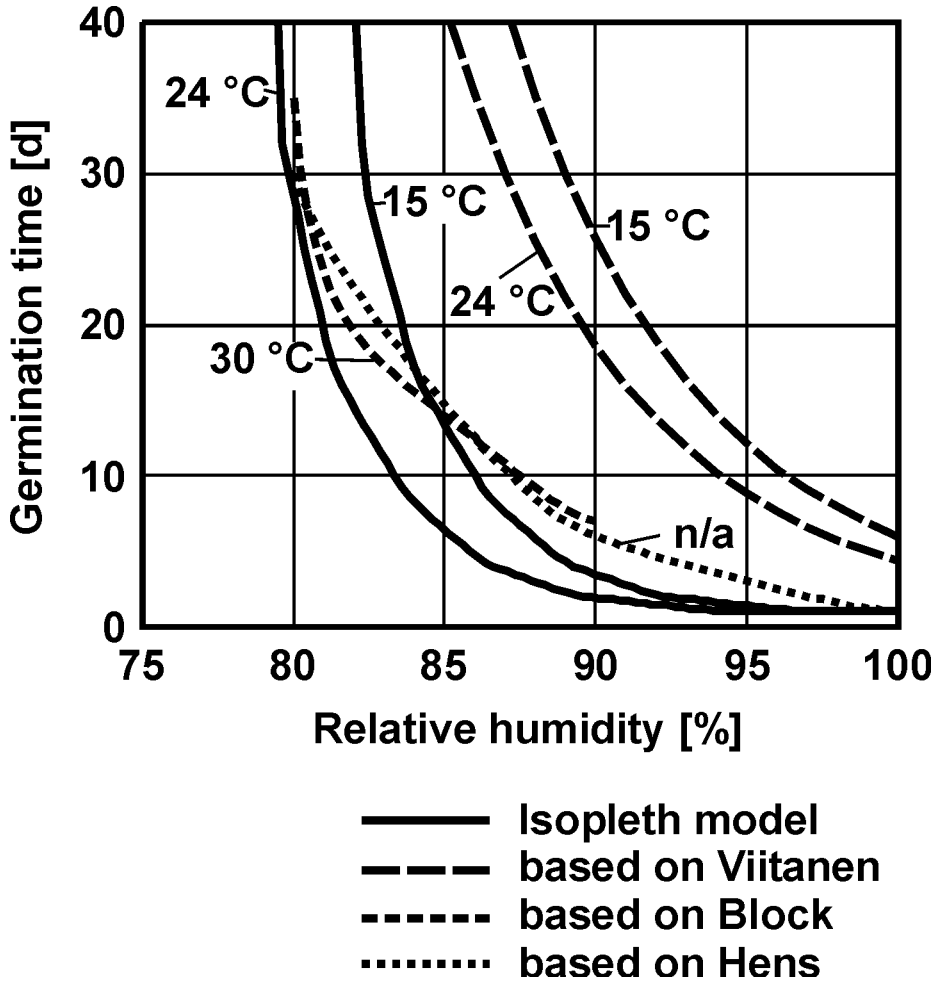


Fig. 50 Spore germination times in dependence on the relative humidity.

The spore germination times determined with the biohygrothermal model under stationary conditions, assuming the substrate category II, are compared with the germination times indicated in literature, either measured times (Block [11], Hens [47]) or times calculated with the model according to Viitanen [137, 138].

