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Testing damage functions for mould growth

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ABSTRACT

Four models of mould growth risk from air temperature and relative humidity have been tested against observations within a range of properties. The Climate Notebook Mould Risk Index and WUFI-Bio mould growth index were found to best correlate with the visual observations of mould growth. All models failed to predict mould growth in some instances. Other sources of water, held in glues and due to dust-particulate-induced condensation, have been investigated.

INTRODUCTION

Mould has been described as the single greatest risk worldwide arising from incorrect climate (Michalski 2007). There are four main genera of fungi that affect collections worldwide, these being *Cladosporium, Alternaria, Aspergillus* and *Penicillium* (Florian 2002). Mould growth occurs in two distinct stages. Firstly, germination of conidia – often incorrectly called spores (Florian 2002) – must occur. After this mould begins to grow; hyphae are produced which secrete enzymes at their tips. These enzymes dissolve certain substrates, which are used as a food source for further growth (The National Trust 2006). Mould can also cause discolouration, either from the fungal growth itself or through staining, caused by the secretion of fungal pigments into the substrate (Florian 2002).

Mould outbreaks can be extremely resource-intensive to remediate. Future climate predictions indicate an increase in mould growth in many UK sites (Lankester 2013).

In some situations, often historic buildings, full environmental control is not possible and knowing the risk of mould growth is essential for effective management.

At least four models have been proposed to predict mould growth on wood (or other materials) from environmental conditions (temperature and relative humidity/RH). These have been tested against mould observations on wooden substrates in a range of properties. Where the models do not predict mould that has been observed to grow, further measurements have been undertaken to elucidate the situation.

The moisture content of mould spores is often the limiting factor in their growth. This moisture can come from a number of sources: building faults, leaks and condensation can all transport water onto/into an object. The equations only take into account the air temperature and RH.

Mould growth will only occur when specific conditions are met. These are referred to as favourable conditions (Hukka and Viitanen 1999, Brimblecombe 2010). Occasionally, critical relative humidities are quoted as minimum requirements of mould growth, for example 62% (ASHRAE 2013), 65% (The National Trust 2006), 70% (Florian 2002) and 80% (Sedlbauer et al. 2003). These specific conditions vary depending upon the species of mould and the substrate (Moon and Augenbroe 2003). A critical humidity alone is often insufficient and could overestimate potential mould growth as other factors, such as time and temperature, are also important (Atersy 1969, Hukka and Viitanen 1999, Moon and Augenbroe 2003, Isaksson 2010, ASHRAE 2013).

Other factors are taken into account using the isopleth system (Sedlbauer et al. 2003), reproduced in Figure 4. This accounts for temperature, relative humidity, substrate and time. The lowest isopleth for mould (LIM) is a similar notion to the critical humidity, but accounts for these other important factors. The RH required for germination when temperature is high, is similar to the values of critical humidity stated. As temperature decreases, the humidity required for germination increases. There is also data for growth after germination, which behaves differently to that required for germination.

Isaksson et al.

This dose-response function predicts the onset of mould growth on spruce and pine sapwood. It is based on experimental data for mould growth on wood (Isaksson 2010) and allows for variations in the environment over time.

This method can be calibrated to substrates other than pine and spruce sapwood via experimentation, and hence be more generally applicable. This work uses the pine sapwood reference example under constant conditions of 20°C and 90% RH. Twenty-nine days (Nref) were required for mould growth to initiate under these conditions. Spruce sapwood required 38 days for mould to germinate.

A total daily dose (D) is calculated. This is the product of two components, dependent upon the daily average temperature (Td) and relative humidity (RHd). This is expressed in days, and is equal to 1 where the temperature and relative humidity are equal to that of the reference conditions (20°C and 90%). Negative daily doses are possible when conditions are unfavourable, providing a setback for the germination process; however, the accumulated daily dose can never be negative.

Hukka and Viitanen

This model also simulates mould growth on pine and spruce sapwood. It is based on previous regression models for mould growth on those materials (Hukka and Viitanen 1999). A number of equations combine to form this model, which takes into account fluctuating conditions when calculating possible mould growth. While this model was developed for spruce or pine wood, it is argued that the form of the model is valid for other wooden materials (Hukka and Viitanen 1999).

