MACKINTOSH ENVIRONMENTAL ARCHITECTURE RESEARCH UNIT
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# ENVIRONMENTAL ASSESSMENT OF DOMESTIC LAUNDERING

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FINAL TECHNICAL REPORT PROJECT MODULE 1:

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## EPSRC CONTRACT: EP/G00028X/1 Porteous et al, 2012 (see front cover)

### TECHNICAL REPORT PROJECT MODULE 1:
### PART A EXECUTIVE SUMMARY OF FINDINGS OF MEARU HOUSING SURVEY
### 22 case studies monitored over 2 weeks, drawn from survey total of 100 households

## PREFACE

The underlying aim of PM 1 was to explore the range of environmental impacts arising from domestic laundering, the initial survey of 100 households yielding at least 20 volunteers for more in-depth monitoring over a 2-week period, and both providing an adequate range of demography and house type, as well as facilities and habits relative to their washing, drying and ironing.

Parallel with PM 1, PM 2 has been conducting a series of laboratory tests on common existing finishing materials found within housing, specifically in order to define moisture buffering potential for passive drying (as well as other 'wet' activities), this information adding to the modelling capability of PM 3. PM 3 is also able to draw on typical laundering scenarios from PM1 using a limited range of house types, with iterative modelling to explore the influence of key variables for whole-house 'as found' and 'improved' situations, as well as for 'quarantined' drying cupboards.

The findings summarised below are elaborated in Parts C and D relative to the survey findings, in particular the in-depth data from the 22 specific case studies detailed in Part B.

## CONCLUSIONS

1.0 Housing provision – its characteristics across a wide range of types in terms of age, form and construction influences the diversity of drying methods adopted, with passive indoor drying dominating, but lacking the means of isolating and exhausting moisture and mould spores; and, overall, many of the 100 respondents perceiving drying in particular as a problem or issue.

1.1 There is a lack of dedicated drying spaces, utility rooms or other potentially suitable spaces in which to dry clothes passively without adversely affecting other rooms or spaces (Observation 16.3, Part D). However, most dwellings could be adapted to provide this facility, sometimes by restoring what was built to its original use – see also conclusion 8 below.

1.2 Only half of the respondents in the 100 dwelling survey declared access to outdoor or covered semi-indoor drying, and almost half of that number indicated drawbacks including lack of security and lack of line-space (Observation 16.7, Part D). Again, there is scope for improving existing provision – see conclusion 8 below.

1.3 A large proportion of respondents who considered access to sunshine relevant to indoor drying perceived this as 'good' (84% – 57 ex 68). This partly reflected the age and type of stock surveyed – e.g. high-rise built in 1960s and 1970s with main rooms facing east and west, and low-rise from the same period with main rooms from east through south to west. Again this suggests scope for future enhancement that exploits solar energy – see conclusion 8 below.

2.0 Environmental context – this mitigates against passive indoor drying and ironing, the twinning of poor air quality and high moisture levels indicating lack of adequate ventilation control relative to the intensity of occupation, with high ambient humidity an added, and partly seasonal, factor.

2.1 The spot readings taken during daytime for 100 households do not promote confidence in terms of an environment that can readily accommodate additional moisture inputs from laundering activities. Observation 15.3 and Summary Table 3.5 in part D highlight this in terms of averages, where vapour pressure (VP) is above desirable maxima in terms of dust mite growth. Summary Table 1.c shows that equivalent VP means for living rooms and bedrooms are slightly higher for the 22 case studies monitored over two weeks, despite the seasonal shift of emphasis from winter (circa one third in winter ex 100) to summer (circa one third in summer ex 22). Summary Table 1.b shows that the mean maxima VP for this smaller group are approximately 50% higher than the equivalent spot means for the cohort of 100.

2.2 The respective 100/22 cohort seasonal shift of emphasis from winter to summer is reflected in somewhat lower mean $CO_2$ values (living rooms 22% less; bedrooms 12% less); but the mean maxima are again significantly higher than average spot values (living rooms 87% more; bedrooms 108% more). The bedroom maxima reflect poor air quality overnight.

2.3 The association between high $CO_2$ and high moisture was particularly evident in surges attributed to intense periods of occupation, and usually also accompanied by a rise in temperature – e.g. Figs. 2.1 and 2.2, Case Study 2 (CS 2), Part B. Such a surge could also mask moisture added due to passive drying, as could other moisture injections.

2.4 Although, as stated in 2.1, the effect of passive indoor drying in terms of raising moisture levels was in many cases masked or partly masked by other influences (presence of occupants, cooking etc.), it was possible to measure the typical impact overnight in the absence of other influences, a rise in vapour pressure of approximately 0.38 kPa (CS 4 notes, Part B); and ironing tests indicated that this activity would significantly less than this amount at circa 0.15-0.2 kPa (15.2, Part D, and Appendix 1 notes). Such increases in humidity, in particular due to indoor drying, would not be particularly consequential if it were not for the prevailing high levels (per 2.0 above), and the evident association with higher mould spore counts (see 4.0 below).

2.5 Part of the problem with respect to indoor drying per 1.1 and 2.0 above lies in lack of a specific facility for this, which is heated and ventilated independently of the main spaces in the dwellings; and prevailing high means and maxima in main spaces makes them particularly vulnerable to any additional migrating moisture. Note that it is the RH maxima (Summary Table 3.6 and observation 15.5, Part D), not temperature maxima, that correspond with the highest absolute moisture levels indicated by vapour pressure (VP) and risk high concentrations of water-soluble VOCs (e.g CS 6); Also all mean VP levels for the sample of 100 are above the maximum recommended value in terms of dust mite numbers (Summary Table 3.5 and observation 15.3). The 22 case studies examined in Part B again bear out this tendency, with the highest values often occurring during evenings, especially in living rooms, or overnight in bedrooms.

2.6 Those who passively dried indoors, with windows liberally opened during autumn, tended to have rather high absolute moisture (VP) levels, even though the air quality ($CO_2$) was reasonably good, at least on average – e.g. Case Study 3. This indicated that better control of ventilation was required, both to exhaust moist air at source, and any VOCs associated with it, and to limit ingress of damp ambient air at certain times of the year and/or in humid weather conditions.

2.7 Similarly regarding inadequate control of ventilation, migration of moisture from one space to another, for example kitchen to living room as indicated in Case Study 7, would mean that further moisture from passive drying of washing loads would add to an already poor situation.

3.0 Seasonal influences – these are relatively complex as they include perceptual responses of occupants to the prevailing weather, with autumn in particular tending to exacerbate moisture levels due to indoor passive drying or other causes.

3.1 Respondents from the 100 cohort initially surveyed had an optimistic view of ‘access to sunlight’ and ‘good access to sunshine’ – see observations 16.0-16.2 in Part D. Observation 5.12 in Part C, where this initial positive view coincided with those of the 22 case studies who passively dried within rooms, found that actual conditions on the first day of monitoring were in fact frequently sunny.

3.2 Where either perceptions or reality lead to window opening while heating is still used, or even boosted, and passive drying is present, it will have an impact on energy for space heating that can at least partly be attributed to the issue of laundering. For example, Part D’s observation 14.1 gives detailed data with respect to this issue in spring, 14.5 for autumn and 13.1 for winter.

3.3 Observation 1.1 in Part C tells us that, for the 22 case studies, autumn and winter have the highest $CO_2$ levels; and observation 1.2 informs that absolute moisture levels (VP) are highest in autumn, with the next worst in summer – suggesting some ambient influence in this regard.

3.4 Observation 1.4 in Part C remarks on the mould spore count ($CFU/m^3$) being highest in winter and spring compared with the two warmer seasons of summer and autumn. However, although this concerns the influence of spore transfer from outside to inside via open windows, observation 5.2 suggests another stronger explanation – see conclusion 4.0 below.

4.0 Moisture, visible mould and mould spores – three key relationships are evident: (a) there is no consistency between visible mould and spore count (observations 4.0-4.4); (b) effective ventilation is critical for activities that involve rapid moisture production; (c) despite several confounding variables, the indications are that slowly drying fabric has an association with relatively high spore counts, which could constitute a health problem for atopic occupants.

4.1 With regard to ventilation control, a factor evident from the survey was that awareness of built-in mechanical extract in high-rise towers was poor, as was overall awareness of manual versus automated control – see observations 3.5 in Part C and 14.11 in Part D. Also more than one fifth of the 100 cohort passively dried indoors in the absence of any mechanical extract – see observation 12.3 in Part D. In such cases, ventilation control would be reliant on window opening and operation of trickle vents (none of the dwellings surveyed having mechanical heat recovery).

4.2 There was no evidence that presence or absence of extract fans either helped or hindered relative to presence of mould. More than half of the 100 households had mould in at least one room, and nearly 80% of these had at least one mechanical extract – see 16.5, Part D.

4.3 Trickle vents were not used in almost half the households in the 100 cohort, and variable control of trickle vents was also patchy – see 3.6 and 3.7, Part C, and 14.10, Part D.

4.4 The explanation for the relatively high moisture levels and poor air quality reported under conclusion 2.0 above appears in part to relate to inadequate means, and in part to inappropriate usage, of ventilation control. It was further evident from monitoring of 22 case studies that the presence of mould is usually associated with high moisture levels, but that does not mean that high moisture levels will necessarily result in mould, as dew point of bounding surfaces is dependent on the temperature regime and air movement (observations 3.0 and 3.1 in Part C).

4.5 While there is no consistent association between mould spore count (CFU/m$^3$) and visible presence of mould (Summary Table 1.a, Part C), there is an apparent association between absence of indoor passive drying and the CFU count, which consistently tends to be lower when it is absent than when it is present (observation 5.0 and 5.2, Part C). This tentative hypothesis is upheld despite analysis of various confounding variables (observations 5.1 and 5.3-5.12). The high spore counts associated with the presence of passive indoor drying are also of a level whereby the health of atopic occupants could be adversely affected.

5.0 Thermal energy impact of passive/active indoor drying – basic analysis in PM 1 indicates a significant addition to space heating demand due to this activity, but dynamic modelling in PM 3 will provide further detail of this related to the key variables of boosted heating and ventilation.

5.1 There is convincing evidence from both the initial survey of 100 households and also the monitoring of 22 of these over a two-week period that passive, and sometimes also active, indoor drying impacts significantly on space heating demand during the heating season.

5.2 The analysis of Case Study 2, Part B, provides ballpark estimates for the theoretical increase in energy demand for three scenarios. Observation 7.3, Part C, compares this to the equivalent energy for tumble drying (see also conclusion 6.0 below). Although this rude comparison appears to favour the tumble dryer, once respective figures are presented as primary energy, the comparison reverses (without including extra heating load due to window opening to facilitate venting of tumble dryers), noting the influence of primary electrical energy on $CO_2$ emissions.

5.3 As indicated in 5.0 above, modelling in PM 3 will enable more accurate assessment of the thermal impacts of passive indoor drying for various scenarios relating to ventilation rate and demand temperature – both in terms of additional energy demand and rise in moisture level.

6.0 Electrical energy impact of the three laundering activities – this was found to be a significant proportion of the overall consumption for lighting and appliances, particularly when expressed as primary energy related to the Passivhaus limit of 120 kWh/m$^2$; and, per 5.2 above, primary energy used by tumble dryers would be significantly more than added thermal loads from passive drying.

6.1 It is firstly important to note that for all appliances there was a considerable range of electrical consumption found, varying with different modes of expressing this – see observation 7.1 in relation to Summary Table 2.a, Part C. There was also less directly measured data available for tumble dryers than for washing machines, and ironing has been based on estimates, backed up by knowledge of appliances, diary notes and measured trials (observation 15.2 and Appendix 1).

6.2 It was also found from the relatively small number of case studies, 22 dwellings, that median and geometric means were significantly below arithmetic means (observation 7.2 and 8.1, Part C), and therefore subsequent estimates relative to benchmarks for total predicted power consumption used both; and also gave comparisons for delivered/consumed and primary energy, using a standard grid conversion coefficient for the UK (Summary Table 2.b).

6.3 Based on an annual benchmark figure of 35 kWh/m$^2$ for total delivered power consumption for lighting and appliances, the median average for laundering appliances for the 22 case studies was found to be 11.1% and the mean average 18.4% – see observation 8.1 in Part C.

6.4 Based on an annual benchmark figure of 76 kWh/m$^2$ for total primary power consumption for lighting and appliances available in a 'Passivhaus', the median average for laundering appliances for the 22 case studies was found to be 14.0% and the mean average 23.3% – see observation 9.1 in Part C. However, this estimate was qualified to take account of actual boiler efficiencies found in field studies, as opposed to theoretical values, and the respective median and mean proportions attributable to laundering rose 19% and 31% – observation 9.2, Part C.

6.5 Referring to conclusion 5.2 above, and bearing in mind respective differences between case studies used to establish approximate relativity between passive indoor drying and tumble drying, there is convincing 'energy-efficiency' evidence against indiscrimate passive indoor drying as well as tumble drying – see observations 7.3 and 7.4, Part C.

7.0 Scope for passive drying improvement – arising from the above, there is a strong case for amendment to statutory building standards to provide: firstly, a specific facility for indoor passive drying that is both larger than the present standard and isolated or 'quarantined' with its own source of heating (ideally fortuitous) and ventilation exhaust; and secondly, a secure and convenient outdoor or semi-outdoor space that is both covered and solar enhanced.

7.1 For indoor passive drying that meets the above conditions, there are two options: a) an enclosed drying cupboard that has a minimum uninterrupted hanging space of 1.75 m$^3$, with specific minimum dimensions – width 1.0 m, depth 0.6 m, height 1.4 m – to enable flexibility without compromising viability (e.g. 1.2 wide, 2.4 high; 2.0 m wide, 1.4 m high); b) a defined space of the same minimum volume and specific dimensions as a) within a larger utility room that satisfies the requirements of 7.0 in terms of 'quarantined' heat and ventilation, and which allows for any other moisture producing activity or appliance. It is recommended that unless an adequate automated rate of extraction can be guaranteed during drying periods, bathrooms should be specifically excluded as a suitable space for this purpose (16.6, Part D), and all drying spaces must have appropriately controlled extract, which can provide an adequate volume flow rate.

7.2 Use of specific hygroscopic internal linings in dedicated drying spaces may curb RH spikes; laboratory testing in PM 2 and advanced modelling in PM3, which exploits PM2's findings, providing guidance in terms of heat and ventilation – time-switched ventilation at 30 m/s during drying cycles advised, with the aim being to eliminate risk of mould growth.

7.3 The opportunity should be taken to link requirements for indoor passive drying to improved standards for ventilation control in the remainder of the home. This should recognize the drive towards airtight building envelopes, but also acknowledge the weakness of current statutory standards for mechanical ventilation in that they do not guarantee the capability of an adequately variable supply rate to ensure 8 l/s for each occupant of a room, taking account of normal social activity in a home. Such a supply system should not involve opening windows or associated devices other than from a suitable preheated source (e.g. solar air collector; dynamic insulation component), but may include a MHRV system that can guarantee a sufficient variable supply.

7.4 For outdoor or semi-outdoor drying, the potential divides into private and shared spaces, which are solar enhanced. A private facility of this nature could involve the upgrading of an existing opportunity – e.g. a transparent canopy to provide rain protection over a pulley or similar device on a balcony (recessed, partly recessed or projecting from facade) or garden (lean-to or freestanding). Alternatively, a facility may be added where none exists – e.g. balconies to flats. A shared facility could provide similar opportunities for enhancement – e.g. rooftops, semi-enclosed rooms, back courts – with the potential for integration of active solar thermal or photovoltaic (PV) arrays, depending on overshading. With new-build housing, similar private/communal solar and weather-proofed provision can be required by means of appropriate statutory standards.

7.5 The housing section of the Technical Handook for Scotland should be reviewed and amended to incorporate the recommendations embodied in 7.0-7.4 above.

8.0 Scope for improvement to laundering appliances – the survey indicates particular potential for washing machines and tumble dryers, the former possibly linked to grey water heat recovery and both capable of mitigating thermal demand as well as further reducing electrical demand.

8.1 94 of the 100 surveyed households owned their own washing machines, 60% of these A-rated and nearly 30% B-rated (observation 12.1 and Summary Table 3.1, Part D); most of the rest making use of communal facilities in their block or scheme, and one of whom among the 22 case studies used both the communal washing machine and an individual one in the home (CS 10, Part B). Ownership of tumble dryers was much lower than that for washing machines – one third of the 100 used one, just under one quarter in their own home and the balance in community or commercial facilities. But only 5% used a tumble dryer exclusively due to awareness of expense and heavy energy use (observation 12.2, Part D). 99 of the 100 owned/used a steam iron, with significant range in power output (12.3, Part D), and the amount of the wash loads that were claimed to be ironed was also significant – more then three quarters ironing all or half their washing (15.2, Part D). Conclusions 6.0-6.5 above address the power use of three appliance categories measured or estimated for the 22 case studies. Together with the levels of ownership and usage evident from the larger cohort of 100, this forms the basis for potential mitigation.

8.2 Modern condenser sensor tumble dryers with integral heat pumps use approximately half the full-cycle power of the vented type with heating elements or standard condensing types, both commonly found in this survey of 100 and the monitored group of 22. One may conclude, given the awareness of electricity consumption in this regard, that greater ownership of more efficient appliances might lead to greater usage; this supposition being in accordance with the Khazzoom-Brookes Postulate (Monbiot, 2006). Therefore, the proposals for improved statutory standards for passive drying (conclusion 7.5 above) are seen as the optimum method of mitigation.

8.3 For the domestic washing machines monitored for the 22 case studies, the factorial range measured per hour of running time or per cycle was 4.0-5.0 (see observation 7.5 and Summary Table 2.a, Part C). The key variables were evidenced as cold or hot feed and normal operating temperature, the energy efficiency rating not always being a reliable guide. Some hand washing was also relatively common, but of a minor nature; and although some use was made of communal or commercial facilities, both among the 22 case studies and in the larger survey of 100 dwellings, the convenience of individual appliances in the home is unlikely to diminish significantly. Therefore, the most appropriate method of reducing the energy impact of washing would seem to be a holistic integrated approach: grey water may be recycled for flushing WCs, including that from washing machines, but saving only a small amount of $CO_2$; while, more usefully, the holding tank for this is used as the ambient source for water-source heat pumps (see 11.0-11.2, Part C). Depending on overall energy efficiency of a dwelling these could provide domestic hot water, possibly in tandem with solar thermal collectors, and space heating, particularly if this were delivered by low-temperature embedded serpentine systems. Solar PV arrays to power such heat pumps, net over a year, would further reduce carbon emissions.

8.4 The habit and extent of ironing is very much a cultural issue. Appliance ouput varies by a factor of 2.4 (observation 12.3, Part D), but consumption is not directly proportional to maximum power (Appendix 1 notes). It is also suggested that the improved statutory standards advocated for passive indoor drying, with improved hanging space, should lead to less need for ironing and less risk of VOC release – dependant on the level of individual care taken at hanging stage.

8.5 Despite relatively low usage of communal laundering facilities within housing schemes, in turn subject to low availability, and corresponding low usage of commercial laundrettes, these facilities do offer a route to lower energy consumption per unit mass of washing and drying (Menon, Porteous & Musa, 2010), with further renewable potential. It is also one that has scope for further improvement, apart from use of ozone without heating to replace detergents with heating. If the drained ouput of grey water from washing and air from drying were used as the ambient sources for a heat pump (similar to conclusion 8.3 above), and the system coupled to solar thermal array of evacuated tubes (more effective than flat plate collectors for high temperature output) and a PV array of such a size that its net annual output aligned with the demand from the heat pump, the energy demand and carbon emmissions from drying would be significantly reduced.

PART B THE RANGE OF IMPACTS – varying demography & house types/facilities

Domestic laundering: analytical notes from 22 case studies monitored over 2 weeks, with reference to questionnaires and survey data from total of 100 households. The section starts with key outcomes from all 22 case studies to rapidly provide a sense of narrative; followed by more detailed notes.

Case study No 1: Frequent washer, using communal tumble drying exclusively; summer monitoring, flat in tower block; electric heating; laundering for 3 persons

Key findings:

a) Convenience of communal drying advantageously limits moist air in flat, but seems to attract heavy usage – 3.5 times higher than geometric mean of 10 case studies who machine-dry; by contrast annual washing machine consumption using appliance in the home is 25% less than the geometric mean for 20 ex 22 case studies – estimated total, including ironing estimate, 6.1 times geometric mean for 21 ex 22 case studies (664 kWh/p-y* cf. 108.6); noting that the 10 tumble dryers in this last comparator are included in the geometric mean for 21. [*p-y = person-year]

b) Even without passive drying indoors, and even though air quality is good and spore concentration reasonable, the mean vapour pressure (VP) is above the recommended dust mite threshold of 1.13 kPa at circa 1.2 kPa in living room and bedrooms. Indoor influences may include ironing, which is well above average – more than four times greater than the geometric mean – but there is evidence that the liberal opening of windows during summer results in correspondence between peaks in ambient humidity and that indoors.

Case study 2: Frequent washer, passive drying in several indoor spaces, windows open, heating turned up; winter monitoring, flat in traditional stone-built tenement; gas central heating; laundering for 7 persons

Key findings:

a) Contrast with CS 1 – passive indoor drying in winter corresponds to high spore concentrations and poor air quality even though the combination of heating and open windows has kept vapour pressure (VP) levels somewhat lower than CS1 (means just within recommended maximum).

b) The extra burden on space heating attributable to passive indoor drying is significant.

c) Washing machine consumption per person is below the geometric mean for 20 ex 22 case studies, and fairly minimal ironing at about half the geometric mean and absence of tumble drying results in modest electrical consumption for laundering – estimated total 49% geometric mean for 21 ex 22 case studies (53 kWh/p-y cf. 108.6).

Case study 3: Frequent washer, part tumble, part passive drying indoors, windows open, heating on; autumn monitoring, flat in early 1990s tenement, fast response construction; gas central heating; laundering for 3 persons

Key findings:

a) Similar pattern of laundering to CS 2 above for smaller household, and even more liberal window opening influencing indoor humidity; but uses tumble dryer for part of most washes. Overall spore count lower, but VP averages slightly higher than CS 1 at circa 1.3 kPa.

b) The extra burden on space heating attributable to open windows while heating is used, in turn possibly motivated by partial passive indoor drying is likely to be significant.

c) Washing machine consumption per person is more than twice the geometric mean for 20 ex 22 case studies, as is the ironing (data for 19 ex 22), while that for partial tumble drying is some 80% less for the smaller number of 10 using them – estimated total 2.5 times geometric mean for 21 ex 22 case studies (267 kWh/p-y cf. 108.6).

Case study 4: Relatively frequent washer, some tumble drying, some external passive drying and passive drying in living room with window closed, heating on; spring monitoring, maisonette in 4-storey 1960s cavity brick building, heavy construction; electric heating; laundering for 2 persons

Key findings:

a) Electrically heated as CS 1, and advantage taken of overnight storage charge to facilitate partial passive drying (identifiable moisture release with closed windows); overall spore

concentration on high side (700-900 CFU/$m^3$), air quality poor with mean $CO_2$ over 1,000 ppm and mean VP 1.2 kPa living room and 1.3 kPa bedroom.
b) Space heating unlikely to have been affected by laundering habits, although average temperatures are rather high at 22.5ºC in living room and circa 20ºC in bedrooms.
c) Washing machine consumption per person is 58% higher than the geometric mean for the 22 case studies, while that for partial tumble drying is 52% less than that for the 10 users, and no ironing was declared during the two weeks of monitoring – estimated total 1.5 times geometric mean for 21 ex 22 case studies (162 kWh/p-y cf. 108.6).

Case study 5: Energy-intensive washing, all tumble drying, heating on; autumn monitoring, flat in 4-storey 1970s 'no-fines' semi-heavy construction, dry-lined internally; electric heating; laundering for 3 persons

Key findings:

a) Electrically heated as CS 1 and 4, all windows are liberally opened (bedrooms daytime only), and no passive drying occurs; spore concentration reasonably low at circa 500 CFU/$m^3$, but bedroom air quality very poor – mean $CO_2$ of over 2,200 ppm in one case – and rather moist (1.3-1.5 kPa means) with surface mould present; this due to intensity of occupation with closed windows in evenings and overnight – i.e. ambient conditions not particularly influential.
b) Space heating again unlikely to have been affected by laundering habits; rather infuence of high average temperatures in bedrooms – mean >21.0ºC in one cf. <19ºC in living room.
c) Washing machine consumption per person is extreme at 4.5 times higher than the geometric mean for the 22 case studies, while that for partial tumble drying is 30% higher than that for the 10 users, and ironing estimated as approximately half the geometric mean (data for 19) – estimated total 4.2 times geometric mean for 21 ex 22 case studies (455 kWh/p-y cf. 108.6).

Case study 6: Infrequent washing, all tumble drying, heating on; autumn monitoring, top flat in 3-storey 1993-4 brick-cavity building, insulated internally - i.e. light construction; gas central heating; laundering for 3 persons (2 adults plus infant)

Key findings:

a) Gas heated as CS 2 and 3, and no passive drying indoors; but overall spore concentration high (living >1,000; bedroom 1 >1,600 CFU/$m^3$ plus mould), air quality poor (mean $CO_2$ nearly 2,400 ppm in living; >1,800 bedroom 1; > 1,500 bedroom 2), mean vapour pressure high (1.6 kPa living room and bedroom 1; 1.4 kPa bedroom 2) and mean RH >70% in all spaces – i.e. spore concentration tracks low ventilation rates rather than presence of indoor drying in this instance.
b) Space heating likely to have been only marginally affected by laundering habits, although RH >70% and temperature >18ºC or 19ºC while window ajar during tumble drying to accommodate extract hose does not constitute a favourable environmental scenario.
c) Washing machine consumption per person contrasts with CS 5 at less than one third of the geometric mean for the 22 case studies, that for partial tumble drying is 27% lower than geometric mean for the 10 users (both reflecting 3 cycles in two weeks), and ironing is also estimated as 30% lower than the geometric mean (data for 19) – estimated total 1.3 times geometric mean for 21 ex 22 case studies (143 kWh/p-y cf.108.6).

Case study 7: Fairly infrequent washing, all passive drying, heating on; spring monitoring, flat in 4-storey 1970s 'no-fines' semi-heavy construction, dry-lined internally; electric heating; laundering for 3 persons

Key findings:

a) Electrically heated flat as Case Study 5, heating boosted to assist passive drying with windows shut; spore concentration high (living and bedroom 2 almost 3,000 CFU/$m^3$ plus surface mould), air quality poor (most mean $CO_2$ readings > 1,000 ppm and maxima > 4,000 ppm in living and bedroom 2), mean vapour pressure rather high (1.4 kPa living room, 1.2 bedroom 1; 1.35 bedroom 2) and mean RH 50-60% in all spaces.
b) The extra burden on space heating attributable to passive indoor drying may not be significant, given the closed windows, but the environmental consequences appear to be serious (see a)).
c) Washing machine consumption per person is 62% of the geometric mean for 20 ex 22 case studies, and fairly minimal ironing at about half the geometric mean and absence of tumble drying

results in low electrical consumption for laundering similar to CS 2 – estimated total 35% geometric mean for 21 ex 22 case studies (38 kWh/p-y cf. 108.6).

**Case study 8: Moderate washer, some tumble drying, some internal passive drying, heating on; autumn monitoring, flat in 3-storey 1960s cavity brick building, heavy construction**; gas central heating; laundering for 2 persons

Key findings:

a) Gas heated as CS 2, 3 and 6, but with combined use of partial tumble drying, plus steam ironing in bedroom to full dryness, and some passive drying in bedrooms; overall spore concentration reasonably low (living > 630; bedrooms 510 and 595 CFU/$m^3$ plus mould); air quality rather poor (mean $CO_2$ > 1,000 ppm and max. almost 3,000 ppm in bedroom 2); mean vapour pressure high (1.35 kPa living room to 1.4 kPa bedroom 2) and mean RH > 70% in both bedrooms; temperatures quite low in both bedrooms (mean 16ºC bedroom 1, 17ºC bedroom 2).
b) No extra burden on space heating attributable to modest passive indoor drying, but steam ironing of damp items from tumble dryer appears to coincide with RH >90% in bedroom, while temperature relatively low and windows seldom opened, minimising ambient influence.
c) Washing machine consumption per person is 2.8 times higher than the geometric mean for 20 ex 22 case studies, tumble drying 40% more than the geometric mean for 10 ex 22, and ironing some 3 times the geometric mean, results in fairly high electrical consumption – estimated total 3.7 times that of geometric mean for 21 ex 22 case studies (406 kWh/p-y cf. 108.6).

