University of Strathclyde

Energy Systems Research Unit
in collaboration with
Department of Bioscience/ Biotechnology

Development of a technique for the prediction/alleviation of conditions leading to mould growth in houses

J A Clarke, C M Johnstone, N J Kelly, R C McLean
Energy Systems Research Unit

J G Anderson, N J Rowan, J E Smith
Department of Bioscience and Biotechnology

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D McCarron, Project Officer

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Energy Systems Research Unit
Dept. of Bioscience and Biotechnology

Email esru@strath.ac.uk
Phone +44 141 552 4400 X3986
Fax +44 141 552 8513

Table of Contents

Executive Summary

This research study was funded by a Scottish Homes Research and Innovation Sponsorship Award. A successful case for support was made in October 1994 after proposals had been invited nationally by Scottish Homes under the general theme of *Improving the Physical Quality of Scottish Housing*. The project commenced in February 1995 and this final report was delivered in April 1996.

The project set out to review the literature on mould species, as they affect buildings located in cold, wet climates, and thereby develop a model of their growth characteristics. By placing this model within a building energy simulation program, ESP-r, the intention was to create a tool for the assessment of the mould alleviation potential of building design and operational changes.

From an extensive literature review, six mould species were selected on the basis of their known prevalence in UK houses and their moisture requirement characteristics. This mould set, namely, *Stachybotrys atra, Ulocladium consortiale, Cladosporium sphaerospermum, Penicillium chrysogenum, Aspergillus versicolor* and *Aspergillus repens* comprise mould representatives ranging from very hydrophilic (wet requiring) types, through intermediate types to very xerophylic (dry tolerating) types. From an analysis of best published data, the growth requirements of the six moulds, as influenced by temperature, moisture levels and to a lesser extent substrate type, were used to develop a model of mould growth on construction materials. This model was incorporated within the ESP-r building simulation system. ESP-r's algorithm for moisture flow within porous constructions was then customised to enable predictions of the times required for establishing particular surface temperatures and relative humidities, the principal determinants of mould growth, thereby facilitating predictions of the likelihood of mould growth on susceptible surfaces.

The mould prediction system can be used in several ways: to predict the growth of a particular named species of mould (species for which data is held - currently six); to predict the growth of certain groups of moulds, which have moisture requirements falling within defined ranges; and to predict, for moulds in general, surface conditions which will either promote or prevent the occurrence of any mould growth.

The modelling data incorporated so far, which reflects the level of current knowledge, is best able to predict mould growth under steady state conditions. The predictive system has, however, been extended to a limited extent, based on expert opinion formulated using a structured approach, to anticipate mould growth behaviour under transient conditions. Further studies are required to generate key experimental data on mould growth behaviour in response to the fluctuations in temperature and moisture conditions as typically found on the internal surfaces of problematic house types in the UK. This extension of the mould growth database would considerably improve the integration of biological and physical parameters in the ESP-r system and consequently enhance its predictive capabilities.

Although not yet optimised, the system currently represents an advanced predictive tool. To test the system, a mould infested house in Edinburgh was analysed for surface relative humidity and temperature changes at the site of mould growth and for types of moulds present and their growth characteristics. The study found good agreement between predictions and monitored data.

This report describes the project's outcome in terms of:

- the epidemiological background describing the impact of indoor moulds on health;
- the findings from an extensive literature review;
- the growth characteristics of the six prevalent mould species;
- the form, validity and applicability of the extended ESP-r system;
- and the required future work.

The outcome of the project, which was undertaken as a joint engineering and bioscience study, is new interdisciplinary knowledge - in the form of mould growth characteristics integrated with engineering concepts - and a state-of-the-art prediction program which can be applied to existing and new buildings in order to appraise potential engineering solutions to mould alleviation.

Finally, it is recommended that Scottish Homes explore ways by which the new mould-risk assessment tool can be made available to professionals involved with the design, management and refurbishment of Scottish homes.

1. Project Background

1.1 The Context

Dampness and mould growth are recognised as major problems affecting a significant proportion of houses in the UK and certain other countries. Approximately 2.5 million UK residences (250,000 in Scotland) are affected, with well documented cases for Europe and North America (Dales et al 1991a,b, International Workshop on Health 1992, Hendry and Cole 1993). Singh (1995) has estimated the cost of repairing the damage caused by timber decay in the UK housing stock to be approximately £400M per annum.

Apart from aesthetic considerations there is now considerable epidemiological evidence to support the view that mouldy housing has a detrimental effect on the physical and mental health of children and adults residing in such environments (Martin et al 1987, Platt et al l989, Lewis et al l989, Flannigan et al 1991, Dales et al 1991a,b, Hendry and Cole 1993, Paton 1993). This is a cause for concern, especially since many individuals spend up to 90% of their day indoors (Ott 1988).

High levels of airborne spores may occur due to growth of fungi on walls and furnishings in addition to other internal/ external sources. Data from the 1991 Scottish housing condition survey (Scottish Homes 1993) indicate that around 12.3% of Scottish houses are affected, with inadequate heating, insulation and ventilation cited as the principal causal factors.

Respiratory and/or allergenic symptoms, principally in children, have been diagnosed, particularly in atopic individuals (Burr et al 1988, Hunter et al 1988, Strachan 1988). A range of other symptoms, including nausea and vomiting, breathlessness, backache, fainting and nervousness have been reported by adults (Platt et al 1989, Morris et al 1989). While the precise mechanisms for these symptoms are not clearly understood, toxic fungal metabolites, particularly mycotoxins and possibly volatile organic compounds produced by moulds are increasingly being implicated. Recent research in Canada (Miller 1994) has drawn attention to the synergistic effects between toxin-producing fungi and other biological contaminants (e.g. dust mites and endotoxins), as well as inorganic contaminants such as ozone and nitrogen oxide, as effectors of respiratory health.

Based on an examination of the incidence of moulds within Scottish dwellings, and an epidemiological assessment of the inhabitants (Lewis et al 1989, Platt et al 1989), it was concluded that there exists a significant correlation between the incidence of mould spores and ill-health. Subsequent research (Smith et al 1992) demonstrated the potential toxicity of many of the collected fungal species to normal human fibroblast lung cells in *in vitro* culture. The genus *Penicillium*, one of most prevalent fungal groups found in damp Scottish homes, accounted for the majority of the cytotoxic strains identified. A significant finding was that at least 37% of the isolated fungal spores were associated with mycotoxins and that this represents a substantial risk factor for the occupants, particularly children and house-bound adults. The elimination or reduction of the conditions for fungal and mycotoxin production within the home should therefore be a priority: a conclusion which is in line with the international consensus that extensive fungal growth within the indoor environment is not acceptable from a medical or hygienic point of view.

1.2 The Need

The key question is how best to alleviate the problem. While the use of biocidal materials on walls (Hunter and Bravery 1989) and carpets (Gettings et al 1990) may be appropriate in some circumstances, it is generally agreed that removal of the conditions which promote mould growth, principally dampness, is the preferred strategy.

While resources are being directed to improve the housing stock, and will undoubtedly limit condensation and mould growth, there remains an inadequate understanding of how the interaction of building materials with their environments can create micro-climates which promote the initiation and spread of moulds. More accurate predictions of mould growth is possible using available biological and engineering information but only if this can be synthesised in a multidisciplinary approach. The main objective of this study was therefore to assess the feasibility of producing a tool for the prediction of dampness and mould growth in buildings.

1.3 Engineering Aspects

All too often the failings associated with a building's construction or environmental systems do not appear until post occupancy. In many cases these failings have had a dramatic impact on the building's life expectancy. One approach to the problem is to facilitate rigorous performance appraisals prior to construction. To enable this, there has been a significant worldwide effort to develop computer tools capable of assessing the dynamic energy and environmental performance of existing and new buildings. The International Energy Agency, for example, has undertaken two major research programmes - *Condensation and Energy* (Hens and Senave 1991) and *Heat, Air and Moisture Transport* (Hens and Kumaran 1994) both of which have resulted in algorithms for the prediction of localised environments within buildings.

At the start of the current project, these and other related theories had been incorporated within the ESP-r system for building energy/environmental simulation (Clarke 1985). ESP-r is used extensively throughout Europe (Wouters 1993) and has been the subject of several multi-national validation trials (Jensen 1993). Within this project, ESP-r was extended in terms of a) the customisation and experimental testing of its moisture flow algorithm, b) the addition of mould growth knowledge and c) the development of a mould risk assessment facility.

This new version of ESP-r can be used to determine:

1. the likelihood of mould occurrence for a given case;
2. rank ordered measures for alleviation of mould problems;
3. the applicability of a given solution to other cases.

1.3.1 The ESP-r System

The ESP-r system is capable of modelling the heat, power and fluid flows within combined building and plant systems subjected to control actions. As shown in Figure 1, the package comprises a number of interrelating program modules addressing project management, simulation, results analysis, database management and report generation.