The model calculates the mould index (M, no units). The value of M is based upon an existing index of the visual appearance of the material under study. A value of zero indicates no mould growth; 1: some growth detected with microscopy; 2: moderate growth under microscopy (>10% coverage); 3: growth detected visually; 4: growth detected visually (>10% coverage); 5: growth detected visually (>50% coverage); 6: growth detected visually (100% coverage). Therefore, a value of M=1 is critical and indicates initiation of mould growth.

Mould Risk Factor – Climate Notebook, Image Permanence Institute

This calculation is included in the Climate Notebook software. It is a general index and not specific to wood. It is based on studies of common mould species (*Aspergillus* and *Penicillium*) growing on wheat at different temperatures and relative humidities (Nishimura n.d.). Mould spores of the species that survive in most heritage environments (conidia) can survive in a dormant state for many years in unfavourable conditions. When conditions become favourable, the conidia eventually germinate, grow and release more spores. Each temperature and RH data pair is compared to the experimental data and the fraction of the way to germination calculated. These values are summed. A value of 1 represents germination under ideal conditions: darkness and still air. The higher the value, the more potential for mould growth. Once germination has occurred, if the conditions become unfavourable for a period of 24 hours the mould is assumed to have died and the value is set back to zero. If conditions become unfavourable before germination (value <1) then the value remains constant.

WUFI-Bio

WUFI-Bio is a transient biohygrothermal model. It is based on the fact that a mould spore has an osmotic potential (described in the model as a moisture storage function) which allows it to take water from its environment. The water content of the spore alters with changing air temperature and RH. Germination occurs after a critical moisture content is reached. These values have been determined experimentally. The model allows three classes of substrate: optimum, bio-utilisable (includes pine wood) and less bio-utilisable (most hardwoods fall into this class) (Hukka and Viitanen 1999). The software produces three outputs: mould growth in mm/year, mould index and a colour risk index (green, amber and red). The mould index is based on that of Hukka and Viitanen (1999), but modified by the substrate class.

The four models and their results are summarised in Table 1.

Observed mould events

English Heritage is systematically collecting all observed instances of damage to its collections, including mould growth. When an instance is observed, the date is recorded, images are taken and the previous year's environmental data is highlighted and stored separately from normal back-up procedures. This data provides a database against which to test damage functions, although some reservations have to be stated about the exact date that damage is observed. Thirteen mould outbreaks (from four properties) are shown in Table 2. The RH accuracy of the monitoring data is included. Sensors were calibrated annually with three point RH calibrations. All sensors had an air temperature accuracy at or below 0.2°C, which will not affect the mould risk calculations.

The Isaksson and Hukka models failed to predict mould growth in almost half of the instances observed. The Climate Notebook software performed somewhat better. All the WUFI-Bio indices performed poorly in the first three properties examined. They did perform much better in the much higher RH conditions in Dover Castle Secret Wartime Tunnels.

Table 1
Mould risk models

model	Isaksson	Hukka	CNB
Index	D (daily dose), D= Td x RHd. Td = exp (0.74 x ln(T/20)) RHd = exp (15.53 x ln(RH/90)) D/Nref (Relative dose) Nref=29 days (germination on pine sapwood, 20C, 90%)	M (mould index) dM/dt = [1/7 x exp (-0.68 x ln(T) – 13.9 x ln(RH) + 0.14W – 0.33SQ + 66.02)]K1K2 M=1, critical: iniciation of mould growth	Max MRF (max mould risk factor)
Interpretation	number of days till germination (D=29, D/Nref=1)	0: no growth 1: some growth visible under microscope 2: moderate growth visible under microscope, coverage more than 10% 3: some growth detected visually, thin hyphae found under microscope 4: visual coverage more than 10% 5: coverage more than 50% 6: tight coverage, 100%	0: mould is not a problem 0-1: progress towards mould germination >1: mould has most likely germinated
reference	[11]	[6]	[12]
model	**Wufi Bio**		
Index	Mould growth (biohygrothermal model)	Mould index (Hukka and Viitanen model)	Colour code
Interpretation	mm/year	0: no growth 1: some growth visible under microscope 2: moderate growth visible under microscope, coverage more than 10% 3: some growth detected visually, thin hyphae found under microscope 4: visual coverage more than 10% 5: coverage more than 50% 6: tight coverage, 100%	green: mould growth is below 50mm/year, mould index of approximately 0.5 yellow: mould growth is between 50-200mm/year red: mould growth exceeds 200 mm/year, which corresponds to a mould index of approximately 2
reference	[8]		

