

House Dust Mites and the Built Environment: A Literature Review

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Background

This is the first interim report for the EPSRC project “A Hygrothermal Model for Predicting House-Dust Mite Response to Environmental Conditions in Dwellings”. This report is a literature review divided into three sections, the first two review the house-dust mite physiology and ecology and the third reviews modelling and monitoring of the hygrothermal environment in beds and bedrooms. This report will remain as a working document throughout the two-year research project.

1. HOUSE DUST MITE ECOLOGY

Mites are arthropods within the class Arachnida (Figure 1). The term house dust mite generally refers to those species belonging to the family Pyroglyphidae which is a member of the mite suborder, Astigmata.

| | |
|-----------------|------------------|
| | Animalia |
| <i>Phylum</i> | Arthropoda |
| <i>Class</i> | Arachnida |
| <i>Order</i> | Acari |
| <i>Suborder</i> | Astigmata |
| <i>Family</i> | Pyroglyphidae |
| <i>Genus</i> | Dermatophagoides |
| <i>Species</i> | pteronysinus |

Figure 1 Classification of the HDM *Dermatophagoides pteronyssinus*

In total 13 species have been found in house dust and recorded from locations throughout the world, including the United States and Hawaii, Canada, Europe, Asia, the Middle East and parts of Australia, South America and Africa (Blanco 1996; Colloff 1998). However, 3 species *D. pteronyssinus* (DP), *D. farinae* (DF) and *Euroglyphus maynei* (EM) are most common comprising up to 90% of the HDM fauna (Blythe *et al.* 1974; Blanco 1996). Other recorded species and their distributions are shown in Table 1. A number of these species of HDM may be more widely distributed than is presently recorded, primarily due to the lack of investigations in some areas of the world. Additional mites occurring in house dust are the glistening mites (family Tarsonemidae), storage mites (families Acaridae, Glycyphagidae and Chortoglyphidae) and the predatory mites (family Cheyletidae), however these groups will not be examined in depth.

Despite their wide geographic range, there are differences in the distribution of common species (Table 1 - maps from Bronswijk 1981). In general DF is more commonly found in North America and other regions with prolonged dry weather whilst DP is abundant in areas with constantly higher humidity such as the UK (Platts-Mills and Chapman 1987). Within mattresses in homes in the UK, DP is usually the most abundant mite species, followed by EM, although there is some variation in the proportions of these two species (Table 2). For example Rao *et al.* (1975) found that 90% of the Pyroglyphid mites in their samples from Cardiff were DP and 9.9% EM, compared with Blythe *et al.* (1974) who reported that only 67% of their Pyroglyphid mites were DP and the remaining 33% EM. In general studies have recorded no DF in samples and speculate that conditions within the UK may be too cool and damp for the survival of this species (Blythe *et al.* 1974; Abbott *et al.* 1981; Hart and Whitehead 1990; Wanner *et al.* 1993). However, Rao *et al.* (1975) and Colloff (1987) both found a small number of this species although this represented less than 0.5% of the total Pyroglyphidae collected. Walshaw and Evans (1987) stated that there was a strong correlation between the density of EM within a mattress and the social class – with increasing numbers as social class declined – however they did not examine this relationship with DP. Colloff (1991a) also showed that EM occurred more frequently in samples from homes which he graded as damp.

Table 1. Species of Pyroglyphidae present within house dust and their recorded locations (Reproduced from Bronswijk 1981 and Colloff 1998)

| Species | Locations |
|-------------------------------------|-------------------------------------------|
| <i>Dermatophagoides evansi</i> | N. America, Europe |
| <i>D. farinae</i> | Common throughout studied regions, not UK |
| <i>D. halterophilus</i> | Singapore, Spain, tropical regions |
| <i>D. microceras</i> | Europe |
| <i>D. neotropicalis</i> | Tropical regions |
| <i>D. pteronyssinus</i> | Common throughout studied regions |
| <i>D. siboney</i> | Cuba |
| <i>Euroglyphus maynei</i> | Common throughout studied regions |
| <i>Hirstia domicola</i> , | Present throughout studied regions |
| <i>Malayoglyphus carmelitus</i> | Israel, Spain |
| <i>M. intermedius</i> | Present throughout studied regions |
| <i>Pyroglyphus africanus</i> | S. America |
| <i>Sturnophagoides brasiliensis</i> | Brazil, France, Singapore |

In other areas of Europe, Australia and New Zealand DP is usually the dominant species. (Blythe 1976; Bronswijk 1977; Crane *et al.* 1998; Dharmage *et al.* 1999), however this is not always the case. Solarz (1997) found that in mattress dust samples from the Czech Republic DF dominated, representing 62.7% of the total mite population whilst DP comprised 28.8% and EM 1.4%.

In contrast to Europe and Australasia, DF is generally the most abundant species within the USA (Wharton 1976). Arlian *et al.* (1982) found that 12 of the 19 homes they examined within Ohio were infested with only DF, whilst none contained DP alone. In homes where both species were present DF was generally dominant comprising between 74 and 93% of the total mite population with the remainder being DP. Similar results were recorded by Wharton (1970) who collected samples from a range of geographical locations throughout the USA. He found 21 of the 39 homes he examined supported DF only, although in 5 homes he reported finding DP only. He also noted that when both species were present DF was always found in greater numbers than DP, with up to 69 per gram of dust compared with 9 per gram for DP. Similarly Allen *et al.* (1988) found that where both species were present in Cincinnati, DF dominated in 62% of houses, but in New Orleans and Memphis the reverse was true with DP being the dominant species in 65 and 58 % of the houses respectively. Mulla *et al.* (1975) also reported that, within California, DP was more common than DF. Of the homes they examined, 29% supported DP alone compared with 21% containing DF alone and the remainder both species. The houses they surveyed were all within 24km of the Pacific Ocean and they noted that DP numbers were greatest near the coast whilst DF increased in abundance further inland. None of these studies cited reported finding EM within their samples.

In addition to differences in distribution species may also show behavioural differences enabling them to occupy different niches within the same habitat. For example Bronswijk (1981) reported findings from a study by Wharton which noted that although DP and DF occupied the same niche DF tended to crawl on top of the substrate whilst DP remained beneath it.

It is difficult to generalise about where HDMs are most abundant within houses since population size may be influenced by a number of factors, including variations in the microclimatic conditions. However mattresses are generally considered the main living and breeding ground for HDMs since they provide ideal environmental conditions and a plentiful supply of food, but this is not always the case. Arlian *et al.* (1982) found a living room carpet in Ohio, which supported a population of HDMs, primarily DF, seven times larger than that found in the mattresses. Rao *et al.* (1975) also found 2 homes out of 35 in his UK study where mite populations were higher on floors than in mattresses. However in the remaining 33 homes floor dust contained only 10% of the number of mites of mattress dust from the same house. The species composition of mites within dust from the two samples was also shown to be considerably different. DP were less abundant in floor dust, comprising only 66 % of the total population compared with 90 % in mattress dust. Non pyroglyphid mites (e.g. *Cheyletus*) and unidentified specimens accounted for 11 and 22 % of the total number of mites respectively. Colloff (1991a) also found differences between floor dust and that on the surface of mattresses within the UK with EM being present at a mean density of 34.4 mites m² mattresses compared to 5.6 mites m² in carpets. He speculates that this may be due to mattresses retaining moisture for longer periods than carpets and therefore providing a more suitable habitat for EM. The thickness of the mattress may also be a factor. Walshaw and Evans (1987) found EM comprised 18% of the total mite population examined from living room carpets and 25% from bedroom carpets. In contrast to this Hunter *et al.* (1996) recorded a very low number of EM within carpets and found that this species accounted for 0.4% of the total number of mites in the living room carpet and 1.3% in the bedroom. Other soft furnishings may also support HDMs and Mitchell *et al.* (1969) found that mite density was greater in frequently used furniture than pieces rarely used. This is likely to be due to the greater number of skin scales supplying food for HDMs and the higher moisture content of furniture which is used regularly.

In humid areas almost all homes may support HDMs whilst in drier climates and at higher altitudes fewer homes contain mites and, when present, their population densities are lower (Spieksma 1971). Vervloet *et al.* (1982), for example, found fewer house dust mites in high mountain areas of Switzerland where the internal RH never exceeded 50 % at temperatures between 18 and 22°C than in regions at lower altitude.