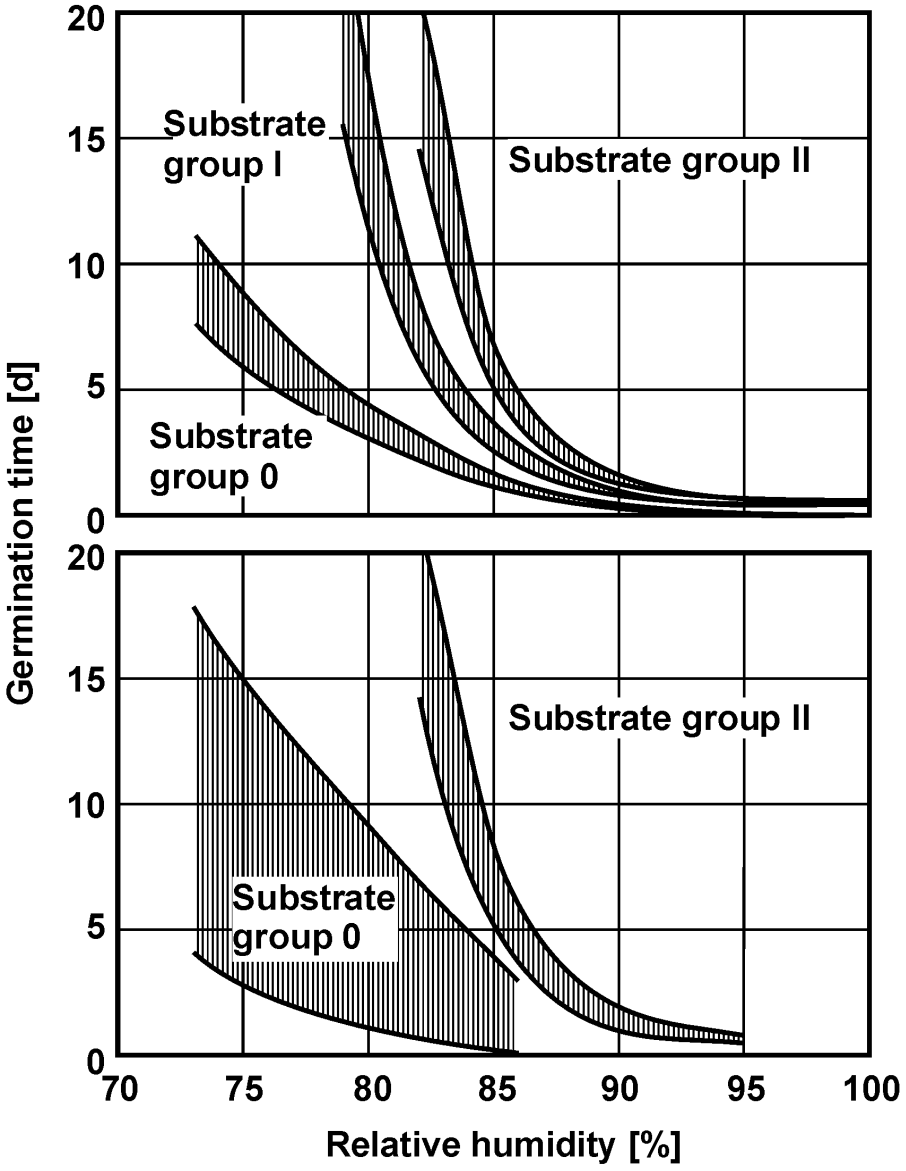


Fig. 51 Spore germination times in dependence on the relative humidity and various substrate groups.

Above: variation of the s_d value.

Below: variation of the initital moisture content.

This figure shows the spore germination times determined by the biohygrothermal calculations in the course of the sensitivity analysis. The hatched area marks the fluctuation ranges, with the upper limit describing the bigger s_d value and the lower initial moisture content respectively.

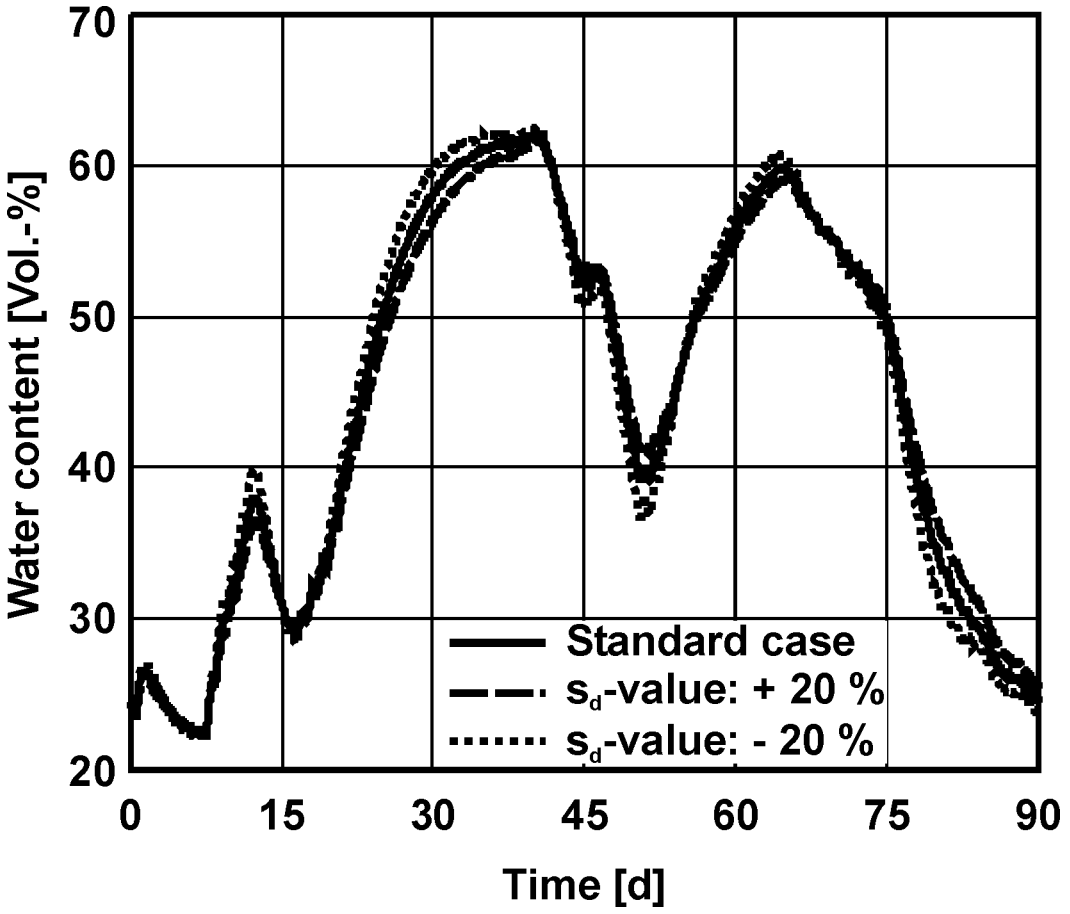


Fig. 52 Time course of the moisture content inside the spore in dependence on various s_d values.

This figure shows the moisture contents inside the spore determined by the biohygrothermal calculations in the course of the sensitivity analysis, with variation of the s_d value, in case of spore germination on the vapour seal of paper foil in a gable roof which is vapour-proof at the outside (time section from Figure 43 bottom).