Table 2
Observed mould outbreaks and model results

Property	Location	Isaksson	Hukka	CNB	WufiBio		
		D (n days to germination)	M	Max MRF	Mould growth (mm/year)	Mould index	Colour key
Down house	Drawing room	no mould	0	1.05	0	0	Green
Kenwood house	Furniture store	no mould	0.044	2.28	6/0	0.01/0	Green
Osbourne House	Swiss Cottage Museum case A	no mould	0	0	0	0	Green
	Swiss Cottage Museum case B	550	0	0.69	0	0	Green
	Swiss Cottage Museum case C	no mould	0	0.15	0	0	Green
Dover Castle Secret Wartime Tunnels	Naval ops	163	1.12	14.67	225/80	2.75/0.3	Red/yellow
	Gun ops	224	0.86	11.34	150/55	1.7/0.3	Yellow
	Repeater station back	147	1.53	16.88	300/160	4/1.6	Red/yellow
	Battery passage back	16	4.41	95.96	1200/800	6	Red
	Battery passage front	28	4.14	92.3	1100/750	6	Red
	Repeater station front	450	1.4	8.84	130/27	1/0.05	Yellow /green
	Admiralty casemate front	no mould	0.97	6.12	25 / 3	0.05/0	Green
	Admiralty casemate back	no mould	0.58	3.24	1/0.2	0	Green

Table 3

Observed mould outbreaks and model results in Dover Secret Wartimes Tunnels

Location	Isaksson	Hukka	CNB	Wufi Bio	Location	Isaksson	Hukka	CNB	Wufi Bio
NO1	■	■	■	■	ADF1				
NO2			░		ADF2				
NO3					ADF3			■	
NO4	■	■	■	░	ADF4				
NO5			■		ADF5				
NO6			■		ADF6				
NO7	■	░	■	░	ADF7				
NO8	■		■		ADF8				
GO1	■		■	■	ADF9			■	
GO2					ADF10			■	
GO3				■	ADF11			■	
GO4			■	■	ADF12			░	
GO5		■	■	■	ADF13			░	
GO6				■	ADF14			░	
GO7				■	ADF15				
GO8	░		■	■	ADF16		░	■	■
GO9			■	■	ADF17			■	
GO10	■	■	■	■	ADF18				
GO11	░		■	■	ADF19			■	
GO12	■		■	■					
RF1					RB1	■		■	■
RF2			■	■	RB2		■	■	■
RF3	░		■	■	RB3			░	■
RF4		■	■	■	RB4			░	■
RF5			■	■	RB5	■		■	■
RF6				■					
RF7				■	ADB1		■		■
RF8			■	■	ADB2			■	
RF9			■	■	ADB3			■	
RF10					ADB4			■	
RF11					ADB5	■	■	■	■
RF12	░	■	■	■					
RF13	░	■	■	■					
RF14	░		■	■					

NO	Naval Operations
GO	Gun Operations
AD	Admiralty Casemate Front
ADB	Admiralty Casemate Back
RF	Repeater Station Front
RB	Repeater Station Back

Black cells where the model predicts mould growth
Grey cells were index is within 30% of that stated for mould growth

In the Secret Wartime Tunnels under Dover Castle, the permeable chalk construction generates very high relative humidities and mould is a constant problem. The cleaning and observation of mould is closely monitored and recorded. Table 3 shows the instances of observed mould and is colour coded to whether each model would have predicted mould in the time interval since the last clean. The actual numbers have not been included for brevity. In all these instances the T/RH sensor was placed beside/under the area/object showing the most frequent mould growth. Whether the models predicted mould growth in each of the 63 instances is shown in Table 3. Overall, the predictions from Climate Notebook and WUFI-Bio again agreed more closely with the observed mould growth. All models failed to predict (or nearly predict – the grey cells in Table 3) some instances where mould was observed to grow.