Since HDMs are not the only arthropods living in house dust it is likely that there is some interaction with other species. Potential predators of HDMs include silverfish, dust lice, pseudoscorpions and other predatory mites. The adults and deutonymphs of *Cheyletus aversor*, for example eliminated a well-established culture of DF within 20 days (McGarth 1971 – cited from Bronswijk). However, this particular species has not been reported as naturally occurring within house dust and Bronswijk *et al.* (1971) found other *Cheyletus* spp. were unable to control HDM populations under laboratory conditions. Typically cheyletid mites found in house dust (e.g. *C. malaccensis*) constitute only a small proportion of the total number of mites and are present mainly in carpets rather than mattresses (Rao *et al.* 1975). In comparison to HDMs their numbers are also lower than would be expected in a predator-prey population equilibrium (Colloff 1991b) and they are therefore not suitable contenders for biological control.

Previous studies have also suggested that in the absence of suitable prey, Chelytus mites may not only bite humans in self-defence, but feed on their body fluids (Yoshikawa 1980; Htut 1994).

It is not known whether any factors limit the population size of HDMs within mattresses. The majority of biological populations are limited by space, but this factor may not be of great importance for mites in mattresses. It is known that HDMs and food are more common at the top surface of foam and sprung mattresses (DeBoer and Kuller 1994; Hay 1995), however providing food is available and conditions are suitable HDMs may be present throughout solid foam mattresses (DeBoer and Kuller 1994). If this were the case the potential space for HDMs is vast in comparison to their size and, although such a factor should be taken into consideration, it may therefore not be of importance in limiting their population size. Predation, as discussed above, may have a small impact on HDM numbers in carpets, but is unlikely to be a significant limiting factor in mattresses. Quantity of food is also unlikely to limit the HDMs population size since a person typically produces 0.5-1g of dead skin per day whilst several thousand mites are able to survive for months on just 0.25g of food (Korsgaard 1998). However, food quality may influence population size since feeding rates and therefore nutritional uptake and reproduction are affected by the moisture content of food (Arlian 1992). At high humidities moulds may also restrict the growth of HDM populations either due to their physical presence or by producing toxins (Arlian *et al.* 1998, Asselt 1999). It would therefore appear that the HDM population size will be primarily influenced by the physical factors of temperature and humidity which are known to affect both reproduction and development rate (Arlian *et al.* 1983; Arlian *et al.* 1998; See Physiology Review).

1.1. The colonisation of buildings by HDMs

The majority of Pyrogliphid mites are found exclusively on birds or within their nests. Of the 46 recognised species 62% are restricted to this habitat, whilst only 29% are found in house dust and just 13% exclusively so (Colloff 1991b). The nest dwelling species virtually all have restricted distributions and are parasitic, unlike the ubiquitous, free living HDMs (Colloff 1998). It is likely that HDMs were also originally nest dwellers that moved to occupy human beds at the time of the first settlements (Colloff 1998). They are generally found in houses that provide them with the humidity conditions they require and are particularly prevalent in bedrooms. HDMs need some help to relocate and colonise new areas. They may be moved between locations in infested furniture, use another animal species for transport (phoresy) or be carried by humans and their pets. Bronswijk (1974) noted that clothing was often infested with HDMs and in new buildings their populations did not become established until humans were present.

It is likely that complete colonisation of a new house with dust mites takes more than a year and numbers may continue to increase for up to ten years due to the accumulation of dust (Bronswijk 1981). Initially fungal feeding mites, springtails and dust lice will colonise new houses, but these will be succeeded by HDMs as the house loses its initial moisture load following construction (Bronswijk 1981). Mulla *et al.* (1975) reported a positive correlation between the age of a house and the number of mites in a mattress whilst Hunter *et al.* (1996) found a higher number of mites in older carpets, although the relationship between age and population size was not significant. In contrast to this Hart and Whitehead (1990) and Solarz (1997) both showed no correlation between the age of carpets or mattresses and the number of mites present. For example, Hart and Whitehead (1990) found a 6 month old mattress supported a population of 318 mites per 0.1g of dust whilst a 25 year old mattress contained just 1 mite per 0.1g of

dust. It was, however, noted that some mattresses were vacuumed which decreased the numbers of mites and higher numbers of DP were present in homes over 10 years old compared with younger houses. Differences between mite numbers in mattresses and carpets may be related to their age, but they will also be influenced by a number of other factors such as room temperature, humidity, vacuuming and type of mattress or carpet.

In addition to the time taken for mites to colonise houses and the increase in dust in older buildings, HDMs may also be influenced by differences in building construction and occupant behaviour. Hart and Whitehead (1990) suggest that more efficient insulation and central heating in newer homes creates a warmer, drier environment which is detrimental to mite survival, however Korsgaard (1982) states that modern homes which are more airtight increase indoor humidity thus favouring HDM populations. This situation is exacerbated by the large quantities of water vapour emitted from the kitchen and bathroom, often with insufficient ventilation. This may be particularly problematic where *en suite* bedroom facilities are present (Whitrow 1993). Central heating has enabled the temperature within our homes to be raised, whilst the increasing price of fuel has led to a reduction in ventilation by the addition of improved insulation and double glazing designed to reduce drafts (Bronswijk 1981). This increased temperature and production of water vapour provides ideal conditions for the proliferation of HDMs whilst populations of other invertebrates have declined, therefore reducing the incidence of competition and predation.

1.2. Methods of Control

Many studies have been carried out on methods to control and eradicate HDM populations. Strategies have included vacuuming (Hughes and Maunsall 1973), encasing mattresses in plastic covers (Walshaw and Evans 1986; Howarth *et al.* 1992), removing carpets (Dybendal *et al.* 1989), washing at high temperatures (Andersen and Rosen 1989; McDonald and Tovey 1992), steam cleaning (Colloff *et al.* 1995), using electric blankets (Mosbech *et al.* 1988; DeBoer 1990), freezing with liquid nitrogen (Colloff 1986), spraying with acaricides (Le Mao *et al.* 1992) and using of dehumidifiers (Hyndman *et al.* 1997) and mechanical ventilation systems (Harving *et al.* 1994; Fletcher *et al.* 1996). It would be almost impossible to discuss all of these methods in depth and this review is therefore restricted to studies that have attempted to control HDM populations by manipulating the temperature and humidity of their environment.

Korsgaard (1983) demonstrated that within Denmark winter humidity was central to the survival of HDM populations. By reducing humidity during these critical months the level of HDMs within a building could be controlled. Hyndman *et al.* (1997) used a dehumidifier to decrease RH in bedrooms within the UK during the period February to September, and showed that this significantly reduced HDM populations in mattresses. However they concluded that mites may have moved deeper into the mattress and were therefore not collected using their sampling method. Other studies using dehumidifiers have not succeeded in reducing HMD populations within occupied houses (Yoshikawa *et al.* 1988; Custovic *et al.* 1995). However, the periods of such studies have been short and there may not have been sufficient time for a reduction to occur. Yoshikawa *et al.* (1988), for example ran a dehumidifier for 10 hours per day for 2 months whilst Custovic *et al.* (1995) ran their study for 3 months.

Mechanical ventilation with heat recovery (MVHR) units may also be used to reduce humidity. This method consists of a heat exchanger and pump. Cold outside air is ducted into the building and warmed using heat recovered from warm air that is going outside. Such a system allows the ventilation rate to be controlled and may be used in conjunction with a dehumidifier.

A number of studies have shown that MVHR causes a significant reduction in HDM populations or allergen concentration within Scandinavia (Korsgaard 1988; Harving *et al.* 1994; Wickman *et al.* 1994; Emenius 1998). Here the dry cold winters are suited to this type of control, whilst in regions with warmer, wetter winters this method may not be as successful. Within the UK results have been varied with some studies reporting that MVHR had no influence on HDM numbers and others finding a decrease. Fletcher *et al.* (1996) failed to demonstrate a significant reduction in mite numbers in North West England by using MVHR, primarily because RH was rarely reduced to below 60%. Warner *et al.* (2000), however did find that MVHR, coupled with daily vacuuming, reduced HDM populations and allergen concentration, but not to a low enough level for there to be significant improvements in asthma patients. Crane *et al.* (1998) found similar results in New Zealand where MHVR reduced humidity to below CEH for only 39% of the time and did not significantly reduce the HDM population.

Other UK studies have shown there may be some benefit in installing MVHR. Within a laboratory study, Htut *et al.* (1996) found that a MVHR unit exchanging air at a rate of approximately 3.5 air changes per hour maintained the RH at, or below, CEH for a period of 8 weeks. During this time the population of HDM was decreased to almost zero within 4 weeks. However, in subsequent summer months no reduction in humidity was possible using MVHR and mites levels increased. McIntyre and Edwards (1992) also found an overall reduction in HDM numbers within the bedroom carpet, although this too was under winter conditions and they did not consider the mattress population where fluctuations in temperature and humidity may still have favoured HDMS.