**Case study 9: Moderate washer, passive drying in two indoor spaces, windows open, heating not used; summer monitoring, flat in traditional stone-built tenement;** gas central heating; laundering for 2 persons (2 during monitoring, but 4 normally)

Key findings:

a) Gas heated as CS 2, 3, 6 and 8, all indoor passive drying in kitchen and living room, and some evidence of moisture impact from this; highest levels in bedrooms (1.69 and 1.75 kPa) due to migration from within and/or without while $CO_2$ remains low (max. 772 ppm); Spore concentration high in living room (1,275 CFU/$m^3$), kitchen (1,610) and bedroom 2 (1,655), again indicating possible influence from inside and outside migration; visible mould in bathroom only.
b) Passive indoor drying likely to impact on space heating demand in heating season, especially if liberal window opening continues.
c) Washing machine consumption per person is 2.5 times less than the geometric mean for 20 ex 22 case studies, ironing is judged to be close to the geometric mean and absence of tumble drying results in low electrical consumption for laundering, the lowest of all the case studies – estimated total 28% geometric mean for 21 ex 22 case studies (30 kWh/p-y cf. 108.6).

Case study 10: Moderate washer, passive drying in two indoor spaces, windows open, heating sometimes used; summer monitoring, flat in 1960s cavity-insulated tower block; electric heating; electric heating; laundering for 2 persons

Key findings:

a) Electrically heated (storage plus direct appliance), some indoor passive drying in kitchen and living room, and liberally ventilated during daytime; use of communal laundry for part washing and drying; highest moisture levels in main bedroom (1.35 kPa) corresponding to high $CO_2$ with window shut (> 1,000 ppm from 2200-0900, when max. 2,400 ppm), but also evidence of ambient humidity influence indoors via windows; spore concentration reasonably low (mean living + bedrooms 640 CFU/$m^3$), visible mould in main bedroom.
b) Fan heater used to boost passive indoor drying at end of May; likely to impact on space heating demand in heating season, especially if liberal daytime window opening continues.
c) Washing machine consumption per person is 18% above the geometric mean for 20 ex 22 case studies, ironing is judged to be 60% of the geometric mean, but estimated tumble drying in the communal laundry is estimated to be 2.4 times more than the geometric mean for 10 users – estimated total 4.2 times geometric mean for 21 ex 22 case studies (459 kWh/p-y cf. 108.6).

Case study 11: Moderate washer, tumble drying in dwelling, windows closed, heating not used; summer monitoring, maisonette in 1960s cavity-insulated tenement block; electric heating; laundering for 3 persons

Key findings:

a) Electrically heated (storage plus direct), tumble dryer plus minimal passive drying indoors, but frugally ventilated (e.g. trickle vents living room; average 15 minutes/day window open bedroom 1, 5 minutes bedroom 2, 6 minutes kitchen); relatively low spore concentrations (595 CFU/$m^3$ living room, 750 bedroom 1), but high moisture (mean 1.66 kPa bedroom 1, 1.48 living room; maxima circa 2.0 kPa) and poor air quality (most means > 1,000 ppm) – indicates high CFU concentration not dependant on moisture level alone.

b) Any passive drying, but more particularly steam ironing in this case (half tumble drying ironed) at low rates of ventilation liable to be very problematic in winter, given summer moisture levels.

c) Washing machine consumption per person is 20% above the geometric mean for 20 ex 22 case studies, ironing is judged to be 70% of the geometric mean, estimated tumble drying is 99% of the geometric mean for 10 users – estimated total 2.1 times the geometric mean for 21 ex 22 case studies (133 kWh/p-y cf. 108.6); noting effect of only 10 tumble dryers in last comparator.

Case study 12: Frugal washer, hand washing, mixed tumble and passive drying in dwelling, windows opened, low heating; summer monitoring, flat in 1960s tower block; electric heating; laundering for 1 person

Key findings:

a) Electrically heated (storage); all hand wash, partial use of tumble dryer (10 minute cycles common) plus mix of passive drying indoors and outdoors and circa half washing ironed in living room; well ventilated by opening windows during monitoring; medium spore concentrations (865 CFU/$m^3$ living room, 890 bedroom); generally low moisture (mean 0.71 kPa bedroom and living; maxima reflect peak ambient conditions) and good air quality (max. living room > 1,000 ppm).

b) Indoor passive drying and steam ironing could be more problematic in winter when window opening is occasional (per questionnaire), but tenant seems aware in this regard.

c) Washing machine consumption is zero; measured tumble drying is 35% of the estimated geometric mean for 10 users; ironing is judged to be 70% of the geometric mean – modest estimated total 59% the geometric mean for 21 ex 22 case studies (64 kWh/p-y cf. 108.6).

Case study 13: Moderate washer, no washing/drying appliance in dwelling, windows closed, low heating; summer monitoring, flat in 1960s cavity-insulated tenement block; electric heating; laundering for 1 person

Key findings:

a) Electrically heated (storage); some light hand wash, with prevailing use of laundrette, including ironing; poorly ventilated with trickle vents not adjusted, but mean $CO_2$ below 1,000 ppm; fairly low spore concentrations (545 CFU/$m^3$ living room, 550 bedroom); generally high moisture (means 1.25-1.27 kPa in main spaces; maxima circa 1.6 kPa living and bedroom).

b) No significant domestic laundering impacts foreseen for heating or moisture, including winter, although handwash and 'pulley' drying in bathroom could induce mould if no ventilation.

c) Estimated washing machine consumption is 9% above the geometric mean for 20 ex 22 case studies; measured tumble drying is 32% lower than the estimated geometric mean for 10 users; ironing is judged to be 50% above the geometric mean – estimated total 70% above the geometric mean for 21 ex 22 case studies (185 kWh/p-y cf. 108.6); noting again the effect of only 10 tumble dryers in this last comparator.

Case study 14: Moderate washer, passive drying in dwelling, windows open, heating not on; summer monitoring, flat in modernised traditional stone tenement block; gas central heating; laundering for 2 persons

Key findings:

a) Gas heated; passive drying in bedroom compensated by liberal window opening in summer, mean $CO_2$ well below 1,000 ppm; moderate spore concentrations (700 CFU/$m^3$ living room and bedroom); generally high moisture (means circa 1.2 kPa) reflects ambient conditions.

b) Significant domestic laundering impacts likely for heating or moisture, or both, in winter.

c) Estimated washing machine consumption is 21% above the geometric mean for 20 ex 22 case studies; but the absence of ironing and tumble drying gives a moderate total – estimated total 41% below the geometric mean for 21 ex 22 case studies (64 kWh/p-y cf. 108.6).

Case study 15: Frugal washer, Machine and hand washing, passive drying outside and inside dwelling, windows opened, low heating; autumn monitoring, 1990s semi-detached house; gas central heating; laundering for 1 person (2 present during monitoring)

Key findings:

a) Gas heated; passive drying outside continues in autumn; mean $CO_2$ <1,000 ppm, but maxima above by 25-90%; reasonably low spore concentrations (548 CFU/$m^3$ living room; 560,550 bedrooms 1 & 2); generally high moisture (means circa 1.4 kPa in bedrooms, 1.3 kPa living; maxima up to 1.75 kpa; mean RH close to or above 70%) reflects ambient conditions.
b) Significant domestic laundering impacts likely for heating or moisture, or both, in winter; with passive drying acknowledged in living room with heating boosted and windows open.
c) Estimated washing machine consumption is 47% of the geometric mean for 20 ex 22 case studies; ironing 71%; and the absence of tumble drying gives a low total – estimated total 70% below the geometric mean for 21 ex 22 case studies (32 kWh/p-y cf. 108.6).

Case study 16: Moderate washer, machine washing, passive drying outside and inside dwelling, windows opened, low heating; spring monitoring, house in 1990s terrace; gas central heating; laundering for 2 persons

Key findings:

a) Gas heated; passive drying outside supplemented by drying cupboard off hall and airer in hall; $CO_2$ up to 5,000 ppm maximum reading at times, indicating patchy ventilation; moderate spore concentrations (725 CFU/$m^3$ living room/bedrooms mean); generally high moisture (means 1.3-1.4 kPa, hall max. of 3.84 kPa due to people; high moisture inside not due to ambient conditions.
b) Any laundering impact due to indoor passive drying likely to be in hall, with heat from boiler usefully exploited for drying in hall cupboard.
c) Estimated washing machine consumption is 78% above the geometric mean for 20 ex 22 case studies; ironing 50% above; but the absence of tumble drying gives a reasonable total – estimated total 3% below the geometric mean for 21 ex 22 case studies (105 kWh/p-y cf. 108.6).

Case study 17: Moderate washer, machine washing, passive drying outside and inside dwelling, windows opened, low heating; spring monitoring, flat in 1960s tower, heavy construction, dry-lined internally; electric heating; laundering for 2 persons

Key findings:

a) Electrically heated; passive drying outside plus drying indoors in hall or living room; good air quality – max. $CO_2$ just over 1,000 ppm, mean 551 ppm in living, reflecting good ventilation in sunny weather (73% above April average); moderate spore concentrations (935 CFU/$m^3$ living room); generally low moisture (mean <1.0 kPa living), again reflecting fine ambient weather.
b) Laundering impact on heating or moisture due to indoor passive drying likely in hall and living room, when weather not favourable for outdoor drying – i.e. especially autumn and winter.
c) Estimated washing machine consumption is 39% of the geometric mean (61% below) for 20 ex 22 case studies; ironing 31% above; but the absence of tumble drying gives a low total – estimated total 69% below the geometric mean for 21 ex 22 case studies (34 kWh/p-y cf. 108.6).

Case study 18: Moderate washer, machine washing, passive drying inside dwelling, windows opened, no heating; spring monitoring, flat in 1960s tower, heavy construction, dry-lined; electric heating; laundering for 1 person

Key findings:

a) Electrically heated; passive drying indoors in kitchen, bathroom and living room; good air quality – max. $CO_2$ in living just over 1,559 ppm, but means <600 ppm in all spaces, reflecting good ventilation in same sunny weather as CS 17; high spore concentrations (2,960 CFU/$m^3$ living room); generally low moisture (means <1.0 kPa), again reflecting fine ambient weather.
b) Laundering impact on heating or moisture due to indoor passive drying likely in living room as CS 17, permanent mechanical extract should help in kitchen and bathroom.

c) Estimated washing machine consumption is 69% above the geometric mean for 20 ex 22 case studies; ironing 50% above; but the absence of tumble drying gives a reasonable total as CS 16 – estimated 3% below the geometric mean for 21 ex 22 case studies (105 kWh/p-y cf. 108.6).

Case study 19: Low-moderate washing, all passive drying, heating not on much; spring monitoring, flat in tower block, 1970s 'no-fines' semi-heavy construction, dry-lined internally; electric heating; laundering for 2 persons

Key findings:

a) Electrically heated; passive drying indoors in kitchen and bedrooms, plus some communal; poor air quality – $CO_2$ >3,000 ppm for lengthy periods, although all means <1,000 ppm except kitchen; high spore concentrations (>1,000 CFU/$m^3$ in all spaces); moisture means >1.0 kPa and significant peaks (e.g. 2.98 kPa bedroom 1), even though fine ambient weather.
b) Laundering impact on heating or moisture due to indoor passive drying likely in kitchen and bedrooms during autumn and winter.
c) Estimated washing machine consumption is 94% of the geometric mean for 20 ex 22 case studies; ironing 41% above; but the absence of tumble drying gives a relatively low total – estimated 41% below the geometric mean for 21 ex 22 case studies (64 kWh/p-y cf. 108.6).

Case study 20: Low washing, all passive drying, heating to assist drying; spring monitoring, flat in tower block, 1970s 'no-fines' semi-heavy construction, dry-lined internally; electric heating; aundering for 3 persons (2 adults plus infant)

Key findings:

a) Electrically heated; passive drying indoors in living room, kitchen, bathroom and bedrooms, and some hand washing; poor air quality – $CO_2$ >1,000 ppm for lengthy periods with maximums between 4,000-5,000 ppm, although some means <1,000 ppm; high spore concentrations (>1,000 CFU/$m^3$ in all spaces; baby's room >3,000 CFU/$m^3$); high moisture corresponds with high $CO_2$ even though fine ambient weather, indicating poor ventilation.
b) Laundering impact on heating or moisture due to indoor passive drying likely to be significant in all rooms used for drying during autumn and winter.
c) There is no tumble dryer and no data for washing machine or steam iron consumption.

Case study 21: Moderate washing, all passive drying, heating to assist drying; spring monitoring, flat in tower block, 1970s 'no-fines' semi-heavy construction, dry-lined internally; electric heating; laundering for 4 persons (2 adults, two young children)

Key findings:

a) Electrically heated; passive drying indoors in living room and second bedroom with open windows and some heating (direct electric); moderate air quality – mean $CO_2$ <1,000 ppm except living room, with maximum 2,121 ppm; high spore concentrations (most >1,000 CFU/$m^3$ ); some moisture peaks coincide with washing/drying activity, when ambient weather has low VP.
b) Laundering impact on heating or moisture due to indoor passive drying likely to be more acute in living room and and second bedroom during autumn and winter.
c) Estimated washing machine consumption is 81% of the geometric mean for 20 ex 22 case studies; ironing 40% below; and the absence of tumble drying gives a relatively low total – estimated 57% below the geometric mean for 21 ex 22 case studies (47 kWh/p-y cf. 108.6).

Case study 22: Low-frequency washing, all passive drying, open windows to assist drying; winter monitoring, flat in tenement, modern brick-clad construction, dry-lined internally; gas central heating; laundering for 2 persons

Key findings:

a) Gas heated; passive drying in living room while windows open; but air quality poor, mean $CO_2$ >1,000 ppm in all rooms and maxima 3,000-4,000 ppm, indicating patchy ventilation; high spore concentrations (>1,000 CFU/$m^3$ in all rooms except bathroom); high moisture peaks in living room and kitchen, while means circa 1.0 kPa; moisture inside not due to ambient influence.
b) Laundering impact due to indoor passive drying likely to be significant in winter in living room.
c) Estimated washing machine consumption is 62% of (38% below) the geometric mean for 20 ex 22 case studies; ironing 70% below; and the absence of tumble drying gives a low total – estimated 63% below the geometric mean for 21 ex 22 case studies (40 kWh/p-y cf. 108.6).

FREQUENT WASHER, USING COMMUNAL TUMBLE DRYING EXCLUSIVELY; SUMMER MONITORING, FLAT IN TOWER BLOCK

Case study No 1: This flat is located in a tower block with a communal tumble drying facility on the ground floor, the cost of which is built into the rent. This person did the washing at home, the drying in the communal facility and steam-ironed roughly half of her dried items at home in the kitchen. She estimated that she spent approximately 6 hours weekly on laundering activities.

The total number of drying loads over 11 days was 15 – an average of 1.36 per day, but this was for two households – the tenant and her grandson and partner. At 5.35 kW for the heating element plus 0.6 kW for the motor (Speedqueen/Huebsch Dryer 220, described as a 'Commercial Homestyle Heavy-Duty Dryer'), holding 8 kg wet washing (92 litres), and the heater on for the duration of 45 minute cycles, the consumption per cycle would be 4.46 kWh. However, we may only assume that the 0.6 kW motor runs continuously throughout a cycle, while the 5.35 kW dryer may pulse off and on, depending on the size and moisture content of the load; and the agent for the manufacturer is not able or willing to provide a typical figure. Rather, we may assume that it is liable to operate its dryer throughout a cycle when moisture content of heavy material brings the total 'wet' weight up to the appliance's limit; whereas a light, partial load would not do this. In order to provide a likely range, comparison is made with two similar appliances, where manufacture's estimates of typical energy use per cycle is available: a) 8 kg capacity Siemens WT36V398 vented tumble dryer with electric heating element at 3.5 kWh/cycle; b) 7 kg Bosch WTV74105 vented tumble dryer at 3.92 kWh/cycle, suggesting a value close to the Speedqueen maximum at 8 kg. Therefore, the Siemens appliance may be more directly comparable to the Speedqueen. On this assumption, the daily energy consumption for Case Study 1 is 1.36 x 3.5 = 4.76 kWh, or 1.59 kWh/person; and, extrapolating for one year, respective consumption is 1,737 kWh for three persons or 580 kWh per person.

The total number of washing loads in the same period was 7 – an average of 0.64 per day, or 0.32 loads per household. At 0.52 kWh/load measured consumption (six loads of 60-70 minutes, averaging 0.45 kWh, and one 80 minute and assumed hotter load of 0.91 kWh), the daily consumption per household is therefore estimated to be 0.166 kWh, or 0.11 kWh/person; and extrapolating this indicates 60 kWh annually per household –120 kWh for the total of 3 persons, 14.5 times less than drying estimate – or 40 kWh/person. It may be noted that the particular appliance in this case is a Hoover Nextra HNL 662, with a triple-A energy rating. It would also appear to have been used economically as the typical duration of a cycle given online for cottons is 1 hour 46 minutes, and 51 minutes for 'easy care'. In any event, if the total consumption in this case is divided by the total duration, the mean hourly average consumption is 0.48 kWh. Fig. 1.1 shows the profile for two wash loads in rapid succession for the 19th June. Note that the second cycle is longer and hotter than the first, with the peak power use twice as great as that of the first at just over 0.45 kWh for a 10-minute recording period.

The consumption for ironing based on a 2.2 kW steam iron operated for half an hour per half-load ironed indicates an average consumption of 0.283 kWh per session of ironing (see Appendix 1, giving data for controlled tests of three irons); or circa 44 kWh per year, based on an average of six ironing sessions in fourteen days as during the monitored period. Note that this is more than the estimated 40 kWh/person consumed for washing, the evidence of the diary suggesting that the ironing was for the grandmother alone, rather than for all three people. This seems high relative to most of those that follow, but the occupant does seem to be a dedicated ironer.

Despite the heavy energy penalty of the drying in particular (but not to either householder given the rental structure) the environmental benefit is that this part of the process does not add moisture to the indoor environment. One would expect low RH and vapour pressure in June, with windows liberally opened. This is generally the case, and exceptions appear to be due to ambient conditions and open windows allowing warm, moist air to migrate indoors from outside. For example the maximum vapour pressure (VP) for bedrooms 1 and 2 of 1.78 and 1.80 kPa occur in the afternoon of June 22nd 2009 when the ambient mean RH is 79.3%, temperature 18.1ºC and VP >1.6 kPa (or >10 g/kg mixing ratio). Similarly, when the maximum RH occurs in the bedrooms of 72.4% and 66.7% on the morning of 24th June, the mean ambient RH is 92.8% and temperature 15.8ºC, well over 1.6 kPa and 10 g/kg. See Tables 1.1 and 1.2 for bedroom data.

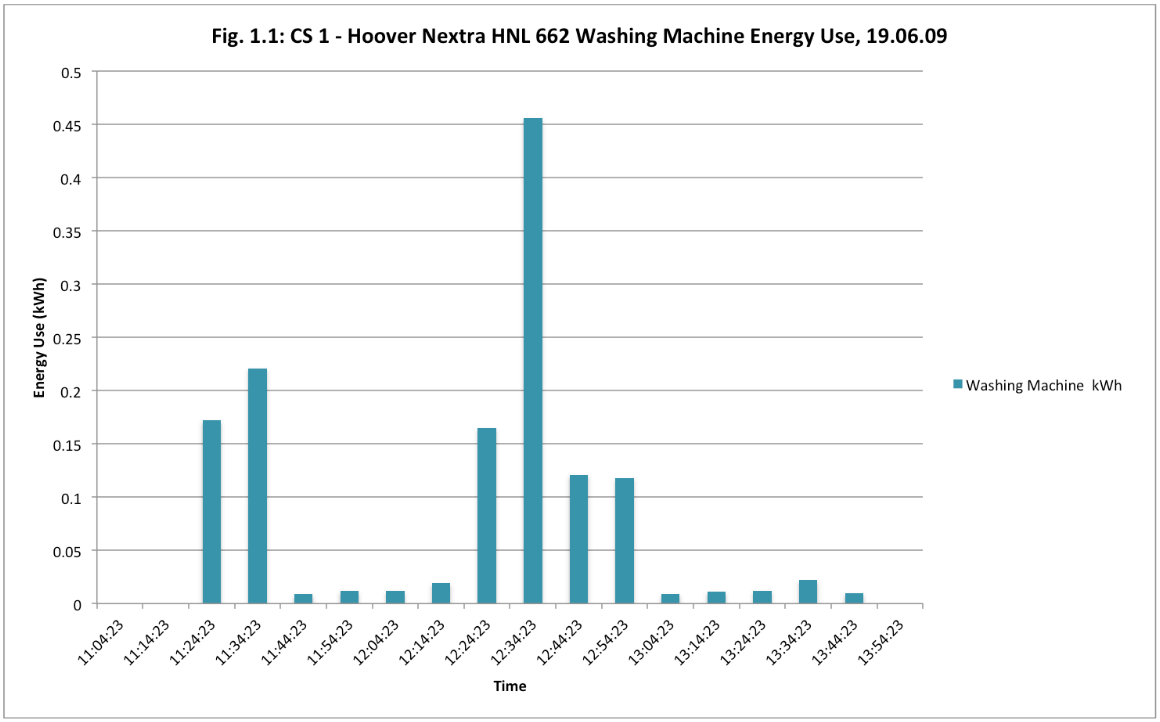



Table 1.1 Environmental conditions in Bedroom 1 for 10th – 24th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 719 | 1,070 | 532 | 22.0 | 24.1 | 18.5 | 1.21 | 1.80 | 0.69 | 45.8 | 72.4 | 26.2 |

Table 1.2 Environmental conditions in Bedroom 2 for 10th – 24th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 656 | 1,108 | 450 | 21.9 | 23.3 | 19.0 | 1.19 | 1.78 | 0.71 | 45.4 | 66.7 | 26.9 |

Similar to bedrooms, the maximum RH of 61.2% for the living room occurs at 09.24 on 24th June while ambient humidity is high at 73.3% and 15.3ºC. Similarly the maximum VP occurs at 16.54 on 22nd June; both thus again confirming the significant influence of outdoor moisture conditions while windows are open – see Table 1.3.

Table 1.3 Environmental conditions in Living room for 10th – 24th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 691 | 1,013 | 490 | 22.6 | 24.5 | 20.3 | 1.18 | 1.63 | 0.66 | 43.0 | 61.2 | 23.9 |

Again in the kitchen, when one might have expected cooking to have produced the maximum RH and VP, the maxima correspond to moist ambient conditions – the RH peak occurring on 22nd June at 08.14, while the VP peak is on the same day at 17.04 – see Table 1.4.

Table 1.4 Environmental conditions in Kitchen for 10th – 18th April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 646 | 973 | 472 | 23.1 | 25.4 | 17.7 | 1.25 | 1.68 | 0.65 | 44.2 | 61.5 | 23.8 |

Duplicate air samples, using SAS super 180$^{TM}$, one with malt extracts agar (MEA) and the other with potato dextrose agar (PDA) as the medium for microbiological identification, were taken in five spaces within each home at the time of setting up sensors and other equipment (all between 9.0 a.m. and 12 p.m.); and occupants were advised to go on with normal indoor activity before and during the air sampling. The spaces were: living room, bedroom(s), hall, kitchen and bathroom. Plates were incubated at 23ºC for four days or until visible growth appeared; thereafter counted and corrected for statistical possibility of multiple particles passing through the same hole according to manufacturers' guidance. The concentration of colony forming units (CFUs) per cubic metre of sampled air is found by: X = Pr x 1000/V (CFU/m$^3$); where V = volume of air sampled; Pr = probable count obtained by positive hole correction of r = CFUs on plates. Isolates are later sub-cultured on to MEA and PDA for further identification – in some cases to species level and in others only to genus level, based on growth and colony characteristics on media plates and microscopic examinations as described by Samson et al (2002), cited by Herbarth et al (2003). This applies to all further case studies 2-22 described hereafter.

The CFU counts were also low in all rooms (<700 CFU/m$^3$) the methodology for. Mould types partly corresponded to those frequently found by Haas et al (2007) in summer (Cladosporium and Penicillium), but winter-dominant Aspergillus was also found, and others like Mucor. The fact that there were roughly twice as many drying loads as washing loads, suggests that the Speedqueen was found to deal with the smaller amounts effectively within the 45-minute cycle. What is of interest is that the ambient spore concentartions, which are expected to be fairly high in summer, do not appaer to have influenced indoor spore concentrations in the same way that ambient moisture has.

Because the monitoring of this case study took place in summer, the benefit of machine drying outside the home was not apparent. The householder opened windows for approximately 12 hours daily in most rooms, and this is also reflected in the $CO_2$ figures – typically in the 'desirable' range below 700 ppm.

FREQUENT WASHER, PASSIVE DRYING IN SEVERAL INDOOR SPACES, WINDOWS OPEN, HEATING TURNED UP; WINTER MONITORING, FLAT IN TRADITIONAL STONE-BUILT TENEMENT

Case study 2: This is a flat for a large household of two parents and five children. The intensity of washing, method of drying, with gas central heating and radiators boosted and augmented by a coal-effect gas fire to facilitate this, and windows simultaneously opened to modify the effects of moisture – all this in the coldest winter month of January – undoubtedly has a large impact on fuel consumption. Moreover, due to the open windows, and probably due to ambient conditions of cold and fairly dry air at this time of year, there are no evident peaks in vapour pressure that match the drying periods. The peaks of vapour pressure that occur in rooms where drying also took place generally appear to correspond with peaks in $CO_2$, suggesting a correspondence with intensity of occupation rather than drying.

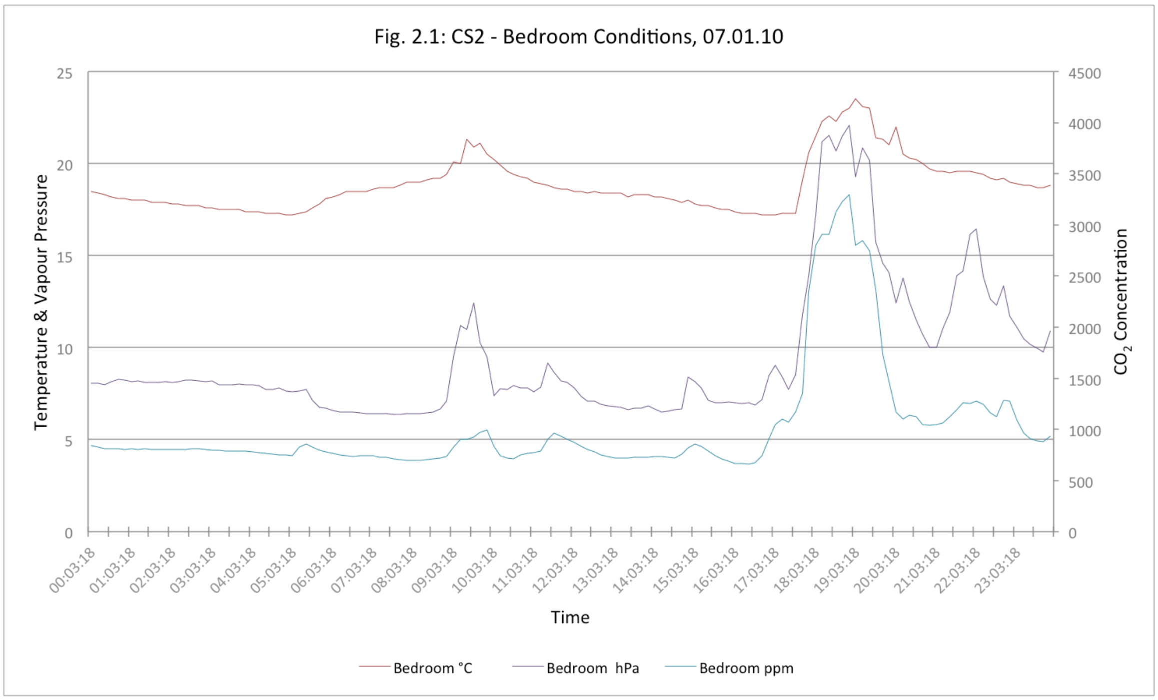



Fig. 2.1 illustrates the situation for 7th January, 2010 in Bedroom 1. In the two hours forty minutes between 1443 and 1723, the mean vapour pressure is 0.75 kPa, and the mean $CO_2$ is 808 ppm, indicating good air quality. However, in the next period of two hours fifty minutes from 17.23 to 20.13, the vapour pressure peaks at 2.21 kPa, with mean 1.70 kPa, while $CO_2$ also surges up to a mean of 2,317 ppm, having peaked at 3,296 ppm – some 230% above today's recommended maximum of 1,000 ppm or 8 l/s for each person (Appleby, 1990) originated by Pettenkofer in 1872 (Porteous, 2011). At this point the temperature has also peaked at 23.5$^{o}$C and RH at 78.6%.