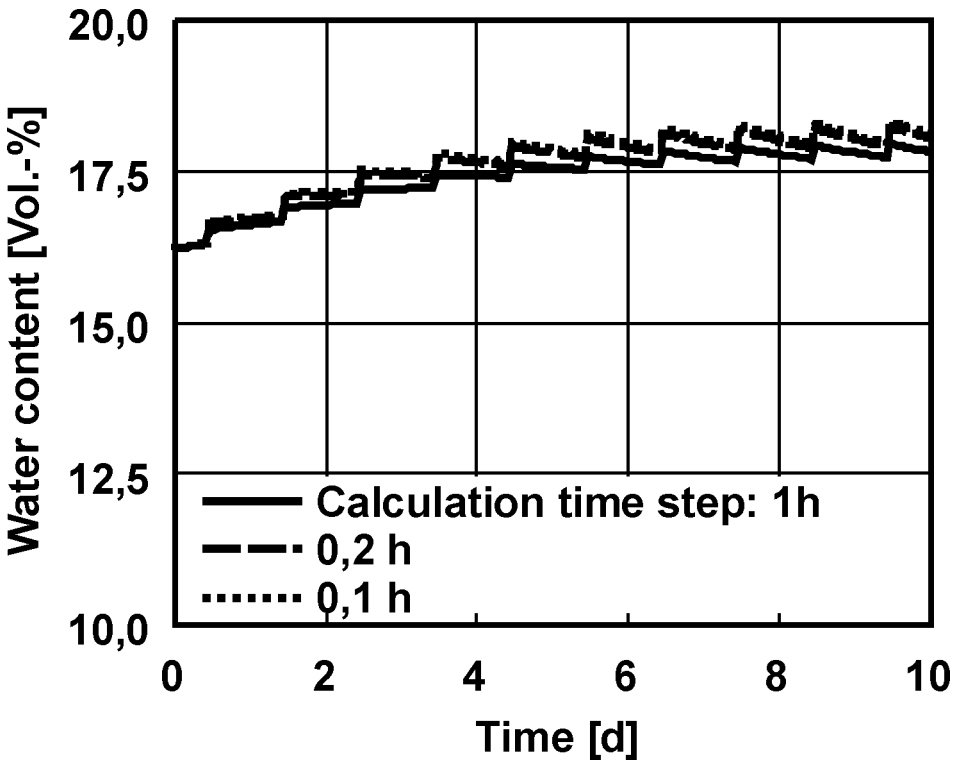


Fig. 53 Time course of the moisture content in the spore in dependence on various calculation time steps.

Data applied:
boundary conditions (as in the test stand [37]):
relative humidity: 95 %
temperature: 18,5 °C
time of influence per day: 3 h
other time: 60 % relative humidity and 26.1 °C.

This figure shows the moisture contents inside the spore determined by the biohygrothermal calculations in the course of the sensitivity analysis, with variation of the calculation time step.

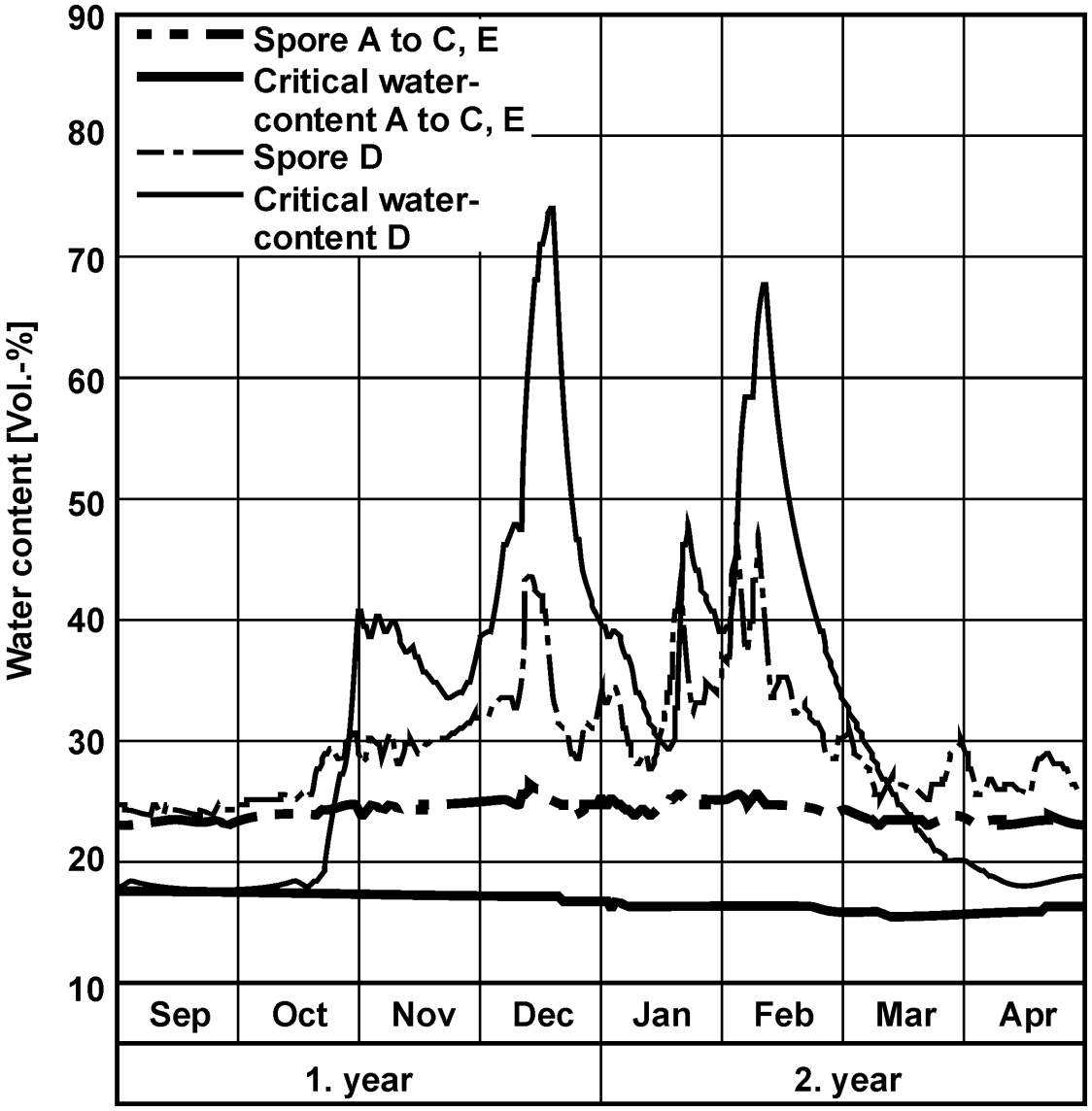


Fig. 54 Time courses of the moisture contents inside the spores.