Other methods using changes in temperature and humidity to kill mites have also been attempted. Mosbech *et al.* (1988) and DeBoer (1990) both attempted to reduce mite populations using electric blankets (See The Bed Environment) whilst other studies have examined the effects of washing at high temperatures. McDonald and Tovey (1992) found washing bedding at 55°C killed all mites present whilst reducing the temperature to 50°C killed only half. Tovey and Woolcock (1994) demonstrated that exposing carpets to sunlight for 6 hours created a microenvironment lethal to mites, and when dust was removed from it and cultured no mites were present. Even a month later mite numbers were significantly lower in treated carpet compared to untreated carpet. However, such a strategy would only be suitable in warm climates and in houses where carpets or rugs could be removed. In Switzerland bedding is traditionally aired out of the bedroom window during the day. This exposure to sunlight may have the same effect in reducing mite numbers as Tovey and Woolcock (1994) have demonstrated in carpets.

It is likely that HDM control may not be achieved using only one of the methods outlined above, but will need an integrated strategy combining changes in occupant behaviour with changes in the heating and ventilation of the building, in particular the bedroom.

1.3. Sampling methods

It is difficult to compare HDM counts from different studies since methods used for collection and analysis of samples often vary.

Abbott *et al.* (1981) found brushing yielded significantly fewer mites than vacuuming for both mattress and carpet samples. Blythe *et al.* (1974) found similar results, but also noted differences in mite population structure with the smaller species and life cycle stages (larvae and nymphs) often being underestimated in brushed samples. For example, in samples from the same bed they found 59 pyroglyphid mites per 0.1g of dust from a brushed sample of which 36% were EM compared to 498 mites per 0.1g of dust, of which 74% were EM in vacuumed samples. More recently brushing has become a redundant method and samples are generally collected by vacuuming. However, Bischoff *et al.* (1992) reported that even vacuuming a 1m² area of carpet for 2 minutes may removed only 10% of the HDM population. Hay (1995) vacuumed the surface area of a sprung mattress and recorded a population density of 3-46 living mites m⁻², three orders of magnitude lower than the estimate of 8,200-26,800 m⁻² obtained by extracting mites from a core taken from the upper 1.5cm of the same mattress. This demonstrates, not only the inefficiency of vacuuming, but also that HDMs are not restricted to the mattress surface.

Live mites will use their hooked legs to cling to the substrate on which they reside and, although repeated vacuuming of an area has been shown to decrease the number of mites present (Hill 1998), it does not remove all living individuals. Live mites can be removed by exploiting their natural response to changes in light and humidity. To extract mites from textiles an adhesive film may be stuck to one side of the surface area and heat applied to the other. As the temperature increases mites will migrate away from the heat, since it decreases humidity, and towards the adhesive surface. The population of mites on the adhesive film can then be counted. This method has been shown to remove up to 65% of live mites present (Hill 1998). Tovey (Colloff 1991b) developed this method for use on surfaces where only one side can be accessed. Instead of applying a strong source of heat to the underside of the surface a hot water bottle is applied to the upper surface. The idea of this method is that the heat is mild so humidity is not significantly decreased, but mite movement is increased therefore making them more likely to be caught.

The application of heat can also be used to extract mites from precollected dust samples. Bronswijk (1973) found a Tullgren funnel extracted 40-60% of live HDMs. This method samples only live mites in a mobile state as opposed to other common extraction techniques such as flotation and suspension, which collect all stages. However, it does enable mites to be kept alive.

Estimates of population size based on numbers of mites per unit weight of dust are difficult to compare between habitats. Abbott *et al.* (1981), for example, reported that the surface of innersprung mattresses yielded similar number of mites per gram of dust to foam mattresses 746 and 706 mites g⁻¹ respectively. However, when the number of mites m⁻² was examined innersprung mattresses contained 2489 mites m⁻² compared to only 720 mites m⁻² in foam mattresses. This was due the mass of dust collected from the innersprung mattresses being over three times greater than that from foam mattresses. Floor dust will, in general, contain material that is heavier, such as sand and grit, than dust collected from a mattress and comparison of such data will give misleading results. Blythe (1976) recorded 276 mites 0.1g⁻¹ of dust in a

mattress and 16.9 in a carpet. However when he expressed this as number of mites 100cm^{-2} the carpet had higher numbers with 32 compared to 9.7 in the mattress. The number of mites per unit area is, therefore, a more satisfactory measurement for mites collected in different locations (although this still does not take into account the substrate thickness).

The position a sample is taken from may also influence the number of mites recovered. On mattresses it is known that dust distribution, and therefore the presence of HDMs, is influenced by the pattern of seams and buttons. For example, Blythe (1976) sampled a 10 x 10cm square of mattress with a seam running across the centre and found that over 80% of the mite population was collected from within 0.5cm of the seam.

2. HOUSE DUST MITE PHYSIOLOGY

The majority of work discussed below has been conducted under steady state laboratory conditions using cultured populations of house dust mites (HDMs). These have been maintained on a highly nutritious diet, under optimum conditions and results may therefore not be comparable to similar experiments on 'wild' HDMs. This is supported by Colloff (1987) who found significant differences between the development of eggs from laboratory and 'wild' HDM populations. In cool, dry conditions (20°C, 60% RH) laboratory eggs took longer to develop and mortality due to dehydration was 7 times higher than 'wild' eggs which appeared to be resistant to dehydration under these conditions. However, in warm, semi-humid conditions (30°C, 80% RH) eggs from the laboratory took less time to develop than 'wild' eggs and mortality was 4 times lower.

A considerable amount of research has concentrated on the American house dust mite, *Dermatophagoides farinae* (DF), however wherever possible this review concerns work conducted on the European mite *D. pteronyssinus* (DP).

2.1. General Ecology

DP females weigh approximately $5.8 \pm 0.2\mu\text{g}$ (fresh weight) whilst males are approximately half the size, $3.5 \pm 0.2\mu\text{g}$. A total of 72 and 74% of male and female weight is water, respectively (Arlian 1975a). Due to their large surface area to volume ratio the loss of water from the HDMs body surface by evaporation is a problem. However, they minimise this loss by having an impermeable exoskeleton and reducing water loss associated with body processes (See Water Balance)

At optimal conditions (23°C, 75% RH) development from egg to adult (DP) takes approximately 1 month. The duration of each developmental stage and the period of the quiescent phases are shown in Figure 2. Arlian *et al.* (1990) found no significant difference between development time of males and females, the lifespan of adult males was found to be 77 days compared with 45 for unmated adult females and 31 for mated adult females. At the end of each intervening active stage is a quiescent period lasting a third to half of the time of that life stage (Arlian *et al.* 1990).

During their adult lifespan DP females have been shown to produce between 40 and 80 eggs (Colloff 1987). DF females are able to live considerably longer than DP (100 and 31 days respectively), due to an extended post egg period. However, the reproductive period and number of eggs produced were similar for both species. After death the bodies of HDMs desiccate and are present as crisp, flattened flakes. They are persistent and often comprise up to 80% of the total mattress population.

There is some contention about whether DP forms a quiescent protonymph stage similar to the overwintering stage in DF. DeBoer and Kuller (1997) state that the quiescent stages within DP are "Relatively brief and never (as far as we know) prolonged". In a later paper DeBoer *et al.* (1998) reported that in the carpeted ground floor of Dutch houses, where temperature fluctuated around 16°C, DP adults remained active throughout the winter. Their population the following Spring was then built from these mature mites, rather than quiescent protonymphs. Eggs of DP have also been shown to remain viable after 7 months at 10°C, 60% RH and may therefore survive overwintering (Colloff 1987). However, Arlian *et al.* (1983) considered the seasonal dynamics of both *Dermatophagoides* species together. They found a seasonal variation in lifestages present with an increase in tritonymphs during

Spring followed by an increase in larvae as adults developed and their eggs hatched. However 63% of the homes they investigated were infested only with *DF* and none with only *DP* (Arlian *et al.* 1982). The increase in tritonymphs they observed during Spring may be due to *DF* being the dominant species and overwintering as a quiescent protonymph. In their work on the development of *DP* at different humidities Arlian *et al.* (1990) found quiescent protonymphs were not formed even at low humidities. However, the conditions under which their mites developed were otherwise favourable and the food supplied was highly nutritious (animal protein and yeast). They therefore suggest that the possibility should not be ruled out of an extended quiescent protonymph stage being triggered in certain circumstances, such as a combination of unfavourable RH, temperature, crowding and food supply.

If *DP* can form a prolonged quiescent protonymph stage, as in *DF*, this would ensure its survival during adverse conditions. The quiescent protonymph of *DF* consumes 28.5 times less oxygen per hour than an active protonymph and has a half life of water exchange of almost 160 days, compared to just 20 hours for an active protonymph and 28 hours for an adult (Arlian *et al.* 1983).