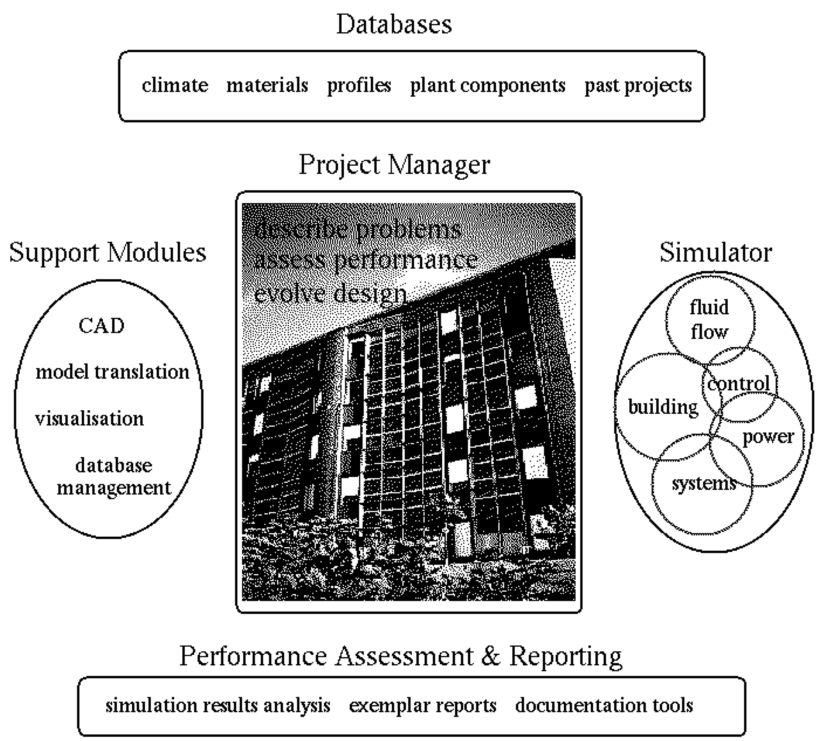

Figure 1: The ESP-r system.

One or more spaces within a building are defined in terms of geometry, construction and usage profiles. These spaces are then inter-connected to form a building, in whole or in part, and, optionally, the leakage distribution is defined to enable air flow simulation. The plant network is then defined by connecting individual components. Finally, the multi-space building and multi-component plant are connected and subjected to simulation processing against user-defined control. The entire data preparation exercise is achieved interactively, and with the aid of pre-existing databases which contain standard constructions, event profiles and plant components. The process of problem definition, simulation and analysis is coordinated by a central Project Manager which supports the importing/exporting of building geometry from/ to CAD packages and other specialised simulation environments for lighting simulation, etc.

ESP-r is equally applicable to existing buildings and new designs, with functionality which allows users to answer questions such as:

- What are the energy demands, when do they occur and what are the principal causal factors?
- What will be the effect on energy and comfort of design changes such as increased insulation, glazing replacement, draught sealing or heating system/ control upgrading?
- How does comfort and air quality vary throughout the building?
- What benefits will result from the incorporation of passive solar features such as sunspaces?
- What is the optimum arrangement of constructional elements to minimise the possibility of condensation and (because of the developments within this project) mould growth?

and so on. This allows the user to understand better the interrelation between design and performance parameters, to then identify potential problem areas, and so implement and test appropriate building, plant and/or control modifications. The design which results is more energy conscious with better comfort levels and air quality throughout.

1.4 Objectives and Project Method

The project - an interdisciplinary engineering and bioscience study - set out to research and utilise existing information on the types of moulds found in damp houses. The aim was to establish mould growth characteristics and to incorporate these within the ESP-r system. ESP-r was then applied to a Scottish Homes' house with known mould infestation to verify the model and demonstrate its applicability in relation to the types of problems confronting Scottish Homes. In this way a state-of-the-art analysis tool would be created and its use to appraise engineering solutions to mould alleviation demonstrated.

The specific project objectives were to:

1. Identify and quantify the moulds which are problematic as a result of the Scottish climate and housing types.
2. Develop a model of the multiple-parameter process which gives rise to micro-climates which encourage mould infestation and regeneration.
3. Incorporate the developed model within the existing ESP-r system and prove robustness by comparisons with data obtained from a mould infested house.
4. Demonstrate the application of ESP-r to assess engineering, as opposed to biological, solutions.

From previous studies on the mould flora of UK houses (Hunter et al 1988, Flannigan and Hunter 1988, Lewis et al 1989), it is known that the predominant mould genera are *Penicillium, Cladosporium, Aspergillus* and *Sistotrema*, with the first three genera particularly important because of their toxigenic potential. The ability of these moulds to utilise nitrogen-poor substrates, and survive at relatively low moisture levels, are features which contribute to their success in colonising the internal surfaces of domestic dwellings. Moreover, their ability to produce aerial spores allows their rampant spread.

Although a large literature exists on the general growth requirements of moulds, critical information on the key parameters which affect mould growth at internal building surfaces has only recently become available. Studies by the UK Building Research Establishment (Hunter and Bravery 1989, Grant et al 1989) and at other research centres in Europe, the USA and Canada, have determined the moisture requirements of some predominant moulds. Such studies have involved laboratory investigations of mould growth under varying conditions of temperature and surface moisture when applied to a variety of building materials, particularly gypsum-based finishes and carpets (the latter being a source of a wide range of fungal substrates derived from human, plant and animal sources).

Much information is therefore available on the nutritional and environmental requirements for the growth of a limited number of moulds. The study method was to research this existing information with the intention of developing a mathematical model of the limiting conditions for mould growth for the different principal species. This model would then be incorporated within ESP-r in order to predict local micro-climates on the basis of the various thermodynamic interactions over time. In this way, the essentially steady-state biological data could be placed in a dynamic context and the risk of mould occurrence determined for operating regimes likely to occur in practice.

2. Project Outcome

Figure 2 summarises the project’s structure and deliverables.

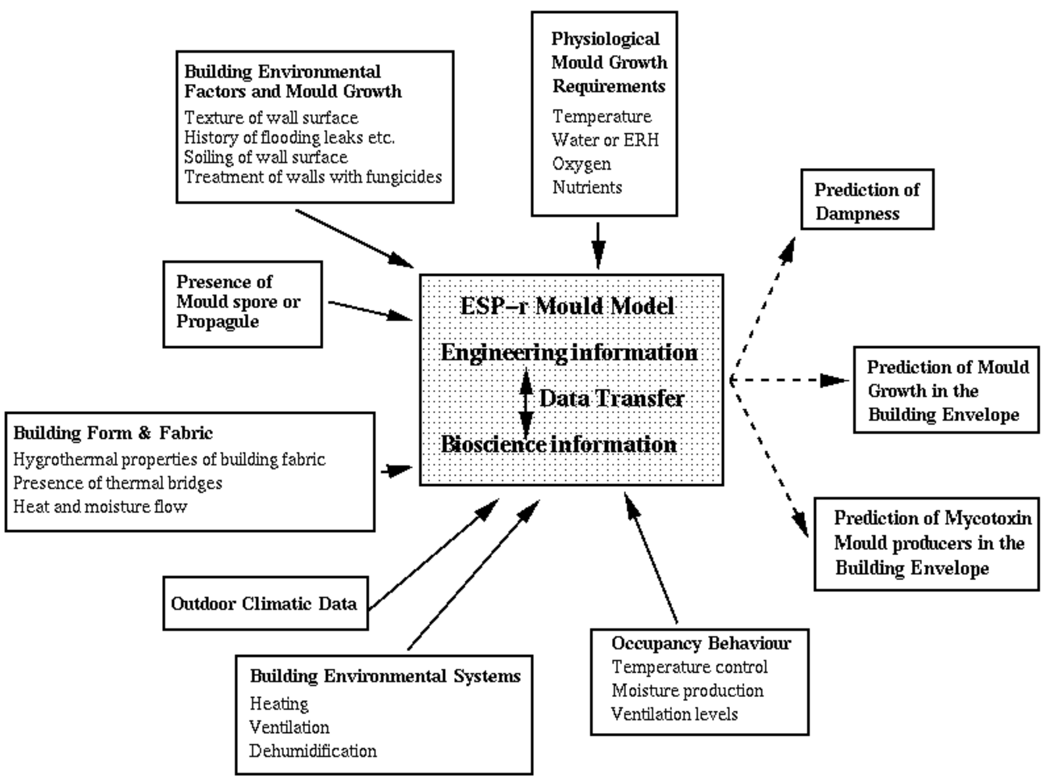

Figure 2: Project structure and deliverables.

The project's deliverables include:

1. A bibliography of relevant publications on mould growth (see Section 2.1 and Appendix 1).
2. A synthesis of these publications in relation to the cause, effect and alleviation of indoor moulds (see Section 2.2 and Appendix 2).
3. The identification of the principal mould types and the development of growth limit curves for each type (see Section 2.3).
4. The ESP-r system, extended to include a database of mould types and a growth risk assessment facility (see Section 2.4).
5. Application of ESP-r to a mould infested house to test the mould model and demonstrate the system's applicability in relation to the appraisal of engineering approaches to alleviation (see Section 2.5).

2.1 Compiled Bibliography

In the course of the project an extensive literature review has been conducted and a substantial bibliography compiled. This bibliography is given in Appendix 1.

2.2 Literature Review

The results from the literature review are given in Appendix 2. The outcome is the identification of the principal moulds affecting Scottish houses and, for each mould, the elaboration of growth limit curves, relating local surface relative humidity and temperature, below which the mould will not sustain growth.

2.3 Prevalent Representative Moulds

As detailed in Appendix 2, six main mould species have been selected and their limiting conditions for growth identified. The species are *Aspergillus repens*, *Aspergillus versicolor, Penicillium chrysogenum, Cladosporium sphaerospermum, Ulocladium consortiale* and *Stachybotrys atra*. These moulds, the majority of which are among the most common within Scottish buildings, have been selected to represent species with differing requirements for moisture (relative humidity levels). For example, *Aspergillus repens* was chosen as an example of a xerophilic mould (i.e. one that grows at relatively low moisture levels), requiring around 75% RH to grow whereas, at the other extreme, *Stachybotrys atra* (a wet loving fungus) requires a RH in excess of 97%. The other species chosen for incorporation into the model fall into relative humidity growth zones between these two extremes. Consequently the model, while based on the growth characteristics of six moulds, should be viewed as representing the behaviour of different moisture requiring physiological groups of moulds and as such can be used for predicting the growth (or non growth) of many other species. The moulds selected for modelling, with the exception of *Aspergillus repens* are known producers of mycotoxins. Figure 3 summarises the growth limits for each mould group.