Data applied:
exterior climate according to Figure 22
interior climate according to Figure 23
substrate category II according to Figure 34 bottom.

This figure shows the moisture contents of the spores existing on the wall surfaces of plaster calculated by the biohygrothermal model for the cases A to E from Table 20. The courses of the critical moisture content from which on germination takes place are represented by solid lines.

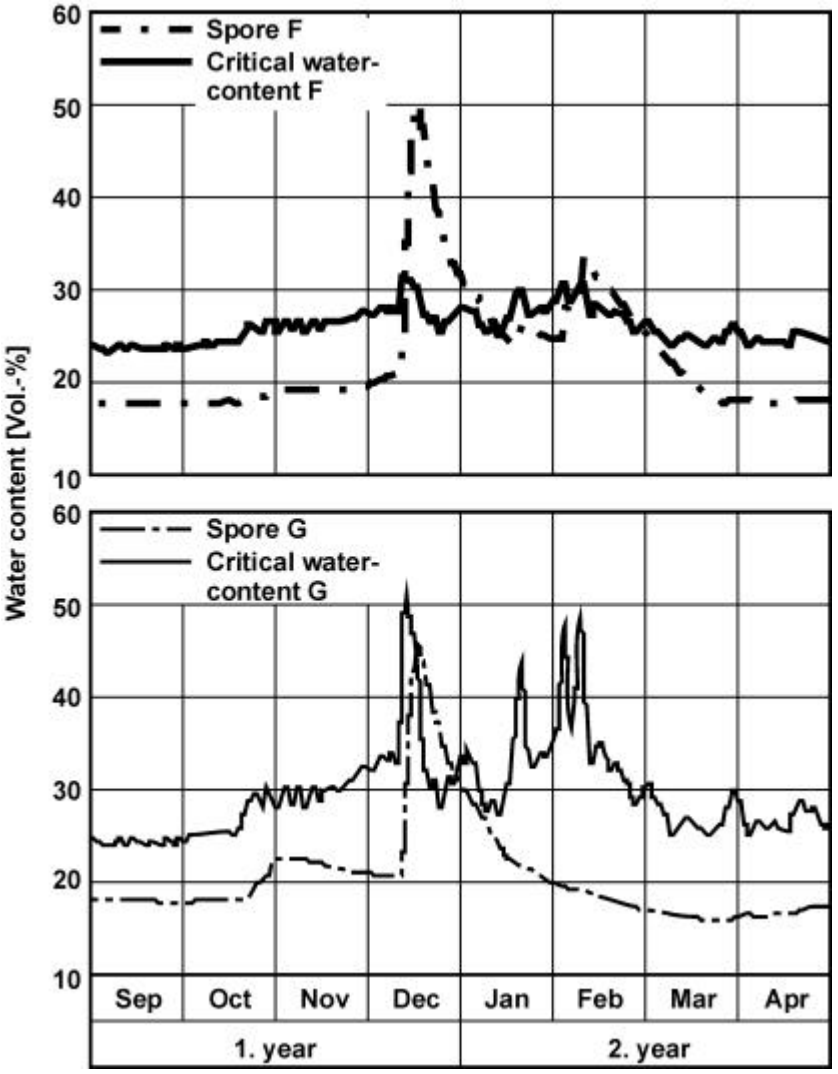


Fig. 55 Time courses of the moisture contents in the spores for the cases F (above) and G (below).

Data applied:
exterior climate according to Figure 22
interior climate accordig to Figure 23
substrate category II according to Figure 34 bottom.

This figure shows the moisture contents of the spores existing on the wall surfaces of plaster calculated by the biohygrothermal model for the cases F (above) and G (below) from Table 20. The courses of the critical moisture content from which on germination takes place are represented by solid lines.

Fig. 56 Temperature distribution at a window frame of plastic, calculated with a finite-difference program [130].

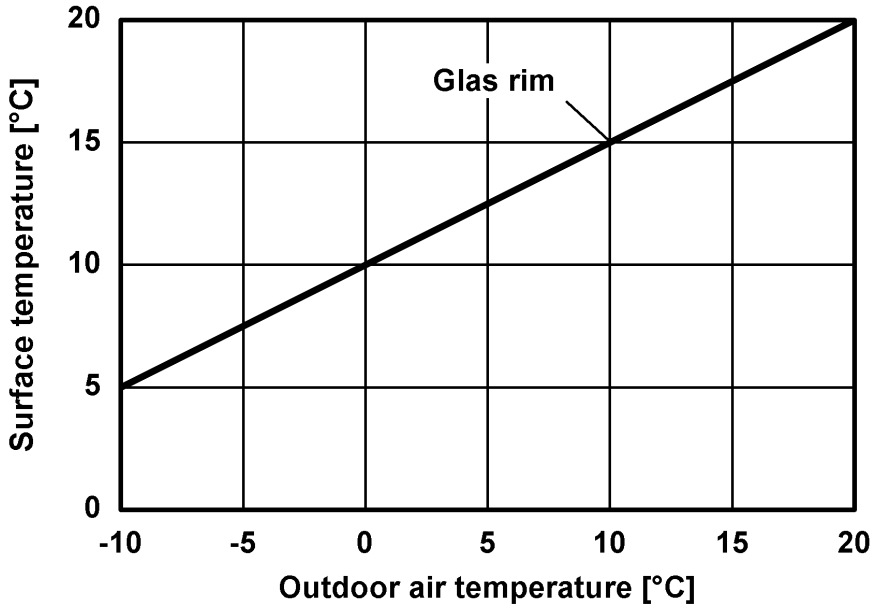


Fig. 57 Inner surface temperature at the glass edge in dependence on the outside air temperature.