Pollen, spores of microorganisms, fungal mycelia, bacteria and skin scales have all been found in the gut of *Dermatophagoides* spp. (Bronswijk 1973). Several thousand mites are able to survive for months on 0.25g of food and since a person typically produces 0.5-1g of dead skin per day food quantity is not a limiting factor in mite growth and development (Korsgaard 1998). However, freshly shed skin may be dry and indigestible and mites therefore prefer older skin scales with a higher moisture content (Maunder 1990). Bronswijk (1981) reported that *DP* grew better on skin which had previously been partially digested by *Aspergillus amstelodami* than skin with no fungal treatment whilst Douglas and Hart (1989) concluded that no experimental studies provided definite evidence of this. However, they did show that small quantities of *A. penicilloides* may be of nutritional value as a source of nutrients (Douglas and Hart 1989; Asselt 1999).

2.2. Relative Humidity

Relative humidity (RH) is an important factor affecting HDM reproduction and survival. Critical Equilibrium Humidity (CEH), for *DP*, is 73% at 25°C, below which transpiration of water from the mite to the atmosphere is greater than the sorption of water by the mite from the atmosphere and dehydration occurs (Arlian 1992). Above CEH water is gained by sorption and an active mechanism (See Water Balance). Arlian (1975b) suggests that CEH is not a single value, but is more likely to cover a range of humidities across a transition period during which gradual physiological changes occur to maintain water balance.

A low RH may cause a decline in the HDM population. At 40-50% RH individual adults survived for no longer than 8-11 days, however a population consisting of all life stages survived for 10 weeks, but decreased in numbers (Arlian *et al.* 1998). Increasing RH to above 85% may also be detrimental to mite populations. Mould growth under these conditions may inhibit mite survival either directly due to its physical presence or via the production of toxins (Arlian *et al.* 1998, Asselt 1999). A fluctuating environment with periods of high RH to maintain their water balance and low RH to minimise mould growth may therefore be preferred by mites (Arlian *et al.* 1999).

A number of studies performed *in situ* measure RH or temperature at a single point in space and at set times during the day (e.g. Korsgaard 1983) or consider mean readings over a period of time (e.g. Arlian *et al.* 1983; Htut *et al.* 1996). Such measurements may not be good indicators of mite survival since CEH needs only to be exceeded for part of the day to enable egg production and a population increase to occur. If only mean values for RH and temperature are recorded these periods of optimal conditions may be overlooked. DeBoer *et al.* (1998) found *DP* populations survived for 10 weeks at 16°C when 1.5 hours of moist air (76%) was given to them per day (remainder of the day 36%), although egg production did not occur unless the period of moist air was increased to at least 3 hours and a population expansion was not possible until 6 hours of moist air was given. Decreasing the period of moist air caused the egg to adult development time to increase (Arlian *et al.* 1998). For example, when *DF* eggs were exposed to 75 % RH for 8 hours and 0 % RH for the remainder of the day development from egg to adult took 69 days compared to 44 days when exposed to 75 % for 24 hours. This increased development time would lead to a decline in population levels and therefore a decrease in faecal pellets and allergen.

Adult male HDMs have a higher water turnover rate and are more susceptible to death at dehydrating conditions than females (Arlian 1975a). They have been shown to cluster in groups of 5 to 25 to decrease their surface area to volume ratio and minimise water loss. Glass *et al.* (1998) found isolated males lost 2.63% of their body water per hour compared to 1.48% when clustered in a group of 6. Arlian *et al.* (1998) reported differences in the sex ratio of HDMs depending on the RH under which populations developed. At a constant 75% RH male to female ratio was approximately 50:50, but when RH was 75% for 8 hours per day and 0% for the remainder of time three quarters of the eggs developed into males. Females are more resilient at low RHs than males and are therefore more likely to survive a reduced RH. This shift towards the production of males may therefore be a mechanism to maintain an even sex ratio.

Bronswijk (1973) showed seasonal fluctuations in the abundance of HDMs mirrored changes in the absolute indoor and outdoor humidities (Figure 3) whilst Arlian *et al.* (1983) found a significant correlation between mite abundance and RH ($p < 0.01$). In both cases increased populations occurred during periods of increased humidity. During the humid summer months Arlian *et al.* (1983) found live mites constituted 90% of the population compared with less than 50% during winter. Korsgaard (1983) demonstrated that humidity levels during the winter months were critical in controlling HDMs. His study showed homes with very few mites during the winter months also had low counts during other seasons despite an increased humidity. In general HDM populations within the UK have been shown to peak during late summer (Blythe 1976; Hunter *et al.* 1996). However, although Carswell *et al.* (1982) recorded a peak in EM abundance at this time of year, *DP* reached its maximum population between March and May.

At a microclimate level mite survival is not dependent on absolute humidity. At 20°C, 79% RH and 27°C, 56% RH the absolute humidity is equal, but under the latter conditions mites die.

2.3. Water Balance

HDMs obtain their water in 4 ways:-

1. Ingestion with food,
2. Production of metabolic water from the oxidation of carbohydrates and fats,
3. Passive absorption,
4. Active absorption from unsaturated air via the “pump” (see below).

Water is simultaneously lost:-

1. By transpiration or evaporation to ambient air from the pump,
2. By evaporation through the permeable surfaces of the body,
3. In digestive secretions and reproductive fluids,
4. During other functions such as feeding, excretion and oviposition (Arlian 1992).

The moisture content of the food that mites eat tends to be in equilibrium with ambient air and Arlian (1977) reported that both feeding rate and water intake were directly influenced by ambient RH (see Table 2). Below CEH mites consumed less than 5% of their body weight per day, compared to 10-51% above CEH.

| RH % | Food consumed /day/mite g (dry weight) | % of body weight | Water obtained g |
|---------|-------------------------------------------|------------------|---------------------|
| 22.5 | 0.05 | 0.9 | 0.003 |
| 65 | 0.25 | 4.8 | 0.035 |
| 75 | 0.51 | 10.3 | 0.088 |
| 85 | 2.44 | 50.9 | 0.510 |

Table 2: Feeding rates and water consumed by DP when fed on yeast at specific RHs (from Arlian 1977)

The higher feeding rates at higher RHs resulted in proportionately higher faecal production. Arlian (1992) surmised that the higher nutritional intake is also likely to result in increased reproduction and egg laying. He pointed out the significant potential benefits that would thus result from reducing RH from 85% to 75%. Even though this is still above CEH, the weight of food (yeast) consumed would be reduced by nearly 80% from 2.95µg per mite per day to 0.60µg, which in turn would lead to a commensurate decline in egg production, a reduction in population levels, a decrease in faecal production and therefore a lowering of *Der p1* allergen levels.

However, even at 85%RH, Arlian (1977) found that the rate of water sorption from food (µg/h) was only 16% of total water intake (for DF), which fell to less than 5% at 75%RH. For DP, Arlian (1977) reported that below CEH water gained by feeding was less than 9% of that transpired. Nonetheless, feeding below CEH may supply HDMs with at least some water in certain circumstances. When confronted with a dehydrating environment where food is readily available mites may chose to feed or fast. He suggested that feeding may be motivated by the mite's water balance rather than hunger. If sufficient water for survival can be gained by feeding mites may feed even if not hungry, but if sufficient water for survival cannot be gained during feeding mites may change their behaviour to minimise water loss or move to more favourable conditions. but above CEH water gained by feeding made up a significant part of the total water gained. However above CEH this water would be surplus since enough is taken up by sorption alone.

HDMs may obtain some metabolic water from the oxidation of carbohydrates and fats although this is unlikely to be a significant method of water production (Arlian 1977).

An idea of the combined effect of the different methods of water sorption for DF is provided by Wharton (1978), calculated from observations of Arlian and Wharton (1974) – see Table 3. It was found that once fully hydrated at CEH (70% at 25°C for DF) and above, DF’s water mass was constant for all values of RH, rates of sorption being balanced by rates of transpiration. According to this model, active sorption from the “pump” contributes nothing below CEH, but at CEH it provides more than 50% of the total water requirement. Thereafter, as RH increases, the contribution of the pump falls away to about a third at 100% RH.

| Ambient RH | Total water mass | Calculated water mass sorbed passively | Calculated water mass sorbed actively |
|------------|------------------|----------------------------------------|---------------------------------------|
| % | µg | µg | µg |
| 0.0 | 0.000 | 0.000 | 0.000 |
| 22.5 | - | 1.480 | 0.000 |
| 52.5 | - | 3.452 | 0.000 |
| 70.0 | 9.589 | 4.603 | 4.986 |
| 75.0 | 9.589 | 4.932 | 4.657 |
| 85.0 | 9.589 | 5.589 | 4.000 |
| 92.5 | 9.589 | 6.083 | 3.506 |
| 100.0 | 9.589 | 6.576 | 3.013 |

Table 3: Observed total water masses for DF at 25°C for different ambient RHs and the calculated contribution of the passive and active components of sorption (from Wharton 1978).