Note also that it has been recommended that moisture levels above a mixing ratio of 7 g/kg or a vapour pressure of 1.13 kPa is likely to increase problems from dust mites (Platts-Mills, and De Weck, 1989; Niven et al, 1999); while Cunningham defines 'critical equilibrium humidity', below which mites cannot survive and reminds us" "neither absolute humidity or relative humidity alone determine risk for the viability of mites." (1998) In these terms, the target of Niven et al of 45% RH or 7 g/kg at 21ºC lies comfortably below Cunningham's 'equilibrium humidity' of 48.7% or 8.8 g/kg at 21ºC. Note also that 23.5$^{o}$C and RH at 78.6% is significantly above 'equilibrium humidity' for mites, which would be 57% or 10.5 g/kg at that temperature. Critically for health, a causal relationship has been found by the Committee on the Assessment of Asthma and Indoor Air between dust mites and incidence of asthma (Institute of Medicine, 2000). Moreover, Niven et al cited work which found that spikes of humidity of as short a duration as 1.5 hours increased mite survival significantly (de Boer and Kuller, 1997). Although, ‘critical eqilibrium humidity’ for mites continues to rise with temperature, relevant for micro-sites such as bedding, the Platts-Mills and de Weck and Niven et al threshold of 7 g/kg (1.13 kPa) appears pragmatic in terms of typical room conditions, where temperatures are likely to fall into the ‘teens’ while RH is well above 50%.

The above data suggest relatively intense occupation of the room, with the window closed. But although any evident connection with indoor drying, which did take place in the bedroom according to the diary, is masked by the presence of the room’s inhabitants, the rate of increase of its vapour pressure in this manner is of interest. For example, when the vapour pressure is at 2.2 kPa, condensation would occur on the inside face of the window falls below 19°C. There is also a second peak in vapour pressure from 21.03 to 23.43, and in this case the correspondence with a rise in $CO_2$ is significantly less pronounced. It increases by about 240 ppm compared with an increase of 2,224 ppm in the earlier spike – a factorial differential of over 9. The corresponding increase in vapour pressure is 0.64 kPa compared with 1.22 kPa in the earlier part of the evening. Therefore it seems possible, if not probable given the evidence from the diary, that the some of the increase in moisture is attributable to the passive drying of wash-loads.

Fig. 2.2: CS2 - Bedroom Conditions, 10.01.10

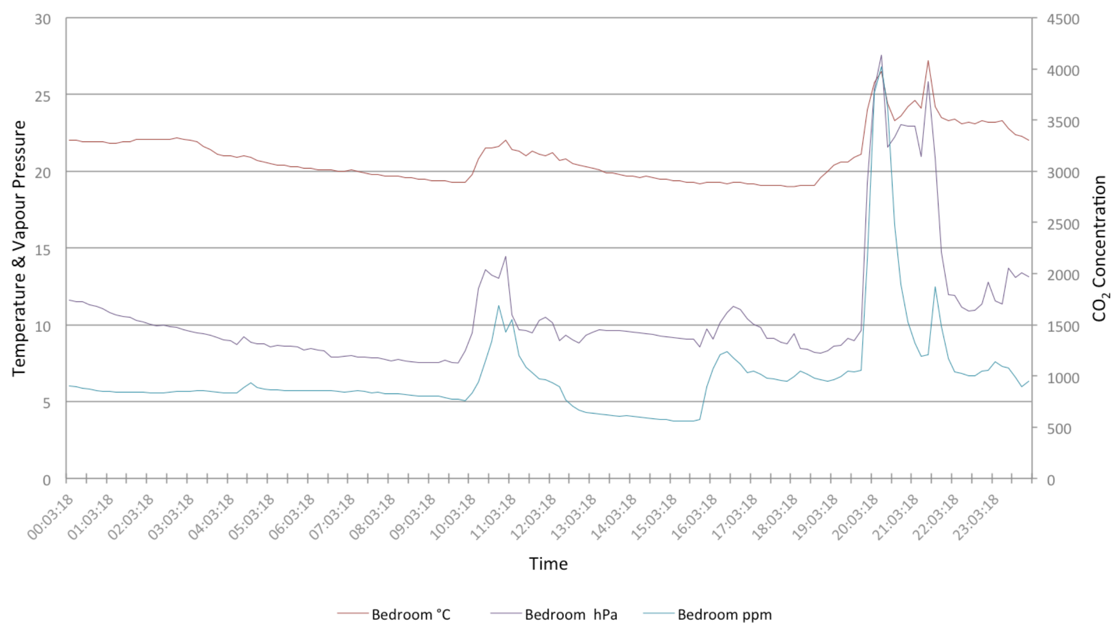



Fig. 2.2 illustrates a similar situation for 10th January 2010 in Bedroom 1. In the two hours ten minutes between 17.23 and 19.33, the mean vapour pressure is 0.87 KPa, and the mean $CO_2$ 990 ppm, indicating reasonable air quality. However, in the next period of two hours fifty minutes from 19.33 to 21.53, the vapour pressure peaks at 2.76 kPa, with mean 2.06 kPa, while $CO_2$ also surges up to a mean of 2,053 ppm, having peaked at 4,018 ppm – some 300% above the recommended maximum. At this peak, the temperature also attains 26.5°C and the RH 79.7%. This again suggests relatively intense occupation of the room, with the window closed. However, in the last part of this period from 21.13 to 21.53, the mean vapour pressure remains relatively high at 1.89 kPa, peaking at 2.58 kPa, but the $CO_2$ drops down to a mean of 1,385 ppm – i.e. only 38% above the desired maximum level. Both temperature and RH also remain quite high in this period - a mean of 24.5°C and 60.7%, and maximum of 27.2 °C and 71.6%, respectively. One explanation for this is that during this period of 40 minutes, occupants have left the room, and the presence of the drying washing is now making itself felt without their presence. The possibility that the moisture generated by the occupants’ presence does not dissipate as quickly as the $CO_2$ seems to be negated by the difference compared with the same sort of situation with the first

evening peak on the 7th January, where respective vapour pressure and $CO_2$ profiles match more closely for the period in question. At any rate, the ambient conditions on the 10th at this time – temperature 2ºC, RH 72.5%, and low VP of circa 0.44 kPa – do not seem to have been influential.

There are other instances of vapour pressure peaks in Bedroom 1 coinciding with $CO_2$ peaks: e.g on the 6th, 9th and 11th of January, with respective vapour pressure values in kPa of 2.50, 2.50 and 2.69, corresponding with $CO_2$ concentrations in ppm of 4,031, 3,408 and 2,970. Equivalent peak temperature and RH values are 23.8ºC, 26.0ºC, 25.2ºC and 84.8%, 74.3%, 83.9% RH, albeit the respective maxima sometimes occurring at slightly different times. Ambient conditions at these times are cold, but also relatively dry – e.g. –1ºC and 0.38 kPa on the 6th; and –1.4ºC and 0.52 kPa on the 11th. In each case both vapour pressure and $CO_2$ levels are normal on each side of the peaks of 2-3 hours in the early part of the evening. This indicates a regular pattern of intensive occupation of this room, with all key environmental indicators well above optimum maxima; which means that not only will the air quality be poor during these periods, but also the risk of mould growth will be quite high as the room becomes uncomfortably warm and humid.

Note also that Olaf Adan's frequently cited PhD thesis found a risk of mould growth associated with short peaks of high humidity (Adan, 1994, as cited in: Ginkel & Hasselaar, 2005; Straube and deGraauw, 2001; Viitanen & Ojanen, 2007). Even though, the occupancy may be masking the impact of any passive drying that also occurs, and the diary in this case tells us that radiators in bedrooms living room and hall are used, as well as hanging damp items over doors, the moisture from this must have some impact. The diary lists drying of this nature occurring as follows: in the evening of the 7th; all day on the 8th, 9th and 10th; afternoon and evening of 11th; all day on 13th and 14th; and evening on the 15th. Again, there are peaks in all measurements in bedroom 1 on the 13th, 14th and 15th (the only one where measurements were taken). Although the diary stops at this point, the pattern in the bedroom is repeated until the 19th January, with similar peaks in all the measurements occurring on the 16th, 17th (two occasions) and the 19th. Mould was recorded as present on walls, with a CFU count of 915/$m^3$ for the sample taken on 6th January (no breakdown of spore types available). In this instance the value for the living room was somewhat higher at 965/$m^3$ even though the moisture level was lower – maximum 0.87 kPa cf. 2.5 kPa on 6th January; mean 0.94 kPa cf. 1.12 kPa. However, taken over the whole two-week monitoring period the moisture differences are also slight, and one should be wary of regarding the CFU count on a specific day associating with other environmental indicators on the same specific day. Table 2.1 summarises the key data on all these occasions for bedroom 1.

Table 2.1 Bedroom 1 moisture and $CO_2$ peaks in January 2010

| Date | Max $CO_2$ (ppm) | Max VP (kPa) | Max RH (%) | Max T ($^oC$) |
|---|---|---|---|---|
| 6th | 4,031 (18.53) | 2.50 (18.43) | 84.8 (18.53) | 23.8 (18.53) |
| 7th | 3,296 (18.53) | 2.21 (18.53) | 78.6 (18.53) | 23.5 (19.03) |
| 8th | 1,092 (17.13) | 1.31 (17.13) | 68.3 (17.13) | 16.8 (17.13) |
| 9th | 3,408 (20.23) | 2.50 (20.33) | 74.3 (20.33) | 26.0 (20.33) |
| 10th | 4,018 (20.13) | 2.76 (20.13) | 79.7 (20.13) | 26.5 (20.13) |
| 11th | 2,970 (18.53) | 2.69 (18.53) | 83.9 (18.53) | 25.2 (18.53) |
| 12th | 1,075 (09.23) | 1.66 (09.23) | 61.8 (09.23) | 23.2 (09.43) |
| 13th | 2,928 (14.13) | 2.69 (14.13) | 81.5 (14.13) | 25.7 (14.13) |
| 14th | 4,090 (18.53) | 2.86 (18.53) | 82.2 (18.53) | 26.6 (18.53) |
| 15th | 3,395 (17.43) | 2.97 (17.43) | 80.6 (17.43) | 27.0 (17.43) |
| 16th | 3,758 (18.13) | 2.81 (18.03) | 76.3 (18.13) | 28.4 (18.03) |
| 17th | 2,970 (19.53) | 2.69 (19.53) | 83.9 (19.53) | 25.3 (19.53) |
| 18th | 1,075 (10.53) | 1.66 (10.23) | 61.8 (10.23) | 23.2 (10.43) |
| 19th | 2,913 (23.13) | 2.64 (23.13) | 83.8 (23.13) | 24.9 (23.13) |

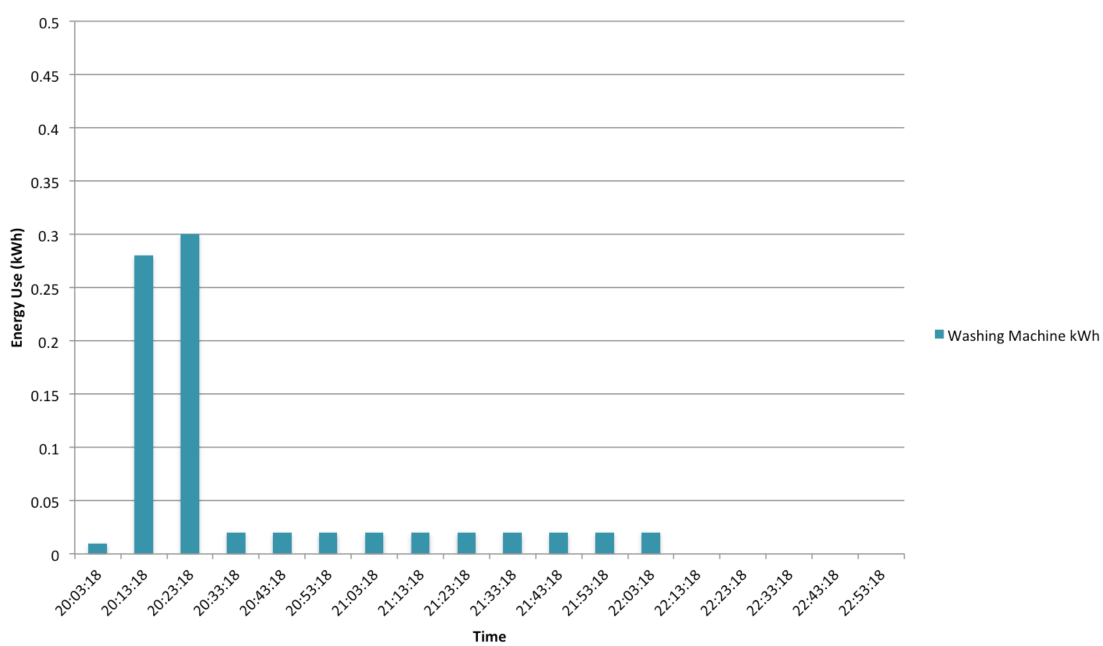
Note: 24-hour time of peak value given in parenthesis after each reading.

Another aspect of passive indoor drying in this case is off-gassing of volatile organic compounds (VOCs), in particular  from the fabric softener used. Recent work  in Seattle has shown that one of the gases emitted by fabric softeners is acetaldehyde, noting that this could be a 'secondary pollutant resulting from a reaction between product ingredients' (Steinemann et al, 2011). Such ingredients might include terpenes such as limonene, commonly found in detergents and fabric softeners. Acetaldehyde is classified as a probable human carcinogen by the US Environmental Protection Agency (EPA) and listed under several other acts or standards – e.g. Hazardous Air Pollutant under the Clean Air Act;  Air Contaminant under the Occupational Safety and Health Act (Steinemann et al, 2008). A list of chemicals found in fabric softeners compiled for EPA in the 1990s also includes limonene and desribes it as carcinogenic (Kendall, 1995).

The concentration of water soluble VOCs such as aldehydes have also been shown to increase with humidity (Arundel et al 1986). Hence it is reasonable to conclude that humid interiors, at least in part due to passive indoor drying, would tend to increase the environmental impact of VOCs such as acetaldehyde where fabric softeners are used, such as in this case study. Although this suggests a health implication, it is important to stress that neither the work of Steinemann's team in Seattle, nor the present study in Glasgow, either sought to produce, or has produced, any evidence of an association between use of fabric softeners or detergents and the health of the occupants in question.

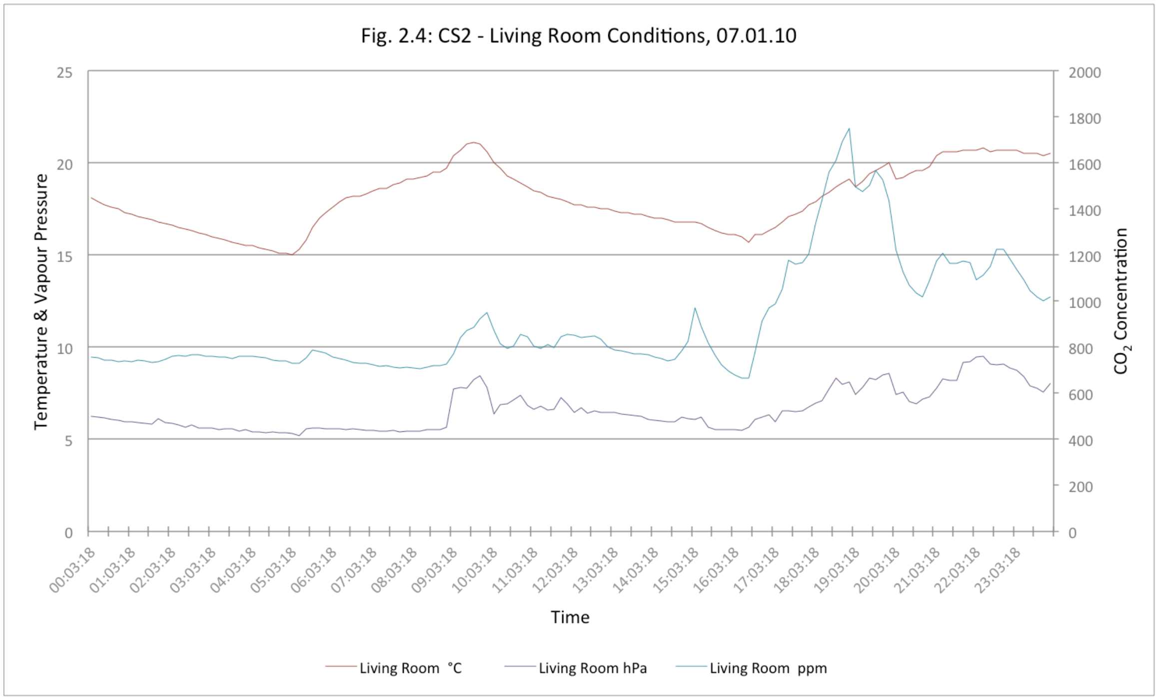
The total number of washing loads measured over 13 days was 16 – an average of 1.23 per day, but this was for a large household of two parents and five children.  At a mean average of 0.75 kWh/load as measured (total 12 kWh), the daily consumption per household is thus estimated to be 0.92 kWh, or 0.132 kWh/person; and extrapolating this indicates 337 kWh annually per household or 48 kWh/person (young children possibly exacerbating the consumption).

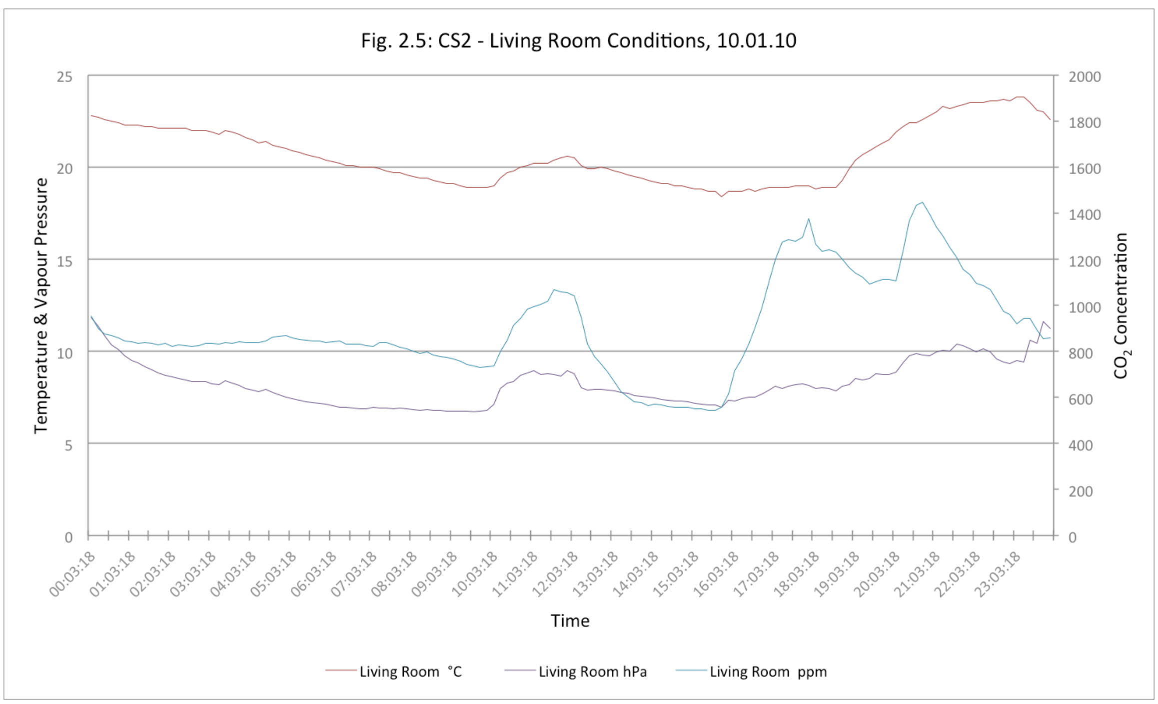
**Fig. 2.3 CS 2 - Bosch Maxx Washing Machine Energy Use, 18.01.10**




In this case, if the total consumption over the monitored period of 12 kWh is divided by the total duration of washing cycles, the mean hourly average consumption is 0.5 kWh, just above the 0.48 kWh value for Case Study 1. The appliance in this case is a Bosch Maxx, with online information estimating 0.9 kWh for a colourfast cotton cycle at 60$^{o}$C. The measured consumption averaging 0.75 kWh per cycle probably reflects the cooler washes that are both advised, and also that have become normal. It may be noted also that ironing was recorded as nominal in this household. Fig. 2.3 shows a typical wash cycle for 18th January, with the maximum 10-minute initial heating period consuming 0.3 kWh.

Two small amounts of ironing and one longer ironing session are acknowledged during the two weeks of monitoring. Using a 2 kW Morphy Richards steam iron, and assuming 1.25 hours of ironing weekly at 0.28 kWh per half hour of use, the annual estimate is a very modest 36 kWh, approximately a ninth of that estimated for washing, and contrasting with the relative estimates for Case Study 1 above. (see Appendix 1, giving data for controlled tests of three irons).



Without detailed modelling of this particular house type, it is hard to be exact concerning the energy impact of the boosted heating in conjunction with open windows during a cold winter period – ambient mean of 1.94$^{o}$C and 77.5% RH over monitored period of ten wash days, with the first six days averaging only -0.96$^{o}$C and 79.4% RH. However, while graphs indicate the impact of the regime on indoor temperature and moisture (vapour pressure) – see fig. 2.4 and 2.5 above, it is possible to gain a sense of the energy consequences with ballpark figures using steady-state 2-zone, refined-BREDEM methodology (Anderson et al, 1984); taking average values for solar radiation and temperature for January – approximately 1.0 K higher than the measured mean value at 3.6$^{o}$C.

If we assume Scottish Space Standards from 1985, still used as a benchmark by housing associations, a 2-storey terraced house for a family of 7 persons (flats not normal for this size of family), indicates a minimum floor area of 114.5 m$^2$.

If we then assume an intermediate terrace location and Scottish Technical Handbook 2007 (TH07) default standards for U-values, we can compare 3 scenarios:
a) with mechanical heat recovery ventilation (MHRV) and assuming an 'all-day' 16-hour heating regime to a demand temperature of 21$^{o}$C (mean 20.4$^{o}$C in living room of CS 2 for 10 wash days);
b) without heat recovery and with the same heating regime;
c) without heat recovery, ventilation rates doubled and demand temperature raised 2 K to 23$^{o}$C.

Further assumptions are that a 91% laboratory efficiency MHRV will be modified by a factor of 0,85, assuming insulated ducting, to give an in-use efficiency of 77.35%, and respective 'effective' hourly air changes:
scenario a) zone 1 (living plus kitchen) and zone 2 (rest of house) values of 0.39 and 0,34 ac/h;
scenario b) 1.00 and 1.07 ac/h;
scenario c) 2.00 and 2.14 ac/h.
Finally, for all scenarios, east/west glazing for zone 1 is assumed to be 15% floor area; and 10% for zone 2; with appropriate incidental gains relative to today's lifestyle aspirations.

Results for space heating demand using this basic analysis are as follows:
Scenario a)    638 kWh for January, or approximately 21 kWh per day
Scenario b)    1,314 kWh for January, or approximately 42 kWh per day
Scenario c)    2,711 kWh for January, or approximately 88 kWh per day

Thus, in round terms we can see that the energy demand doubles, moving from MHRV to natural ventilation; and more than doubles again when thermostat setting is raised by two degrees, while the ventilation rate doubles. Such differences would increase if the energy efficiency were below that assumed – i.e. below TH07 standard -– and/or in an end-of-terrace or semi-detached location. Dynamic computer modelling in PM 3, took a notional semi-detached house model, a 'representative seasonal week' in winter and a London climate; and then compared a MHRV value of 0.4 ac/h and insulation to passive house standards, to typical insulation values at 0.6 ac/h and 1.5 ac/h – i.e. a smaller order of difference to above scenarios a, b and c in terms of ventilation, but with the notional house rather less well insulated than TS07 (wall U-value 0.45; roof 0.39, floor 0.59, windows 3.3 W/m$^2$K). Respective energy consumption was found to be 0.61, 1.94 and 4.44 kWh/m$^2$ for the week's simulation. If these values are multiplied by 114.5 m$^2$ (as scenarios a-c above) and divided by 7 days, respective values are 10, 32 and 73 kWh/day. In other words, the dynamic modelling for a warmer climatic location, and a particular December 'representative seasonal week' compares quite reassuringly with the cruder BREDEM-based broad-brush analysis. Such a ventilation increase in the dwelling as a whole might realistically represent found conditions, where occupants passively dry washing inside habitable rooms.

Further notes regarding the likely impact of indoor drying in terms of moisture released are given under CS 4, and further modelling reported for an assumed washing and drying regime over an entire year is reported under CS 5.

FREQUENT WASHER, PART TUMBLE, PART PASSIVE DRYING INDOORS, WINDOWS OPEN, HEATING ON; AUTUMN MONITORING, FLAT IN EARLY 1990S TENEMENT, FAST RESPONSE CONSTRUCTION

Case study 3: In many respects the pattern of laundering in this household is similar to case study 2 above. First surveyed as a household of three adults and one infant aged two, by the time of durational monitoring the household had apparently diminished by one adult, and adopted a very intensive washing pattern for a total of three inhabitants. Heating is by gas boiler, and although passive drying on radiators and airers is used, mainly in the living room, with windows open and heating on (19th October to 3rd November), tumble drying is used for at least part of most washes (domestic appliance in flat) and roughly half of each washing load is ironed – i.e. there are commonalities with Case Study 1 in this regard. The dwelling in this case is a flat in the New Gorbals, built post-1991 Scottish Building Standards in a construction that is effectively lightweight – i.e. wall and ceiling linings are light, thus providing a relatively rapid response to heat inputs.

The main difference compared with No 2 is that there is an even more liberal regime with regard to open windows: recorded in the diary as open all day in the living room, kitchen, and all bedrooms. This is certainly evidenced by the $CO_2$ levels – see Tables 3.1-3.3. With this open window regime, the heating maintains quite high temperatures, with a living room mean of 21.5$^o$C, bedroom 1 mean of 20.75 $^o$C and bedroom 2 mean of 19.0 $^o$C. Although the combination of heat and ventilation masks much of the effects of passive drying and ironing in the living room on a frequent basis, there will be a significant energy penalty for this as indicated above for case study 2. The other point to note is that although the vapour pressure does not have the extreme maxima of No 2, the levels are still often above the 1.13 kPa level advocated as an upper limit relative to dust mite propagation by Platts-Mills and De Weck: the living room averages 1.34, has a minimum of 0.85 and a maximum of 1.74 over the period; while corresponding figures for bedroom 1 are 1.28, 0.79 and 1.88 kPa. Given the time of year and Glasgow's rather humid autumnal weather, this is not surprising. It should also be noted that mean vapour pressures in living room and bedrooms 1 and 2 are fairly similar at 1.34, 1.28 and 1.32 kPa respectively; while CFU counts are also close and not high at 550, 595, 640 CFU/m$^3$. The lack of respective ranking is therefore not particularly surprising, and certain types of mould (e.g. Aspergillus and Penicillium) correspond to expectations for autumn and presence of mould (on kitchen wall only), while others are less attributable (e.g. Cladosporium more common in summer).