Depending on the outside air temperature, the room side surface temperature at the glass edge bond is indicated in the stationary case for an indoor air temperature of 20 °C.

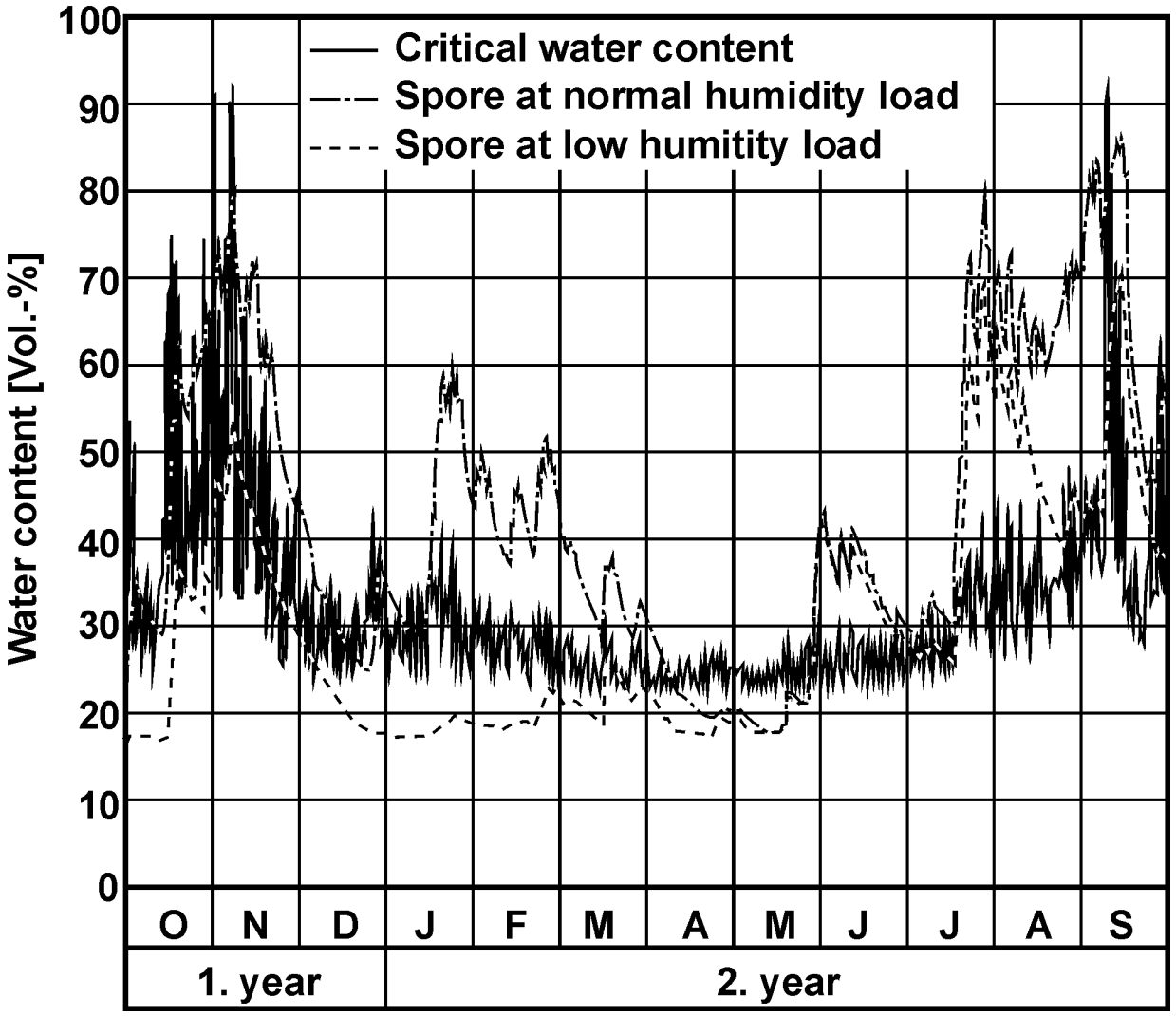


Fig. 58 Time courses of the moisture contents inside the spores in dependence on different indoor climatic boundary conditions.

Data applied:
exterior climate according to Figure 22
interior climate (normal and low moisture load) according to Figure 23
substrate category II according to Figure 34 bottom.

This figure shows the moisture contents inside the spores existing on the window frame that were determined by means of the connection between the surface temperature at the glass edge and the outside air temperature, shown in Figure 57, and by means of the biohygrothermal model. The course of the critical moisture content from which on germination takes place is represented as well.