The active uptake of water is associated with the paired supracoxal glands (internal, posterior to legs I). They secrete a hygroscopic salt solution containing NaCl and KCl (Wharton *et al.* 1979) which flows down a duct to an opening above legs I and onto the supracoxal plate (Figure 4). The solution then flows along the podocephalic canal, an open groove in the supracoxal plate, and across the palps to the prebuccal cavity. This has deep grooves thereby enlarging its surface area. As it flows the solution absorbs more water from the air than it loses by evaporation, as long as RH exceeds CEH. This water enriched solution is then removed from the prebuccal cavity into the pharynx, by the pharyngeal pump. It is then pumped through the oesophagus to the gut where water and salts are absorbed through microvilli and pass into the haemolymph (liquid part of blood). The supracoxal glands are bathed in haemolymph and reabsorb the salts for the cycle to begin again. A minimum of 0.2µg of salt is present within the solution (Wharton *et al.* 1979).

Below CEH water is lost to the air from the solution as it travels along the podocephalic canal. As the water content decreases solutes precipitate out making the glands less permeable and eventually forming a plug at the duct opening, therefore blocking them to prevent further water loss (Wharton *et al.* 1979). This build up of salt causes feeding and movement to be considerably reduced below CEH (Arlian 1977). Arlian and Wharton (1974) observed that, in DF, it took 14 hours for transpiration from the pump to become negligible. Once humidity increases to above CEH again the hygroscopic nature of the material enables water to be reabsorbed, the salt deliquesces and flow is resumed. Wharton *et al.* (1979) found that on moving dehydrated DF to moist air approximately 3 hours was required for rapid uptake of water to begin. However they give no values for the humidities used.

When water losses and gains within the HDM are equal their water mass remains constant. However, a net loss of water will occur when transpiration is greater than sorption and a net gain of water when sorption exceeds transpiration. Arlian and Wharton (1974) noted that when DF was kept above CEH the pump operated at full capacity, below this value it cut off completely. Above CEH the uptake of water, at a constant temperature, is proportional to RH since it is dependent on the number of water molecules present in the air. Therefore predessicated mites will rehydrate faster at 95% RH than 70% RH (Arlian 1992). The loss of water is unrelated to RH, but is a fixed percentage of the volume of water remaining within the body and the permeability of the cuticle (Arlian and Wharton 1974). However, above CEH transpiration appears to be proportional to RH as it compensates for water sorption.

When mites containing tritiated water are exposed to non-tritiated atmospheres at low RH their tritium content has been shown to decrease more rapidly during the initial hours than later hours (Wharton 1978). Below the CEH there are, in effect, 2 water compartments within HDMs which lose water at different rates – a small compartment (water in the pump) which loses water rapidly to enable waterproofing to commence and a larger, slow compartment (water in the main body) (Figure 5). A fully hydrated female contains approximately 9.6 μ g of water, of which 3 μ g is present in the small compartment (Arlian and Wharton 1974; Wharton *et al.* 1979).

Above CEH the pump and body function as a single water compartment and water is no longer lost from the pump. However, 2 compartments have been identified at both 40 and 75% RH in DP , despite 75% being above CEH and therefore a humidity at which water should not be lost from the pump (Arlian 1975b). It may be that 75% RH is so close to CEH that the pump is not fully functioning. This supports the idea that there is a range of RHs over which an organism makes physiological changes to maintain its water balance, rather than a single CEH value.

Active life stages of the HDM are able to actively extract water from unsaturated air to replace that lost from the body, provided RH exceeds their CEH. The energy expenditure to maintain water balance is relatively small. For example, in order to sorb water at 8 μ g hr^{-1} DF uses 0.08-0.12% of the calories it generates at 25°C, 75% RH (Arlian 1975b). If RH is increased a lower % of calories are used since the vapour pressure against which water must be moved is lower.

Under dehydrating conditions HDMs show a reduction in oxygen consumption which is greater than the decrease accounted for by reduced activity at these RHs. Gaseous exchange is likely to occur across the same surface as water exchange and, since these surfaces become waterproofed at low RHs there is a reduction in gas exchange and an associated decrease in oxygen consumption (Arlian 1975a).

2.4. Influence of Temperature

A decrease in temperature leads to an increase in mean development time of HDMs at all stages of the life cycle as shown in Figure 6 (Arlian *et al.* 1983; Colloff 1987). Increasing the temperature from 23 to 35°C has been shown to accelerate development by 2.3 times (Arlian *et al.* 1990). Despite this, greatest population growth for DP occurs at 25°C and 75% RH since higher temperatures also affect other survival factors. At 35°C, for example, both fecundity and longevity were significantly reduced compared with 23°C (Arlian *et al.* 1990).

Extremes of temperature may have adverse effects on a population. Periods at very high temperatures, e.g. 6 hours at 51°C or 24 hours at 45°C (both at 60% RH) will cause the death of *DP* (Kinnaird 1974). However this species is relatively resistant to low temperatures with a 6 hour exposure at -15°C resulting in only 60% mortality (compared with 100% mortality in *DF*) and 100% mortality not occurring till -28°C. Increasing the time of exposure to cold conditions causes an increase in mortality, with only 15% of individuals surviving following a 3 week exposure at -1°C (Bronswijk 1981).

Arlian and Dippold (1996) examined the effect of temperature on the life cycle of *DF* and compared it to a similar study on *DP* (Arlian *et al* 1990). They found that *DP* was able to develop under a far wider range of temperatures than *DF*. Both species were able to develop at 25 and 30°C, but at 16°C only 2% of *DF* developed compared with 59% of *DP* whilst at 35°C development was 15 and 87% respectively.

As temperature increases CEH also rises (Arlian and Veselica 1981). This is likely to be the result of the properties of the hygroscopic solution of NaCl/KCl and the fact that its saturated vapour pressure is different at different temperatures (See Appendix – to follow). Varying temperatures also affect the permeability of the transpiration surfaces with the cuticle being more permeable and therefore losing water more rapidly at higher temperatures (Arlian and Veselica 1982). It is possible that transpiration is more affected by temperature than the active mechanism. However, this has not been studied in depth.

When subjected to increasing temperatures at an RH of 50% *DP* females showed a decrease in the time to achieve 100% mortality (Table 4) (Arlian 1975a). However when the RH was increased to 75% at 25°C and 34°C survival time was increased to 97% after 9 days and 68% after 12 days respectively. From this it appears that RH is more important than temperature in determining the length of mite survival.

| Temperature (°C) | RH (%) | LT ₁₀₀ (days) |
|------------------|--------|--------------------------|
| 25 | 75 | ** |
| 28 | 50 | 10 |
| 31 | 50 | 8 |
| 34 | 50 | 6 |
| 34 | 75 | *** |

** 97% survival after 9 days.

*** 76% survival after 8 days, 68% survival after 12 days.

Table 4 The time taken to achieve 100% mortality (LT₁₀₀) in populations of *DP* adult females exposed to different combinations of temperature and RH (Reproduced from Arlian 1975a).

2.5. The Bed Environment

Hughes and Maunsell (1973) reported that when a bed was occupied the relative humidity fell due to the heat given off by the human body. Cunningham (1998) demonstrated that whilst a bed was occupied the temperature of the sheets beneath the occupant reached around 35°C whilst RH fell to less than 50%. If these conditions were continuously maintained in the lab a population of HDMs would decline, however fluctuations in RH and temperature within the bed creates periods of suitable conditions for their survival. Andrews *et al.* (In Press) found no significant difference in mortality between individuals of *DP* kept in a steady state at 26°C, 76% RH and those maintained for 7 days in a simulated bed environment of fluctuating temperature and RH as measured from the sheet under the occupant (Figure 7).

DeBoer and Kuller (1997) measured changes in temperature and RH of a mattress before, during and after a bed was occupied for 90 minutes (Figure 8). When the bed was unoccupied RH 4.5cm under the upper surface of the mattress was above CEH therefore enabling mite survival. However, once the bed was occupied temperature immediately under the occupant increased and, even with the extra moisture from the occupant, there was insufficient to maintain the RH above CEH due to the increase in temperature. The bed immediately under the occupant therefore appeared to be more suitable for mites when unoccupied. Once the person leaves the temperature decreases and excess moisture from their presence may provide a period of high RH sufficient for egg production and development (3 hours; DeBoer *et al.* 1998) even if it subsequently declines to below CEH. Therefore although the bed is unsuitable whilst occupied it is the presence of a body for a period of time which creates an optimum habitat.