Tables 3.1-3.3 summarise data for the whole period of monitoring; while Table 3.4 focuses on one day, divided into an evening time zone, and the earlier period of the day. Table 3.4 in particular shows that vapour pressure (VP) can be quite high while air quality is good; thus reflecting open windows but with moist ambient air entering the rooms.

Table 3.1 Environmental conditions in Bedrm 1 for 19th October - 3rd November 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 694 | 1,273 | 491 | 20.8 | 27.4 | 16.5 | 1.28 | 1.88 | 0.79 | 51.9 | 74.0 | 35.1 |

Table 3.2 Environmental conditions in Bedrm 2 for 19th October - 3rd November 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 747 | 2,124 | 425 | 19.0 | 28.1 | 15.6 | 1.32 | 1.70 | 0.88 | 59.9 | 75.9 | 35.0 |

Table 3.3 Environmental conditions in Living rm for 19th October - 3rd November 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 715 | 1,402 | 476 | 21.5 | 23.9 | 18.9 | 1.34 | 1.74 | 0.85 | 52.3 | 67.1 | 38.5 |

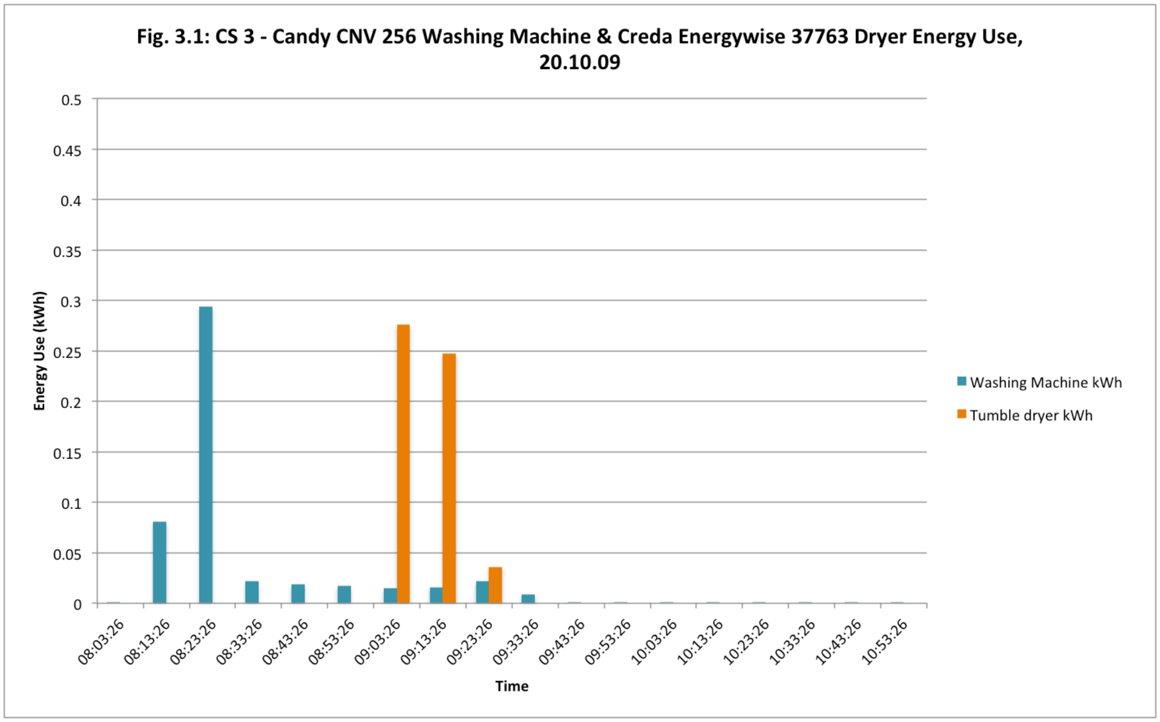
The mean ambient RH on that day, 30th October, was 88% and the temperature very stable with a mean of 13.7ºC, maximum approximately 15.0ºC and minimum 13.0ºC. Indeed the ambient conditions were similar on the two days either side of the 30th, when the maxima for bedrooms 1 and 2 occurred respectively. For bedroom 1, 1.88 kPa occurs at 20.13 on the 31st when the temperature in the room is 23.7ºC, RH 62.3% (above 'critical equilibrium humidity' for dust mites, Cunningham, 1998) and $CO_2$ 859 ppm; and mean ambient RH 87% and temperature 13.4ºC. For bedroom 2, 1.70 kPa occurs at 18.23 on the 29th, when inside temperature is 19.3ºC, RH 75.9% (far above 'critical equilibrium humidity' for mites) and $CO_2$ only 505 ppm; and ambient RH is 85% and temperature 13.5ºC giving a VP of circa 1.3 kPa. In other words, it is possible that humid ambient conditions combined with the open windows has a considerable influence in this instance; and this is contributing to the likelihood of excess mite growth – hence asthma risk.

Table 3.4 Environmental conditions in evening and rest of the day for 30th October

| Room/time | Temperature (ºC) | | | Vapour Pressure (kPa) | | | $CO_2$ (ppm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | mean | max | min | mean | max | min | mean | max | min |
| Liv/1745-0000 | 22.7 | 23.7 | 21.5 | 1.49 | 1.61 | 1.38 | 703 | 890 | 580 |
| Liv/0000-1745 | 21.6 | 22.6 | 20.9 | 1.45 | 1.74 | 1.28 | 602 | 811 | 511 |
| Br1/1745-0000 | 22.0 | 23.6 | 18.0 | 1.44 | 1.70 | 1.26 | 708 | 992 | 581 |
| Br1/0000-1745 | 20.4 | 22.3 | 18.5 | 1.37 | 1.59 | 1.19 | 592 | 785 | 527 |
| Br2/1745-0000 | 19.8 | 20.5 | 18.7 | 1.48 | 1.62 | 1.37 | 663 | 877 | 528 |
| Br2/0000-1745 | 20.7 | 16.9 | 1.42 | 1.55 | 1.22 | 703 | 956 | 440 | 20.7 |

The total number of washing cycles (two very long) over 15 days was 26 - an average of 1.73 per day, this for a relatively normal household of grandparent (assumed), one parent and one child aged two. At 0.55 kWh/cycle, daily consumption for the household is estimated to be 0.95 kWh, or 0.32 kWh/person; and extrapolating this indicates 346 kWh annually per household, or 115 kWh/person. While the young child possibly exacerbates the consumption, it is relatively significantly greater per person than that of the large family in Case Study 2, or the three adults in Case Study 1. However, if we look at the energy consumed per hour of running time during cycles, the appliance in this case a Candy CNV 256, we have a total of 12.26 kWh over 35 hours 10 minutes, which gives a modest figure of 0.35 kWh/hour. In this instance there seems to be a significant standby addition, which brings the total consumption up to 14.9 kWh, and dividing this by the same total time for cycles, the hourly load rises to 0.42 kWh - still lower than either Case Study 2 or 1 above. Like the Hoover Nextra HNL 662 of Case Study 1, this appliance is triple-A rated (i.e. A for Wash, Energy and Spin), and in this instance there is an online estimate of 1.14 kWh for a full 6 kg load at 60ºC. To summarise, we have what seems to be an economic appliance in terms of its hourly consumption while running, but its estimated consumption per person in this 3-person household over a year is considerably higher than either Case Study 1 or 2. In other words, it seems that the relative intensity of washing is higher.

The total number of tumble drying cycles over 15 days was 18 - an average of 1.2 per day, but in this case, this figure (12% less than that for Case Study 1) dealt with only a proportion of the total washing load, with relatively brief cycles the most usual - one may assume that cost may have been an inhibiting factor, heavier items taking a heavy electrical toll. The total consumption over 15 days was 15.89 kWh, 0.88 kWh/cycle or 1.06 kWh/day, implying 387 kWh per annum - less than 130 kWh per person. In this case, although the Creda Energywise dryer is supposed to be vented from the kitchen, on nearly each occasion it was used there was a corresponding period of increase in RH and VP. These rises were typically fairly modest – RH up some 5% and VP up 0.13 kPa, less on 30th October cited above – and may well have been due to back-venting through the kitchen window, which was normally open all day during this autumnal period of monitoring. The effect of the added moisture also migrated to the living room, even as $CO_2$ levels fell – e.g. increasing from 50.5% to 56% on 19th October, while the kitchen rose from 57.0% to 61.6% –- and also to the hall and even the bedroom on occasions.



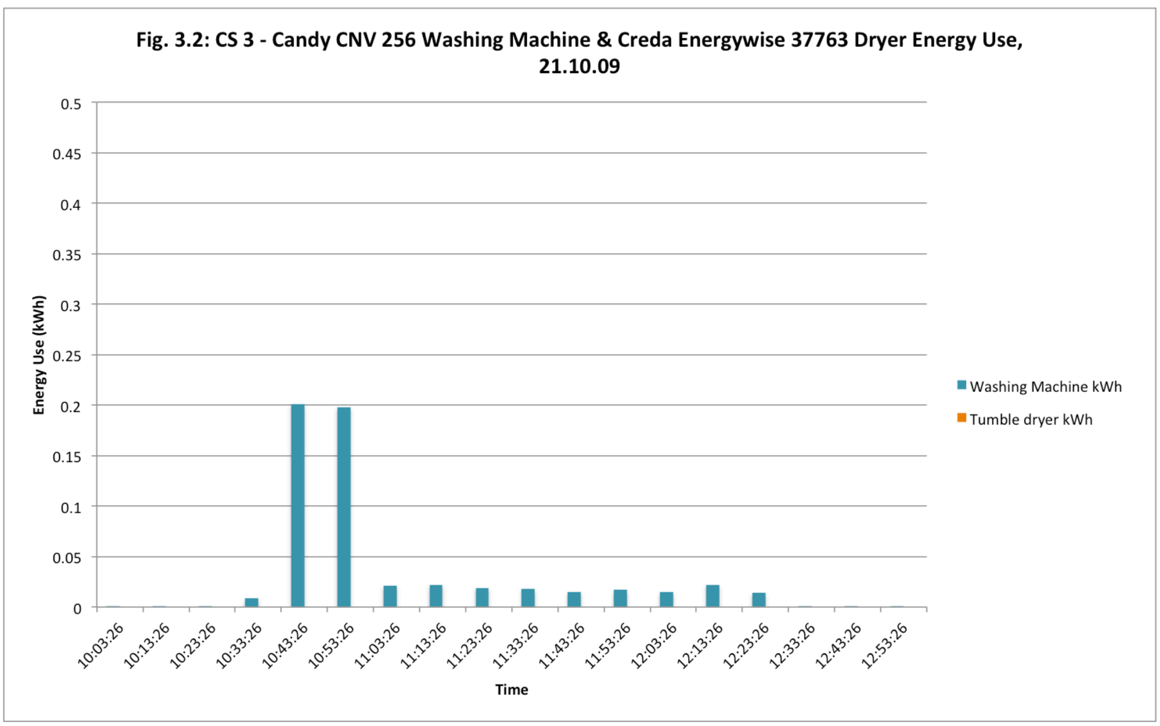




Fig. 3.1 shows a washing cycle on the 20th October, which overlaps with a half-load tumble drying cycle. The explanation for the overlap is that the drying is assumed to be a 'left-over' from the previous day's three washing cycles, only two of which were dried. This, and/or the brief duration, would explain the modest 0.56 kWh use of energy by the tumble dryer in this case. It was also one of only four of the 18 drying cycles where there was no significant increase in RH and VP. Fig 3.2 shows a more sustained triple drying cycle on the 21st October, again overlapping with a washing cycle. This time the total drying consumption is approximately 2.6 kWh, and again the relatively light energy consumption may be explained by partial passive drying on radiators. However, in the first of these cycles RH increases from 58.8% to 64.6% and

VP from 1.30-1.47 kPa, while $CO_2$ remains steady and low between 615-650 ppm, and temperature is also stable between 20-21ºC.

Another 13 cycles display similar characteristics, with evidence of migration of moisture to other spaces in the flat – e.g. 19th October living room RH increases at the same time as tumble drying from 50.5% to 56% while $CO_2$ falls, and on the 21st and 25th October there are indications of migration in living room, hall and a bedroom. As the kitchen window was open at all times, it seems likely that back-venting of the moist output was occurring, or that the dryer was simply allowed to ventlate into the kitchen since it aws perceived to be well-ventilated. Clearly, at this time of year and with the temperature maintained in the kitchen, this will have much the same energy consequences as the passive drying regime in CS 2, this in addition to the high primary energy consumption of the dryer itself.

It may be noted that values for consumption per cycle given by manufactures (based on full loads of cotton material) vary from 1.85-1.9 kWh for the most efficient A-rated 7 kg condensing types with heat pumps (e.g. John Lewis JLTDC 12; AEG T59850) to 3.5 kWh for C-rated 8 kg vented models with heating elements (e.g. Siemens WT36V398), and 4.5 kWh for 9kg condenser models (e.g. Hoover VHC391T) The model used in this case, a Creda/Electra Energywise 37763, is estimated to use 3.25 kWh/cycle - i.e. medium performance in terms of the range available today.

The average energy consumption/cycle given on the Internet by Sust-it for a range of 26 different dryers is 3.0 kWh. However, in some cases, by going to direct information from the manufacturer, this average adjusts slightly upwards to 3.16 kWh. In this regard, one may note that an official report in 2007 gave an average UK value of 2.5 kWh per use, and 354 kWh/year for each drier (BNW06: Assumptions underlying the energy projections for domestic tumble driers, Market Information Programme, first created 25/05/06, updated 13/08/07, last reviewed 18/01/08). One may note in relation to Case Study 3, that although the measured value per use is significantly lower than the BNW06 value, the extrapolated total for the year is somewhat greater. This implies significantly more frequent use than envisaged by BNW06, but each use comprising very much lighter drying loads.

In any event, the estimated usage in this case is a modest fraction (approximately one seventh) of the estimated value for Case Study 1, making use of the 'free' communal facility, and it is also only 12% more than the consumption for washing per person. Therefore, it perhaps suggests a middle road for sensible use of domestic tumble dryers. It doesn't free the dwelling from passive drying, as for Case Study 1, but it lowers the environmental burden of passive drying compared with Case Study 2. The dryer was operated over a total of 99 x 10 min slots, with a mean average power use of 0.96 kW over that time (15.92 kWh total). Since the dryer will not be on for all of the 10 min slot at the beginning and end of each cycle, and since the dryer is rated as 1.02 kW, it may be assumed that the dryer operates at full power nearly all of the time that it is on.

The consumption for ironing per household based on a 2.0 kW steam iron operated for approximately half an hour per half load ironed indicates average consumption of 0.28 kWh (see Appendix 1, giving data for controlled tests of three irons). As there was the equivalent of 9 half-load sessions of ironing over 2 weeks, this indicates circa 66 kWh annually or 22 kWh/person. Although this is not insignificant, in this instance it is approximately one fifth of the extrapolated load for washing.

RELATIVELY FREQUENT WASHER, SOME TUMBLE DRYING, SOME EXTERNAL PASSIVE DRYING AND PASSIVE DRYING IN LIVING ROOM WITH WINDOW CLOSED, HEATING ON; SPRING MONITORING, MAISONETTE IN 4-STOREY 1960S CAVITY BRICK BUILDING, HEAVY CONSTRUCTION

Case study 4: This household of two adults is interesting in terms of the time of year – spring, but still with a heating demand – with some opportunity to take advantage of outdoor drying as well as indoor drying and partial use of a tumbler dryer. Unlike case studies 2 and 3, the heating here is by electric storage units, the standard provision in these dwellings as built being one unit in the living room and another in the main circulation space. This is significant in relation to overnight drying in the main living space … to be elaborated below; but it is worth noting that the average temperatures are maintained at quite a high level – 22.5ºC in living room and circa 20ºC in bedrooms. The mould spore counts are in the moderate range below 1,000 CFU/m$^3$, and visible mould itself was only recorded in the bathroom.

The total number of washing cycles recorded in the diary over 14 days was 13 – an average of 0.93 per day, this for a relatively small household of a young adult (18) and an elderly adult (63). However, the monitoring took place over 19 days from 3$^{rd}$ to 22$^{nd}$ April, with a total consumption of 8.656 kWh in 13 cycles averaging 0.666 kWh; or 0.46 kWh/day, or 0.23 kWh/person.day. Extrapolating this indicates 168 kWh annually per household, or 84 kWh/person. As for CS 3, it is greater per person than that of the large family in CS 2, or the three adults in Case Study 1. In this case the model of washing machine is the same as CS 1, the Hoover HNL 662. However, the pattern of use here is different, with a predominance of relatively short cycles, and the mean average consumption per hour of running time in this case is 0.81 kWh, excluding standby usage or 0.88 kWh including standby usage. Overall, this difference compared with the 0.48 kWh per hour for CS 1, or 0.72 kWh/cycle cf. 0.52 kWh/cycle, suggests hotter wash temperature settings in addition to a penalty for relatively short cycles.

The tumble dryer was used only twice during the 14-day period, one and a half loads being recorded.  This was not directly measured, but the manufacturer's estimate for the appliance, a vented 8 kg-load Hoover Nextra, is 3.96 kWh per full load (In this case, the questionnaire declared it was a condensor type, which is possible by conversion). Thus the total consumption for 14 days would be of the order of 5.94 kWh, averaging 0.424 kWh/day; and extrapolating for the year (tentatively on such low usage) indicates 155 kWh or 77.5 kWh/person. Such frugal use is to be welcomed in one sense, and also involved no evident increase in moisture  in the host room unlike CS 3, but it also raises a question as to whether the household needs the appliance at all.  Even though it may well have been used more heavily in winter, it indicates a flexible attitude, one open to pragmatic plurality of drying methods; and, like CS 3, the projected energy impact is in stark contrast to CS1 with its intensively used, but notionally free, communal facility.

Although the questionnaire indicates using a 2.0 kW Morphy Richards steam iron in the kitchen, there is no record of this activity in the 2-week diary during monitoring. It is not therefore possible to estimate the annual consumption, although, as for CS 3, the estimate per half hour of use is 0.28 kWh.

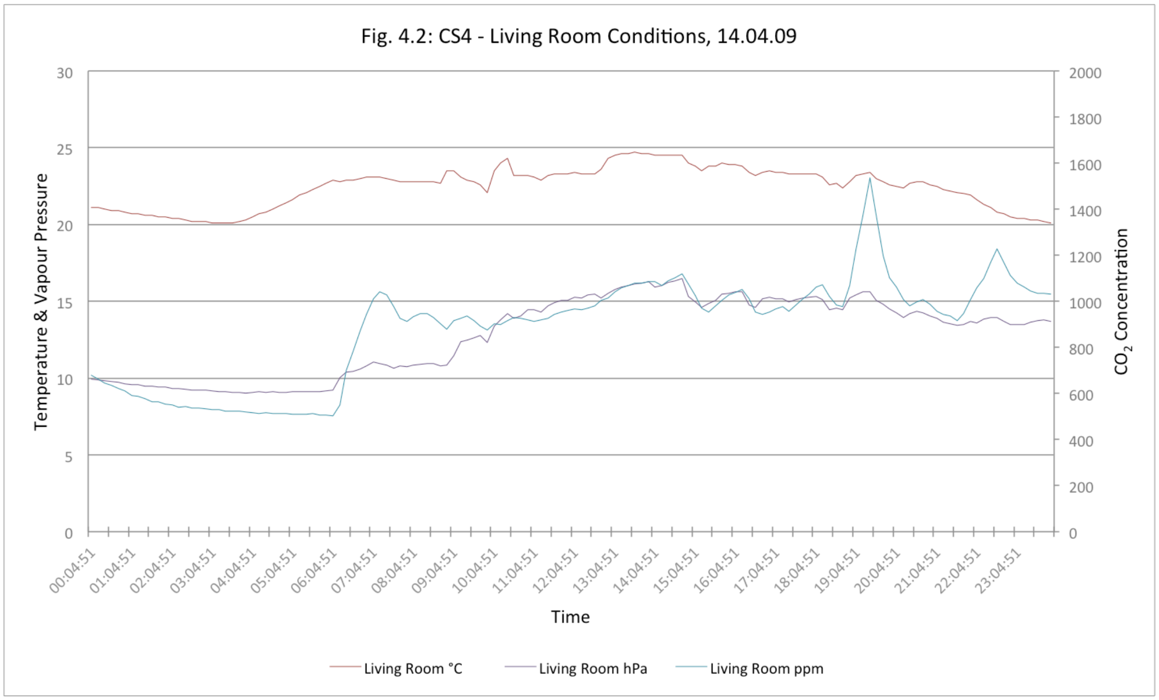
What is of greater interest here is the manner in which the occupants have taken advantage of the given heating system whereby the storage units receive a nocturnal charge. For example, we have a full washing load, with its cycle from 22.24-23.24, dried overnight in the living room, it is assumed with the window closed as the diary mentions when windows have been opened for any length of time. Here Fig 4.1 shows the vapour pressure beginning to rise just after the end of the wash cycle from about 1.4 kPa, eventually peaking at 1.78 kPa at 8.30 a.m. and having a mean of 1.63 kPa over this period. Meanwhile, because the room was without occupants during the same period, the $CO_2$ values correspondingly fall – from about 1,450 ppm at midnight to about 750 ppm at the same time as the vapour pressure maximum, and averaging 1,138 ppm. There is therefore no doubt that the gradual rise in vapour pressure corresponds with the release of water vapour while drying, starting relatively steeply before slowing. This will have been partly due to the gradual increase in temperature due to the storage charge, and partly to the diminishing amount of moisture left in the washed items. The final fall-off in vapour pressure is fairly rapid once dry, and occurs before the room responds to other moisture inputs during the day from the occupants. Indeed during the remainder of the profile on the 10th April, we can see correspondence between $CO_2$ and vapour pressure that is likely to have been caused by human presence rather than due to any further influence from drying off a wash load.

Experiments as part of PM 2 of this study showed that a wash-load of some 15-17 items (dry weight 3.8-4.8 kg) would emit some 2.0 to 2.5 kg (or litres) of water vapour during drying; this over a period of about seven hours, with 88% of moisture loss occurring in four hours – i.e. 0.45-0.55 kg/hour – while RH averages circa 47.5% and temperature circa 21ºC. The volume of the living room in CS 4 is some 43.6 $m^3$, indicating a dry air mass of 96 kg (43.6 x 2.2). If the VP is at 1.17 kPa (7.3 g/kg) before drying commences – i.e. lower than the starting point of 1.4 kPa cited here in CS 4, and we then assume an air change rate of 1.0 ac/h, and 500 g of moisture added in an hour, the mixing ratio would be raised by 5.2 g/kg – and the RH would go above 80% at 21ºC. However, we know that the CS 4 vapour pressure never rises more than 0.38 kPa (circa 2.4 g/kg). Therefore, some 50% of the moisture must have been absorbed within fabric and furnishing; or the air change rate was greater; or migration occurred within the dwelling; or the load in question at CS 4 released less moisture than that based on the PM 2 experiment. This analysis at least serves to highlight some of the environmental issues at stake for passive drying.

Fig. 4.1: CS4 - Living Room Conditions, 10.04.09


On the 14th April, when the half load of washing was tumble dried, the remaining two loads were again dried in the living room. However, while once again the vapour pressure rises, this time from about 1.0 kPa at just before 9.0 a.m. up to 1.65 kPa at 2.44 p.m. with a mean of 1.46 kPa, the effect due to the drying washing is masked to some extent by a corresponding increase in $CO_2$ – see Fig. 4.2. This rises from 880 ppm to 1,121 ppm during the same period with a mean of 978 ppm, indicating that the room was occupied but that the air quality remained reasonable. Nevertheless, although some of the rise in vapour pressure must be associated with the presence of occupants, its overall rate of increase (over 0.5 kPa in 5.75 hours) is more rapid than that in Fig 4.1 where drying occurred without occupants, or indeed where the rise in vapour pressure could only be attributed to occupants. In the latter regard, we can for example take the period of just over 5.25 hours on the 10th April, starting at 16.44 and ending at 22.04 when the vapour pressure rises from 1.6 kPa to 1.75 kPa. Thus, not only is there evidence of the impact of the drying washing, but also there is evidence that it is raising moisture levels well beyond the Platts-Mills recommended 'dust mite' limit of 1.13 kPa (7 g/kg mixing ratio) as well as the Cunningham cited

(Arlian and Veselica, 1981; Arlian 1992) ‘critical moisture equilibrium’ for mite growth – mean temperature in this period of 23.1ºC, and mean RH of 60.6%.




In this regard, it is useful to compare these specific drying periods with the averages for the entire period in living room and bedroom 1 from 8$^{th}$ to 22$^{nd}$ April – see Tables 4.1-4.2.

Table 4.1 - Living room moisture (kPa) and $CO_2$ (ppm) mean, min. and max., April 2009

| Mean $CO_2$ | Min $CO_2$ | Max $CO_2$ | Mean VP | Min VP | Max VP |
|---|---|---|---|---|---|
| 1,097 | 503 | 2,058 | 1.22 | 0.68 | 1.79 |

In the case of the maximum VP, it is quite possible that ambient influence has made itself felt via an open window – the time of occurrence is 08.34 on the 10th April, when ambient RH is high at 82.6%, temperature 10.75ºC, and VP circa 1.07 kPa. Certainly moisture from presence of occupants is unlikely to have been influential, $CO_2$ being a modest 747 ppm at this time.

Table 4.2 - Bedroom 1 moisture (kPa) and $CO_2$ (ppm) mean, min. and max., April 2009

| Mean $CO_2$ | Min $CO_2$ | Max $CO_2$ | Mean VP | Min VP | Max VP |
|---|---|---|---|---|---|
| 1,295 | 588 | 2,455 | 1.31 | 0.78 | 1.63 |

In the case of bedroom 1, the situation regarding moisture is less clearcut. The maximum VP occurs at 10.24 on the 10th April when the $CO_2$ level is high at 1,561 ppm. The ambient RH is also reasonably high at 77.8%, while the temperature is 10.3ºC and VP circa 0.96 kPa, but it seems probable that under-ventilation overnight helped to build up moisture inside the room.

Moreover, although the mean moisture levels are lower than during the specific drying periods, the mean $CO_2$ levels are not. Also, overall, both indicators are exceeding benchmark maxima.

The CFU counts for mould spores average 767 CFU/m$^3$ for living room and bedrooms, while the kitchen is somewhat higher at 865. Again, mould types include the common ones, Aspergillus, Cladosporium and Penicillium (Haas et al, 2007), but seasonality and association presence or absence of mould itself is largely a matter varying proportionality (not available in the analysis).

ENERGY-INTENSIVE WASHING, ALL TUMBLE DRYING, HEATING ON; AUTUMN MONITORING, FLAT IN 4-STOREY 1970S 'NO-FINES' SEMI-HEAVY CONSTRUCTION, DRY-LINED INTERNALLY

Case study 5: This household of three adults makes interesting comparison with Case Study 3, given the similarity in window opening habits and time of year. However, in this case there is an electric storage heating system and no passive drying is carried out.

Although the structure is different in this case, a 'no-fines' load-bearing wall system, dry-lined internally and now also insulated externally, the environment in terms of thermal response will be similar, with only the means of heat emission differing significantly.

Washing was recorded in the diary for six days out of the two-week monitoring period from 12-26$^{th}$ October, and, like other case studies above, on some washing days more than one full load was washed giving a total of 10 loads. Therefore the frequency of washing is not as great compared with some other case studies, for example Case Study 4 above. However, in this case the total measured energy consumption was 27.48 kWh, which worked out at 1.96 kWh/day or 0.65 kWh/person day. Extrapolating this indicates 715 kWh annually for the household, or 238 kWh/person. This is more than twice the estimated annual rate per person for Case Study 3 and nearly three times and six times respectively as much as Case Studies 1 and 4.