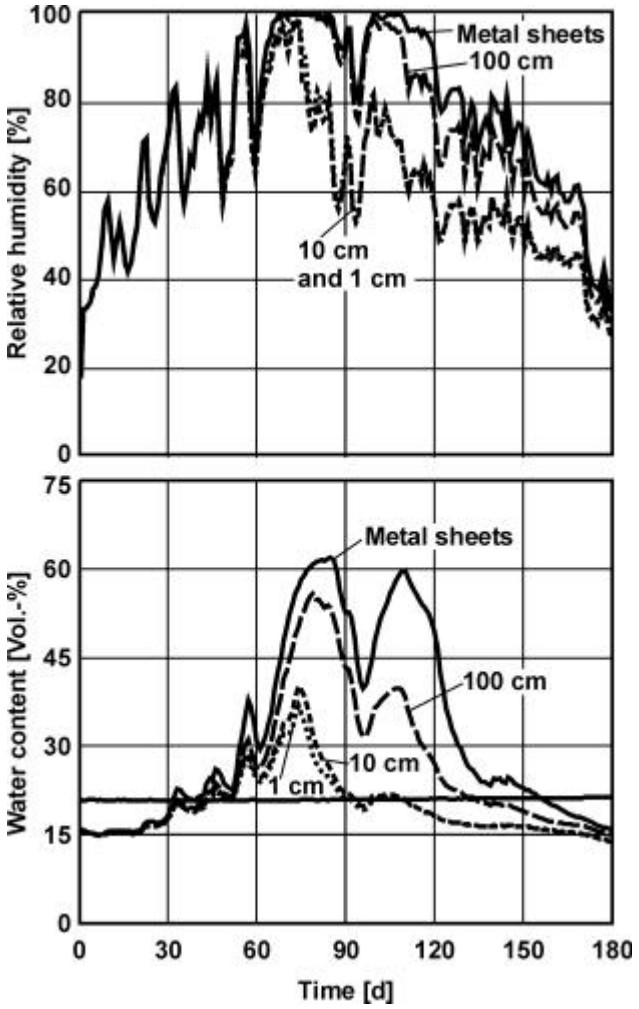


Fig. 59 Time courses of the relative humidities at the vapour seals of paper foil and plastic foil measured and calculated by the WUFI program respectively, for different assumptions of the outside vapour diffusion resistance of a gable roof (top illustration) as well as the moisture content in the spores existing on the vapour seals (bottom illustration).

Data applied:
exterior climate according to Figure 22
interior climate (normal moisture load) according to Figure 23
substrate category I for paper foil according to Figure 34 bottom
substrate category II for plastic foil according to Figure 34 at the top
outside vapour diffusion resistance: 1 cm, 10 cm, 100 cm, nearly infinite (varies).

The course of the critical moisture content from which on germination takes place is marked by the nearly horizontal line.

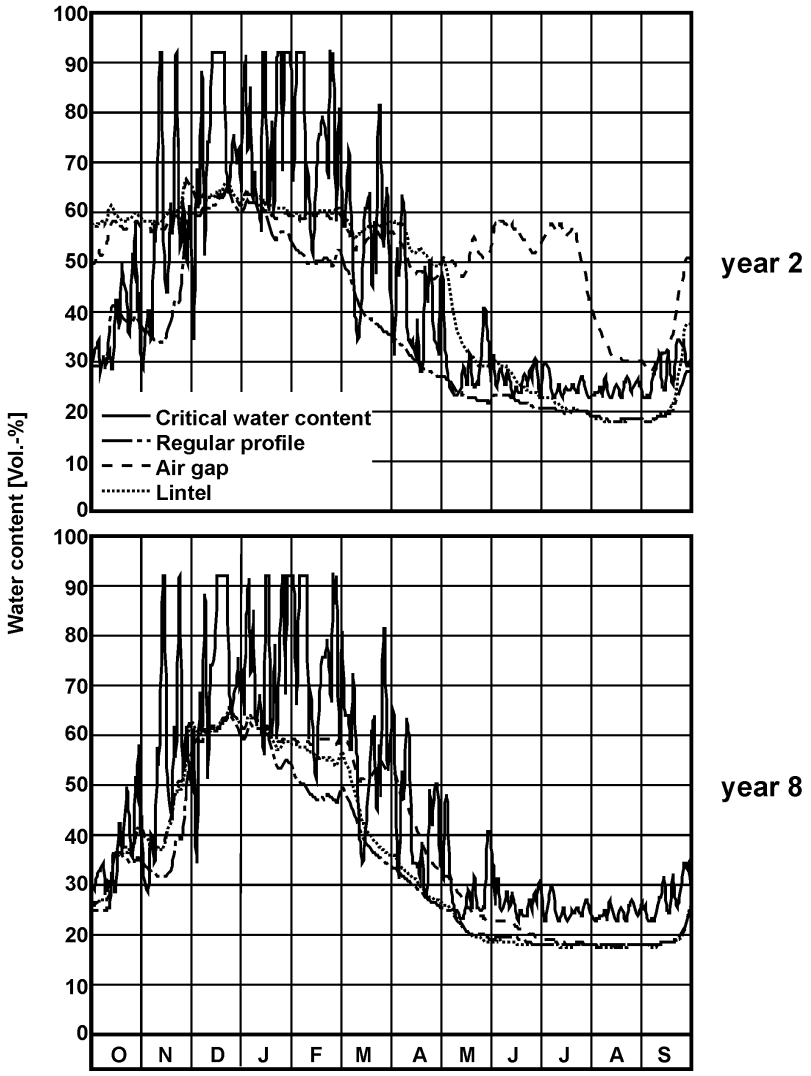


Fig. 60 Calculated time courses of the spore moisture content at various positions of the exterior plaster of an external wall.

Above: 2nd test year, Below: 8th test year.

Applied data and boundary conditions:
climate data: according to data record [53]
wall structure: ETICS on concrete as wall material
Investigated positions:
- undisturbed area
- plate joint (ETICS)
- window lintel.

The course of the critical moisture content is shown as well; is applies to all wall positions and shows from which value on germination takes place.

Fig. 61 Vertical section through the construction of a hybrid heating system to be tested for mould fungus formation with the storage element wall according to [91].

Fig. 62 Distribution of the surface temperatures of the collector element shown in Figure 61 along the area of the outer (left-hand side) and inner (right-hand side) air duct marked in the vertical section, in dependence on the component height for different variants.

Standard: U-value of the glazing unit: 4 W/(m² K); wall thickness: 8 cm; 6 cm insulation
Variant 1: like standard; U-value of the glazing unit with heat protection glass: 2 W/(m² K); wall thickness: 36 cm
Variant 2: like standard; 12 cm insulation of the storage wall.