Koekkoek and Bronswijk (1972) recorded the temperature and RH in the lower part of the pillow case (Table 5). They reported an increase in both temperature and absolute humidity (AH) during the beds occupation, with similar patterns of change occurring during Autumn (October/November), Winter (January/February) and Spring (March). They found that the increased AH was large enough to cause an increase in RH, despite the rise in temperature. This is in contrast to Cunningham (1998) and DeBoer and Kuller (1997) who both recorded a decline in RH near the occupant. However in their studies the RH of the unoccupied bed exceeded CEH, whilst Koekkoek and Bronswijk (1972) found CEH of the bed prior to occupation was exceeded only during Autumn, when RH was far greater than the two other seasons.

In the above studies measurements of RH and temperature were taken directly below the occupant or beneath the pillow, but no consideration was given to differences across the mattress surface although the presence of a body will undoubtedly cause temperature and moisture gradients to occur.

| Location | Time | Variable | Dates | | |
|----------|---------|----------|------------------|---------------|----------------|
| | | | 26/10 – 10/11 | 20/1 - 2/2 | 15/3 - 24/3 |
| Room | 24 hr | Temp °C | 14 | 14 | 20 |
| | Average | RH % | 90 | 52 | 46 |
| | | Abs g/kg | 9 | 5 | 7 |
| Pillow | 19.00 | Temp °C | 15 | 14 | 20 |
| | | RH | 78 | 56 | 53 |
| | | Abs g/kg | 8 | 5 | 8 |
| | 03.00 | Temp °C | 26 | 28 | 29 |
| | | RH | 84 | 64 | 58 |
| | | Abs g/kg | 18 | 16 | 15 |
| | 11.00 | Temp °C | 16 | 16 | 20 |
| | | RH | 79 | 57 | 53 |
| | | Abs g/kg | 9 | 6 | 8 |

Table 5 Changes in mean temperature and RH in bedroom air and between the pillow and mattress for an occupied during three periods, Autumn, Winter and Spring 1970-71. Pillow measurements shown before, during and after occupation of the bed (Adapted from Koekkoek and Bronswijk 1972 and Bronswijk 1981).

Bronswijk (1973) noted that dust was only found to a depth of 12mm within a mattress and concluded it was therefore unlikely that mites were present at a greater depth. Hay (1995) found DP throughout the top 1.5 cm of a sprung mattress (at greater depths the mattress became hollow) and reported that the population was evenly distributed through this depth. However in a 12 year old foam mattress DeBoer and Kuller (1994) found suitable food present to a depth of 20mm and a few mites survived in the centre of the mattress. In a study on the horizontal distribution of dust mites Mulla *et al.* (1975) found considerably more towards the edge rather than the centre of a mattress (Figure 9). This was generally due to changes in the number of dead mites and may have been caused by their accumulation at the mattress edges rather than the movement of live mites to optimal conditions.

Exposing the mattress to unsuitable temperature and humidities have both been experimented with as methods to control HDM populations. By placing an electric blanket on a bed DeBoer (1990) forced HDMs to migrate away from the upper mattress layers, but in areas which the blanket did not cover mites were still present throughout all layers. He concluded that electric blankets reduced the population of HDMs by 19-84% directly beneath the electric blanket, but did not consider horizontal movements of mites to uncovered areas. Similar reductions in mite numbers and a decline in allergen concentration were found by Mosbech *et al.* (1988) when using an electric blanket in conjunction with regular vacuuming. However, they state that the reduction may have been due to mites migrating to the mattress interior rather than their removal and consider the decline insufficient to benefit allergic patients already possessing infected mattresses. Hart and Whitehead (1990) also reported on difference between HDM population size in beds with and without electric blankets, possibly due to the blankets being turned on for a shorter period of time than either of the above studies.

3. HYGROTHERMAL ENVIRONMENT IN BEDS AND BEDDING

3.1. Modelling

There exists a vast range of hygrothermal models that can be used to examine the environmental conditions in buildings. These models range from very simple steady-state calculations to very complex transient models requiring a significant amount of numerical analysis and the use of computers.

Various simple steady-state thermal and moisture models have been published (Loudon 1971) (BSI 1989) (CEN 1997) and are generally easy to use. However, due to their crude nature they require relatively little input data and provide crude predictions of environmental conditions. More complex hygrothermal models have been produced including models that account for moisture absorption and desorption (Jones 1993, 1995), models which incorporate more sophisticated thermal models, such as the BREDEM-12 model (NES 1994), and complex transient models which account for a large number of input parameters (El Diasty et al 1992, 1993) (Letherman 1988, 1989) (Isetti et al 1988) (Kusuda 1983) (De Wit 1990) (Gan 1996) (Kerestecioglu et al 1989).

Reviews of computer based combined heat, air and moisture models for building analysis have been carried out (Trechsel 1994) (IEA 1996). Altogether, thirty-seven models from Europe and North America have been described and arranged into nine classifications according to model complexity. The nine classifications, the models, their dimensionality and their country of origin are shown in Table 6 below.

| <i>Classification</i> | <i>Model name</i> | <i>Dimension</i> | <i>Country</i> |
|---------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Type 1:</i> Steady-state Glaser scheme of heat conduction and vapour diffusion with constant material properties | WAND HYGRO BRECON 2 | 1D 1D 1D | Belgium Netherlands UK |
| <i>Type 2:</i> Steady-state Glaser scheme of heat conduction and vapour diffusion, corrected for capillary moisture transfer | GLASTA COND | 1D 1D | Belgium Germany |
| <i>Type 3:</i> Non steady-state heat and vapour transfer | HAMPI | 1D | Canada |
| <i>Type 4:</i> Non steady-state heat, vapour and liquid transfer | HMSOLVER LATENITE MATCH LTMB CHEoH TONY V30 V320 WFTK WUFIZ JOKE HYGOTHERAN P1200A VADAU FUKT 74:6 NEV 3 MOIST | 2D 2D 1D 1D 2D 2D 1D 2D 1D 1D 2D 1D 1D 1D 2D 1D 1D 1D | Belgium Canada Denmark France France France France France Germany Germany Germany Israel Sweden Sweden Sweden Slovakia USA |
| <i>Type 5:</i> Steady and non steady-state heat and air transport | NATKON WISH 3-D ANHCOMP | 2D 3D 2D | Belgium Netherlands Sweden |

| | | | |
|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|----------------------|---------------------------------------------|
| <i>Type 6:</i> Steady-state heat, vapour and air transport, constant materials properties | KONVEK EMPTEDD | 3D 1D | Belgium Canada |
| <i>Type 7:</i> Steady-state heat and air transfer and non steady-state vapour transfer | WALLDRY | 1D | Canada |
| <i>Type 8:</i> Non steady-state heat, vapour and air transfer, material properties a function of moisture and temperature | HAM TCCC2D HORSTEN ID-HAM | 1D 2D 2D 1D | Belgium Finland Netherlands Sweden |
| <i>Type 9:</i> Non steady-state heat, vapour, liquid and air transfer, material properties a function of moisture and temperature | HYGRAN24 WALLFEM TRATMO2 DIM25 | 1D 1D 2D 2D | Belgium Canada Finland Germany |

Table 6 - Heat, air and moisture transport models (IEA 1996)

The large majority of these models remain research tools that are not generally available within the public domain. Eight of the models are commercially available including GLASTA, EMPTEDD, MATCH, COND, ANHCOMP, ID-HAM, BRECON 2 and MOIST (IEA 1996).

The BRE Domestic Energy Model (BREDEM) is a thermal model that has been developed over the last 20 years and is used to predict the energy consumption in dwellings. The BREDEM models account for two different zones within a dwelling, zone 1 which is the living room, which is heated to a higher temperature than the rest of the house which is zone 2. There are currently three versions of BREDEM mainly in use including BREDEM-8, a monthly model, BREDEM-12 an annual model, and BREDEM-9, a simplified single zone annual version which forms the basis of the Standard Assessment Procedure (SAP) for Building Regulations compliance.

The BREDEM-8 model has recently been developed to include a steady-state moisture model (Loudon 1971) which allows the prediction of the average monthly relative humidity in both zones of a dwelling (Pretlove 2000). A description of the development and application of this model has been published (Oreszczyn and Pretlove 1999). The BREDEM-8 Loudon model has been shown to predict the average monthly relative humidity in a dwelling with a reasonable level of accuracy. The BREDEM-8 Loudon model has a number of significant advantages over other simple models:

- The model has been developed to predict the average airspace relative humidity in both zones in a dwelling and also the micro-environmental conditions of relative humidity at surfaces.
- The model predicts hygrothermal conditions on a monthly basis, which allows the variations in seasonal relative humidity to be examined.
- A moisture production rate algorithm has been incorporated, which accounts for all of the relevant categories of moisture production using a minimum number of input parameters.
- Regional climatic data (temperature and vapour pressure) is incorporated into the model and therefore geographical variations in relative humidity can be examined.