These curves (or isopleths) define the minimum combination of RH and temperatures for which mould growth will occur. Below these limits, growth is not sustainable. Two points are important to note:

1. These curves correspond to steady state conditions and hence the need exists for a mapping to the case of transient conditions as occur in practice. This is the function of the ESP-r encapsulated system.

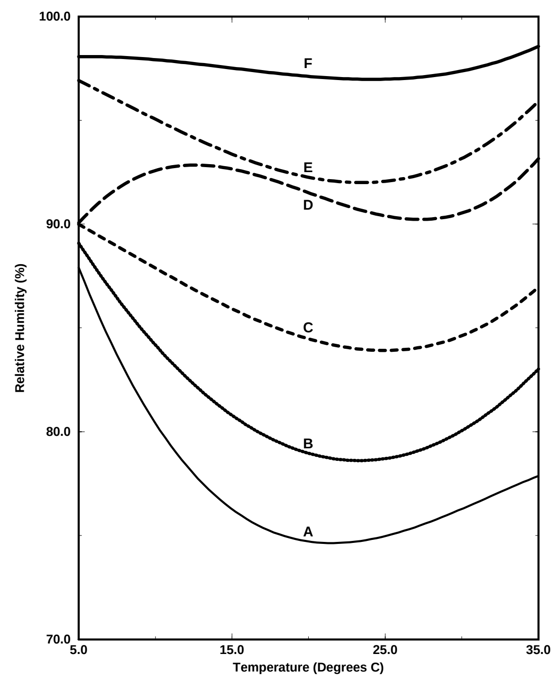

Figure 3: Limiting growth curves for six representative mould species.

A - highly xerophilic (dry loving)
B - xerophilic
C - moderately xerophilic
D - moderately Hydrophilic
E - hydrophilic
F - highly Hydorphilic (wet loving)

2. Moulds corresponding to higher level growth curves may initiate growth because of the respiratory-related moisture release of already established moulds corresponding to lower growth curves. This phenomenon - local surface relative humidity elevation - must be included within any mould prediction algorithm.

2.4 The ESP-r Mould Program

A mould growth prediction facility has been added to the ESP-r system. This comprises three components: a database of moulds holding descriptive details and growth limits, a mathematical model of the time evolution of local surface temperature and relative humidity (Nakhi 1995) and the means to relate these two components in terms of mould initiation behaviour.

2.4.1 The Moulds Database

The growth curves of Figure 3 are held within the ESP-r database in the form of coefficients defining the temperature/RH curves. In order to assess the risk of mould infestation, uncertainty bands are applied to these curves as shown in Figure 4 for the case of Penicillium chrysogenum. Within this figure, the ‘C’ line corresponds to the practical growth limit line of Figure 3 - i.e. to the case of standard building materials. The ‘C''’ line defines, for the same mould type, the limiting growth limit line for a highly nutritious substrate such as foodstuffs or laboratory culture media - i.e. the optimum growth condition. Finally, the 'C'' line defines the case of a building material where the nutritive status has been enhanced by adulteration with a carbon source. Based on these data, it is possible to determine the growth probability zones as indicated.

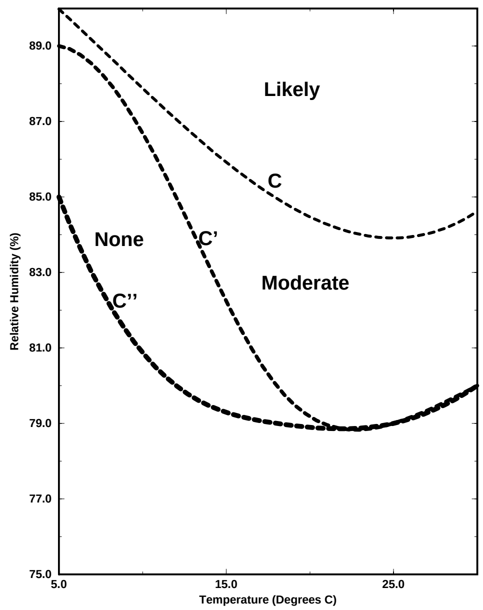

Figure 4: Risk assessment categories for Penicillium chrysogenum.

It should be appreciated that these risk categories are not based on experimentally derived data but on expert opinion interpreting the likely effect on the growth of the six modelled species as conditions move in incremental steps above and below the isopleth curves of Figure 3 which have been constructed from best available experimental data.

The model can be used to predict and analyse several aspects of the domestic mould growth problem as follows.

1. To predict the growth risk of a named mould species. Growth risk predictions can be made on any species (currently 6) for which a full data set has been entered into the model. This could be important with, for example, *Stachybotrys atra* which is a known harmful mycotoxin producer and which might require targeted control measures in the domestic environment.

2. To predict the growth risk from moulds falling within different moisture bands. Moulds selected for incorporation into the model were chosen on the basis of both prevalence and as representatives of differing moisture requiring categories of moulds. Thus, very hydrophilic (wet loving) moulds are represented by *Stachybotrys atra*; fairly hydrophilic moulds are represented by *Ulocladium* and *Cladosporium spp*; fairly xerophylic (tolerating dryish) conditions are represented by *Penicillium chrysogenum* and *Aspergillus versicolor*; and very xerophilic moulds are represented by *Aspergillus repens*. This risk prediction of a specific moisture requiring mould category could be useful with, for example, consideration of problems caused by the fairly xerophilic *Penicillium chrysogenum/Aspergillus versicolor* category, which occurs at very high frequencies on indoor surfaces of damp Scottish houses.

3. To predict conditions which will prevent any mould growth. As stated above, *Aspergillus repens* data have been incorporated into the model as a representative of the very xerophilic mould type. Although some minor refinement of these data may still be required, this sets the baseline level below which mould growth will not occur, thereby providing an ideal target for the built environment.

It is emphasised, however, that the above predictive functions are based on steady state conditions. To some extent theoretical predictions can be made, based on expert opinion, of mould growth behaviour under transient conditions. Good quality experimental data are urgently required to allow more accurate prediction of mould growth on the internal surfaces of houses in response to the localised temperature and humidity variations most characteristic of houses in the UK. This extension and refinement of the mould database would considerably improve the integration of biological and physical parameters in the ESP-s system and consequently greatly enhance its mould prediction capabilities.

2.4.2 Mould Risk Assessment

The ESP-r system, with its moisture flow and mould database extensions, is able to represent a building at some specified overall level of resolution, with an enhanced resolution at some surface(s) of concern, e.g. at a point where a known thermal bridge exists, where insulation levels are inadequate or where there exists a local moisture source. This allows the system to predict local surface temperature and RH profiles in the context of the overall environmental performance of the building. The theoretical basis of ESP-r, and its treatment of moisture flow in a manner which is fully integrated with the other heat and fluid transfer processes, is reported elsewhere (Clarke 1985, Nakhi 1995).

As shown in Figure 5, the predicted local surface conditions can be associated with the growth limit curves for selected mould species.

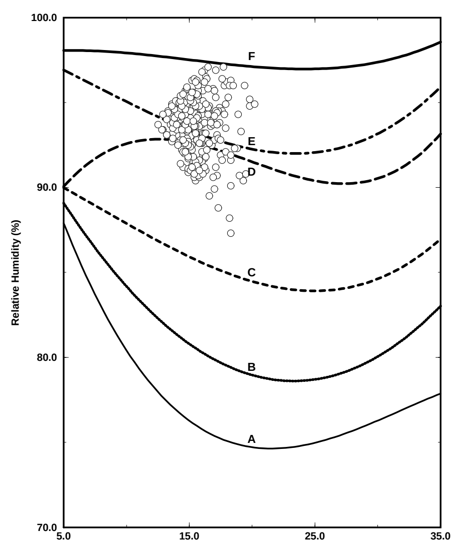

Figure 5: Predicted surface conditions superimposed on mould growth limit curves.

On the basis of the growth risk data (Figure 4), an assessment is automatically made of the length of time that conditions remain within each of the five growth categories. This, in turn, supports an assessment of the overall risk of mould growth under transient conditions. This assessment is, as has been previously stated, currently based expert opinion and requires future validation.

2.5 Model Validity and Applicability

In order to test the model it was considered appropriate to compare the mould prediction data, incorporated into the model from literature sources, with "real" data which could be obtained from a mould contaminated house in Scotland. A link was therefore established with another Scottish Homes' project underway at Napier University (MacGregor and Taylor 1996) where a house in Edinburgh known to exhibit mould growth (Figure 6) was being monitored.

Figure 6: Mould growth in the monitored house.

Samples were taken at the wall surface where mould growth had occurred. As is generally the case, mould infected areas usually contain various species of moulds which develop during the prolonged colonisation period. Different species can develop since each type can take advantage of suitable temperature and water activity levels which occur transiently at susceptible wall surfaces in affected houses. Thus more xerophilic types gain an advantage when moisture levels decrease and conversely more hydrophilic types can reactivate and regrow when moisture levels rise, for example during periods of condensation.