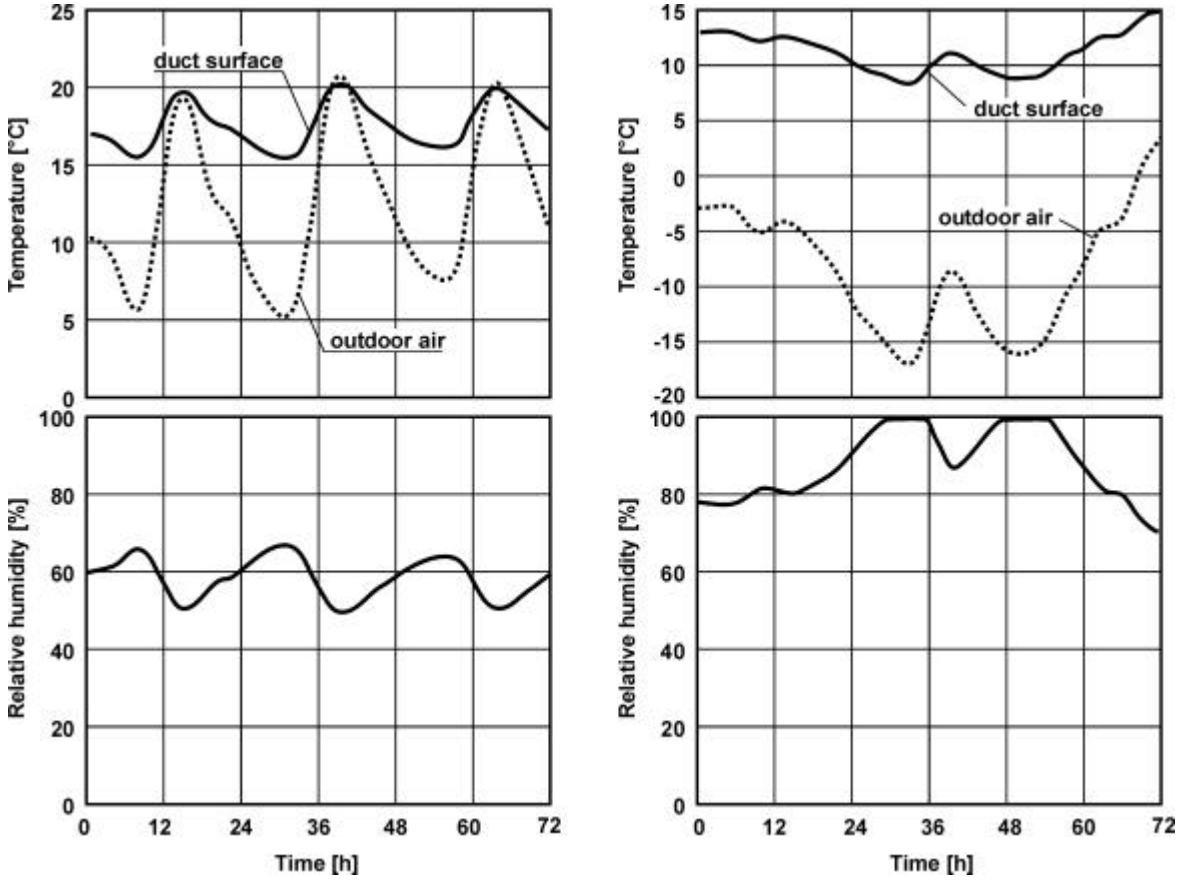


Fig. 63 Three-day course of the temperatures (upper illustrations) of the outside air and at the inner duct surface as well as of the relative humidity occurring there (bottom illustrations) for a typical autumn period (illustrations on the left) and a typical winter period (illustrations on the right) at assumed indoor air temperatures of 20 °C, a relative humidity of 50 % and a storage wall thickness of 8 cm.

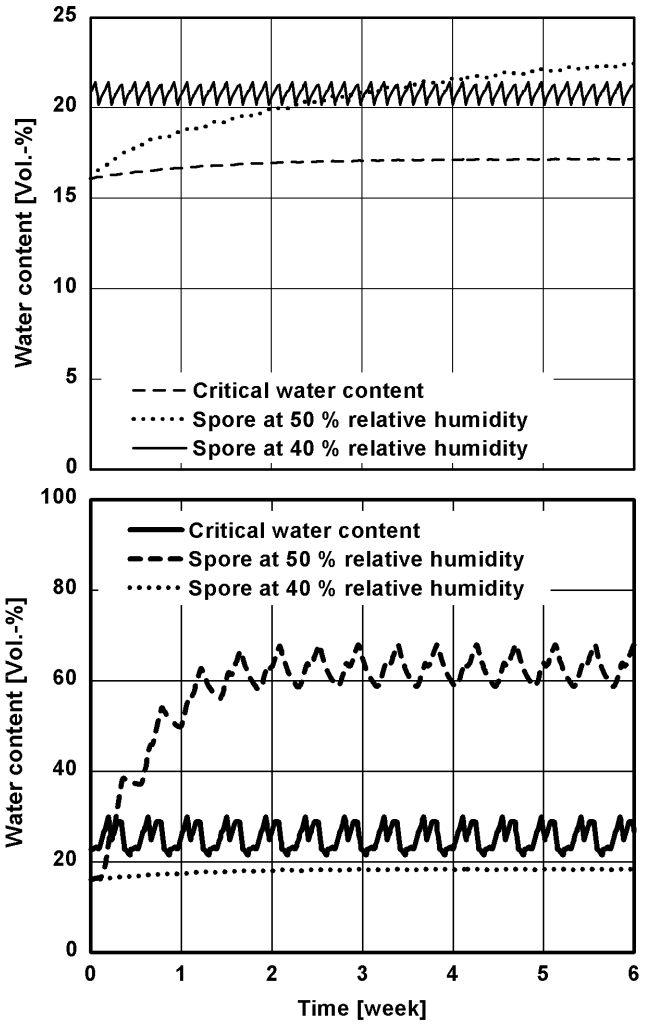


Fig. 64 Calculated time courses of the moisture content inside the spores existing on the inner duct surface for different climatic boundary conditions.