The BREDEM-8 Loudon model also has a number of limitations:

- The model is unable to predict what will happen in an individual bedroom. It has to be assumed that the average bedroom conditions will be those relating to zone 2.
- Steady-state conditions are assumed, even though in reality conditions in a dwelling will constantly be varying.
- The ventilation rate algorithm is crude, even though it is known that ventilation is a key parameter affecting the relative humidity in a dwelling. The ventilation rate is assumed to be constant throughout the dwelling and throughout the year.
- Moisture generation is assumed to be the same in all areas of the dwelling, which is unlikely to reflect the different zones of moisture concentration.

3.1.1. Beds

Based on experimentally measured data and simplifying assumptions Cunningham (1999) produced an analytical model of the microclimate within a bed, developed specifically to investigate the microhabitats of bio-contaminants. This one-dimensional model treats the bed as a homogeneous slab of finite depth. The model allows transient temperature, and vapour pressure to be calculated as a function of depth within the bed for the time period immediately after occupation.

Vapour pressure is assumed to be the moisture driving potential. The model assumes linear gradients of temperature and vapour pressure as initial conditions and boundary conditions of constant temperature and vapour pressure at the top and bottom of the bed. These assumptions are justified by the experimental data, with temperature and vapour pressure at the top of the bed being relatively stable after occupation.

Initial conditions; Linear gradients of temperature, T, and vapour pressure, P

$$T(t=0) = T_{\text{start}} - (T_{\text{start}} - T_{\text{bottom}})x/l \quad \text{and} \quad P(t=0) = P_{\text{start}} - (P_{\text{start}} - P_{\text{bottom}})x/l$$

Boundary conditions; Constant temperatures and vapour pressure at top and bottom of bed

| | | |
|--------------|----------------------------|----------------------------|
| Occupied bed | $T(x=0)=T_{\text{start}},$ | $T(x=l)=T_{\text{bottom}}$ |
| | $P(x=0)=P_{\text{start}},$ | $P(x=l)=P_{\text{bottom}}$ |

| | | |
|----------------|--------------------------|----------------------------|
| Unoccupied bed | $T(x=0)=T_{\text{end}},$ | $P(x=l)=T_{\text{bottom}}$ |
| | $P(x=0)=P_{\text{end}}$ | $P(x=l)=P_{\text{bottom}}$ |

The top of the bed has depth, $x=0$, the bottom $x=l$. T_{start} is the initial temperature at the top of the bed and T_{bottom} the initial temperature at the bottom of the bed. T_{end} is the final temperature at the top of the bed following occupation.

The differential equations governing transfer of heat and moisture are written in terms of dimensionless constants. The equations are solved by standard methods. Values are chosen for these dimensionless quantities to fit the predicted to results to the experimental data.

The comparison between experimental and calculated relative humidity in the bedding was found to be good at the upper surfaces of the bed, and poorer in the central sections. This is to be expected as the conditions at the surfaces are set by the boundary conditions. The limitation of Cunningham's model is that it uses fixed boundary conditions, it can only be applied to the bed after occupation, and effectively only models the time taken to reach an equilibrium of moisture and temperature within the bed after the switch of boundary conditions. It cannot be used to model the bed after disoccupation or used with varying boundary conditions, it is reliant on fitting the model to experimental data to estimate the dimensionless variables needed to solve the equations. The interesting aspect of the work is the assumption, based on experimental observation that the temperature and vapour pressure directly below the occupant are fixed. The methods of solving the differential equations are very simple and limited by the assumption of fixed boundary conditions, yet the model shows that the interior of the bed can be modelled by applying the driving equations of transfer of heat and mass.

The mathematical methods used by models more commonly used to investigate moisture movement in building elements when exposed to varying temperature and RH at the internal and external surface could be used to model the bed environment, however the hygrothermal properties of the bedding would be needed.

3.1.2. Bedrooms

The environmental conditions of temperature and relative humidity in a bedroom are significantly different to other rooms within the same dwelling. Bedrooms are generally occupied over night when the rest of the dwelling is unoccupied and when the heating system is not being used. The living room area in a dwelling is generally heated to a higher temperature than the rest of the dwelling during periods of occupancy in the heating season.

Few hygrothermal models account for different spaces within the same dwelling and are generally used to predict average conditions within the whole dwelling over a period of time. The current British Standard for condensation in buildings, BS5250: 1989 (BSI 1989), incorporates a very crude method for predicting the relative humidity and is unable to account for separate spaces within a dwelling. Models that predict average dwelling conditions tend to under-estimate the average temperature in the living room and over estimate the average temperature in the remainder of the house. As a result, predictions of relative humidity are over-estimated in the living room and under-estimated in the remainder of the house, which includes the bedrooms.

The BREDEM-8 Loudon model is able to predict the hygrothermal conditions in two zones within a dwelling and is therefore suitable as a tool for predicting the environmental conditions in the bedrooms in a dwelling.

3.2. Human physiology in beds

Although much is written about human physiology and comfort in buildings little work has been identified covering people in modern beds. Some work relating to people lying on top of beds which has been developed for patients undergoing operations. This is of little relevance to this study.

In the case of somebody asleep in a bed almost all the energy released by the oxidation process in the human body is converted into heat as very little is converted into mechanical motion. The bodies thermoregulatory system aims to maintain a constant internal body temperature (36.4 to 37.2C). Under steady state conditions this will result in an energy balance whereby the metabolic rate equals the bodies heat loss. Thus the metabolic rate when sleeping (41 W/m²) is equivalent to the following:

1. Heat loss by water diffusion through the skin
2. Sensible radiant and convective loss from the skin to the bed clothes
3. The heat loss by evaporation of sweat
4. Latent respiration heat loss
5. Dry respiration heat loss

The last two of these do not occur in the bedding unless the person sleeps with their head under the bedclothes and so can be ignored in most situations. Ideally bedclothes will be adjusted to prevent sweating and so this form of heat loss is ignored in conditions of thermal comfort (this factor needs checking – experimental monitoring in beds may help identify if this is true. This is supported by a statement in Fanger 1970, that sweating does not occur and the mean skin temperature is 33-34C for sedentary people. This only leaves 1 and 2 above.

Sensible radiant and convective heat loss

Measurements undertaken by Fanger show a mean surface temperature of 34.5C for thermal comfort to be achieved at low metabolic rates. The simplest assumption when modelling an occupied bed is therefore to assume all internal bedding has a boundary condition of a fixed temperature at 34.5C when occupied. Again this effectively assumes that the bedding is adjusted to maintain this comfort condition, i.e. less bedding in summer and more in winter. In practice this will not always happen a more sophisticated model would adjust the temperature to accommodate the metabolic heat gain.

Heat loss by water diffusion through skin

This is not subject to thermoregulatory control but is simply controlled by the vapour pressure difference across the skin and the vapour resistance of the skin. This vapour resistance has been measured by Inouye et al for sedentary subjects under comfort conditions at $7.9 \times 10^8 \text{ Ns kg}^{-1}$ (Source: Fanger, "Thermal Comfort", 1970). The skin vapour pressure is simply the saturated vapour pressure at the skin temperature 34.5C for low metabolic activity.

Note, significant variations from the steady state may occur in beds. Primarily associated with preconditioning of the bed or body before the subject goes to sleep. For example, taking a hot bath before going to bed results in considerable heat storage in the human body which is subsequently released in the bed thereby adding to the metabolic heat gains within the bed. Alternately we have all experienced the discomfort associated in getting into a cold bed, or getting into bed after rapid exercise.

In addition, the circadian rhythm results in a daily variation (0.3 to 0.5C) in the bodies core temperature with the maximum occurring before going to sleep and the minimum some time before awakening. It also appears that during D-sleep, which typically accounts for 20% of sleep time in adults rising to 50% in new-born children, our core-temperature is hardly controlled and so we operate similarly to cold-blooded creatures, (Microsoft Encarta, 1997)! The above simple steady state analysis will therefore only be applicable to adults

Typical sleep patterns ranging from 16-18 hours for new born babies to 7 to 8 hours in adulthood. Source: Microsoft Encarta 97.

3.3. Hygrothermal properties of beds and bedding

The process of developing a model requires the adoption of equations that address the conservation of mass, energy and momentum and represent physical transport processes. The use of transport equations introduces the need for transport properties of the medium, and the use of conservation equations requires the introduction of capacitive and storage properties. These properties must be determined by experimentation. Therefore the success of the model depends on both the detail and sophistication of the mathematical formulation, and the accuracy of the physical properties of the materials. The aim of such models is to calculate Temperature and Moisture Content within the material. An excellent review and database of material properties used in hygrothermal models is given by IEA (1996) in Task 3 of Annex 24.