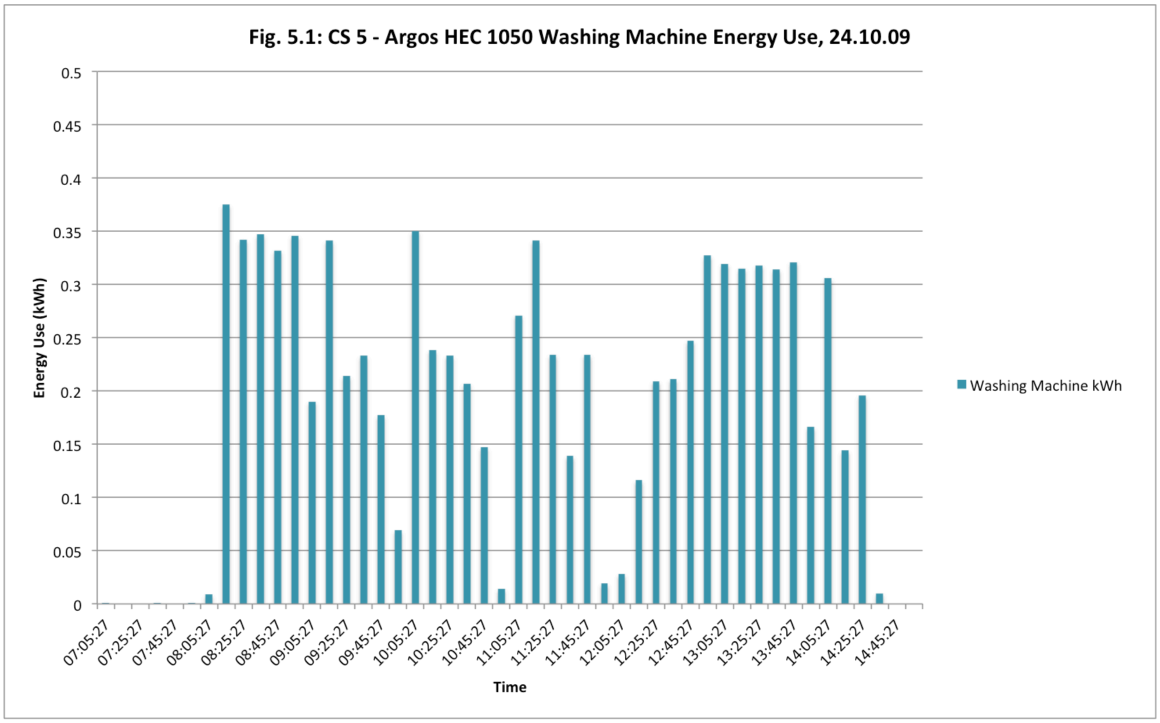
The explanation for this is not simple. Although the consumption was measured, and may be assumed as a known quantity, it is sometimes difficult to equate the cycles with what is recorded in the diaries. For example, on the 24$^{th}$ October "one full wash" is recorded in the diary. But this runs from 07.55 until 14.35 with two apparent pauses, where the recorded consumption over 10 minutes drops to a low level of less than 20 Wh. Even so the last apparently uninterrupted cycle lasts for a period of three and a half hours from 11.05 to 14.35, and consumes 4.8 kWh. Not only is the longest cycle for cottons mentioned in a review of this particular appliance, an Argos HEC 1050, only two and a half hours, but also the typical consumption per cycle is given as 0.95 kWh. Nevertheless it is advertised as having an A rating for Energy, if only a B for Wash and C for Spin (1,000 rpm), the last of course having implications for drying. Over the monitoring period it would appear that there might have been 14 cycles, some as short as fifty minutes, and denoted a "half load" in the diary; and with durations of three hours being fairly typical of a full load. At any rate, if one assumes 14 cycles from the recorded evidence, the average consumption per cycle is 1.96 kWh, more than twice the amount indicated in the online review.

Other customers have raised the issue of long cycles, and the running cost implications, in reviews. This negative factor is assumed to reflect the low initial cost:

"This was bought for my son, who has just got a flat and it is all we could afford, so at least it does the job. However, It does take a long, long time to wash the clothes. It only has a cold infill hose, so part of the time taken is heating the water to the temperature chosen. We put the setting on 30 degrees and the wash took nearly two and a half hours. The other cycles are not much better. The spin on it is good and the clothes are well wrung out. The drawer for the powder does not pull out very far, so you have to aim the powder carefully. Definitely would not buy one again as what we saved on the machine will be spent on electricity due to the length of the cycles."

Fig. 5.1 gives an indication of the extraordinarily lengthy set of cycles on the 24$^{th}$ October, starting at 08.05 and finishing at 14.25, and consuming almost 9 kWh of electricity.

For Case Study 5, if the total consumption is divided by the total duration, the mean hourly average consumption is almost exactly 1.0 kWh, more than twice the modest 0.48 kWh of Case Study 1, with the Hoover Nextra HNL 662, with its triple-A rating. On the other hand it is only 12% greater per hour compared with the appliance used by Case Study 1, which has the same appliance as that of Case Study 1.




Unfortunately, it was not possible to measure the consumption of the Zanussi TD 524 tumble dryer in this case. The manufacturer's estimate of drying time for a full load that has been spun at 1,000 rpm is 80-95 minutes; and the average consumption per cycle is given as 3.5 kWh, energy efficiency class D (data from Electrolux in Sweden). According to the diary for this household, seven full washing loads were tumble dried from the 12$^{th}$ to 26$^{th}$ October, and since there is no indication that any passive drying occurred, it must be assumed that all machine-drying took the loads to full storable dryness. This then indicates consumption over two weeks of 24.5 kWh. Extrapolating this gives 637 kWh annually for the household or 212 kWh per person. This may be compared with the high estimate for CS 1 of 580 kWh per person, using the communal 'free' facility, and the very low measured consumption for partial use of 77.5 kWh per person for CS 4.

Like CS 4 above, the questionnaire indicated that this was a condensor type of dryer. However, the quoted model is again a normal vented type, and in this case no mention is made of convertors to a condensing type in the manufacturer's technical instruction booklet. Moreover, there is clear evidence of moisture rising during the periods given for tumble drying in the diary, and these are more significant than those noted above for CS3. On three occasions the increase in RH is over 20%, on two occasions over 25% and on one occasion over 30%. In the last case $CO_2$ falls from 787 ppm to 570 ppm, indicating not only that presence of occupants did not contribute to the hike in humidity, but also, as for CS3, that the host kitchen was well ventilated during a period in autumn when heating is used. In some of the drying cycles, there is again evidence that moisture has migrated to the living room – e.g. 15th October: kitchen RH rises from 67.8% to 88.7% (VP up from 1.42-2.00 kPa), while living room rises from 65.7% to 86%. However, on other occasions, the intervening door appears to have been closed: on 20th October, the kitchen RH increases from 56% to 88.9% (VP up from 1.26-2.38 kPa) during drying, while the temperature averages 21ºC, rising from 19.4ºC to 22.5ºC and the $CO_2$ falls; but the radical effect is not reflected in the living room on this occasion. On only one of the seven drying days is the effect of moisture masked in any way by a corresponding increase in $CO_2$, indicating that any moisture increase may have been due to occupants themselves. This occurred on the 17th October, when the RH rise was marginal compared to the other six days. This gives rise to the question as to whether this may have been the only day that the dryer was appropriately vented to the outside. Regardless, CS 5 again illustrates that there is a potential energy and environmental penalty associated with the use of tumble dryers, additional to direct electrical use.

Some ironing (half load) in a bedroom was noted, but no time given, for the first day of washing recorded in the diary, and again for the second day, but no further details are given in relation to this activity. The Iron in this case is a 1.3 kW Carlton D1900, and pro rata the experiments shown in Appendix 1, it is estimated that it would use approximately 0.257 kWh for each half hour of use. What is acknowledged in the diary might approximate to 1.0 hour, implying circa 15 kWh annually. However, if a similar proportion of all the dried loads were also ironed, the estimate would be four times as great – i.e. circa 60 kWh.

Having established that no drying of washing loads occurs passively within this flat, it is of interest to appraise habits with regard to heating and ventilation, and to compare the environmental consequences of those habits with other case studies. The three occupants in this case were mature students, and used bedrooms as bed-sitting rooms during evenings, and it would appear that, as a consequence, the living room was occupied rather occasionally in comparison with more typical family usage. The diary also notes that heating was 'on' throughout the monitored period, and that windows were opened liberally throughout the day in all main spaces, as well as during evenings in the living room. Despite this, due to the autumnal ambient humidity, the internal vapour pressures remain relatively high in rooms at times when $CO_2$ levels are reasonably low (i.e. not occupied and windows open), as well as when rooms are occupied, when windows are assumed to be closed and the $CO_2$ levels are very high. Table 5.1 summarises respective values for a particular, but typical day, during the monitoring period - the 15$^{th}$ October.

Comparing these data with the equivalent for Case Study 3, we may note a similar range of vapour pressures and temperature, especially for the bedrooms in the latter case, while $CO_2$ levels are significantly higher for Case Study 5 compared with 3. This suggests that although the bedrooms of CS 5 are more intensively used than those of CS 3, moisture levels can increase independently depending on window opening and time of year.

Table 5.1 Environmental conditions in evening and rest of the day for 15$^{th}$ October

| Room/time | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | $CO_2$ (ppm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | mean | max | min | mean | max | min | mean | max | min |
| Liv/1745-0000 | 18.7 | 19.7 | 17.6 | 1.52 | 1.95 | 1.28 | 769 | 922 | 622 |
| Liv/0000-1745 | 18.1 | 18.6 | 17.2 | 1.42 | 1.53 | 1.31 | 710 | 926 | 608 |
| Br1/1745-0000 | 20.1 | 21.0 | 18.6 | 1.50 | 1.59 | 1.32 | 1,952 | 3,508 | 639 |
| Br1/0000-1745 | 19.5 | 20.6 | 18.6 | 1.49 | 1.62 | 1.30 | 2,226 | 4,394 | 614 |
| Br2/1745-0000 | 19.8 | 21.4 | 16.5 | 1.50 | 1.66 | 1.23 | 1,681 | 3,638 | 615 |
| Br2/0000-1745 | 21.5 | 24.3 | 17.5 | 1.65 | 1.96 | 1.26 | 2,439 | 4,173 | 603 |

As one might expect, peak conditions for the bedrooms occur between midnight and the morning. In Bedroom 1, the $CO_2$ level drops below 1,000 ppm from 0925-1955; and in Bedroom 2 from 0955-2035. There are three key points to make about these data compared with other case studies where passive drying indoors was an influence. To preface these, it should be noted that respective maxima do not necessarily occur simultaneously, although relationships are evident. For example, when bedroom 2's maximum temperature of 24.3$^oC$ occurs, the $CO_2$ is at 3,854 ppm; when the 4,173 occurs, the temperature is at 23.9$^oC$; and when 1.96 kPa occurs at 08.25, the temperature is 23.5$^oC$. In this last case $CO_2$ is still high at 4,111 ppm, RH at 67.9%, but the temperature outside is fairly low, having descended to 7ºC overnight and is consequently fairly dry. Hence the evidence indicates that in this case under-ventilation has resulted in humid conditions with poor air quality, and the three points now follow.

Firstly, the maximum values of vapour pressure in the living room and bedroom 2 are greater than those in Table 4.1 and 4.2 for Case Study 4, where passive drying was a known factor - in the living room at least. In other words, an identified influence on moisture levels due to passive drying is not necessarily as serious as another influence attributable to occupancy control habits such as closed windows in bedrooms overnight. It then poses the question of what the impact of passive drying might have been for CS 5. A total of 12 litres/day is claimed to be typical for all moisture inputs for a household of three (Tenwolde and Pilon, 2007). However, it would appear that it would only approach such a value if normal inputs were exeeded or if two wash-loads were dried in one day. Inputs might comprise 3.4 l for respiration and transpiration, 0.8 for cooking and dish-washing and 1.9 for showering etc. Two 17-item wash-loads are predicted to add 5.0 litres of water vapour (from the PM 2, experiments cited in CS 4 notes above). This corresponds reasonably convincingly with the range cited by TenWolde and Pilon in 2007 – 2.2-2.95 kg/wash (Angell and Olson, 1988). Thus, in this circumstance, the total moisture release for the washing day would rise to 11.1 ltres of which the drying contributes 45%.

Secondly, even without any passive drying as in this particular case study, one may note that such conditions can be fairly extreme. One may judge that 24.3$^{o}$C in a bedroom overnight is excessive, and certainly the range of vapour pressures during this period are well above the 1.13 kPa (7 g/kg mixing ratio) dust mite threshold of Platts-Mills and De Weck (1989) or Niven et al (1999). If we take the particular case of bedroom 2 at 08.25 on 15$^{th}$ October, the $CO_2$ is 4,111, the vapour pressure 1.96 kPa, RH 67.9% and temperature 23.5$^{o}$C – also significantly above Cunningham's cited 'critical equilibrium humidity' for mites at that temperature (1998). Even though the RH threshold of 70% is not breached, these values suggest an unhealthily stuffy and warm room prone to boost dust mite colonies, and so one that would not treat sufferers of asthma kindly. Also, the 15$^{th}$ October was not the most severe in terms of poor air quality. Bedroom 1 exceeded 5,000 ppm from 0235-0935 on the 22$^{nd}$; and bedroom 2 from 0515-0825 on the 17$^{th}$. Overall, the results indicate the risks attached to keeping relatively tightly sealed windows (double-glazed uPVC in this case) closed overnight in small bedrooms with low ceilings. Also, the inhabitants admit to not using trickle vents, claiming not to understand how to use them. It is unsurprising, given these data, that mould was recorded in the questionnaire in bedrooms.

What is perhaps surprising is the modest level of the CFU count: 430 CFU/m$^3$ in Bedroom 1, and 515 in Bedroom 2; and similar values in the living room and kitchen: 585 and 435. As with other case studies, the triad of Cladosporium, Penicillium and Aspergillus are all present. However, what is more tempting in terms of association is the fact that the low CFU count relates to the absence of passive drying of wash-loads within main rooms.

Thirdly, findings for this household tempt a theoretical question leading on from the conjecture in the previous sentence: What if passive drying occurred in conjunction with such usage? We have evidence of relatively stable achieved temperatures in the living room with the window open. We may assume a fairly modest heating cost given the typical mean daily ambient temperatures at this time of year just below 10$^{o}$C and taking into account solar and incidental gains. The impact of any passive drying in that space might therefore have been anticipated as minor. However, at the time in the evening of 15$^{th}$ October (2009) when the temperature is 19.5$^{o}$C, and vapour pressure is 1.95 kPa, the RH is 86%, which would have been sensed as excessively humid. Any added moisture to this already moist situation could have invoked a serious tipping point. We know from Case Study 4 that passive drying added 0.38 kPa during the initial period of moisture loss, which, if added to Case study 5 on that particular evening, would have boosted RH close to 90%.

PM 3 dynamic modelling of the notional semi-detached house mentioned in regard to CS 2, assumed smaller (compared with values given under CS 4 above) but more frequent wash loads dried in a living room, with its doors closed, over a full year. In other words only one room is assumed to increase its ventilation rate significantly and that for the defined drying period of 7 hours, but the heating regime is also boosted during that period. By modelling an entire year rather than a 'representative seasonal week' in December, the internal base temperature will frequently be not far above, and also below, ambient temperature. Nevertheless, modelling indicated increases for each month of the year. The net result is a predicted increase in energy consumption commensurate with that noted for CS 2 in the coldest winter month In a Scottish climate location (Dundee) the simulation predicted a rise of 3,595 kWh/year from about 7,000 kWh – i.e. more than 50%. Using the same notional area to that used in CS 2 for a seven-person family (114.5 m$^2$), this suggests over 30 kWh/m$^2$ increase due to drying; but for a more typical 5-person house envisaged in the model (89.0 m$^2$) the increase would be 40 kWh/m$^2$.

Annual tumble drying in PM 3 at the frequency of CS 2 is estimated to consume 1,404 kWh, or 16 kWh/$m^2$. However, this delivered electricity and assuming a primary to delivered efficiency factor of 0.325, the primary electrical consumption would be 4,320 kWh or 48.5 kWh/$m^2$ for a 89 $m^2$ house. Assuming the additional calculated space heating by the passive regime is for gas, a primary to delivered efficiency factor of 0.9, and a boiler efficiency of 0.9, the primary addition for passive drying to space heating is 4,438 kWh. In other words, although the consumer's energy usage of tumble-drying is predicted to be well below the extra required for passive drying, respective primary consumptions are similar.

However, in relation to the above comparison, it may be noted that the PM 3 estimate of 1,404 kWh for annual tumble drying at the frequency of CS 2's 7-person washing is four times greater than the value of 354 kWh estimated by DEFRA's Market Transformation Programme, Briefing Note BNW06 (2008a). It is also more than twice as great as the estimated value for this particular 3-person flat (637 kWh). One can only assume that the DEFRA value takes account of the prevalence of partial tumble drying, which was indeed found to be commonplace in the Glasgow survey. This of course suggests that the typical energy penalty is more likely to be a combination of that for increased space heating and that used by a tumble dryer. However, if 637 kWh for CS 5 is divided by 0.325, we get a primary energy figure of 1,960 kWh, which the modelling indicates could well be similar to that for passive drying; noting that the frequency of washing, and therefore passive or active drying, assumed in the PM 3 modelling is significantly more than would be normal for a 3-person household (2.3 times for the ratio of 7 to 3 persons).

INFREQUENT WASHING, ALL TUMBLE DRYING, HEATING ON; AUTUMN MONITORING, TOP FLAT IN 3-STOREY 1993-4 BRICK-CAVITY BUILDING, INSULATED INTERNALLY – I.E. LIGHT CONSTRUCTION

Case study 6: This household of two fairly young adults, with a 1-year old child when surveyed, used their washing machine and tumble dryer only three times during the fortnight of monitoring. The consumption of both appliances was measured in this instance. Although the demographics of the three inhabitants in this case varied from Case Study 5, there are other common factors, in particular extremely poor environmental conditions within the main bedroom overnight.

Machine washing was recorded in the diary for 19-20th October, 29-30th October and 31st October to 1st November out of the two-week monitoring period from 19th October to 3rd November 2010. Therefore the frequency of washing is significantly less than other case studies above. In this case the total measured energy consumption was 1.78 kWh, or 0.13 kWh/day or 0.043 kWh/person.day. Extrapolating this indicates 46 kWh annually for the household, or 15.7 kWh/person. Thus the relative infrequency of wash cycles has resulted in a remarkably low predicted annual load. The diary also declares one instance of hand washing on 1st November and the diary entries generally seem conscientious in terms of accuracy. The other point to note is that although the normal temperature for a wash cycle is given as 30°C, it is also recorded as 'cold feed' and the initial warming energy load in each cycle is quite high. Regardless of this, the energy consumed per cycle by the Hotpoint Aquarius averages 0.6 kWh and the energy per hour of use is 0.51 kWh - i.e. comparable with Case Studies 1 and 2.

The total number of tumble dryer cycles as one might expect matched that of the washing cycle, although up to a day apart. Unlike Case Study 3 these cycles dried the whole washing load, with respective cycles of 1 hour 50 minutes, 1 hour 40 minutes and 1 hour. Total consumption by the White Knight HT appliance over 14 days was 13.86 kWh, 4.62 kWh/cycle or 0.99 kWh/day, implying 361 kWh per annum - circa 120 kWh per person. This of course reflects the frugality of the washing regime over the period of monitoring, and we may note that it is 57% of the estimated consumption per person for CS 5. In this case the tumble dryer is worryingly located in one of the bedrooms, although reportedly properly vented to the outside when in use. Measured vapour pressure and RH values tend to support this, at least on two of three occasions. Although high in the bedrooms during the periods of drying, they were not appreciably higher than other nights when drying was not taking place. However, on the first night that a drying cycle was measured, RH rose from 65.5% to 73.5% while $CO_2$ fell from 1,259 ppm to 698 ppm and temperature rose by a degree or so – i.e. changes of of an order of magnitude similar to that of CS 3 rather than CS 5.

The questionnaire indicates that approximately half of each dryer load is ironed, but diary information is flimsy in this regard. It is a reasonable assumption that this would prevail for each load, in which case the three drying cycles over two weeks might amount to at least 1.5 hours of ironing. In this case the iron is a 1.3 kW Russell Hobbs, and pro rata the experimental data (Appendix 1) this suggests 0.257 kWh for each half hour as for Case Study 5. If extrapolated on this basis for the year, the estimate is then circa 20 kWh.

Similar to Case Study 5, the environmental data for bedrooms in particular are a cause of concern, but in this case the living room also suffers from extreme maxima of RH and $CO_2$ as well as high average levels. Tables 6.1-6.3 summarise values over the whole monitoring period, noting that the instrument had a maximum $CO_2$ value of 5,000 ppm.

The diary provides some detail as to when windows were opened and for how long, and the questionnaire states that trickle vents were left in the open position at all times on all windows. Table 6.4 summarises the information for the bedrooms.

Table 6.1 Environmental conditions in Bedrm 1 for 19th October - 3rd November 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,824 | 5,000 | 508 | 18.95 | 22.5 | 16.2 | 1.58 | 2.24 | 1.04 | 71.9 | 93.9 | 51.6 |

Table 6.2 Environmental conditions in Bedrm 2 for 19th October - 3rd November 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,578 | 3,119 | 529 | 16.8 | 20.2 | 14.6 | 1.40 | 1.80 | 0.90 | 73.2 | 84.7 | 54.4 |

Table 6.3 Environmental conditions in Living rm for 19th October - 3rd November 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 3,119 | 5,000 | 452 | 18.4 | 21.6 | 15.2 | 1.59 | 2.00 | 1.31 | 74.6 | 85.6 | 64.9 |

Table 6.4 Duration of window opening in Bedrooms 1 (parents) and 2 (young child)

| Date | Bedroom 1 | Bedroom 2 |
|---|---|---|
| 20/10/09 | 1 hr 50 mins | 1 hr 50 mins |
| 21/10/09 | 2 hrs | 1 hr 30 mins |
| 22/10/09 | 1 hr 11 mins | 1 hr 11 mins |
| 26/10/09 | 3 hrs | 3 hrs |
| 29/10/09 | 1 hr 20 mins | 2 hrs |
| 31/10/09 | | 2 hrs |
| 02/11/09 | | 1 hr |

Table 6.4 indicates rather modest amounts of window opening – an average of 0.67 and 0.89 hours/day respectively for the parents' and child's bedrooms. We also learn that the living room window was only occasionally opened during this period and that roughly half of the washing loads were ironed in the living room. However, the most likely cause of excessive humidity in the living room is migration from the adjacent kitchen. For example, at 15.00 on the 29th October, when the maximum RH value of 85.6% is reached in the living room, the kitchen is also over 80%. Both kitchen and bathroom have mechanical extract fans, but these are declared as manually operated, and the kitchen is small. Overall, given the relatively infrequent window opening, it seems unlikely that ambient moisture has been influential. In the bedrooms respective peak VP values of 2.24 and 1.8 kPa occur on 25th October at 19.37 and 1st November at 02.07, with $CO_2$ at 1,313 ppm (2 adults) and 652 ppm (infant). Respective ambient VP were circa 1.2 and 1.0 kPa at these times and the diary records no window opening on either date for the bedrooms. Hence it would appear that ambient influence is not strong in this instance.

It should also be stressed for the bedrooms, that even though no specific moisture impact can be connected directly to the presence of the tumble dryer, nor to ironing, and nor to ambient influence, the environmental conditions are undoubtedly poor. It is not therefore surprising that mould growth was experienced as a problem in Bedroom 1, with the highest RH and vapour pressure values; and also in this case coinciding with a fairly high CFU count of 1,610 CFU/$m^3$ from the air sample taken on the 19th October, when the RH averaged 61% and the vapour pressure averaged 1.6 kPa. In this regard it is relevant to note that Arundel et al (1986) found that formaldehyde concentrations due to off-gassing were directly proportional to RH at a given temperature. One may assume that the same will apply for all water soluble VOCs.

Again the common triad of mould types are present with others, and it is tempting to explain the high CFU count in terms of the dryer exhaust kept inside the flat even though there is no evidence of this. Further, the maximum vapour pressures in Tables 5.1-5.3 have the same ranking as the respective CFU counts: 1,610/2.24 bedroom 1; 1,045/2.0 living room; 650/1.8 bedroom 2; thus conforming to an anticipated association between CFUs and moisture levels. Overall, the data suggests a possible moisture threshold, say above 70% mean RH, in turn linked to poor air quality, above which a high spore concentration is more likely.

FAIRLY INFREQUENT WASHING, ALL PASSIVE DRYING, HEATING ON; SPRING MONITORING, FLAT IN 4-STOREY 1970S 'NO-FINES' SEMI-HEAVY CONSTRUCTION, DRY-LINED INTERNALLY

Case study 7: This is the same type of house as Case Study 5, but with an entirely different drying regime at a different time of year. The occupants are three adult students aged from 21-22. Thus the demography is also similar to Case Study 5.

Washing was recorded in the diary for three days out of the two-week monitoring period from 7-21st April, with a total of four cycles. Therefore the frequency of washing is not significantly greater than Case Study 4 above. In this case the total measured energy consumption was 3.74 kWh, which worked out at 0.27 kWh/day or 0.09 kWh/person.day. Extrapolating this indicates 97.5 kWh annually for the household, or 32.5 kWh/person. This is just more than twice the estimated annual rate per person for Case Study 6, but only one seventh as much as Case Study 5. This is therefore a fairly moderate regime. The energy consumed per cycle by the Indesit 1263W appliance in this case averages 0.935 kWh, 55% higher than Case Study 6, and the energy consumed per hour of use is 0.68 kWh, 33% higher than Case Study 6.

The method adopted for passive drying was an airer in the living room either on or close to the radiator, and it should be noted that heating was used during the period of monitoring. It was also stated by the occupants that windows were not ever opened during periods of drying; and further admitted that heating was turned up to assist drying, and that humidity was perceptible.

The iron in this case is a 1.2 kW Tesco IRSO4B. Although there is no specific mention in the diary about ironing, the questionnaire indicates that less than half the washing is ironed in the living room. Assuming an average of half an hour spent ironing per washing load, and using the measured experimental data for this iron, this would compute to approximately 15 kWh annually.

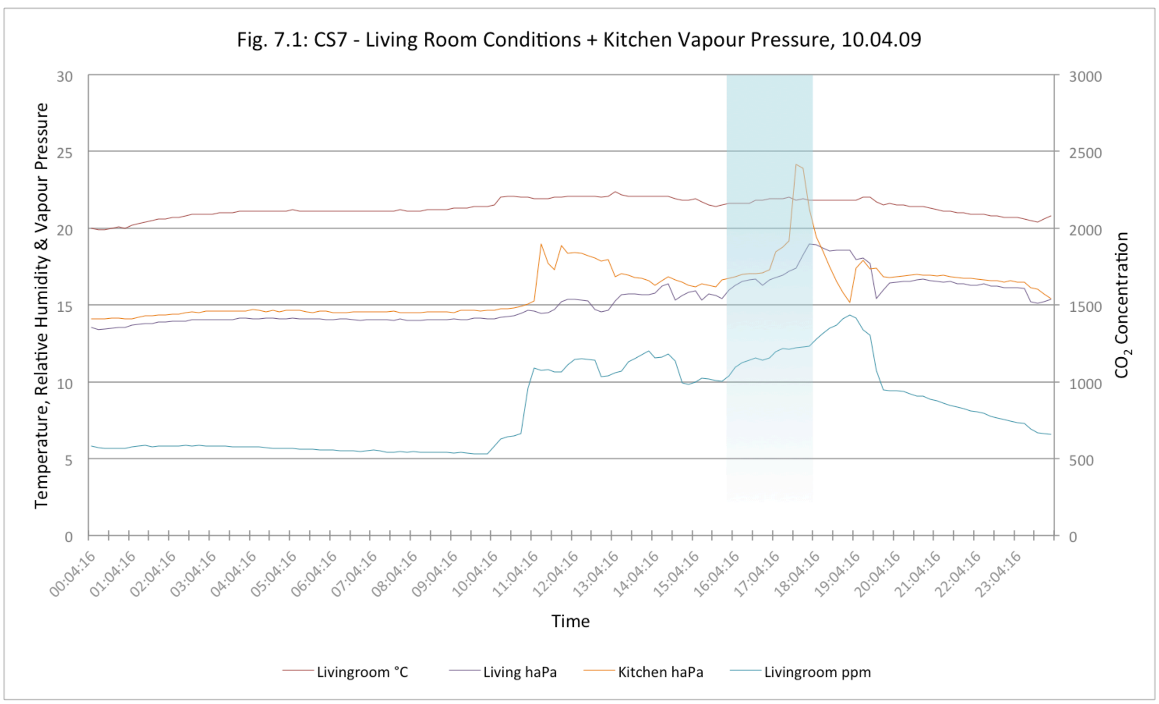



Fig. 7.1 shows an instance on 10th April that coincides with drying washing in the living room and that is partially masked by the presence of occupants, and also quite possibly by migration of moist air from the adjacent kitchen. Over a 2-hour afternoon period from 15.54-17.54 the vapour pressure rises by 0.30 kPa to 1.89 kPa, while $CO_2$ rises by a relatively modest 192 ppm during that period. The kitchen rises by 0.74 kPa up to 2.41 kPa during the same 2-hour time slot.