In order to characterise the mould flora of the affected surface both in terms of species composition and with regard to moisture requirements the following approach was adopted. A 2% malt extract agar (MEA) medium was used and a series of plates were prepared in which the RH value was varied within the range 67.8% to 98.9%. The RH values of the media were confirmed using an aw-West Messer (Lufft) Chamber. Areas of mould growth (Figure 6) were swabbed and the samples spread across the surface of the different RH value, 2% MEA plates. In addition, a series of RH adjusted 2% MEA contact plates were pressed against areas of confluent mould growth on the affected surface.

At the laboratory the contact plates were incubated at 25°C over a 120 day period, with the atmospheric RH adjusted to 98.9%, 94.5%, 88.5%, 81%, 78.5%, 71.2% and 67.8% using glycerol solutions. Incubation of the plates in controlled environments maintained the water activity of the original plates.

The mould species which developed at the different RH levels were identified by conventional microbiological techniques (Samson and van Reenen-Hoekstra l988) as follows. At the low RH values of 85.5% or less only the xerophylic species *Aspergillus versicolor* and *Eurotium herbariorum* developed. At RH values of 88.5% and above, additional mould which grew were *Penicillium spp., Aureobasidium pullulans, Cladosporium sphaerospermum* and *Alternaria alternata*. At RH values of 94.5% and above the previously mentioned species grew together with yeasts which appeared at these high RH values.

In addition to identification of the various mould isolated, the speed of mould development on the range of RH adjusted MEA media was also monitored (Table 2).

Days at 25°C	Relative Humidity (%)								
	98.9	94.5	88.5	85.5	81.0	78.5	74.5	71.2	67.8
0	-	-	-	-	-	-	-	-	-
2	+	-	-	-	-	-	-	-	-
7	+	+	-	-	-	-	-	-	-
16	+	+	+	-	-	-	-	-	-
20	+	+	+	+	-	-	-	-	-
58	+	+	+	+	+	-	-	-	-
97	+	+	+	+	+	+	-	-	-
120	+	+	+	+	+	+	-	-	-
- no mould growth + appearance of mould									

Table 2: Incubation period required for the appearance of mould on 2% MEA plates.

It took only 2 days for mould growth to appear on the 98.9% RH plates, 7 days for growth to appear at 94.5% RH, 16 days for growth at 88.5%, RH, 20 days for growth at 85.5% RH, 58 days for growth at 81% RH and 97 days for growth at 78.5% RH (the mean surface RH as measured on site). No mould development occurred at a RH value lower than 78.5% over the 120 day incubation period.

Figure 7 illustrates the ability of moulds isolated from the test house to grow at different water activity levels over the range 98.9 to 67.8% RH within 58 days at 25°C. It was concluded from this study that the types of moulds recovered and their requirements for specific RH values were consistent with the minimum growth requirements for the types of mould used in the model as identified in Figure 3.

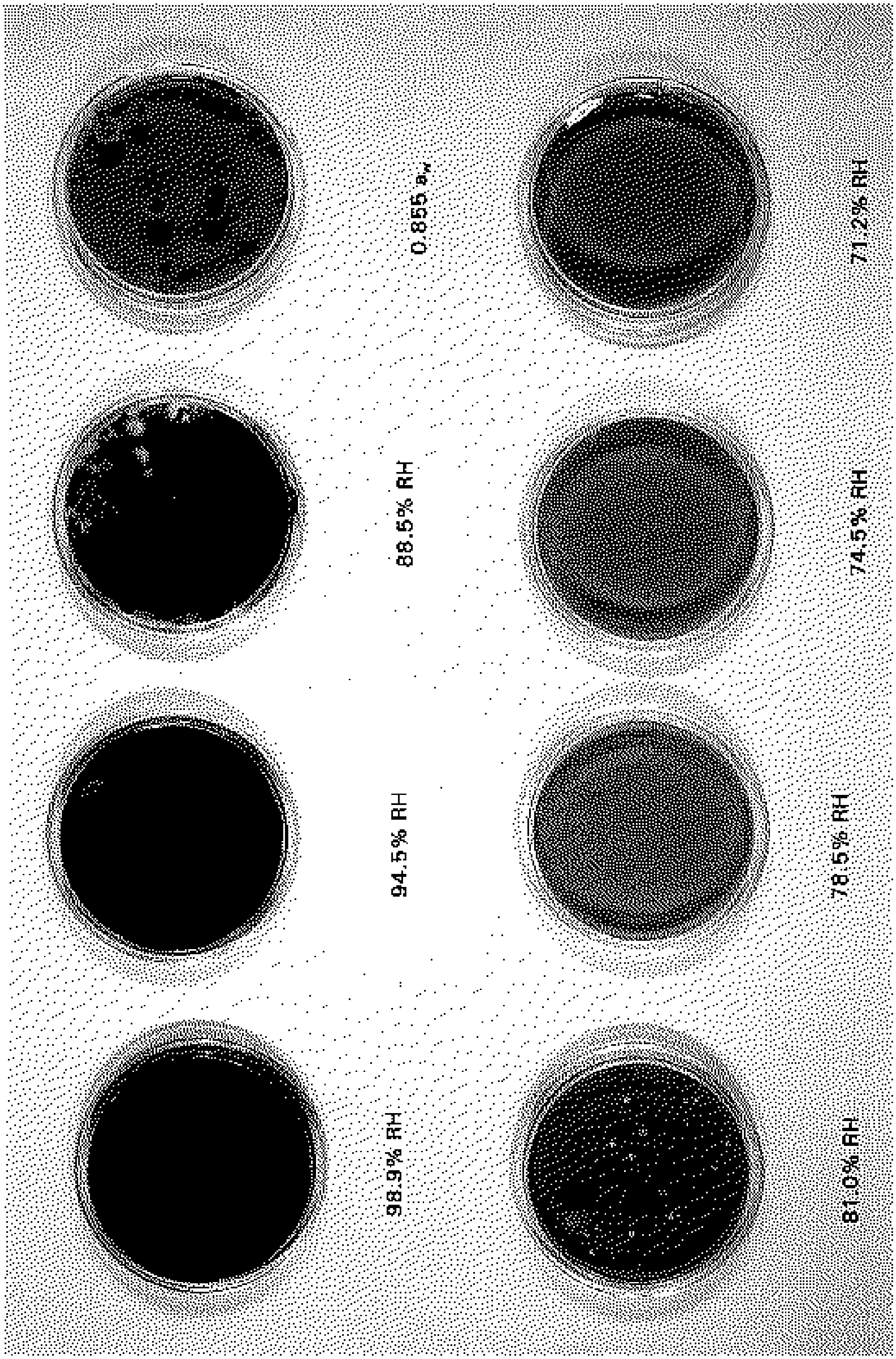

Figure 7: Moulds appearance at different RH values (after 58 days incubation at 25°C).

The Napier University team agreed to collect additional data from their house monitoring exercise to allow comparison with ESP-r predictions. Monitoring of surface relative humidity and temperature in the proximity of the mould was carried out over a one month period, with recordings taken at 1.5 hour intervals.

An ESP-r model of the test house was established (Kelly 1996) and the predictions compared with measurements. The house is a steel framed, three bedroom, semi-detached residence built to a 1940's pre-fabricated style. In places the steel frame results in a major thermal bridge, leading to condensation and mould growth. Insulation levels are generally low with excessive infiltration rates resulting from warped window frames. The building is located on an exposed housing estate.

Within the model, the lower floor comprises a living room, hall, kitchen, bathroom and a store, while the upper floor comprises three bedrooms and an upper hall. The loft space and collector are modelled as separate zones. In the north bedroom (where the monitoring equipment was located), the model is constructed to a resolution which enables the explicit tracking of air and vapour flow (Figure 8). Of particular interest in the simulation was the junction of the north wall and ceiling where mould growth had occurred.

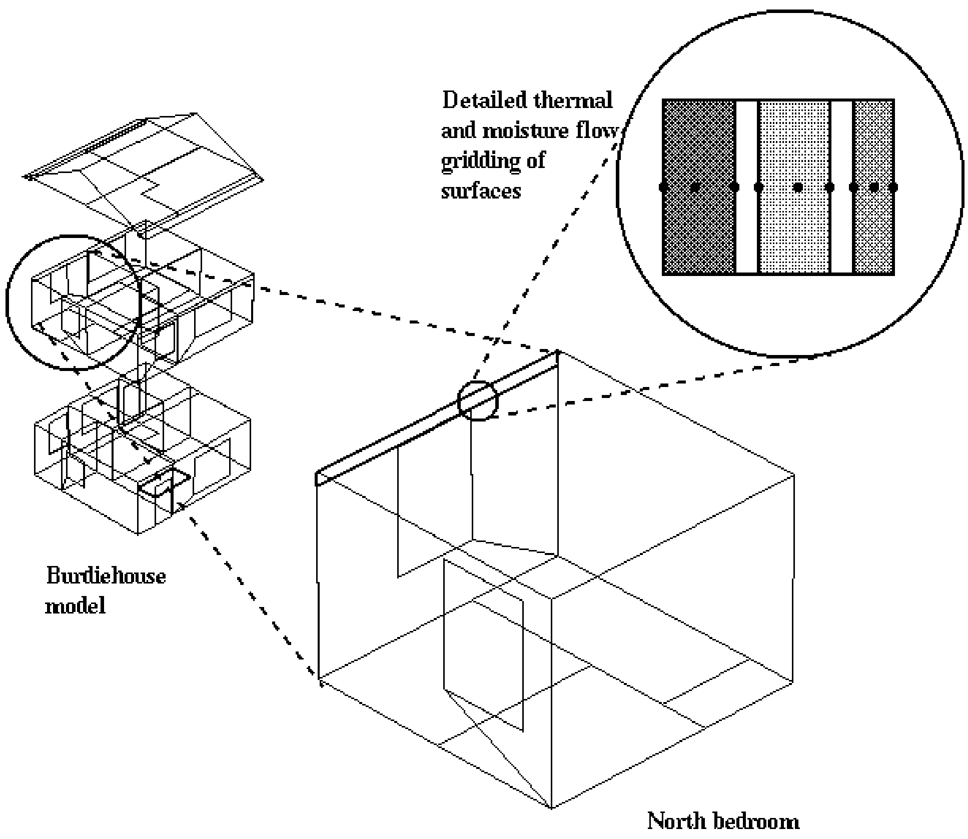

Figure 8: ESP-r model of the test house.