Above: Typical autumn period according to [53].

Below: Typical winter period according to [53].

Applied data and boundary conditions:
exterior climate according to Figure 63
indoor air humidity: 40 %, 50 %, 65 % (varies)
indoor air temperature: 20 °C.

The courses of the critical moisture content from which on germination takes place are marked with solid lines.

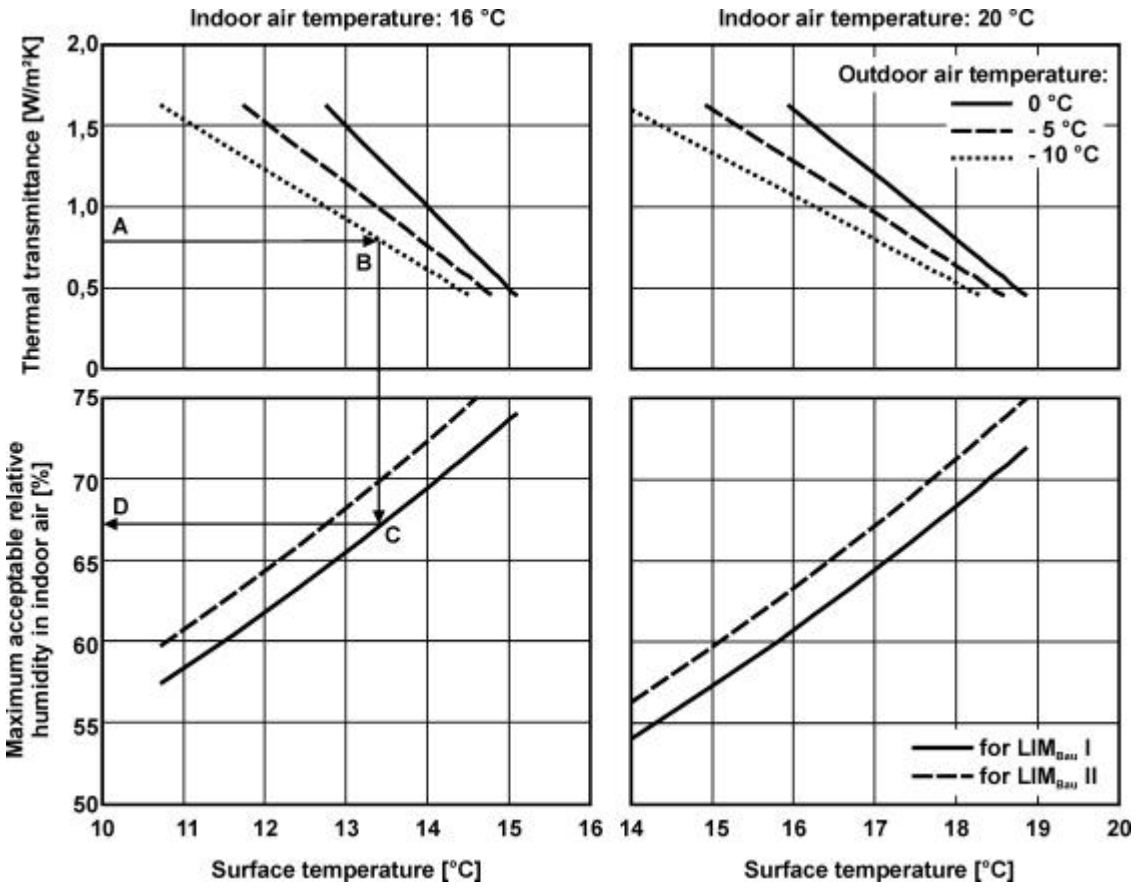


Fig. 65 Nomogram to determine the maximum admissible relative indoor air humidity where mould fungus formation occurs at an external wall when this humidity is exceeded, at an indoor air temperature of 16 °C (left) and 20 °C (right).

Upper illustrations:
Surface temperature in dependence on the heat transition coefficient for different outside air temperatures.

Lower illustrations:
Max. admissible relative indoor air humidity in dependence on the surface temperature for the substrate categories I and II.

Data applied:
LIM_{Mat} curves of substrate categories I and II.

How to use the nomogram:
A: heat transition coefficient is read off
B: surface temperature depending on the outside air temperature
C: relative humidity (D) in dependence on the surface temperature for the substrate categories I and II.

Curriculum Vitae

Biodata

Name:	Klaus Sedlbauer
Date of birth:	December 11, 1965 in Tegernsee
Parents:	Fritz Sedlbauer Hilde Sedlbauer, née Streidl
Marital status:	married since 1991 to Monika Sedlbauer, née Wölzmüller
Children:	Johanna and Benedikt Sedlbauer

Education

9/1972	–	6/1976	Primary school Holzkirchen
9/1976	–	6/1985	High school Miesbach
7/1985	–	9/1986	Military service
11/1986	–	3/1992	Studies of physics at the Ludwig-Maximilian University of Munich Degree: diploma

Business experience

3/1992	–	8/1994	Scientific assistant at the Fraunhofer Institute for Building Physics (IBP) in Holzkirchen and Stuttgart
9/1994	–	8/1997	Group manager at the IBP in Stuttgart
8/1997	–	12/1999	Group manager at the IBP in Holzkirchen
since		1/2000	Deputy head of the department at the IBP in Holzkirchen
since		10/2000	Deputy director of the institute (comm.) at the IBP in Holzkirchen
10/1999	–	9/2000	Part-time lecturer for the subject building physics at the University of Applied Sciences of Munich
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