Regardless of the masking effect of one moisture source over another, one can say that the habit of boosting a heating system in a month of relatively modest heat demand, with predominantly good weather in this particular year, both contribute to overall moisture levels inside the dwelling as well as to consumption of energy. Indeed the figures for the key environmental indicators give cause for concern similar, if slightly less severe, to that of Case Study 4 – see tables 7.1–7.3. Note, however, that both the bedrooms and the living room in Case Study 7 are significantly warmer than those of Case Study 6, and that this will help to modify RH downwards. The maximum VP in bedroom 1 of 1.69 kPa occurs on 21st April at 07.54, with the temperature as high as 25.6ºC and RH at 51.5%. The indicator of the cause of high moisture being associated with inadequate ventilation is the very high $CO_2$ level of 3,807 ppm at this time. Even though ambient conditions at this time also seem moist with RH at 86.3%, the temperature of 9.1ºC corresponds with VP below 1.0 kPa; and had the window been ajar, the $CO_2$ is unlikely to have been nearly so high. Similarly bedroom 2's maximum VP of 1.72 kPa, which occurs at 01.34 on 11th April, corresponds with an even higher indoor temperature of 26.2ºC, RH of 50.7% and $CO_2$ of 1,472 ppm. Again, although the ambient RH at the same time is 87.5%, the low temperature of 4.2ºC gives a VP of just over 0.7 kPa, and the low rate of ventilation seems to be the main culprit.

Table 7.1 Environmental conditions in Bedrm 1 for 7$^{th}$ April – 21$^{st}$ April 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,113 | 3,823 | 438 | 20.0 | 26.4 | 16.2 | 1.21 | 1.69 | 0.91 | 51.5 | 69.2 | 40.2 |

Table 7.2 Environmental conditions in Bedrm 2 for 7$^{th}$ April – 21$^{st}$ April 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,701 | 4,165 | 754 | 20.3 | 26.3 | 18.0 | 1.35 | 1.72 | 1.07 | 56.5 | 63.7 | 45.7 |

Table 7.3 Environmental conditions in Living rm for 7$^{th}$ April – 21$^{st}$ April 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 965 | 4,247 | 448 | 21.4 | 24.8 | 19.5 | 1.42 | 1.90 | 1.07 | 55.8 | 72.6 | 45.2 |

One may also note that the generally high CFU/m$^3$ count in this case, as for Case Study 4, follows the same ranking as the vapour pressure: 2,235 bedroom 1; 2,900 bedroom 2; 2,975 living room. However, while respective maxima of vapour pressures in Case Study 7 are of much the same order as those for Case Study 4, albeit slightly lower, the CFU counts are significantly higher. A possible explanation of this might be the prevalence of particular spore types in different seasons (Haas et al, 2007). For example, Aspergillus is dominant in winter and Cladosporium in summer and high concentrations of Penicillium are found in spring, autumn and winter when mould is present, as it is here in bedrooms, bathroom and kitchen. A related, and more potent, explanation is likely to be association with the method of passive drying, coupled with low rates of ventilation. The questionnaire acknowledged a damp smell in the flat, as well as declaring that windows were never opened, perhaps due to security issues in the ground floor location.

MODERATE WASHER, SOME TUMBLE DRYING, SOME INTERNAL PASSIVE DRYING, HEATING ON; AUTUMN MONITORING, FLAT IN 3-STOREY 1960S CAVITY BRICK BUILDING, HEAVY CONSTRUCTION

Case study 8: This household of two adults bears some comparison with Case Study 4, both in terms of mixed approach to drying and similarity of age and construction – although a flat in this case, with gas CH now installed and double-glazed uPVC windows.

The total number of washing cycles evident from monitoring over 14 days was 17, corresponding with 10 machine loads according to diary. But many of these are brief, 30-40 minutes, and are probably spin cycles associated with hand-washing (acknowledged in questionnaire). The monitoring took place over 14 days from 12$^{th}$ to 26$^{th}$ October, with a total consumption of 11.38 kWh – i.e 0.81 kWh per cycle or day, or 0.41 kWh/person.day. Extrapolating this indicates 296 kWh annually for the household, or 148 kWh/person. In this case the model of washing machine is the Indesit WIA 101. The pattern of use here, with a predominance of relatively short cycles as in Case Study 4, gives mean average consumption per hour of running time in this case is 0.82 kWh including any standby usage - i.e. somewhat lower than Case Study 4; and similarly indicating a penalty for relatively short cycles compared with most others.

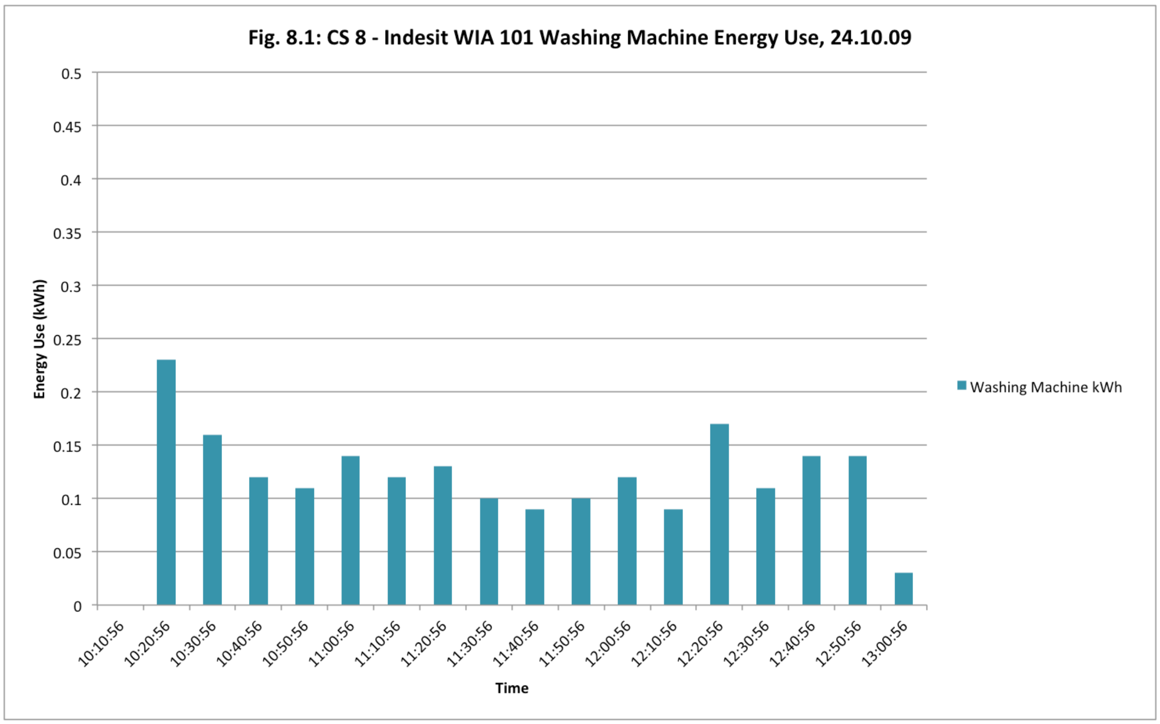



Fig. 8.1 shows the rather unusual cycle for the washing machine on 24th October from 10.20 to 13.00, whereby the energy input is much more even than in other case studies, but consumption during the initial warming period is rather lower. The explanation for this appears to be twofold: firstly, normal temperature for a wash is reported as 80$^{o}$C, which would explain the sustained nature of the consumption; but, secondly, the feed is reported as 'hot', which could explain the relatively low rate of energy consumed to sustain such a high temperature – 2.1 kWh over a 2 hour 40 minute period.

The tumble dryer was acknowledged in the diary as being used only twice during the 14-day period, three full and two half loads being recorded. This was not directly measured, but the manufacturer's estimate for the appliance, a condenser-type 7 kg Indesit IS70C, is 4.38 kWh per full load. Thus the total consumption for 14 days would be of the order of 17.5 kWh, averaging 1.25 kWh/day; and extrapolating for the year (again tentatively based on the relatively low usage) indicates 457 kWh or 228 kWh/person. This is approximately 75% more than CS 3, and nearly twice as much as CS 6, both of which were measured. However, it is only 7.5% more than that of CS 5, which, like CS 8, was estimated. These comparisons perhaps suggest that estimates based on full loads, fully dried, may be misleading, and that in practice, people may tend to economise with partial loads or full loads not taken to full dryness. In this case, RH increased by some 5% to 73.8% on one of three occasions, the host room the bedroom.

An added indicator is that, according to the questionnaire, all loads are ironed before fully dry. The steam iron in this case is a 2.4 kW Tefal (8024H02622); and, assuming 1.0 hours ironing per wash load, the consumption per ironing session (pro rata estimates above) would be 0.57 kWh; and, at the rate of 10 wash loads (as given in diary) ironed every two weeks, this would consume 148 kWh annually. However, if we assume only the four declared tumble dryer loads were ironed in the same period and extrapolate, the ironing consumption would drop to circa 60 kWh.

In this case the temperature regimes and humidity levels in bedrooms are more extreme than the equivalent spring values for Case Study 7 – see Tables 8.1-8.3 below cf. Tables 7.1 to 7.3 above. Temperatures here indicate that bedrooms may have been unheated, and the RH values become very high, with means over 70% and maxima over 90%. The living room is heated in the evenings, but also has quite high moisture levels. It was also stated that ironing was carried out in a bedroom as well as passive drying on a clothes horse, and this may account for some of the moisture high points during the day – e.g. Bedroom 1 has 91.2% RH, 1.64 kPa and 2,478 ppm at 1120 on the 24th October, a morning when two washing cycles occurred; and Bedroom 2 at this time was also high with 88.9% RH, 1.69 kPa and 2,190 ppm. There are also humidity spikes when the $CO_2$ is not particularly high – e.g. on 18th October, a day after four washing loads, Bedroom 2 builds up from 1.2 kPa and 66.4% RH in half an hour to 1.79 kPa and 89.5% RH, while the temperature is 17.5ºC and $CO_2$ 900 ppm, this in early evening at 17.30.This may be associated with ironing, VP returning to 1.2 kPa, one hour forty minutes after it first started to rise. The temperature also rose from below 16ºC during this period and then dropped back again.

Although the living room has a reasonable average temperature and air quality, its moisture level is also rather high. In this case the peak temperature of 27.8$^o$C coincides with the VP peak of 1.75 kPa, while $CO_2$ is at 1,278 ppm, this at 22.10 on the 25th October.

Table 8.1 Environmental conditions in Bedrm 1 for 12th October – 25th October 2009

| $CO_2$ (ppm) | | | Temperature ($^o$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 977 | 2,478 | 586 | 15.9 | 18.0 | 11.8 | 1.37 | 1.75 | 1.05 | 75.8 | 91.4 | 57.7 |

Table 8.2 Environmental conditions in Bedrm 2 for 12th October – 25th October 2009

| $CO_2$ (ppm) | | | Temperature ($^o$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,134 | 2,994 | 600 | 16.9 | 20.8 | 14.1 | 1.40 | 1.91 | 0.94 | 72.8 | 90.4 | 44.7 |

Table 8.3 Environmental conditions in Living rm for 12th October – 25th October 2009

| $CO_2$ (ppm) | | | Temperature ($^o$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 836 | 1,586 | 434 | 19.0 | 27.8 | 15.9 | 1.35 | 1.75 | 0.89 | 61.3 | 76.5 | 36.1 |

Perhaps surprisingly, given the RH levels, the CFU/$m^3$ count for mould spores is relatively low: 510 Bedroom 1; 595 Bedroom 2; 630 Living room. The highest is 680 in the kitchen, the only room to record evidence of mould on the wall. However, the vapour pressure levels are similar to those for Case Study 7, where the CFU count is significantly greater. This again suggests that there is no simple relationship between number of CFUs and the prevalent level of moisture in rooms. Nevertheless, the contrast of drying methods may be of significance in this regard, with the use of the tumble dryer possibly playing a more important role relative to the CFU count than one might expect from the measured VP levels. It may also be seasonally relevant that although the dominant triad of Aspergillus, Claudsporium and Penicillium are present as usual, the number of their variants and other mould types is reasonably limited (Haas et al, 2007).

MODERATE WASHER, PASSIVE DRYING IN TWO INDOOR SPACES, WINDOWS OPEN, HEATING NOT USED; SUMMER MONITORING, FLAT IN TRADITIONAL STONE-BUILT TENEMENT

Case study 9: This case study makes for interesting comparison with that of 2, since the type of accommodation and method of drying are the same, but the season is quite different. The household did not own a tumble dryer and passive drying was mainly by a ‘pulley’ in the kitchen and an airer in the living room. The data was recorded in summer and a liberal regime was adopted with regard to window opening. Despite, or because of, this the CFU count was quite high, indicating a possible relationship to spores entering from outside or generated inside in some manner by the laundering. The number of residents entered on the questionnaire and present for most of the year is four adults, two couples; while the diary correctly records two persons present during the 2-week monitoring period, the indications from $CO_2$ readings that both bedrooms were occupied (i.e. one partner of each couple present).

This issue of the number of occupants is relevant in relation to the washing regime, mainly by a Whirlpool AWM 332, B rated, and also partly by hand-washing. The overall number of cycles during the 2-week period was five, plus one spin cycle to deal with one of the hand washes. The typical temperature used is given as 30$^{o}$C. Total consumption was only 1.633 kWh or 0.327 kWh/cycle (discounting the single spin-only cycle). Extrapolated, this would indicate a very modest annual total of 42.5 kWh, or 21.3 kWh/person (for 2 occupants). This low value is similar to Case Study 17 below. When expressed as energy consumed per hour of running time, the figure is again modest at 0.25 kWh/hr, roughly half that of Case Studies 1, 2 and 6; 2 and 6 also running normally at 30$^{o}$C while 5 at 1.0 kWh/hr indicated 40$^{o}$C. A possible explanation, other than the machine being more efficient than its B-rating suggests, is that the weight of wash loads was lighter than is typical. Another, and more likely, explanation is that it used a hot feed. Certainly its rate of power use while heating up is much lower than, for example, Case Study 2, aiming for the same temperature, or Case Study 5 aiming at 40$^{o}$C. If that is the explanation, it does of course mean that Case Study 9’s excellent performance per hour of running time is due to it having ‘borrowed’ heat from a gas boiler – quite possible since this house does have gas CH.

The iron in this case is a 1.4 kW Swan (DWS 13020). Although the diary makes no mention of ironing, the questionnaire indicates about half of the washing is ironed. On the latter basis, using the pro rata data (Appendix 1) as other case studies and assuming a relatively frugal half hour of ironing per wash load, the extrapolated consumption would be circa 35 kWh annually.

Even though, windows are liberally opened and vapour pressures do not rise to the levels seen in other case studies, the presence of drying washing can be detected in both living room and kitchen. For example, on the 17$^{th}$ June, the day after a night-wash cycle, the vapour pressure (VP) climbs modestly from 1.28 kPa at 1044 to 1.4 kPa at 1344. The living room also has a maximum of 1.69 kPa. Similarly, in the kitchen just after a late evening wash the loaded ‘pulley’ raises the VP from 1.15 kPa just before midnight to 1.35 kPa at 0114, a rise of 0.2 kPa. However, it has to be acknowledged that moisture input from cooking can be a great deal more potent in raising VP, for example raising the vapour pressure from 1.34 to 2.04 kPa in a relatively short period. Also, the VP values in the two bedrooms, with atypical nocturnal maxima of 1.69 and 1.75 kPa, are higher than the levels attributable to drying. Here it is likely that the ambient conditions are responsible. 1.69 kPa occurs at 23.34 on June 22nd, when the indoor temperature is 20.1ºC, RH 70.1%, but $CO_2$ only 587 ppm; while ambient conditions are 13.3ºC, 94.7% and VP circa 1.43 kPa. Similarly 1.75 kPa in bedroom 2 occurs 10 minutes later at 23.44 on 22nd June, with the indoor temperature 20.6ºC, RH 72.3% and $CO_2$ a modest 566 ppm.

The maximum VP in the living room, also 1.69 kPa, occurs at 12.14 the day after a double-washing when the $CO_2$ level is only 609 ppm; but, as it follows the same pattern as all the other rooms, it is likely to be due to ambient humidity and open windows. The indoor temperature at this time of 22ºC and RH of 64.1% gives a VP of circa 1.7 kPa; corresponding with ambient temperature 20.5ºC, RH 72.7% and VP >1.7 kPa. However, all this begs the question of what might occur during the winter, with all four occupants present and either with a much less liberal regime of ventilation, or with much the same degree of open windows, but with the heat turned up as in Case Study 2.

Tables 9.1-9.3 summarise the key environmental values for the monitoring period:

Table 9.1 Environmental conditions in Bedrm 1 for 11th – 25th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 669 | 1,339 | 473 | 19.7 | 23.3 | 17.1 | 1.26 | 1.69 | 0.72 | 54.6 | 70.1 | 29.3 |

Table 9.2 Environmental conditions in Bedrm 2 for 11th – 25th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 632 | 1,374 | 406 | 19.2 | 22.9 | 16.6 | 1.25 | 1.75 | 0.67 | 56.3 | 72.9 | 31.6 |

Table 9.3 Environmental conditions in Living rm for 11th – 25th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 610 | 1,065 | 498 | 19.6 | 23.5 | 16.2 | 1.24 | 1.69 | 0.70 | 54.2 | 67.2 | 27.4 |

Finally, as mentioned above, we may note that despite the summer regime, the CFU count was high: 1,275 CFU/$m^3$ in the living room, and 1,610 in the kitchen. It was also high in the bedrooms, respectively 1,005 and 1,655. This possibly also reflects the vapour pressure levels even though not directly connected to drying clothes, unless by means of migration via doorways. But it may also reflect high outdoor concentrations migrating inside, or indeed a combination of both factors. However, apart from the bathroom walls and ceiling, there was no evidence of mould. In the analysis of air samples, two key types associated with spring to summer headed the list - Cladosporium and Penicilium. However, there were others, including Aspergillus and Mucor, which are more associated with presence of mould and/or winter (Haas et al, 2007).

MODERATE WASHER, PASSIVE DRYING IN TWO INDOOR SPACES, WINDOWS OPEN, HEATING SOMETIMES USED; SUMMERER MONITORING, FLAT IN 1960S CAVITY-INSULATED TOWER BLOCK

Case study 10: This case study makes for interesting comparison with that of 9. Again data was recorded in the early part of summer, and a significant amount of passive drying and ironing occurred indoors. However, in this case a key difference was that the permanent household was smaller (2 adults) and it also made use of the communal tumble drying, as well as a limited amount of washing, in the full laundry on the ground floor of the tower (a more elaborate facility compared with that for Case Study 1 at Westercommon). Another difference was the method of heating, electric storage, and it seems that its use was not significant. However, there is a diary note about an electric fan convector being used to boost heat in the living room on the 29th May, this during the evening while windows were open (a daily habit) and washing was being dried. Similar to Case Study 9, passive drying was also done on a 'pulley' in the kitchen. In this case the CFU count was quite low, which raises the question of significance of the use of the communal laundry for a considerable part of the drying and/or the small number of occupants.

The domestic washing machine used here was a Hotpoint Ultima WMA60, which is A-rated according to the questionnaire, and has a hot feed. The overall number of cycles during the 2-week period was five, plus one that appears to be an extra spin cycle or a very light load. The typical temperature used is given as 30°C. Total consumption was only 2.335 kWh (1.4 times more than Case Study 9) or 0.467 kWh/cycle (counted as 5 cycles). Extrapolated, this would indicate an annual total of 60.7 kWh, or 30.4 kWh/person (2 occupants). This is over 40% higher than Case Study 9 above, but still relatively modest compared with other case studies. However, in this case we require to add an estimate for washes in the communal facility totalling 2.45 kWh (based on 0.7 kWh/cycle). This brings the total up to nearly 4.8 kWh for two weeks or circa 125 kWh (62.5 kWh/person) extrapolated for a full year, roughly three times that for Case Study 9.

When expressed as energy consumed per hour of running time, the figure is again quite modest at 0.305 kWh/hr, 22% greater than Case Study 9 and also running normally at 30°C. Again it seems likely that the explanation is that it used a hot feed. Like Case Study 9, its rate of power use while heating tends to be lower than most other case studies. However, in this case its enhanced performance per hour of running time would be due to it having 'borrowed' heat from an electric 'immersion' heating element as this is an all-electric flat. The other matter of significance to note is that the low CFU count corresponds here with generally much lower levels of moisture (see Tables 10.1 – 10.4); noting that the second bedroom functions as a 'spare room', and setting aside the significance peaks in the kitchen attributable to cooking.

Table 10.1 Environmental conditions in Bedrm 1 for 27th May – 10th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 910 | 2,392 | 351 | 18.9 | 28.3 | 16.1 | 1.15 | 1.35 | 0.96 | 54.2 | 70.7 | 24.4 |

Given that the maximun vapour pressure in bedroom 1 coincides with that of $CO_2$ at 2,392 ppm, it seems likely that lack of ventilation contributes to the humidity. However, at the same time , 04.16 on the 28th May, the ambient conditions are also very humid – 95.4% at 14.2ºC, indicating a VP >1.5 kPa. Hence an open window would have lowered the $CO_2$, but not necessarily the level of humidity inside the room.

Table 10.2 Environmental conditions in Bedrm 2 for 27th May – 10th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 595 | 972 | 403 | 18.6 | 21.5 | 16.0 | 1.12 | 1.34 | 1.02 | 53.3 | 66.9 | 39.2 |

One may contrast the unoccupied second bedroom in this regard. Here the low $CO_2$ indicates lack of occupants, the mean temperature is similar to the main bedroom, and the VP at the same time as that of its peak 1.35 kPa, is 1.17 kPa; the bedroom 2 maximum of 1.34 kPa, occurring during the afternoon of the 28th May, while temperature is 17.6ºC and RH 66.8% (very similar data to bedroom 1 at this time of day). Outside, the weather has remained humid at 84.2% RH and 15.25ºC and VP circa 1.45 kPa. Since both rooms indicated lack of occupants at this time, it would seem probable that windows were ajar and ambient humidity was making itself felt inside.

Table 10.3 Environmental conditions in Living rm for 27th May – 10th June 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 628 | 1,410 | 431 | 20.2 | 33.3 | 16.7 | 1.18 | 1.49 | 1.03 | 50.7 | 68.7 | 21.4 |

The living room is where the ironing occurs, estimated as approximately half of the washing loads in the questionnaire and given as two half-load sessions during the two weeks of monitoring. The iron in this case is a 1.2 kW Micromark (mm9473), and, assuming half-hour ironing periods pro rata previous case studies at 0.233 kWh/session, this would extrapolate to only 12 kWh annually. With regard to the kitchen (Table 10.4), we should also note the low $CO_2$ levels, the maximum value well below the 1,000 ppm benchmark indicating a very efficient level of ventilation, and in considerable contrast to the high maximum of nearly 2,400 ppm in the occupied Bedroom 1 (Table 10.1 above).

Table 10.4 Environmental conditions in Kitchen for 27th May – 10th June 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 437 | 811 | 339 | 21.6 | 30.4 | 17.6 | 1.27 | 1.80 | 1.01 | 49.8 | 71.8 | 26.3 |

Although some influence for such low levels of $CO_2$, in particular in the bedrooms, may be attributed to the time of year and tendency to open windows, this is similar to Case Study 9. Moreover, although the conditions in the respective bedrooms is not specifically relevant to laundering processes, unless by migration, we cannot ignore the fact that the equivalent of three and a half tumble drying loads were dried in the commercial appliance in the communal laundry, estimated to be circa 15 kWh (implying 390 kWh, or 195 kWh/person, annually by extrapolation); leaving apparently three domestic wash-loads to be dried passively within the flat. This compares with five machine loads, plus three hand-washes for Case Study 9. Whatever the causal combination, the overall maxima and average VP values are significantly lower for Case Study 10 than for 9; and this includes the living room and kitchen as well as the bedrooms.

This brings us to the issue of the CFU count, which was in this instance quite low: 678 CFU/$m^3$ in the living room, and 565 in the kitchen. It was also low in the bedrooms, an average of 567 compared to 1,330 in Case Study 9. As for the other case studies above, it is difficult to interpret particular significance of the types of mould spores identified. However, with no mould itself present, these correspond with the selection for spring and summer identified by Haas et al (2007): e.g. Cladosporium, Alternaria and Penicillium. Aspergillus was also present, although Haas et al state that it is more prevalent indoors in summer where there is mould growth evident.

MODERATE WASHER, TUMBLE DRYING IN DWELLING, WINDOWS CLOSED, HEATING NOT USED; SUMMER MONITORING, MAISONETTE IN 1960S CAVITY-INSULATED TENEMENT BLOCK

Case study 11: This case study makes for interesting comparison with that of 10 above. Again data was recorded in the early part of summer, and in this case a minimal amount of passive drying occurred indoors (mini-dryer in bathroom for 'socks and underwear' used on $4^{th}$ day of washing and tumble drying). Roughly half of the tumble-dried washing was often ironed. The permanent household is three adults, including an 18-year old. Like CS 10, the method of heating is electric, mainly by storage, but supplemented by additional appliances. However, the heating was noted as not used during the monitoring period, and it would seem that ventilation relied mainly on trickle vents rather than opening windows, a log of times having been kept by the occupants. In this case the CFU count was reasonably low (comfortably below 1,000 CFU/$m^3$) while the $CO_2$ (as air quality indicator) and humidity levels were frequently relatively high. This again raises the question of significance of the use of tumble-drying for virtually all the washing. Does the absence of damp clothing and so forth have a beneficial effect over and above that conveyed by the usual environmental indicators, temperature, RH, VP and $CO_2$ levels? In other words, would a low CFU count in tandem with fairly high moisture levels reduce the risk of respiratory problems associated with allergens?

The domestic washing machine used here was an Indesit W1 141, which is A-rated according to the questionnaire, and claims a hot feed. The overall number of cycles during the 2-week period was five, plus a number of short cycles that could be for an extra spin cycle or a very light load. The typical temperature used is given as 30$^{o}$C and synthetics are mentioned in the diary. Total consumption was 7.363, some three times greater than the 2.335 kWh of Case Study 10, or 1.47 kWh/cycle (counted as 5 cycles). Extrapolated, this indicates an annual total of 191 kWh, or 63.8 kWh/person (3 occupants). This is similar to Case Study 10 above, once allowance is made for the extra use of the communal facility in that household. Translated to energy used per hour of running time, including all the short cycles and stand-by, the hourly energy usage works out at 0.83 kWh, which is towards the upper end of the range of values for other case studies above. This is possibly surprising, given the alleged hot feed, and it may be noted that typical 10 minute readings during heat-up times in the cycle are significantly higher than for Case Study 9.