Simulations were performed based on climate data collected at the site over the period 10-16 March 1996. The results for the north bedroom are shown in Figure 9. As can be seen, the predictions show reasonable agreement with the monitored data. It should be noted that this comparison does not infer an attempt at ESP-r validation since several parameters were subject to high uncertainty: for example, the effect of occupants in relation to moisture generation and the hygroscopic properties of the building materials.

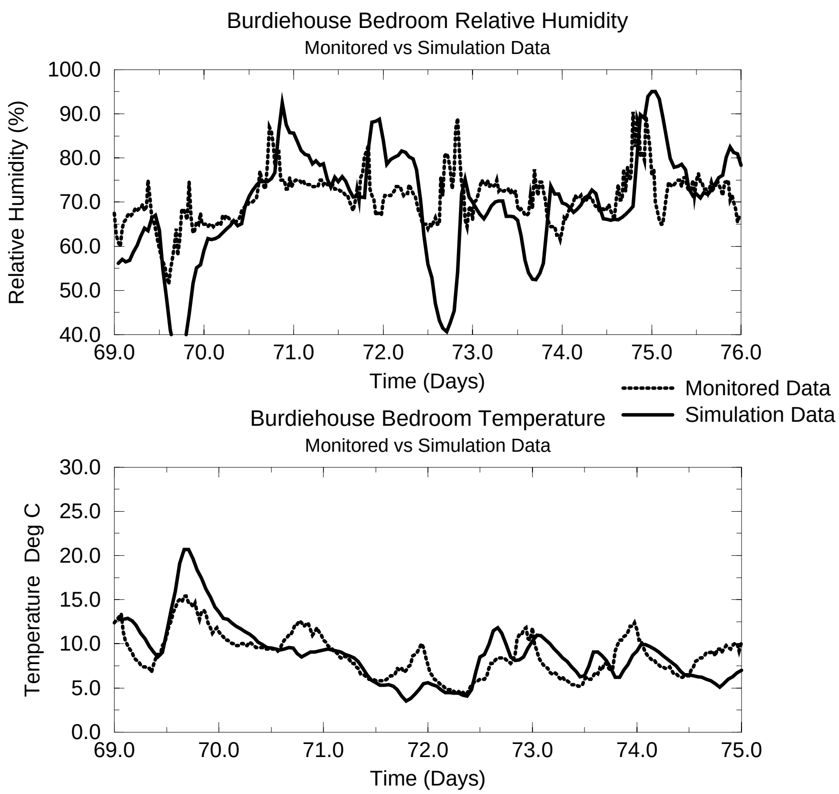

Figure 9: Predicted surface conditions compared with monitored data.

An assessment of mould alleviation measures requires an approach which would be based on:

1. Identification of successful techniques to eliminate problems.
2. Ranking successful techniques on a least cost, priority basis.

For any house, one or more of the following alleviation approaches could be applied and assessed in terms of energy, environmental conditions and cost benefit.

wall insulation upgrade
elimination of thermal bridge
moisture removal at source
improved ventilation schemes
modifications to heating systems
modified control strategies
alternative construction format, materials and surface finishes
user behaviour changes.

In this way ESP-r could be used to to assess whether proposed solutions to mould growth were able to be replicated across the country with similar success.

To demonstrate the applicability of the extended ESP-r system, a series of simulations were undertaken to assess the alleviation potential of increased heat input against improved insulation. The results are shown in Figure 10 for the house as is, and for cases corresponding to 200W continuous heating, 500W continuous heating and 500W continuous heating with improved insulation.

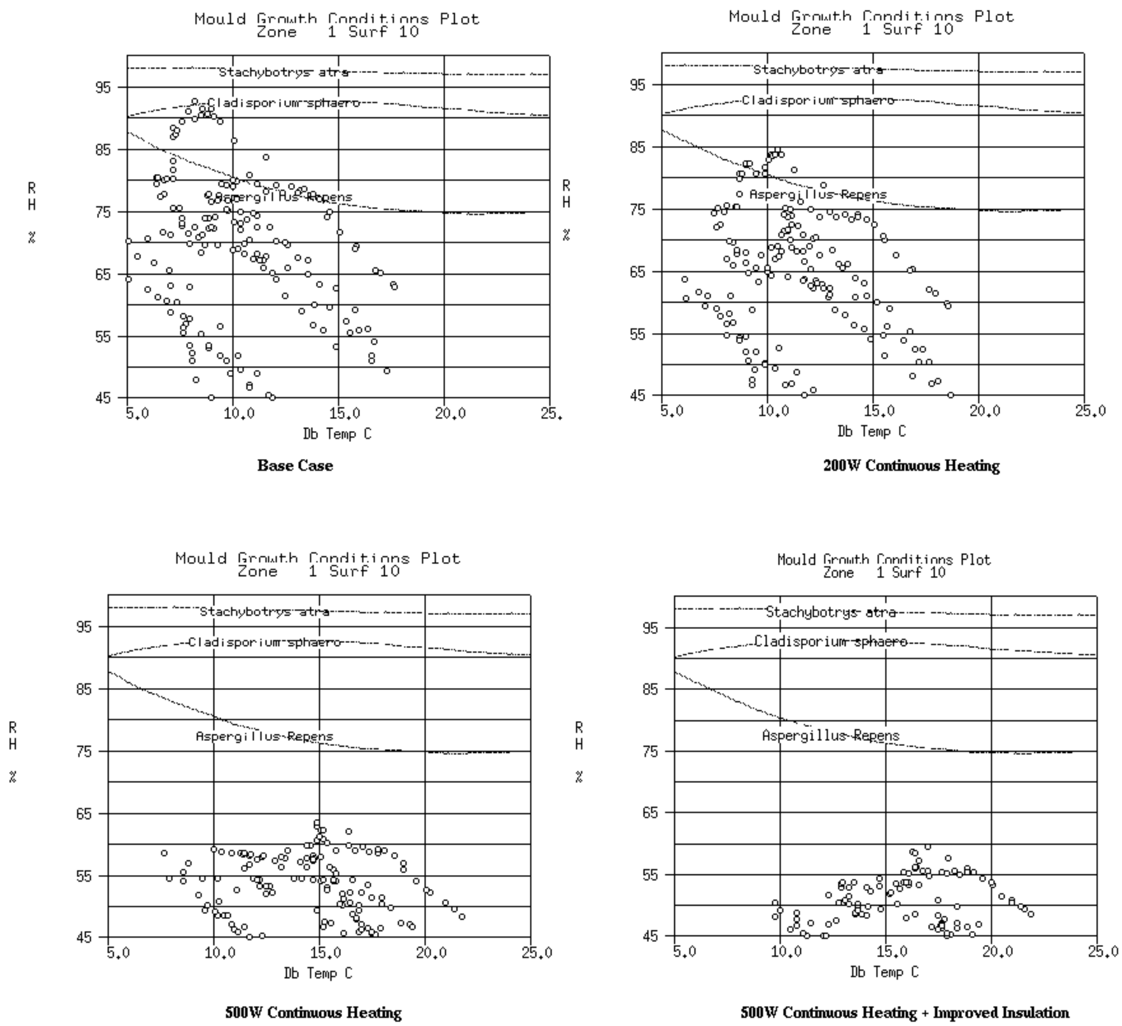

Figure 10: ESP-r predicted effect of mould alleviation strategies.

For the as is case, the environmental conditions are within the mould growth zone for a considerable period of time so that mould growth is deemed likely (in fact it has been observed on this particular surface within the house). The results for the other cases show that by systematically improving the building fabric and heating system, the wall surface conditions can be maintained at values removed from the optimum for mould growth.

3. Conclusions and Future Work

A mould growth algorithm has been successfully added to the ESP-r system for building performance simulation, thus bringing together engineering and bioscience aspects. The system has been applied to a house with known mould infestation and good agreement obtained between predictions and monitored states. The project has therefore built on previous work and evolved an integrated building performance assessment tool for use by Scottish Homes and others.

The next stage will be to explore ways in which this new tool can be used by practitioners concerned to eliminate mould problems at the design stage or through well conceived retrofits.

4. Acknowledgements

The project team are grateful to Scottish Homes for their sponsorship of the research described in this report and to Ker MacGregor and Alex Taylor of Napier University for access to their monitored data set relating to a mould invested house in Edinburgh.

Appendix 1: Project Bibliography

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Appendix 2: Literature Review Outcome

It is evident that mould growth on indoor building materials involves several parameters: the type of the mould, the physiological requirements for growth, and the localised surface conditions (especially in relation to temperature and available moisture). This section covers mould growth in relation to the physiological and biological conditions required for growth, the resulting biodeterioration of building materials, occupant health implications and possible remedial actions.

A2.1 Physiological and Biological Conditions

A building will incur fungal growth when conditions prevail which resemble the natural niche for which the fungus has evolved. While ecology is a study of the interrelationships between living organisms and their environments, building mycology deals with the study of fungi which have direct and indirect effects on the state of the building and the health of the occupants.