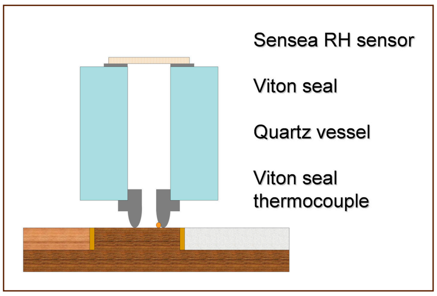
MOULD APPEARING AT RH CONDITIONS BELOW THOSE PREDICTED BY THE MODELS

Isolated location

In Audley End House, a doll's house has been on display for several years. It has an open front covered by a glass sheet with lighting across it to allow secure display. Several instances of mould have been observed on different elements of miniature furniture within the doll's house. Environmental monitoring within the doll's house indicated that RH did not exceed 62%. The Hanwell humbug logger had been carefully calibrated with saturated salt pots traceable to NAMAS (the UK National Measurement Accreditation Service) standards. The calibration was checked annually and salt pots at RHs spanning the complete range were measured. There is no possible way for liquid water to ingress into the doll-house structure; it was separated from the floor by a waterproof, melamine-coated board. Measurement of surface temperatures (Pt100 Platinum surface temperature probes on SR007 logger) over the winter periods confirmed the elements were at least 5°C above dew point at all times and condensation was unlikely.

Water activity measurement

A miniature inlaid table had had several mould occurrences on glue joints (Figure 1). A miniaturised water-activity probe was constructed from a Sensea resistance-based RH probe in an inert cylindrical chamber with a 1-mm diameter opening with a Vicor ORing (Figure 2). A thermocouple was located at the bottom of the Vicor ORing. The Vicor ORing could be gently pushed against an object to measure water activity of the 1-mm diameter surface separated. Water vapour transmission up the cylinder was checked by equilibrating the probe to one RH and placing it above a saturated salt solution at a different RH. The RH equilibrated in the assembly at room temperature (15–25°C) within 120 seconds. The probe was used to measure the water activity across the table surface (Figure 3). As can be seen, the water activity of the two inlaid woods is slightly different at 0.61 and 0.63. The error in the measurement is ± 0.01. Both areas measured, which included glue lines, had much higher water activities of 0.76 and 0.80. The measurement is an average of the 1-mm diameter circle sampled and the water activity of the glue is probably higher still.



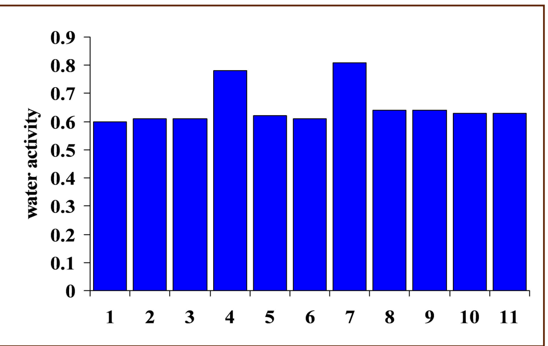


Figure 1
Doll's house table top showing mould along glued joins

Figure 2
Equipment to measure water activity of 1-mm diameter areas

Figure 3
Water activity plotted across the wooden table. Joins are at 4 and 7 mm

This demonstrates that some components can have much higher water activities even after several years. The water activity of the glues and woods has not equilibrated despite several years in an environment between 50 and 62% RH.