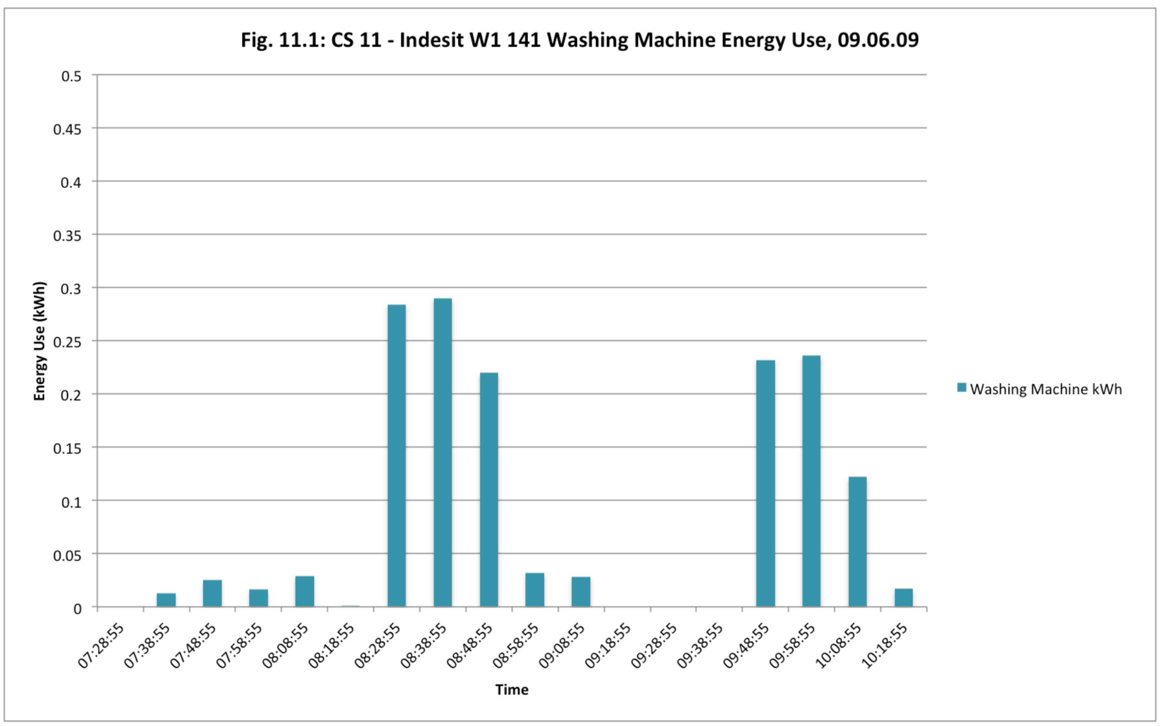


Fig. 11.1 shows another relatively unusual profile for two wash cycles. The maxima for a 10-minute period are lower than most, but more sustained, and overall the consumption for these two cycles of over 1.5 kWh seems high for an A-rated machine, apparently operated at 30°C as a norm. On the other hand, it tallies with the relatively high figure given above per hour of use.

The tumble dryer used here is a White Knight CL 372. This is a compact 3 kg vented model with a normal heating element. It is D energy rated and although no details could be traced for this exact model, a similar D-rated 3 kg Hotpoint V3DOIP is given as 3.73 kWh/cycle. There were five dryer cycles recorded in the diary corresponding to the number of washing cycles; hence indicating consumption over the two weeks as 18.65 kWh, and 485 kWh, or 162 kWh/person, extrapolated over a year. However, it should also be noted that all the cycles were shorter than the maximum for this appliance, averaging some 50 minutes, this likely to be related to the householder's use of synthetic fabrics. It is therefore possible that the estimate is too high.

Although the season (summer), housing location (Wyndford), use of tumble drying and some ironing is common to both this case study and that of CS 10, the differing ventilation regimes lead to a markedly more moist environment, with poorer air quality in the case of CS 11, particularly in the case of the bedrooms – see Tables 11.1–11.3 below.

Table 11.1 Environmental conditions in Bedrm 1 for 29th May – 12th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,414 | 2,543 | 591 | 20.7 | 23.8 | 14.4 | 1.66 | 2.11 | 1.08 | 68.0 | 80.0 | 51.6 |

Table 11.2 Environmental conditions in Bedrm 2 for 29th May – 12th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,592 | 3,104 | 473 | 21.5 | 24.5 | 19.8 | 1.65 | 2.06 | 0.84 | 64.3 | 76.0 | 31.5 |

Table 11.3 Environmental conditions in Living rm for 29th May – 12th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 911 | 1,896 | 539 | 20.5 | 23.9 | 18.5 | 1.48 | 1.90 | 1.15 | 61.1. | 78.7 | 49.5 |

The upstairs is where the ironing occurs, estimated as approximately half of the washing loads in the questionnaire and given as four half-load sessions during the two weeks of monitoring. The iron in this case is a 1.8 kW Breville (IR 27), and, assuming half-hour ironing periods pro rata previous case studies at 0.278 kWh/session, this would extrapolate to some 29 kWh annually. Another issue in this regard is that the RH and VP recorded in the hall is high,with means of 62.6% and 1.54 kPa. This household also uses fabric softeners, and the process of ironing may exacerbate the release of VOCs such as acetaldehyde in this fairly humid space (Steinemann et al, 2008); noting also that the rate of off-gasing of water soluble VOCs such as aldehydes increases proportionately with increasing humidity (Arundel et al, 1986).

Table 11.4 Window opening on washdays during period 29th May – 12th June 2009

| Date | Living | Bedroom1 | Bedroom 2 | Bedroom 3 | Kitchen | Bathroom |
|---|---|---|---|---|---|---|
| 29/05 | Nil | 30 mins | nil | nil | nil | 20 mins |
| 03/06 | Nil | 1 hr | 30 mins | 30 mins | 30 mins | 1 hr |
| 06/06 | Nil | 1 hr | 10 mins | 30 mins | 30 mins | 20 mins |
| 09/06 | nil | 1 hr | 30 mins | 20 mins | 30 mins | 30 mins |

Details are given in Table 11.4 for periods of open windows in various rooms on washdays. It is possible that the location of the maisonette on the ground floor level influenced this degree of frugality, especially for the living room. A clue to this lies in the diary, where it is mentioned that there was reluctance to hang washing to dry outside due to the lack of security, and of course many people perceive the living room window as the most vulnerable for illegal entry. This is also another home where the tumble dryer seems to be adding to the moisture problem – e.g. a spike from 64.5% to 82.4% near the beginning of one cycle; but the effect is more erratic than in other case studies, and the overall problem is one of under-ventilation during a summer period.

In this case the CFU count is very similar for living room and kitchen to the values for CS 10 (given in parenthesis): living room 595 (678) CFU/m$^3$; kitchen 620 (565). The respective kitchens and bathrooms are also quite similar: 620 (565) and 550 (526). Bedrooms 1 and 2 on the other hand are somewhat higher, but still comfortably below 1,000 CFU/m$^3$: 750 (538) and 875 (595). Consequently, we have a situation where air quality is generally rather poor, where the average and maxima VP values in rooms is high enough to cause concern (means significantly above the Platts-Mill and De Weck threshold of 1.13 kPa), and where mould is evident in bedrooms and bathroom. On the other hand, the CFU count is still at a relatively low level.

Thus this case study conforms to a tentative hypothesis whereby, if passive drying inside a dwelling does not occur to a dominant extent, the mould spore count is likely to remain below a threshold of 1,000 CFU/m$^3$. Although the CFU count in the 500-1,000 range may be regarded as 'moderate' rather than 'low' (Ryan, 2002), this could have significant health implications for those sensitized to presence of spores in the indoor environment. It may be noted in this regard that Finland uses a limit value of 500 CFU/m$^3$ for airborne fungal spores for indoor air in urban areas in winter (Ministry of Social Affairs and Health, 2003 (Finland); cited in 'WHO guidelines for indoor air quality: dampness and mould', 2009); and the same value used in earlier Danish research (Reponen et al, 1992). It is estimated that 6-10% of the population and 15-55% of atopics (those vulnerable to hay fever, asthma and eczema) are sensitized to fungal allergens (Committee on the Assessment of Asthma and Indoor Air, Institute of Medicine, 2000).

Herbath et al (2003) also cite a considerable body of research involving epedemiological studies of childern and adults, where various health effects have been observed for airborne mould spores – e.g. chronic respiratory infections, dry cough, eye irritations, skin symptoms, asthmatic symptoms, allergy; and also various non-specific symptoms, such as headache, fever and lack of concentrtaion (Brunekreef et al, 1989; Flannigan, McCabe & McGarry, 1991; Husman, 1996; Pirhonen et al, 1996; Platts-Mills et al, 1997; Peat, Dickerson and Li, 1998; Koskinen et al, 1999; Ross et al, 2000; Burr, 2000).

FRUGAL WASHER, HAND WASHING, MIXED TUMBLE AND PASSIVE DRYING IN DWELLING, WINDOWS OPENED, LOW HEATING; SUMMER MONITORING, FLAT IN 1960S TOWER BLOCK

Case study 12: The dwelling in this case is a 2-apartment flat on the 4th floor of a 26-storey tower block in the 1960s all-electric Wyndford scheme. It is occupied by a single adult who does all his washing by hand, but does possess a tumble dryer, located in the bedroom, which is used carefully after partial drying on a 'pulley' in the bathroom. The questionnaire also mentions a clothes line for drying on the external balcony or veranda, as well as a clothes horse in the living room; neither specifically entered in the diary for the monitored two weeks. This combination of methods and window opening (occasional according to questionnaire, but quite frequently during monitoring period) corresponds with mould spores in the moderate range below 1,000 CFU/m$^3$.

There are four recorded (i.e. measured) uses of the tumble dryer during the two weeks from 21st May to 4th June. The first is on May 25th, the day after a hand washing and partial drying in the bathroom, and is the longest of the three, lasting for some 50 minutes. Over the four cycles, the Hotpoint Aquarius, vented to the outside, consumes 2.2 kWh in a total of 110 minutes – i.e. an hourly average of 1.2 kWh. The 7 kg TVM570P model is rated C, with a typical full cotton cycle expected to last 110 minutes, and consuming 3.98 kWh; which implies a much higher hourly rate of consumption of 2.17 kWh. Thus we may conclude that the occupant's policy of partial drying is responsible for the difference. In any event, if extrapolated at this rate over a year, the total implied is 57 kWh.

The questionnaire also indicates that less than half of all washing is ironed, that by a 2 kW Phillips in the living room, but makes no specific mention of any ironing in the 2-week diary. If one assumes 30-40 minutes monthly is spent on this activity, this suggests an annual consumption of some 4 kWh. Therefore the combined annual electrical load for domestic laundering in this instance is predicted to be in the order of 61 kWh for this occupant.

The 'occasional', sometimes more frequent, opening of windows and the single occupancy seems to provide reasonable air quality – e.g. $CO_2$ 488 ppm mean, 964 maximum and 405 minimum in the living room, and a slightly higher mean of 586 ppm in the bedroom. Here a modest rise of 4.4% from 58.2% to 62.6% RH occurs during the longest period of tumble drying and the air quality in the bedroom reflects the summer opening regime ($CO_2$ < 600 ppm); while in the internal, mechanically ventilated bathroom, the maximum value for RH may be due to bathing or showering rather than to passive drying – see Table 12.1.

Table 12.1 Environmental conditions in Bathroom for 21st May – 4th June 2009

| $CO_2$ (ppm) | | | Temperature (ºC) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min |
| 657 | 1,300 | 496 | 19.4 | 28.2 | 16.8 | 51.9 | 81.2 | 16.3 |

On the other hand, this high value of 81.2% (1.75 kPa), ocurring after midday on 23rd May corresponds with similar high values in other parts of the flat – 70.5% (1.53 kPa) living room, 78.2% (1.86 kPa) hall, 77.8% bedroom (1.75 kPa). Although migration from the batroom remains a possibility, the rather unusual ambient conditions suggest that migration of moist air inwards via windows has played a part. The RH peaked at midday with 97.5%, when the temperature was 11.6ºC and 1.2 mm rain fell within an hour. It may also be noted that mean moisture levels in key rooms reflects the good air quality attributable to window opening and/or low intensity of occupancy by one person – living room and bedroom both having a mean vapour pressure of 0.71 kPa.

As indicated, the count of mould spores is moderate: Living room 865, kitchen 945 and bedroom 890 CFU/m$^3$. In this instance Cladosporium is not present in the list of species, and the list is more extensive than that of Case Study 13 below with a lower count.

MODERATE WASHER, NO WASHING/DRYING APPLIANCE IN DWELLING, WINDOWS CLOSED, LOW HEATING; SUMMER MONITORING, FLAT IN 1960S CAVITY-INSULATED TENEMENT BLOCK

Case study 13: This is a 2-apartment sheltered flat in the same housing scheme as Case Studies 10 and 11. It is of interest in that the single person who occupies it does not own or use her own washing machine or tumble dryer. Instead she uses an off-site laundrette and does some light washing by hand in the bathroom, also making use of a 'pulley' in that space. She also keeps a low level of heat on during the 26th May to 9th June monitoring period, and professedly does not open her windows while heating is on, or use trickle vents. The net result is that, even with single occupancy, the air quality tends to be on the poor side, with averages below 1,000 ppm $CO_2$ and maxima well above this value, and the moisture levels tend towards being too high. However, the maximum values are considerably lower than those for Case Study 11 above, and this undoubtedly reflects the single occupancy. Also, in conformity with the tentative hypothesis outlined above, the CFU count is respectably low. The other related question that may emerge from a comparison of dwellings with a policy of open windows compared to those with closed windows is whether the former group bring in a greater variety of spores from outside (not necessarily greater in terms of CFU/$m^3$). However, the numbers in the sample as a whole are unlikely to confirm or to deny such an association, given variability of location and time of year.

During the two weeks of measurement, the occupant took one full load to the laundrette (washing and drying), and did three hand washes, the first comprising two shirts, the second underwear and the third T-shirts etc. In each case the hand-washed items were hung on the bathroom pulley to dry. Although details of the appliances in the laundrette are unknown, it is reasonable to assume that they will be similar to those used in the communal laundry of Case Study 10, in turn based on manufacturer's estimates. This would suggest a figure of approximately 5 kWh, which when extrapolated implies an annual total of some 130 kWh/person, comprising 18 kWh for washing and 112 kWh for drying. However, we would need to add an allowance for hot water use over the year for washing by hand. At the rate of three hand washes per fortnight, there would be 78 in a year; and if each represented about one tenth of the day's water heating requirements that would imply a total annual consumption of circa 40 kWh (total for year = approx. 1,850 kWh, divide by 365 and multiply by 7.8). This would bring the estimate total washing load up to 58 kWh.

This resident is also unusual in apparently not possessing an iron, but does indicate ironing her entire washing load while at the laundrette. At the rate of ironing a full load every two weeks, this might consume in the order of 15 kWh annually.

Although, it is difficult to isolate any moisture input to the bathroom from washing and drying small numbers of light clothing from that arising from having a bath or shower, each of the three days when hand washing occurred do have two moisture peaks, It is a reasonable conjecture that the morning one might well be due to the hand washing of clothes – see Table 13.1 below. On the other hand, one would not expect a very significant effect from such a small quantity of washing whereby the process of washing and rinsing itself might be as potent as that of drying.

Table 13.1 highest times of moisture in Bathroom on 29th and 31st May and 2nd June

| 29th May | | | 3rd May | | | 2nd June | | |
|---|---|---|---|---|---|---|---|---|
| time | RH(%) | VP(kPa) | time | RH(%) | VP(kPa) | time | RH(%) | VP(kPa) |
| 1020 | 63.1 | 1.75 | 1140 | 59.2 | 1.65 | 12.10 | 50.7 | 1.48 |
| 2030 | 66.6 | 1.83 | 22.30 | 55.7 | 1.59 | 2000 | 59.6 | 1.74 |

The key environmental means, maxima and minima in the main rooms are again included for purposes of comparison with other case studies – see tables 13.2 to 13.4 below.

Table 13.2 Environmental conditions in Bedroom for 26th May – 9th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 850 | 1,653 | 416 | 22.8 | 25.9 | 20.6 | 1.25 | 1.62 | 0.65 | 45.0 | 59.6 | 22.4 |

The maximum VP of 1.62 kPa occurs on 30th May at 04.10, with the temperature maintained at 22.5ºC (night charge period) and $CO_2$ at 1,283 ppm. These conditions are not particularly short-lived and they are also representative of the rest of the flat. The high $CO_2$ level and information provided with regard to windows and trickle vents suggest a minimal influence from outside conditions. However, these conditions prevailed during a settled period of relatively warm weather with sunny days on either side of the VP maximum, and a very similar level of ambient VP day and night of circa 1.6 kPa. In other words, there appears to be an approximate outside-inside moisture equilibrium at this time, where temperature and $CO_2$ are the main variants.

Table 13.3 Environmental conditions in Living room for 26th May – 9th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 972 | 1,857 | 509 | 22.1 | 25.1 | 19.8 | 1.27 | 1.61 | 0.65 | 47.7 | 62.5 | 23.9 |

Table 13.4 Environmental conditions in Kitchen for 26th May – 9th June 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 896 | 1,518 | 387 | 22.0 | 25.9 | 20.0 | 1.26 | 1.83 | 0.62 | 48.0 | 66.6 | 24.2 |

As indicated in the first paragraph, the mould spore count is respectably low – just above or below the 500 CFU/$m^3$ mark: 545 Living room; 570 Kitchen; 550 Bedroom and 460 Bathroom. It is also of interest that the bathroom has the lowest value given that it is intrinsically a 'wet' room regardless of the small amount of clothes drying at roughly 3-day intervals. The other matter of interest, given the regime of closed windows is that there is no evidence of mould growth. Also, although Cladosporium and Aspergillus are present, Penicillium is not. Neither is Alternaria, which was present for Case Study 10, with its regime of open windows. Moreover, both Case Studies 13 and 11 with closed windows have fewer mould species than that of 10 with its open windows, even though the CFU count is similar in all three.

MODERATE WASHER, PASSIVE DRYING IN DWELLING, WINDOWS OPEN, HEATING NOT ON; SUMMER MONITORING, FLAT IN MODERNISED TRADITIONAL STONE TENEMENT BLOCK

Case study 14: This is a household of two adults, which was investigated at approximately the same time of year as the three previous case studies above, but in a different part of the city. Although monitored from the 21st May to 4th June, there was a wash cycle on the 4th June that occurred after measurement ceased. Also, as some sensors appear to have been subject to direct sunlight, only four days out of the two weeks were considered reliable. Unfortunately none of the reliable days include those when washing was being dried passively in the bedroom. Nevertheless, the remaining data is included for completeness. What is of particular interest relative to the last three case studies is that these two residents did dry their washing passively indoors, with a very liberal ‘open window’ regime, and had a CFU count in the ‘moderate’ range comfortably below 1,000 CFU/m$^3$, but well above 500 CFU/m$^3$.

The total energy consumed by the Hotpoint Aquarius Ultima B-rated washing machine during its three cycles and including stand-by consumption, was 4.215 kWh over a period of 12 days. This extrapolates to 128 kWh per annum at 0.35 kWh /day or 64 kWh/person at 0.175 kWh/day. It also comes to an average of 1.375 kWh/cycle, well above the manufacturer’s figure of 0.95 kWh, or 1.05 kWh/hr of use. This is a relatively high figure, especially when the normal was temperature is noted as 30$^o$C. On the other hand, the profile of each cycle confirms that it is a cold feed. As this household did not possess either a tumble dryer or an electric iron, the foregoing estimates based on the recorded data represents their entire energy consumption associated with laundering. It may also be noted that the occupants professed not to turn up the heating to facilitate drying. On the other hand, assuming the window in the bedroom remained open while drying occurred during winter, there would be a considerable additional energy penalty.

Table 14.1 and 14.2 summarise the key environmental data in the bedroom and living room for the days when measurements were not compromised.

Table 14.1 Environmental conditions in Bedroom for 23-25th, 28th May & 4th June 2009

| $CO_2$ (ppm) | | | Temperature ($^o$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 699 | 1,089 | 534 | 19.4 | 21.9 | 17.8 | 1.19 | 1.57 | 0.95 | 53.1 | 68.9 | 41.4 |

Table 14.2 Environmental conditions in Living rm for 23-25th, 28th May & 4th June 2009

| $CO_2$ (ppm) | | | Temperature ($^o$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 709 | 2,341 | 511 | 18.0 | 23.8 | 15.8 | 1.17 | 1.51 | 0.89 | 56.9 | 69.8 | 40.9 |

For the bedroom, compared with Case Study 13 above, the open window regime has resulted in lower $CO_2$, and lower VP, mean and maximum values, and this for two occupants rather than one. Due to somewhat lower temperatures without heating and with an open window, the RH levels are higher than for Case Study 13. But of course it is VP that provides the measure of absolute level of moisture, this reflecting ambient conditions – e.g. the bedroom maximum occurs on a cloudy, damp evening when indoor $CO_2$ is only 633 ppm. The pattern repeats for the living room, except that the maximum value of $CO_2$ is higher at 2,341 ppm, occurring when ambient temperature was low at 6ºC (window shut?) and 4 persons are likely to have been present.

As indicated above, the CFU count is somewhat higher than for Case Study 13 – in a ‘moderate’ range above the 500 CFU/m$^3$ mark: 710 Living room; 650 Kitchen; 690 Bedroom and 710 Bathroom. Again, there is no evidence of mould growth. However, the number of species of spores is greater than for Case Study 13, in conformity with open windows admitting more from outside, and Cladosporium, Aspergillus and Penicillium are all present. Although Alternaria, which was present for Case Study 10 with its similar regime of open windows, is not present here, there are others in common – for example, Ulocladium, Phoma, Aureobasidium, Mucor and Rhizophus. The CFU count is slightly above that of Case Study 10, where part of the washing was also dried indoors, but the similarity of the overall pattern of the CFU analysis conforms with open windows.

FRUGAL WASHER, MACHINE AND HAND WASHING, PASSIVE DRYING OUTSIDE AND INSIDE DWELLING, WINDOWS OPENED, LOW HEATING; AUTUMN MONITORING, 1990S SEMI-DETACHED HOUSE

Case study 15: Although this 3-apartment semi-detached house with two bedrooms was declared as occupied by a single adult at the time of the questionnaire, both bedrooms were occupied during the monitoring period. The situation is further complicated by only one machine wash occurring during this two-week period, and although washing by hand in the bathroom is indicated on the questionnaire, no mention of this is recorded in the monitoring diary. For the purposes of this analysis it is assumed that a 'visitor', who dealt with laundering by using an external source, occupied the second bedroom. The other notable point in connection with the laundering habits of this householder is that she is one of few, and the first of the case studies examined thus far, to dry all washing outside, and this in autumn. Having said that, the questionnaire indicates that indoor methods are used as well, in particular with a clothes horse located close to the radiator in the living room, the house having a gas boiler and radiators in all main spaces. The questionnaire also stated that the living room window was always opened during passive indoor drying, that heating was not turned up to accelerate drying, and that there was no smell of dampness, no mould and no mildew. Finally, in this regard, the mould spore count was in the low moderate range, generally just above the 500 CFU/$m^3$ level.

The Hotpoint Aquarius washing appliance has a cold feed and the normal temperature setting is given as 30°C. The full load on 31st October consumed 0.977 kWh, which extrapolates to a modest 25.4 kWh annually per person (assuming laundering for single householder). The cycle lasted for 1 hr 50 mins, giving an hourly rate of 0.52 kWh.

The householder also has a 1.75 kW steam iron and indicates that approximately half the washing is ironed in the living room – say half an hour per half load. The estimate for this is 0.278 kWh, which, at an assumed average rate of a half load every two weeks, extrapolates to 7.2 kWh annually, less than 30% of the predicted annual estimate for washing.

This household also displays a relatively uncommon degree of moderation with respect to the achieved temperatures, which prevails in all the main spaces. Given the date of the scheme in the 1990s and probable construction with insulated timber frame, it seems likely that the heating was used sparingly during the period of monitoring, with a relatively large range between maxima and minima – see Tables 15.1-15.3 below. While this will have been reflected in low energy consumption, the mean and maximum VP levels are all above the Platts-Mills and De Weck dust mite benchmark of 1.13 kPa, and bedroom RH maxima well above 80% and means over 70% are particularly excessive. Nor are these high RH values brief spikes. The maximum for Bedroom 1 of 85.6% occurs at 09.30 on 18th October, when the temperature is 15.6°C, VP 1.52 kPa and $CO_2$ 1,429 ppm – also significantly above the 'critical equilibrium humidity' for mite growth given by Cunninham (1998). While the last value drops below 1,000 ppm reasonably quickly by 10.10, the RH stays above 70% until 18.30 that evening with the temperature having risen to 17.3°C.

Table 15.1 Environmental conditions in Bedroom 1 for 14th Oct – 2nd Nov 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 996 | 1,878 | 534 | 17.0 | 19.5 | 13.9 | 1.40 | 1.66 | 1.03 | 71.8 | 85.6 | 60.3 |

Table 15.2 Environmental conditions in Bedroom 2 for 14th Oct – 2nd Nov 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 845 | 1,382 | 470 | 17.2 | 19.8 | 14.2 | 1.38 | 1.75 | 1.07 | 70.7 | 83.4 | 55.9 |

Table 15.3 Environmental conditions in Living room for 14th Oct – 2nd Nov 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 785 | 1,244 | 582 | 16.4 | 19.7 | 13.1 | 1.28 | 1.61 | 0.93 | 68.5 | 76.4 | 55.1 |

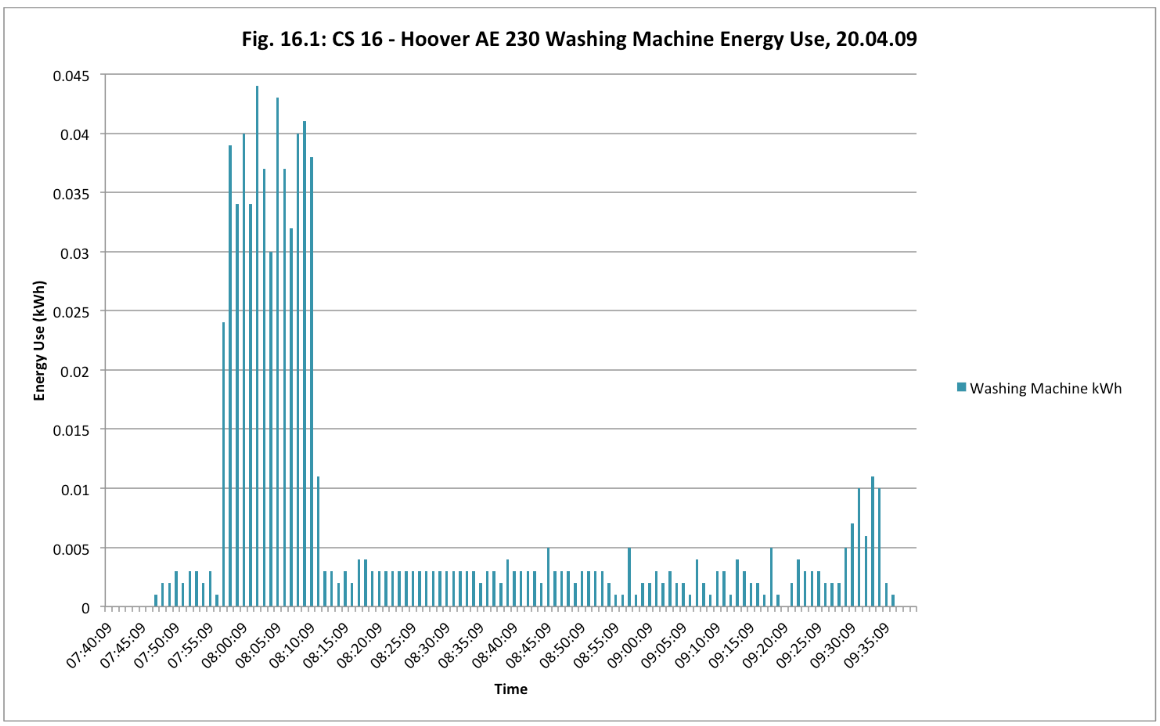
Although these conditions have no tangible relationship with laundering activities during the monitoring period, they are significant in terms of what might happen during winter when nearly all the drying occurs indoors. At this autumn period, with the mean ambient temperature still in double figures and all the washing apparently dried outside, it seems that the VP maxima internally relate quite strongly to conditions outside. For example, the respective maxima of 1.66 and 1.75 kPa in bedrooms 1 and 2 occur at 10.32 on 31$^{st}$ October when the mean daily temperature outside is 13.4ºC, circa 12ºC at 10.30 with a range of only 4K, and mean daily RH is 87% – i.e. a VP of circa 1.33 kPa. $CO_2$ levels inside are also around 1,000 ppm at this time or less, indicating the probability of some ventilation via windows. Similarly the living room maximum of 1.61 kPa occurs at 21.52 on the 29th October, when indoor conditions are respectable in terms of temperature and $CO_2$ (19.7ºC and 1,069 ppm), but too moist (RH 70%), and average ambient conditions for the day are 13.1ºC (range of 2K) and 91% RH, giving a VP approaching 1.4 kPa.