A2.1.1 Commonly Occurring Fungi

Fungi are divided into 2 groups: Eumycota (true walled fungi) and Myxomycotina (wall-less fungi); members of the former group are associated with the colonization of the built environment. The Eumycota group can be further subdivided into Zygomycotina, Ascomycotina, Basidiomycotina, Deuteromycotina and Mastigomycotina (water moulds). There are approximately 200 species within the Zygomycotina group and these possess the common traits of having a mycelial vegetative state, no septae and with asexual reproduction via non-motile spores formed in a sporangium, e.g. Mucor and Rhizopus. Moulds belonging to the Ascomycotina subgroup produce spores sexually in asci and asexually as conidia (which show great diversity in form and arrangement) or by oidia. There are currently more than 29,000 species residing in this group, with Peziza, Chaetomium and yeasts being the most common in buildings. Deuteromycotina is the second largest group of fungi, containing 17,000 species, with reproduction solely by conidia (i.e. there is no sexual state and most of the Deuteromycotina are conidial states of the Ascomycotina subgroup).

The majority of moulds found in buildings belong to the class Hypomycetes, e.g. *Cladosporium, Penicillium, Aspergillus, Trichoderma, Alternaria and Aureobasidium*. The Basidiomycotina group (commonly known as mushrooms) mostly degrade wood and timber in dwellings. These fungi produce the sexual basidiospores exogenously on basidia. Common indoor examples include *Serpula lacrymans (dry rot), Coniophora puteana (wet rot), Coniophora marnorata, Phellinus contiguous, Donkioporiae expansa, Pleurotus ostreatus, Asterostroma, Paillus panuoides and Poria* fungi, including *Amyloporia xantha, Poria placenta, Antrodia serialis and Antrodia sinusoa*. These filamentous fungi are achlorophyllous (i.e. they cannot photosynthesise their food), versatile saprophytic/heterotrophic spore bearing micro-organisms which feed osmotrophically (i.e. they absorb all their nutrients from the aqueous solution which surrounds them even when they are growing on a solid substrate).

Adan (1994) has demonstrated that fungal growth is a superficial surface phenomenon and, as such, mould development can occur if the fungal propagule is present on a wall surface and its specific growth requirements are met. Moulds will therefore grow on the surface of masonry, brickwork, concrete, rendering, tiles, paving, wood, plaster, wallpaper and paint. They are highly diverse and versatile organisms and are capable of adapting readily to different environments.

Indoor fungi normally exhibit four phases in their overall growth cycle: spore activation, germ tube production, vegetative mycelial outgrowth and, finally, asexual or sexual sporulation (Figure A2.1). As moulds propagate and survive through sporulation, the provision of a suitable growth environment at a wall surface may result in the germination of these dormant spores and the production of a germ tube. Germ tubes elongate to form long, thread like, tubular filaments called hyphae which grow over the substrate from which they extract nourishment.

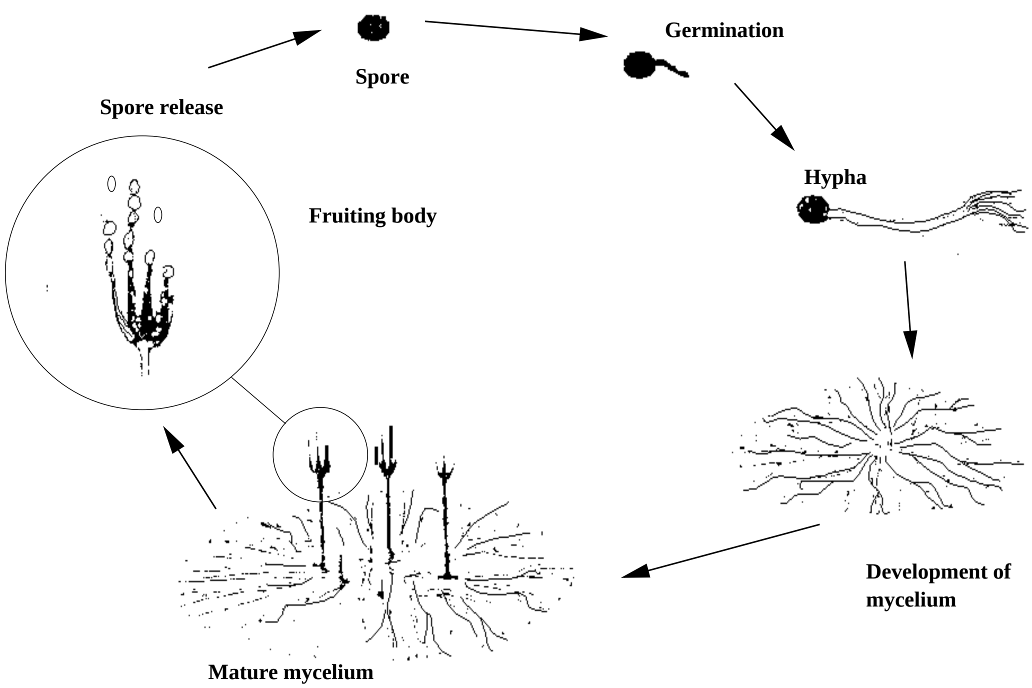

Figure A2.1: Life cycle of a mould fungus (Hans and Sneave 1991).

Microscopic hyphae may be sub-divided into septae (i.e. Ascomycotina, Deuteromycotina and/or Basidiomycotina) or aseptate (i.e. Phycomycetes). Hyphae are surrounded by a well defined cell wall made up of chitin, fungal cellulose and other complex organic molecules - this, in addition to osmotic or turgor pressure, provides the necessary structural integrity. Hyphae extend by apical growth and lateral branching to form a visible mycelium (which constitutes the thallus of a fungus). They may also aggregate to form rhizomorphs (mycelial cords or strands which transport water and nutrients to the growing tip). The thallus is differentiated into a vegetative part, which absorbs water and nutrients, and a reproductive part. Under conditions of nutrient depletion, or due to other changes in the immediate environment, the sections of the mycelium designated for propagation will sexually or asexually produce spores (depending on the mould type). These spores may be dispersed by wind, water or other specific mechanisms of release. Once germinated, and associated with a suitable growth environment, moulds grow, produce metabolites (e.g. mycotoxins) and volatile compounds, and generate new spores.

A2.1.2 Sources of Moulds in the Indoor Environment

Micro-organisms are always present in the indoor air, although their numbers and type change with time of day, weather, season and geographical location. Most moulds enter buildings attached to dust particles (originating from rotting wood, cereal grains, animal feed, compost, biotechnology processes, etc.). The aerobiology of residential buildings, non-industrial work environments and industrial buildings are known to differ. Generally, the source of fungal spores in houses include the outdoor air, food, house dust, house plants, pets, textiles, carpets, etc. Unless there is a source of spores within a building (e.g. damp induced mould), spore concentrations indoors are generally lower than those outdoors, although in winter, when ventilation rates are lower, indoor concentrations can exceed those outdoors. If dry rot is present, it will produce spores prolifically, yielding up to 80,000 spores/m^3.

Generally, the fungal spore count in non-industrial work environments is low because less air enters by natural ventilation, less timber is used in construction, and condensation will usually be avoided by the HVAC systems. On the other hand, air conditioning systems can disperse micro-organisms and much aerobiological interest has been focused on maladies such as "sick building syndrome" and "building related disease".

The aerobiology of agricultural buildings depend on the fungal flora which contaminate freshly handled and stored agricultural products, with the nature and composition of the air spora depending on the way in which the product is handled and on the ventilation rate. Lacey (1973) and Strom & Blomquist (1986) have shown that the level of spores in factories where fungal contaminated products are handled can exceed 108,000 spores/m^3.

Hunter and Sanders (1991) examined data from 26 published aerobiological surveys of the indoor air, mainly from Europe and North America. Their finding (Table A2.1) was that *Penicillium*, *Aspergillus* and *Cladosporium* were isolated in the majority of cases. In an IEA study (Ackermann et al 1969, Benson et al 1972, Solomon 1975), 36 *Penicillium* species and 17 *Aspergillus* species were isolated from indoor air samples. *Aspergillus versicolor* and four *Penicillia* species (*P. brevicompactum*, *P. chrysogenum*, *P. corylophilum* and *P. nigricans*) were recorded by all three research groups. Other isolated fungal species included *Acremonium strictum*, *Alternaria alternata*, *Aureobasidium pullulans*, *Cladosporium cladosporioides*, *C. sphaerospermum* and *Stachybotrys atra*.

Mould	Frequency %	Mould	Frequency %
Acremonium	42	Nigrospora	27
Alternaria	85	Oospora	19
Aspergillus	92	Paecilomyces	42
Aureobasidium	81	Penicillium	100
Botrytis	46	Rhizopus	58
Chaetomium	38	Phoma	65
Cladosporium	92	Scopulariopsis	35
Curvularia	27	Stemphylium	31
Epicoccum	62	Stachybotrys	27
Fusarium	73	Torula	27

Mould	Frequency %	Mould	Frequency %
Geotrichum	38	Trichoderma	50
Gliocladium	23	Trichothecium	27
Helminthosporium	38	Ulocladium	19
Monilia	35	Verticillium	31
Mucor	69		

Table A2.1: Occurrence of common moulds in the indoor air (Sanders and Hunter 1991).