Serious and very extensive mould outbreaks have occurred twice in tunnels below Dover Castle. Mould grows almost continuously in the tunnels (Table 3). While the environmental conditions are frequently such as to support mould growth, the influence of dust on the mould was investigated. Dover tunnels have very high visitor numbers, in a very constrained space, and deposited dust levels on the collection are very high (Thickett 2008). Dust is normally collected for monitoring by deposition onto glass microscope slides (Howell et al. 2003). The slides normally have cover slips attached to keep the dust in situ for transport and measurement, and are transported in polyethylene slide boxes with 5 slides vertically with 1-mm gaps between them. On slide collection, water activity measurements were carried out on a single slide in some of the boxes. The hygroscopic properties of the polyethylene used were checked by exposure to different RHs and weighing. They were not found to be significant, so the box could be used as a container in which to measure water activity. A box was modified by drilling a 3-mm hole into it, inserting a Rotronic Hygroclip I T/RH probe and carefully sealing the hole with a Vicor ORing. Exposed slides were placed in the bottom slot of the box, without a cover slip. The box was placed in a polystyrene box to control temperature, and the RH and water activity were measured after 30 minutes. Trials showed that the reading had stabilised after this period. Results of the monitoring showed the water activity measured of the dust was somewhat higher than expected from the RH measured in the room for the previous one to three days (Figure 4). This is particularly true for dust collected from the front part of Admiralty Casemate, where the mould risk indices failed to predict the mould growth observed. The dust particles are small and would be expected to equilibrate rapidly with the room's RH. Previous work has shown condensation occurring due to dust particles from Dover at between 52 and 56%. There are two mechanisms by which liquid water can be formed on a surface related to dust. Capillary condensation can occur in the small curved volume between inert dust particles and the surface (Xu et al. 2002). Salts present in the dust can deliquesce when their critical RH point is exceeded (Ibid.). The average salt compositions in deposited dust measured in the Dover tunnels were chloride:sulfate 5.73–5.91:1; sodium:ammonium:magnesium 10.71–10.89:0.51–1.23:1 (Thickett 2008). The water activity in a saturated solution of this mixture would be below 0.60. This is considered too low for many mould species to grow.

Measurement of deliquescent and condensing particles

The dust collection and measurement method was modified. Dust was collected on gold-coated microscope slides for seven days. This ensured the particles were relatively widely dispersed on the slide surface, as there were fewer than in the normal 30-day collection period. A metal Peltier cooling cell was placed underneath the slide and the dust was measured in reflectance and not transmitted light mode. This method was developed by

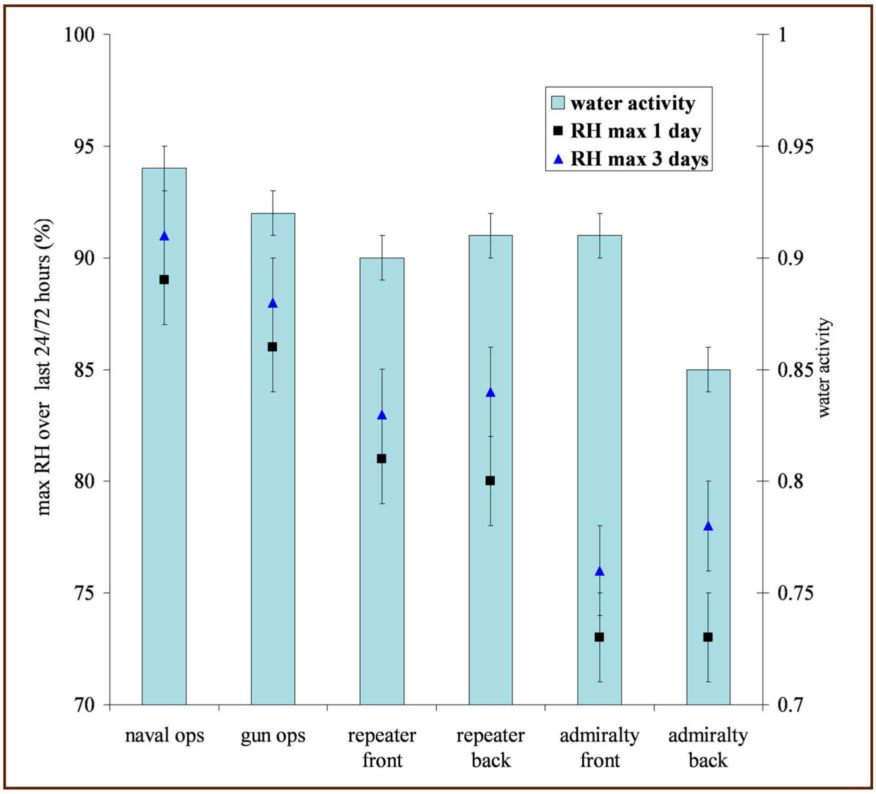


Figure 4
Water activity of Dover dust and maximum RHs from previous 24 and 72 hours