Moisture content may be defined in three ways:

- i) Mass of moisture per unit volume of the dry material, w , kg.m^{-3}
- ii) Mass of moisture per unit mass of the dry material, u , kg.kg^{-1}
- iii) Volume of condensed moisture per unit volume of the material, ψ , $\text{m}^3.\text{m}^{-3}$

The material properties required for the most simple hygrothermal modelling are:

| Property | Symbol | Unit |
|------------------------------|------------|-------------------------------------------------|
| Density of dry Material | ρ | Kg.m^3 |
| Thermal Conductivity | λ | $\text{W.m}^{-1}.\text{K}^{-1}$ |
| Specific Heat capacity | c | J.kg.K^{-1} |
| Thermal Diffusivity * | a | $\text{m}^2.\text{s}^{-1}$ |
| Vapour permeability | δ_p | $\text{Kg.m}^{-1}.\text{Pa}^{-1}.\text{s}^{-1}$ |
| Sorption isotherm Function | F | Kg.kg^{-1} |
| Specific Moisture Capacity * | ξ | $\text{Kg.kg}^{-1}.\text{Pa}^{-1}$ |
| Moisture Diffusivity * | D_w | $\text{m}^2.\text{s}^{-1}$ |

* Note : Thermal Diffusivity can be calculated from thermal conductivity and specific heat capacity, Specific Moisture Capacity can be calculated from the sorption isotherm function. Moisture Diffusion can be calculated from specific moisture capacity, vapour pressure, moisture permeability and dry density.

The isotherm function F gives the moisture content within the material as a function of Relative Humidity θ . It is the equilibrium moisture content that the material would have when exposed to a constant relative humidity. The specific moisture capacity is the derivative with respect to relative humidity of the sorption isotherm.

More complex models include capillary and suction force acting on liquid water and require more data. The properties of most importance are dry density, thermal conductivity and specific heat capacity; these are the most readily available, vapour permeability and the sorption isotherm are the most important properties as regard moisture movement. The greater the number of points on the sorption isotherm curve, the greater the accuracy, similarly it is an advantage to know how all properties vary as a function of both temperature and more importantly relative humidity or moisture content.

It must be noted that most hygrothermal models have been developed to model moisture movement in construction materials such as bricks and concrete. To produce a hygrothermal model of the bed environment data is required on the hygrothermal properties of bedding and textiles.

An excellent source of the above properties for the materials encountered in bedding and mattresses is the book *Physical Properties of Textile fibres*, W.E. Morton and J.W.S. Hearle. All of the properties needed for hygrothermal modelling, or those, which can be used to derive all necessary properties, are tabulated for a number of synthetic and manmade fibres.

It is interesting to note that there exists a property of textiles that is almost identical in definition to the moisture isotherm function of building materials. This property is known as the regain of the textile

Regain (θ) % = kg of water/kg dry material * 100% at a given RH%

The one difference being that regains are commonly quoted as percentages where as moisture contents of construction materials and isotherms are usually quoted as kg/kg. As yet no good data source of the hygrothermal properties of the latex foams used in modern mattresses has been encountered.

3.4. Monitored bedroom conditions

Environmental conditions have been measured in a significant number of dwellings in the UK, and in other European countries, for the last 50 years. Although extensive data is available there are significant limitations with this data:

- Temperature is the main environmental parameter that has been measured in dwellings with relative humidity measurements forming a very small proportion of the data available.
- Most data has been collected in the living room or hall areas in dwellings and therefore the availability of bedroom data is very limited.
- Frequently, surveys are carried out in an attempt to assess problems such as dampness so that appropriate remedial measures can be taken. As a result, the conditions measured in these dwellings will not reflect conditions within the average housing stock in the UK.

The largest survey of English dwellings, carried out every five years, is the English House Condition Survey (EHCS). The EHCS Energy Report, which contains data relating to home temperatures, for the most recently published EHCS (DETR 1998) has yet to be published and therefore the latest data available relates to the EHCS survey carried out in 1991 (DoE 1996). During the EHCS survey of 1991 temperatures were measured inside and outside each dwelling. Relative humidity was not measured, although assessments of dampness and condensation were made as part of the survey.

In the EHCS temperature survey two internal temperatures and one external temperature was measured at each dwelling location. The period of measurement was from February to May 1992. The internal temperature was generally taken in the living room and in the hall, the latter being viewed as a good indicator for the mean temperature of all rooms. The average external temperature measured during the survey was 11°C. The average temperature in the living room was measured as 19.5°C and in the hall 18.3°C. A number of important conclusions were made as a result of the temperature survey:

- Tenure is significant with the average temperature measured in Housing Association and Local Authority dwellings approximately 1°C higher than the average temperature measured in owner occupied dwellings.
- Dwelling age is also significant, with older dwellings found to be colder than new dwellings.
- No significant differences in internal temperatures were found at different geographical regions within England.

A national survey of home temperatures carried out between 1972 and 1982 in one thousand dwellings during the heating season found that the mean living room temperature was 18.3°C and the bedroom 15.2°C (Raw and Hamilton 1995).

Extensive monitoring of internal and external temperatures took place during a two year period at the Pennyland Project (Lowe et al 1985) in Milton Keynes. In 18 dwellings which were well-insulated the

average living room temperature was measured to be 17.8°C and the bedroom 16.5°C. In another 37 dwellings which had very high levels of insulation the average living room temperature was found to be 18.4°C and the bedroom 17.5°C.

Another extensive survey of environmental conditions in dwellings took place at the Milton Keynes Energy Park (MKEP) between 1988 and 1993. Altogether, 160 dwellings were monitored for fuel consumption and of these, 29 dwellings were more intensively monitored with hourly temperature and relative humidity being measured in the living room and hourly temperatures being monitored in the main bedroom and another room. The averages of the data collected during the heating season of October 1989 to May 1990 is summarised in Table 7 below.

| | <i>Temperature (°C)</i> | <i>Relative Humidity (%)</i> | <i>Vapour Pressure (kPa)</i> |
|---------------------|-------------------------|------------------------------|------------------------------|
| <i>Living Room</i> | 20.56 | 43.24 | 1.04 |
| <i>Main Bedroom</i> | 19.67 | - | - |
| <i>External</i> | 8.13 | 78.7 | 0.86 |

Table 7 - Environmental conditions in 29 intensively monitored dwellings a MKEP during the heating season Oct 1989 to May 1990

To summarise, although a great deal of environmental data has been collected in dwellings in the UK, this review has identified that of the very little bedroom data that exists it is primarily restricted to the temperature measurements only.

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Table 2: Abundance of Pyroglyphid mite species within the UK

| Study | Location | Sampling from Mattress / Floor | Total no. of samples* | % of mites Pyroglyphidae | % DP | % EM | % DF |
|--------------------------------|-----------------------|-----------------------------------|--------------------------|-----------------------------|------|------|------|
| Cunnington (1967) | London and S. Wales | Floor | 186 | 82 | 82 | 18 | - |
| Sesay and Dobson (1972) | Glasgow and Edinburgh | Mattress | 486 (60 beds) | 86 | 85 | 15 | - |
| Blythe <i>et al.</i> (1974) | Birmingham, UK | Mattress | 38 | 90 | 67 | 33 | - |
| Rao <i>et al.</i> (1974) | Cardiff | Mattress | 50 | 87 | 90 | 9.9 | 0.1 |
| Carswell, <i>et al.</i> (1982) | Bristol | Mattress | 51 | 76 | 83 | 17 | - |
| Colloff (1987) | Glasgow | Mattress ¹ | 33 (23 homes) | 95 | 93.7 | 6 | 0.3 |
| Colloff (1987) | Glasgow | Mattress | 32 (20 homes) | 95 | 68 | 32 | - |
| Colloff (1987) | Glasgow | Bedroom floor | 27 (23 homes) | 83 | 98 | 2 | - |
| Hart and Whitehead (1990) | Oxfordshire | Mattress & Floor | 60 | 96 | 77 | 23 | - |
| McIntyre & Edwards (1992) | South Wales | Bedroom carpet | 11 | 97 | 98 | 2 | - |
| Hunter <i>et al.</i> (1996) | Avon | Living room carpet | 183 (35 homes) | 97.2 | 99.6 | 0.4 | - |
| Hunter <i>et al.</i> (1996) | Avon | Bedroom carpet | 180 (35 homes) | 96.6 | 98.7 | 1.3 | - |

DP *Dermatophagoides pteronyssinus*, DF *Dermatophagoides farinae*, EM *Euroglyphus maynei*

*Samples each from a separate mattress or carpet unless otherwise stated.

¹Mattresses in homes of asthma patients where mite avoidance measures were regularly carried out