A2.1.3 Requirements for Mould Growth

The environments within which moulds propagate contain physical, chemical and biological elements which influence their establishment and growth: these environments are both complex and dynamic. The filamentous fungi generally require nutrients, oxygen, and suitable pH, light, temperature and water levels to initiate and sustain growth. Different moulds require specific ranges for these properties; outwith these ranges the mould is unable to grow or can do so only at a reduced rate. These properties rarely act independently, e.g. the provision of an optimum nutrient and temperature environment may permit the mould to grow more efficiently near its minimum requirement for water. Most filamentous moulds generally require greater levels of each growth factor as they progress through the four stages in their growth cycle, e.g. the mould may require a more nutritious substrate, a warmer temperature or a greater amount of free water in order to sustain growth from the germinated spore or to sporulate from the vegetative mycelium.

Oxygen

As most indoor moulds are obligate aerobes (i.e. are unable to grow in the complete absence of oxygen), and as mould growth is initially a surface phenomenon, the concentration of oxygen at a wall surface is always sufficient to initiate and sustain growth (Carpenter 1972, Adan 1994).

Nutrients

Moulds commonly inhabiting damp houses are chlorophyllous, requiring organic compounds to provide nourishment. Nitrogen is obtained from organic compounds and moulds can utilise inorganic nitrogen in the form of nitrates and ammonia. Fungi are versatile saprophytic/parasitic organisms capable of secreting various types of enzymes, including cellulases, hemicellulases, proteases, pectinases and lignolytic enzymes, with a remarkable ability to utilise a wide range of carbon/nitrogen sources. Their nutritional demand can normally be met by either the natural organic and/or inorganic constituents present in constructional materials and decorative finishes, or by surface soiling, e.g. as a result of cooking (Pasanen 1992, Adan 1994, Watkinson 1995). House dust, insect fragments and excretions, plant fragments, sand, dander, hair, micro-organisms, pesticide chemicals, starch and pollen grains will all satisfy the nutritional requirements of indoor fungi even in well maintained houses (Sanders and Hunter 1991, Pasanen 1992).

Several researchers have noted that the availability of nutrients plays an important role in the ability of moulds to colonise a surface under adverse growth conditions (e.g. at reduced levels of free water). While the majority of mould studies have used laboratory media and foodstuffs (Snow et al 1944, Block 1953, Ayrest 1969) under steady state conditions, some projects have addressed the issue of mould growth on constructional materials and decorative finishes (Coppock and Cookson 1951, Block 1953, Hallenburg and Gilbert 1986, Grant et al 1986, Pasanen 1989). A small number of studies have examined mould growth under transient conditions of relative humidity and temperature (Adan, 1994), the likely scenario within buildings.

Temperature

Fungi can exist over a wide range of temperatures, below 0°C fungal cells survive but rarely grow, while above 40°C most cells cease growing and die (although some fungi can survive temperatures less than -70°C and greater than 50°C). Between 0°C and 40°C fungal activity will depend on the effect of temperature on enzyme activity. Not all moulds grow over the same temperature range and the ability of a particular mould to develop at either a low or high temperature depends on whether it has been classified as psychrophilic (i.e. fungi which have their maximal growth rates below 20°C), mesophilic (i.e. fungi having their maximal growth rates at temperatures in the range 20°C to 40°C), thermotolerant (i.e. fungi that can grow in temperatures above 40°C) and thermophilic (i.e. fungi having their maximal growth rate above 50°C).

Grant et al (1989) showed that within the temperature range 5°C to 25°C, increasing temperature permitted growth at lower water activity levels. Other researchers have described this phenomenon, where the maintenance of a surface temperature removed from the optimum results in a reduction in the range of water levels permitting germination and subsequent growth (Lacey et al 1980, Magan and Lacey 1984, Mislivec et al 1975, Smith and Hills 1982, Sanders and Hunter 1991).

Water

The availability of free (unbound) water to a growing fungus or dormant fungal spore is the most important requirement for spore germination and growth (Scott 1957). Microorganisms can only grow in aqueous solutions, which can bring nutrients into the cell and dispel waste products to the environment. While intermittent condensation at the wall surface does increase the probability of mould proliferation, the traditional view that condensation has to occur is unfounded. Indeed, condensation (i.e. 100% relative humidity) by itself is unsuitable for sustainable mould growth as pure water is theoretically devoid of essential nutrients. Most filamentous fungi are known to have an optimum moisture requirement which is often significantly below saturation (Grant et al 1989, Hunter et al 1988).

The availability of sufficient water to a growing fungus is governed by the water activity, a_w, which under conditions of local surface thermodynamic equilibrium is equivalent to the relative humidity (RH) (Scott 1975, Ayrest 1969, Sanders and Hunter 1991, Pasanen 1992, Adan 1994). This term, a_w, quantifies the free water available to the fungus and is defined as the ratio of vapour pressure above a material or solution to that of pure water at the same temperature.

While the maximum or upper limit for growth is an a_w less than 1 (pure water), different moulds appear to have different maximal, minimal and optimal a_w values. Moulds satisfy their need for water by either absorbing moisture from the porous surface material, absorbing moisture from the atmosphere (if the RH is sufficiently high) and/or through energy metabolism, i.e. the breakdown of carbohydrates and fats (Coppock and Cookson 1951, Sanders and Hunter 1991, Pasanen 1992). Organisms tend to grow better in a substrate in which a_w is altered by desorption rather than adsorption, with higher a_w values required for growth and sporulation compared to germination. Furthermore, sexual sporulation requires greater a_w levels compared to asexual sporulation. The relationship between the water content of a material and a_w is described by the material's sorption isotherm (which is normally sigmoidal in shape).

With the knowledge that the provision of sufficient water in the form of surface RH is the key to ultimately controlling indoor mould development, any parameter which influences surface RH has the potential to affect fungal growth. Likewise, any parameter which affects the geometry, moisture and/or nutritional composition of a material, particularly at its surface (e.g. pore size distribution, capillary condensation, etc.) can influence the development of a growing fungus. Interior finishes are influenced by their adjacent multi-layered constructions, with the heat, air and moisture transport through the building fabric affecting the surface RH.

Factors known to govern the RH (or a_w) at the wall surface include: the hygrothermal properties of each constructional material, the presence of thermal bridges, ventilation rate at the wall surface, HVAC system capabilities, climate variations, occupant behaviour and moisture sources. Materials and decorative finishes become moist when they have a water or vapour open porosity (i.e. they are hygroscopic); materials such as glass, which have zero porosity, exhibit surface wetting but no mass wetting.

Moulds which appear on a wall surface can be classified as either xerophilic (i.e. fungi capable of growth under dry conditions, e.g. < 85% RH) or hydrophylic (those that require greater amounts of free water to sustain growth, e.g. > 85% RH). This variation in water requirement frequently results in a successive colonisation of a surface by a variety of different moulds (Winter et al 1975, O'Neill 1986, Grant et al 1989). Certain moulds of the genus *Eurotium* or *Aspergillus* are xerophiles and can grow at RH values less than 75%, while members of genera *Penicillium, Cladosporium, Ulocladium* and *Stachybotrys* require higher moisture levels. Magan and Lacey (1984) have shown that *Aspergillus* can only compete successfully with *Penicillium* at higher temperatures and lower water activities. Strong xerophilic species include *Aspergillus halophilicus* and those moulds belonging to the *A. glaucus* and *A. restrictus* groups.

In foodstuffs and damp constructional materials, once colonisation has begun, and provided that the temperature is sufficiently high, progressive deterioration of the substrate will proceed with increasing rapidity as moisture is released via respiration. Colonisation follows a succession in which mould species occupy distinct positions that are very strictly determined by moisture content. Marked population changes occur as the moisture content increases and species which are more competitive at higher moisture contents develop.

Other Factors

Very little research has been done on the influence of pH on mould development, although it is known that most common indoor moulds grow within a pH range of 2.2 to 9.6 (Carpenter 1972). Some moulds grow better in the presence of light, e.g. *Stachybotrys atra*. Apart from requiring a specific growth environment, indoor moulds are often influenced by the competitive effects of other moulds and by the effects of fungicidal agents which are often added to water-based and acrylic paints.

2.1.4 Prevalent Moulds on Indoor Surfaces

The most commonly isolated fungi recovered from damp walls include *Aspergillus*, *Penicillium* and *Cladosporium*. Sanders and Hunter (1991) stated that the general trend in the frequency of occurrence of the other genera was also similar to that recovered from air samples (Table A2.2). Grant et al (1989) revealed that during the early part of winter, when the wall surfaces are relatively dry, xerophilic organisms (i.e. *Penicillium* and *Aspergillus versicolor*) were prominent. As winter progressed, and conditions became wet, *Ulocladium* and *Stachybotrys atra* became dominant. In other studies *A. versicolor*, *P. brevicompactum* and *P. chrysogenum* were again the most common *Aspergilli* and *Penicillia* species isolated from indoor surfaces in Belgium, Italy, The Netherlands, Germany and the UK (Hunter et al 1988, Sanders and Hunter 1991).

Mould	Frequency %	Mould	Frequency %
Acremonium	29	Paecilomyces	29
Alternaria	57	Penicillium	85
Aspergillus	93	Phoma	36
Aureobasidium	64	Scopulariopsis	43
Cladosporium	71	Stachybotrys	29
Fusarium	21	Ulocladium	36
Mucor	36		

Table A2.2: Occurrence of common moulds on wall surfaces (Sanders and Hunter 1991).