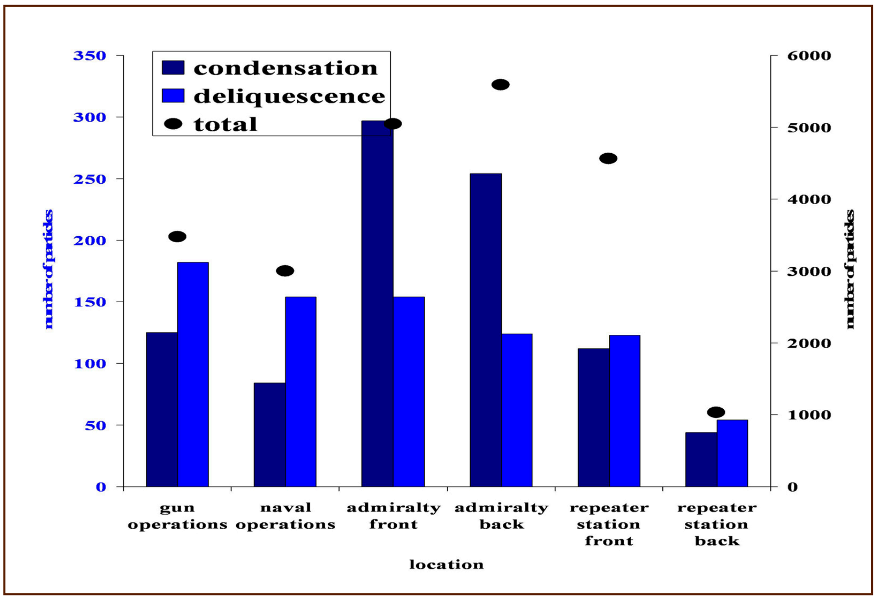


Figure 5
Dover dust, total number of particles observed, number observed to deliquesce and to induce condensation

Xu et al. (2002). A copper plate was placed underneath the Peltier cell to conduct heat away from underneath. A platinum surface temperature probe was connected to the gold-coated slide using an SEM conductive carbon disk. This allowed continuous measurement of the temperature of the top surface of the slide. The surface temperature distribution was measured with an Inframetrics ThermaCam PM 290 thermal camera and found to be uniform across the slide top surface. The dust sample was measured at 40% RH and then again with the Peltier cooling running, to reduce the temperature by 1°C increments, without repositioning the glass slide, so the measurement points were identical. The repositioning was confirmed by subtracting each set of images at a single point. The measurement was run 5 minutes after the temperature stabilised at each temperature and then 30 minutes after that. Each frame was image-processed to identify how many particles had increased in the area. It has been shown that condensation produces a limited amount of water on the surface around a particle. In terms of these experiments, the area of the particle measured at 5 minutes would be very similar to that after 30 minutes. In the case of deliquescence, the particle continues to remove water from the air and the area increases significantly with time. The time interval was selected to ensure that the deliquescence areas from adjacent particles did not merge. This differing behaviour allowed estimates of the number of particles causing condensation and deliquescence to be made for each slide.

Results are shown in Figure 5. A significant proportion of the total particles is causing condensation and deliquescence under the experimental conditions. The sample collected from the front of Admiralty Casemate had a much higher proportion of particles causing condensation than the other samples.

CONCLUSIONS

Of the four models tested, the Climate Notebook mould risk index and WUFI-Bio growth index best correlated with the observed mould growth. Unfortunately, both of these models require some care in data formatting to successfully import it into the software. Generally, better results were obtained with all models at higher RH values. All of the models are described as evaluating the risk of mould growth and the literature associated with each emphasises their limitations for predictive work. Nonetheless, the utility of two of the models has been shown for this, although all failed to predict mould growth in some instances.

One instance of mould growth below the minimum RH from all models was confirmed. The lack of other water ingress into the wooden objects was also verified. In this instance the high water activity of glue joins, even after several years at medium RH levels, appeared to offer a potential reason for the mould growth.

Higher than expected water activity was also measured in dust samples, and an estimate of the number of condensing and deliquescent particles was produced. The location where the models performed worst had a much higher proportion of condensing particles than the other locations where the models correlated better with observations. This appears to be a viable hypothesis for the poor correlation, although further investigation is required.

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