A2.1.5 Resilience of Fungi Under Stressful Conditions

Tolerance to low surface a_w values derives from an organism's ability to modify the internal environment of its cells. Osmoregulatory substances accumulate from the environment and/or are synthesised within the fungus. These depress the internal water potential below that of the external environment, thus ensuring that the organism does not lose water and is able to maintain turgor. Substances such as glycerol and other polyhydric alcohols (polyols which are compatible solutes that do not interfere with normal cell metabolism) accumulate in osmotolerant and xerotolerant fungi at low water potentials and reach a high proportion of the dry weight of cells growing under severe water stress. The major physiological difference between fungi which are capable of growth at low water potentials and those that are not, is that the latter show an increasing tendency to leak polyols from hyphae as the internal concentration increases (fungi tolerant to water stress maintain a high internal concentration of polyols without undue expenditure of energy and avoid the need to divert resources to polyol production at the expense of growth). Ions and non-electrolytes accumulate in hyphae from the external environment - these also serve to lower the internal water potential when the hyphae are subjected to low a_w.

The enzymes of xerotolerant fungi are not adapted to function at low water potentials, and another function of polyols under low water stress seems to be to protect enzymes. Another feature of fungi which inhabit dry environments is that their spores are often adapted to withstand dessication. Fungi living in nutrient poor habitats, and needing to scavenge soluble nutrients, have been shown to have uptake systems with a stronger affinity for their substances than similar fungi which habitually grow in nutrient rich environments. Some fungi obtain part of their nutrients from the atmosphere.

The basic developmental unit of all filamentous fungi is the hypha, a eukaryotic cell unlike those of plants or animals, which polarises all its growth at the end so as to form an elongating filament. Materials for growth are derived mainly from nutrients taken up from the surface over which it is growing, or transported from other parts of the mycelium. As the hyphae elongates, it may develop internal cross walls which are normally perforated by holes so that the cytoplasm is potentially a continuum (these holes may later be occluded, i.e. closed off and the compartments consolidated as the hypha elongates). As the tip grows on, it leaves behind a growing mass of branching mycelium called the colony.

A2.2 Moulds and Building Physics

The relationships between design parameters, building materials, environmental conditions and living organisms is complex. Because mould growth is a surface phenomenon, an engineering approach to mould alleviation requires an arrangement of the building's envelope, materials, operation and occupancy behaviour such that surface relative humidities are maintained below 75%.

Water availability in buildings depends on many factors, such as the occurrence of moisture sources and sinks, the type and capacity of heating systems, ventilation rates, construction material properties and occupant behaviour. In order to avoid moulds, the indoor climate must be maintained at levels which are human acceptable but mould unfriendly. This can be achieved either by the expenditure of energy or through good design practice at the outset, the elimination of building defects during construction and the imposition of sensible operation and maintenance regimes. Building mycology needs to encompass an understanding of the complex interactions between nutrients, organisms and the ever changing micro-environments. Building investigators have frequently failed to diagnose conditions suitable for mould infestation because they have not viewed the problem as a dynamic, complex system.

Fungi often obtain nutrients from cellulosic materials such as wood based products (e.g. textiles and insulating materials) or from non-cellulosic materials such as plastic, glass, electrical equipment, fuel, paints, leather and glues. Indoor fungi isolated from plaster include *Coprinus* (Ink Cap), *Peziza* (Elf Cup) and *Pyronema expansum*; those isolated from stone include *Penicillium, Trichoderma* and *Botrytis*; paint fungi include *Alternaria alternata, Aspergillus flavus, Aureobasidium pullulans, Penicillium expansum, P. purpurogenum, Cladosporium herbarum, Fusarium oxysporum, Paecilomyces variottii, Trichoderma viride, Ulocladium atrum* and *Phoma violacea*; glass, metal and sealant fungal colonisers include *Cladosporium resinae* and some xerophilic species; and those moulds developing on interior furnishings and contents include *Penicillium, Aspergillus, Cladosporium* and *Mucor*.

Even though the impact of fungal growth has been pointed out by several researchers (Morgenstern 1982, Becker 1984, Becker et al 1986, Grant et al 1989), the role of material characteristics (i.e. nutrient and water supply) in fungal deterioration has received only minor attention in building physics. From the following publications - Snow et al 1944, Panasenko 1944, Coppock and Cookson 1951, Block 1953, Armolik and Dickson 1956, Ayrest 1966, Panasenko 1967, Pitt and Christian 1968, Ayrest 1969, Mislivec and

Tuite 1970, Hockering and Pitt 1979, Magan and Lacey 1984, BRE 1985, Andrews and Pitt 1987, Hunter et al 1988, Grant et al 1989, Pasanen 1992 and Adan 1994 - a number of observations can be made:

- Each mould type has separate RH and temperature requirements for germination, vegetative mycelial outgrowth and sporulation, and these requirements will typically differ for each mould.
- The provision of a localised, suitable RH and temperature is sufficient to permit mould growth.
- Moulds require a greater a_w to grow on constructional materials compared to food-stuffs and laboratory culture media.
- Under steady state conditions, common indoor moulds will not colonise building materials below 75% RH.
- Above 75% RH different moulds may successively emerge, and at a greater rate the more elevated the RH.

A2.3 Health Implications

Because people spend long periods indoors, both at home and in the work place, the quality of the indoor environment is of paramount importance. Health and comfort problems associated with the built environment have become a major issue in recent years. Problems associated with buildings have been termed "sick building syndrome" and "building related disease". The former is generally limited to those conditions thought to have a psychological, physiological or chemical basis; the latter relates to conditions with a microbiological/clinical basis. The biological factors implicated in building related disease may include: mould and other fungi, bacteria, viruses, protozoa, pollens, house dust, mites, insect pests, algae and rodents. For some people, ill health may be triggered by non-biological factors such as chemicals and other indoor air pollutants, or by emotional stress, fatigue and/or weather changes. Indeed, these factors burden allergy-prone people further if they are suffering from allergic reactions to biological contaminants. Singh (1993) describes how building design, occupancy behaviour and management can affect the incidence of allergic components.

The inhalation of airborne micro-organisms and their metabolites may cause a range of respiratory symptoms depending on the immunological reactivity of the host and the type of organism present. Some are specific building related diseases which can be identified by immunological or microbiological tests, while others are recognised as syndromes with no readily identifiable cause. Others are non-specific reactions to components of the airborne dust or are poorly defined (e.g. chronic fatigue syndrome or increase in coughing or phlegm). Some of the components of building related diseases include: mucus membrane irritation, bronchitis and chronic pulmonary disease, allergic rhinitis and asthma, extrinsic allergic alveolitis (hypersensitivity penumonitis), inhalation fever, endotoxins, glucans, mycotoxins and volatile metabolites and respiratory infection where fungi are implicated as the aetiological agent.

The elucidation of the causes of building related disease can be a complex process of elimination and supposition. Presently there are no government guidelines or codes of practice on indoor air quality which specifically identify limits for an extended list of pollutants based on a possible total exposure.

A2.4 Alleviating Mould Growth

The traditional approach is to treat the building construction with water repellents and fungicidal agents. However, this simply treats the effect and not the cause. An engineering approach requires that the interior finishes be considered along with their associated multi-layered constructions, with the heat, air and moisture transport processes being manipulated to establish an appropriate surface RH and temperature regime. Tackling mould growth problems in the domestic and work environments requires manipulation of the indoor climate through good building design, construction and management (particularly in relation to ventilation and thermal bridges). A tool for the integrated analysis of the engineering and biological dimensions - as developed in this project - is seen as the essential prerequisite of mould alleviation.

Appendix 3 Glossary

- **achlorophyllous**: organisms that cannot photosynthesise their own food.
- **apical**: concerning the apex or top.
- **asco**: popular abbreviated term for a member of the Ascomycotina.
- **ascospore**: spore originating in an ascus.
- **ascus (plural asci)**: reproductive sac-like cell of the Ascomycotina.
- **aseptate**: without septae, or crosswalls.
- **a_w**: water activity, the amount of free water available to the growing fungus.
- **basidiospore**: spore produced from a basidium.
- **basidium (plural basidia)**: reproductive cell of the Basidiomycotina.
- **conidium**: an asexually formed fungal spore.
- **conidiophore**: a simple or branched hypha on which the condia are borne.
- **epidemiological**: the study of the distribution in human populations of events affecting health.
- **ERH**: equilibrated relative humidity, which is equivalent to a_w under steady state conditions.
- **eukaryotic**: cells which have nuclear chromosomes.
- **filamentous**: composed of fine threads.
- **germ tube**: a thin spot in the apical end of a spore through which the spore may germinate. **habitat**: the immediate environment occupied by an organism.
- **heterotrophic**: using organic compounds as primary sources of energy.
- **holistic**: viewing the problem in a complete fashion, i.e. individual factors should not be analysed separately from one another.
- **hygroscopic**: changing shape in response to atmospheric humidity.
- **hypha (plural hyphae)**: fungal cell.
- **osmotrophically**: fungi that absorb their nutrients from the aqueous solution which surrounds them.
- **lateral**: at the side.
- **mycelium**: the vegetative body of a fungus, a mass of fine thread-like hyphae, the thallus of a fungus.
- **mycologist**: a person studying fungi in a scientific manner.
- **mycological**: pertaining to the study of fungi.
- **mycotoxin** : toxic metabolite produced by fungi.
- **obligate**: one incapable of a free existence.
- **RH**: relative humidity.
- **rhizoid**: a fine mycelial strand at the base of certain sporophores.
- **rhizomorph**: mycelial strands massed into a cord, looking like roots.
- **saprophyte**: an organism feeding on dead organic matter.

- **septate**: having septa.
- **septum (plural septa)**: a cross wall especially in a hypha or spore.
- **spore**: reproductive unit of fungi.
- **substrate**: on which the fungus grows or to which it is attached.
- **thallus**: a vegetative body of the fungus, i.e. the mycelium.
- **ubiquitous**: growing in a wide range of geographic or ecological sites.
- **xerophilic**: preferring dry places, growing under dry conditions.