In this case, the spore counts are all between 500-600 CFU/m$^3$ with the exception of the kitchen at 630 – living room: 548, hall: 521, bathroom: 564, bedroom 1: 560, bedroom 2: 550. Aspergillus, Cladosporium and Penicillium are all present, but the overall number of species is small compared with others with higher spore counts. In this case the low count again corresponds with absence of drying washing within the dwelling (at the time of the monitoring); and, given the evidence of the relatively low average $CO_2$ values, it would also seem to align with reasonably relatively frequent opening of windows, or low intensity of occupation, or a combination of both.

MODERATE WASHER, MACHINE WASHING, PASSIVE DRYING OUTSIDE AND INSIDE DWELLING, WINDOWS OPENED, LOW HEATING; SPRING MONITORING, HOUSE IN 1990S TERRACE

Case study 16: This is a similar age, size and type of house to that of Case Study 15 above, this time located in the Calton area of Glasgow's east end. Here there are two permanent occupants, both elderly adults in this case, who also dried all the washing outside during the period of monitoring. However, the questionnaire confirms that indoor drying occurs as well according to weather conditions – this in a large walk-in store containing the 'combi' gas boiler and designated 'the drying cupboard', and in the adjacent hall on a portable airer. Monitoring started here on the 15th April, 2009, but the recording of data was set too finely, and the readings terminate on 23rd April, one day before the final washing recorded in the diary. The house has two bedrooms, one of which is double and one single (spare room), and, at the time of monitoring, heating was on, but not in the kitchen or bedrooms. It was the normal to open the windows for quite long periods in all main rooms while the heating was on, and to keep trickle vents permanently open – both according to the questionnaire. The spore count in this instance was moderate, but there was evidence of some surface mould (not severe) in the main double bedroom and bathroom.

There were four washing days during the two weeks, three of which were measured within eight days. The total consumption by the Hoover AE 230 A-rated appliance, variously set at 40°C and 30°C, was 2.089 kWh or 0.7 kWh/cycle. The mean average daily consumption of 0.261 kWh extrapolates to 95 kWh/year; and the equivalent figure for each hour of running time is 0.44 kWh. Fig. 16.1 shows the washing profile, in this instance summed at 1-minute intervals, with a total of 0.8 kWh over relatively lengthy cycle of almost two hours, and a norm of 30°C reported. The finer grain of the power pulsing is of interest here compared with the relatively coarse 10-minute tranches used for previous case studies.




Ironing with a 2.0 kW Morphy Richards (40685) is recorded on two of the four washing days, carried out in the kitchen on each occasion, noting that the questionnaire indicates that all clothing is ironed. At any rate, extrapolating from the diary and pro rata the data used above, the predicted annual ironing consumption is some 29 kWh.

The drying cupboard is of particular interest, but the data in Table 16.1 below conforms to the outdoor drying adopted during the measured period from 15th to 23rd April. The maximum RH of 92.6% that occurs in the hall, Table 16.2, is an isolated short-lived spike that appears to be due to migration from the bathroom – although the bathroom was not measured, the timing at 08.14 with the temperature at 24.7°C (morning boost?) and VP at 2.88 kPa makes this the most likely cause. A similar spike in the kitchen of 85.8% (Table 16.3) occurs at 15.47, in all probability due to some cooking activity, with temperature at 22.8°C, VP at 2.38 kPa and 1,547 ppm $CO_2$. It should also be noted that although the diary indicates that windows were open for several hours on the 17th April, a sunny day (5 hours in the kitchen, 4 in the living room and all day in the bedroom and bathroom), the extremely high maxima for $CO_2$ indicate that they must have been closed during periods of occupation. The living room maximum of 4,815 ppm (Table 16.4) may reflect the regular presence of two visitors in the afternoons. However, occurring on 21st April at 15.46, when the temperature was 25.7°C, RH 53.4% and VP 1.76 kPa, this was no isolated surge. Indeed the $CO_2$ level in the living room was continuously over 1,000 ppm from 08.23 on the 21st to 07.20 on the 22nd, with a mean average value of 2,387 ppm; with a lengthy surge in the afternoon (hall as well as living room; VP as well as $CO_2$) indicating some kind of social gathering with low rates of ventilation. In this case it is clear that ambient conditions were not particularly influential, with outside VP some 0.77 kPa in the peak afternoon period.

Table 16.1 Environmental conditions in Drying Cupboard for 15th – 23rd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 996 | 1,878 | 534 | 22.4 | 25.1 | 19.1 | 1.31 | 1.58 | 0.99 | 48.1 | 53.9 | 42.3 |

Table 16.2 Environmental conditions in Hall for 15th – 23rd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,265 | 5,000 | 441 | 21.9 | 34.5 | 16.8 | 1.40 | 3.84 | 0.84 | 52.7 | 92.6 | 29.3 |

Table 16.3 Environmental conditions in Kitchen for 15th – 23rd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,352 | 3,817 | 602 | 22.5 | 29.7 | 16.8 | 1.32 | 2.38 | 0.89 | 48.7 | 85.8 | 28.3 |

Table 16.4 Environmental conditions in Living room for 15th – 23rd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,478 | 4,815 | 505 | 22.0 | 27.0 | 16.0 | 1.26 | 2.20 | 0.78 | 47.3 | 65.5 | 30.6 |

The range of these values is also large, partly reflecting the periods when windows are open or closed, and partly no doubt reflecting the responsive heating regime allied to a relatively lightweight building envelope. Again, although, the data has no specific relevance to the drying regime adopted during that particular period of measurement, the impacts at other times may be significant. For example, will moisture migrate from the drying cupboard and hall into the main bedroom, hence adding to an already identified mould problem?

In this case, the spore counts are somewhat higher than Case Study 15, all between 500-800 CFU/$m^3$ – living room: 765, hall: 630, kitchen 530, bathroom: 775, bedroom 1: 640, bedroom 2: 770. Aspergillus, Cladosporium and Penicillium are again present, but here the overall number of species is quite extensive. Undoubtedly some of these will be due to ambient condition and, overall, it is also possible that the reasonably moderate levels have an association with the combination of external drying and the dedicated drying cupboard inside.

MODERATE WASHER, MACHINE WASHING, PASSIVE DRYING OUTSIDE AND INSIDE DWELLING, WINDOWS OPENED, LOW HEATING; SPRING MONITORING, FLAT IN 1960S TOWER, HEAVY CONSTRUCTION, DRY-LINED INTERNALLY

Case study 17: The two occupants in this case live in a two room, one bedroom, flat in a 1960s 'Bison' system-built tower on the topmost living floor ($7^{th}$) directly below a partly covered communal drying terrace. They certainly make use of external drying, but it is unclear whether they use the communal facility or their own private open balcony. The occupants also tend to bring the partially dried washing indoors to complete the drying process on a portable airer, either located in the hall or the living room. During the April monitoring period the windows were regularly opened while the heating was still used in the living room. However, the questionnaire indicates that they would be closed overnight when the electric storage unit is charged. In any event, air quality is generally good and indoor moisture levels are also reasonable. The spore count is generally in the moderate range, the kitchen just over 1,000 CFU/$m^3$.

The AEG Lavamat 52600, A-rated washing machine had five cycles during the two weeks of monitoring, two of which are described as full loads and three as half loads. The data was collected from $14^{th}$ April until $22^{nd}$ April and captured the two full loads within that 8-day period. This amounted to a total of 0.926 kWh, averaging 0.116 kWh/day or 0.058 kWh/person.day. The average of 0.46 kWh/cycle of such duration (1 hr 10 min average) also corresponds well with technical data given by AEG for this appliance; and 30$^{o}$C was noted on the questionnaire as the normal wash temperature. This extrapolates to a commendably low 21.1 kWh annually for each person, which is similar to Case Study 15; and consumption expressed per hour of running time compares well other appliances at almost 0.4 kWh.

The steam iron used is a 2.2 kW Morphy Richards, and the questionnaire indicates that approximately half the washing loads are ironed. Using the same pro rata data as above this would consume 0.57 kWh for every hour of use, but there is no indication in the diary of this having taken place. On the other hand if half of the washing had been ironed, the annual total might have been of the order of 26 kWh, approximately two thirds of that used for washing.

Having pre-dried the washing outside, there is no evidence of added moisture once taken indoors. However, the summarised environmental data in Tables 17.1-17.3 again provide useful context. In this case, two of the sensors, one in the east-facing bedroom and the other in the south-facing kitchen have evidently been in full 'solar view' for short periods on three days.

Table 17.1 Environmental conditions in Bedroom for $14^{th}$ – $22^{nd}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^{o}$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 828 | 1,671 | 417 | 16.4 | 42.6 | 11.7 | 1.01 | 1.32 | 0.81 | 56.9 | 80.0 | 9.9 |

Table 17.2 Environmental conditions in Kitchen for $14^{th}$ – $22^{nd}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^{o}$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 419 | 745 | 334 | 19.7 | 39.3 | 15.1 | 0.91 | 1.90 | 0.71 | 40.3 | 63.2 | 10.8 |

For example, the bedroom maximum of 42.6$^{o}$C occurs at 10.23 on the $19^{th}$ April, thus depressing RH to the artificially low level of 9.9% while the VP is at 0.84 kPa and $CO_2$ at a commendably low 469 ppm. Total horizontal global solar irradiation that day was 6.11 kWh/$m^2$ compared with an average of 3.53 for April. There are similar spikes on the $20^{th}$, with the temperature at 33.7$^{o}$C at 1029, and on the $22^{nd}$ with 39.9$^{o}$C at 1038. Further spikes occur on the same days in the kitchen – for example, 39.3$^{o}$C occurs on the $19^{th}$ between 0957 and 1000, with RH at 10.9%, VP at 0.77 kPa and $CO_2$ at 369 ppm. However as these spikes are of relatively short duration, and will only slightly boost the mean average temperatures while reducing mean average RH, they have been left in the data sets.

Table 17.3 Environmental conditions in Living room for 14th – 22nd April 2009

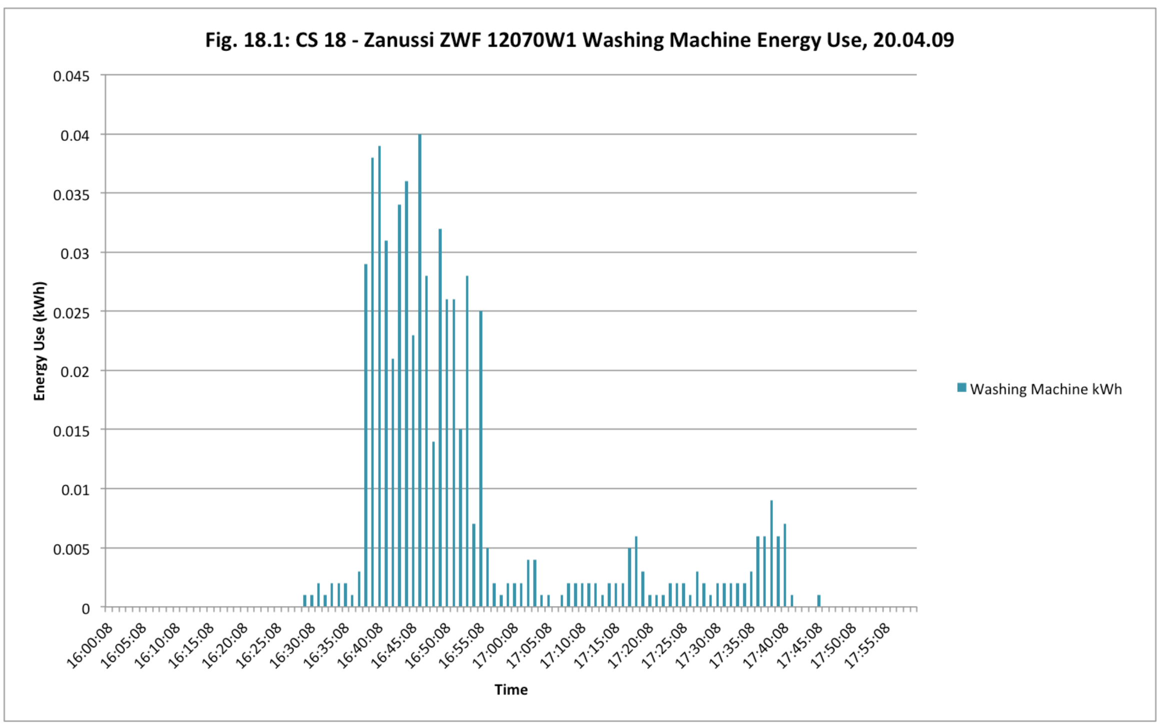
| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 531 | 1,052 | 299 | 22.4 | 28.2 | 18.5 | 0.92 | 1.31 | 0.72 | 33.9 | 42.4 | 23.5 |

One may also notice that without heating at this time of the year the bedroom falls to quite low temperatures, with correspondingly high RH overnight. Has such a regime been used in conjunction with passive drying or steam-ironing, there might have been problems of condensation and mould. However, in this case the spore count is again in the moderate range as indicated earlier – living room: 935, hall: 580, kitchen 1,005, bathroom: 620, bedroom: 620 CFU/$m^3$. Aspergillus, Cladosporium and Penicillium as usual present, and the overall number of species is not as extensive as that for Case Study 3 above. Note that both kitchen and bathroom have mechanical extract, respectively manual and automatic in terms of operation.

MODERATE WASHER, MACHINE WASHING, PASSIVE DRYING INSIDE DWELLING, WINDOWS OPENED, NO HEATING; SPRING MONITORING, FLAT IN 1960S TOWER, HEAVY CONSTRUCTION, DRY-LINED

Case study 18: The flat in this case is in the same Bison block as Case Study 17 above, a main difference being that it is occupied by a single adult, who dries his washing passively within the flat; but, in doing so, maintains the key environmental means, maxima and minima at a quite similar level to those of Case Study 17. The main difference, however, is the spore count, which is high. Given that micro-organisms, including mould spores, tend to relate to skin and clothes, it would seem that the greater presence of drying clothing within the flat may indeed be influential. But how much do the high counts of spores matter? This flat has no reported visible mould, yet counts at this level – circa 3,000 CFU/$m^3$ – are usually associated with damp housing. The question then to address is whether these scores taken in April are representative of former winter dampness, and whether the indoor drying could or would be influential in this regard.

Similar to Case Study 17, the data was recorded for the first eight days of the two-week monitoring period, in this case capturing three out of five washing cycles. The appliance, an A-rated (for energy) Zanussi ZWF 12070W1 used a total of 1.962 kWh from 14th to 22nd April, or 0.854 kWh/cycle. Extrapolated, this implies about 90 kWh for the year, and in terms of energy per hour of use, it gives a value of 0.55 kWh – with the typical wash temperature 40$^{o}$C. Fig. 18.1 may be compared with that of Fig. 16.1 above, in this case 0.6 kWh consumed over approximately one and a quarter hours, and 40$^{o}$C reported as the normal temperature – i.e. CS 18 using a warmer temperature, having a shorter cycle, and consuming less energy compared with CS 16.




Airing devices of different kinds are used in the kitchen, bathroom and living room to dry clothes, and the occupant admits to not only placing portable devices close to the heat emitter in the living room, but also to turning the output up to assist drying. According to the questionnaire it seems that windows are seldom opened, but during the April monitoring the evidence suggests that windows were opened for quite long periods, especially in the kitchen (which also has a mechanical extract, as does the bathroom).

The other relevant factor in terms of energy use and moisture production is the steam iron – a 1.8 kW Russell Hobbs, with ironing done in the living room. Here there is a certain inconsistency of information since the questionnaire indicates that all loads are ironed, but in practice from the monitored fortnight it seems that ironing some half of one load in two seems to be typical. If one assumes an average of half an hour of ironing every week, the pro rata formula used in all case studies would indicate some 15 kWh over a year. There are no discernable rises in humidity in the living room, as evident from Table 18.1 below, with respectably low RH and VP maxima.

Table 18.1 Environmental conditions in Living room for 14th – 22nd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 586 | 1,559 | 451 | 19.6 | 25.5 | 16.0 | 0.91 | 1.22 | 0.67 | 40.3 | 54.5 | 26.6 |

The equivalent values for the kitchen and bedroom are somewhat higher in terms of humidity. Tables 18.2 to 18.3, and in the kitchen there does seem to be a discernable rise, over and above a specific cooking peak, that is tempting to attribute to the impact of a laundering activity. On the 15th April, when the maximum VP of 1.5 kPa occurs at 11.55, this is a peak within a steadier rise from 0.9 up to 1.14 kPa. However, this occurs during the washing cycle, thus negating such a laundering cause, with the steady rise due to presence of the occupant, any visitors (according to questionnaire, two people present in flat during daytime period), and kitchen activity that would produce a relatively uniform and slow release of moisture. Note also that in this case, whether due to better placing of the sensors, or due to the flat being located on the northern side of the block, there are no extreme maxima in terms of high temperatures and correspondingly low RH. Also similar to Case Study 17, the $CO_2$ and VP values indicate that the kitchen was well ventilated, possibly by the mechanical extract; and in this case, the bedroom also maintains good air quality at all times, this despite the questionnaire indicating that windows were rarely opened. Another possibility is that the bedroom is rarely occupied, since the night of 20th to 21st is the only one during the eight days of data collection when there is a distinct rise in $CO_2$ overnight up to the maximum of 801 ppm just after 03.30. In any event, such hypothetical scenarios have no direct relevance to this study, as the bedroom was not used for drying or ironing.

Table 18.2 Environmental conditions in Kitchen for 14th – 22nd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 508 | 791 | 425 | 16.7 | 24.1 | 14.0 | 0.93 | 1.50 | 0.66 | 48.8 | 76.0 | 28.9 |

Table 18.3 Environmental conditions in Bedroom for 14th – 22nd April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 561 | 801 | 429 | 16.1 | 20.8 | 13.0 | 0.93 | 1.50 | 0.66 | 50.9 | 77.2 | 32.8 |

However, given the moisture levels indicated in the above tables and the lack of visible evidence of mould, it is perhaps surprising to find that the mould spore count is so high (factorial differences cf. Case Study 17 in parenthesis) – living room: 2,960 (3.2), hall: 3,135 (5.4), kitchen 1,700 (1.7), bathroom: 2,975 (4.8), bedroom: 2,355 CFU/$m^3$ (3.8). Aspergillus, Cladosporium and Penicillium are once again all present, and, despite large factorial differences in CFU count, the overall number of species is not quite as extensive as that for the neighbouring Case Study 17. The significant difference between the two case studies would appear to be presence versus absence of passive drying indoors. The question then arises as to what other significant differences there might be – e.g. housekeeping standards in terms of regular dusting and vacuum cleaning, disposing of food particles from surfaces and inaccessible corners etc. However, one might expect such other potential influences to be random, whereas the presence or absence of passive drying has been specifically identified for each case study. What is not known is whether the conditions found during monitoring, in this case spring, might have followed very different conditions during the past winter, and whether a high spore count from then might then persist over a period of several months, or perhaps even throughout annual cycles.

LOW-MODERATE WASHING, ALL PASSIVE DRYING, HEATING NOT ON MUCH; SPRING MONITORING, FLAT IN TOWER BLOCK, 1970S 'NO-FINES' SEMI-HEAVY CONSTRUCTION, DRY-LINED INTERNALLY

Case study 19: This is a 2-person household in the 3-apartment flat in a high-rise tower in the Townhead area of Glasgow, using similar construction to that of Case Studies 5 and 7. Heating is again by electric storage units, acknowledged as not generally on during the monitored period. In this case, most of the washing is passively dried within the flat either in the kitchen or in bedrooms, although some drying is reported in the communal facility – availability is an issue in this regard. As with the two case studies above, monitoring was conducted in spring, starting April 16th and measurement of environmental data lasted for the first eight days. The spore count in this flat was also relatively high, all values being above 1,000 CFU/$m^3$.

Only one complete cycle of the B-rated Ariston A1400 washing machine was captured during the first 8 days, this on the 17th April, described as a half-load, lasting for 1 hour 37 minutes, and totalling 0.761 kWh. This works out at 0.47 kWh for each hour of use. The respondent indicated 30°C was the normal temperature setting, and the measured profile of initial heating was commensurate with a cold fill. A further two 'full loads' were washed on the 25th April (after measurement stopped). If computation is based on five half loads in two weeks, using the one that was measured, the extrapolation suggests an annual total of approximately 100 kWh or 50 kWh per person. In addition to this some hand washing in the bathroom is acknowledged – e.g. on the 17th April – which would add an extra water-heating component. The drying on that day was dispersed between the kitchen and the bedroom, the former with windows open all day, the latter for half the day. Both hand washing and machine washing was later all ironed in the living room, which was also acknowledged as having the window open for half of the day during monitoring. The iron in this case is a 1.44 kW Braun, and pro rata the usual data, and assuming two hours of ironing during the two-week period from information in the diary, the annual total would be circa 28 kWh or 14 kWh/person.

Due to the relatively liberal regime of window opening, it was not possible to detect any impact on moisture levels in kitchen, bedrooms or living room. Tables 19.1-19.3 below draw attention to particular RH and VP maxima in bedroom 1. However, the values of 96.5% and 2.98 kPa occur on the 22nd April between wash-days in a short-lived spike of about half an hour within a period of just over an hour when the VP builds up from, and falls back to, circa 1.0 kPa. This might, for example, be due to someone entering the bedroom having had a shower, swathed in damp towels and proceeding to blow-dry a heavy head of hair. The temperature peaking at 24.6°C during this moisture spike adds veracity to such a scenario. It certainly does not appear to relate to migration of moisture from outside to inside. The peak in humidity occurs on a sunny afternoon with ambient temperature 12.4ºC, RH 69.4% and VP circa 1.0 kPa A similar spike on the 17th, which was a washing day, is unlikely to be associated with the passive drying – especially given that it was half load in total dispersed between kitchen and bedroom (which bedroom is not specified). Bedroom 2's maximum of 1.6 kPa occurs on the 18 th at 17.30, on a sunny afternoon when ambient temperature is 10.2ºC, RH 56.5% and VP 0.7 kPa. Indoor $CO_2$ is well below 1,000 ppm, so drying of some kind may be responsible for the relatively high VP. The maximum VP in the kitchen occurs during a long surge in $CO_2$ that appears to be a social event lasting the entire night from 23rd-24th April, and has values above 3,000 ppm from 01.00 to 07.00.

Table 19.1 Environmental conditions in Bedroom 1 for 16th – 24th April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 730 | 2,221 | 372 | 18.0 | 25.5 | 15.0 | 1.10 | 2.98 | 0.76 | 53.2 | 96.5 | 40.2 |

Table 19.2 Environmental conditions in Bedroom 2 for 16th – 24th April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 767 | 2,226 | 308 | 20.6 | 25.4 | 18.9 | 1.09 | 1.60 | 0.81 | 44.9 | 63.4 | 36.1 |

Table 19.3 Environmental conditions in Kitchen for 16th – 24th April 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,637 | 5,000 | 430 | 20.3 | 34.9 | 17.4 | 1.23 | 1.73 | 0.88 | 51.6 | 65.0 | 26.4 |

With regard to the instrument maximum of 5,000 ppm $CO_2$ in the kitchen and the high temperature of almost 35$^oC$, it is possible that the former was due to 'early-hours partying' as suggested above, while the latter was an evening cooking surge. In any event such high values suggest that the kitchen was not always freely ventilated with open windows. By comparison, although conditions in the living room are moderate (Table 19.4), the $CO_2$ maximum is more than twice the recommended 1,000 ppm upper limit, this also occurring in the 'early hours'.

Table 19.4 Environmental conditions in Living room for 16th – 24th April 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 906 | 2,127 | 441 | 20.8 | 24.4 | 14.2 | 1.09 | 1.49 | 0.75 | 44.4 | 57.3 | 34.2 |

As indicated in the first paragraph, the mould spore count is again relatively high (although nowhere near the levels of Case Study 18 above) – living room: 1,305, hall: 1,185, kitchen 1,700, bathroom: 1,045, bedroom 1: 1,115, bedroom 2: 1,205 CFU/$m^3$. Aspergillus, Cladosporium and Penicillium are as usual all present, but the overall list of mould species is relatively short. Pursuing the notion of an association with presence of passive drying, and comparing with Case Study 18, one should acknowledge that the role of the communal drying space may be relevant. Since fungal growth can only occur where moisture is present, it may follow that the more moisture released by passive drying (i.e. the greater the quantity of passive drying in any given dwelling), the greater the quantity of fungal spores (colony forming units); this regardless of whether the release of moisture stresses the environment in terms of excessive VP or RH values.

LOW WASHING, ALL PASSIVE DRYING, HEATING TO ASSIST DRYING; SPRING MONITORING, FLAT IN TOWER BLOCK, 1970S 'NO-FINES' SEMI-HEAVY CONSTRUCTION, DRY-LINED INTERNALLY

Case study 20: This is a 2-person plus infant household in another 3-apartment flat in the same high-rise tower in the Townhead area of Glasgow as Case Study 19 above. Unfortunately both the diary and the dataset of recorded readings are incomplete – only one wash was noted in the diary a week after the instruments were installed, and no power consumption was collected for the washing machine while used. However, there was enough information to know that the regime for drying was similar to that for Case Study 19. Again there is some washing by hand in the bathroom, and portable airers are used in various rooms – kitchen acknowledged in diary, but also living room, bathroom and bedroom mentioned in questionnaire, as well as one of the bedrooms for ironing roughly half of the washing. In this case, both diary and questionnaire indicate that heating is turned up to assist the drying process and that the portable drying devices are positioned close to radiators. The questionnaire also informs that windows are only occasionally opened. All this conveys a 'recipé' for a significant moisture and/or energy penalty, especially in winter. Unfortunately, given the time of year and only one acknowledged washing, no specific impact can be attributed to this activity. However, the mould spore count is similar to that for Case Study 19, with the exception that the second bedroom has a very high reading.

The washing machine in this case was a Beco WM5 100W, with an A-rating for energy and washing, but C for spin at 1,000 ppm. The normal wash temperature was indicated as 30$^oC$, and the manufacturers indicate a wash-time of 150 minutes for a full load. The steam iron is a 1.6kW Frigidaire (FCL8883), which is estimated to use some 0.55 kWh per hour of use. Owing to paucity of further information, annual extrapolations are not attempted in this case.

The data, with the exception of the washing machine's power use, was again collected for the first eight days, and provides some useful insights despite there being no specific laundering events evident – see Tables 20.1-20.4 below.

Table 20.1 Environmental conditions in Bedroom 1 for 10$^{th}$ – 18$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,340 | 4,458 | 387 | 17.6 | 19.6 | 16.4 | 1.20 | 1.62 | 0.92 | 59.4 | 75.7 | 47.3 |

It is immediately apparent that air quality is not good. The 4,458 ppm $CO_2$ maximum occurs at 06.59 on the 12$^{th}$ April, with corresponding temperature 18.6$^oC$, VP 1.6 kPa and RH 74.9%. It is quite possible that both parents and child were occupying the room at this time as the corresponding $CO_2$ reading in bedroom 2 at this time is only 414 ppm. However, bedroom 2's maximum of 1,505 ppm later the same day at 16.54, suggests the child's afternoon sleep.

Table 20.2 Environmental conditions in Bedroom 2 for 10$^{th}$ – 18$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 456 | 1,505 | 375 | 16.9 | 18.3 | 15.3 | 0.90 | 1.08 | 0.61 | 46.7 | 55.8 | 32.8 |

Table 20.3 Environmental conditions in Kitchen for 10$^{th}$ – 18$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 929 | 4,415 | 465 | 18.0 | 20.7 | 17.1 | 1.05 | 1.86 | 0.87 | 50.7 | 86.3 | 37.5 |

The 12$^{th}$ April is also the day for maxima in the kitchen. The $CO_2$ value of 4,415 occurs in the afternoon at 16.31 when the temperature is a reasonable 20.5$^oC$, but the humidity is high at 71.5% RH and 1.72 kPa. The RH maximum of 86.3% occurs in the morning of the 12$^{th}$ at 08.21 when the temperature is somewhat lower at 18.7$^oC$, the VP reaches 1.86 kPa, and $CO_2$ is already above the normal limit at 1,146 ppm. With such values, it is not surprising that there was mould growth on the kitchen walls. The 12th April is also a 'bad air day' for the living room, with the maximum $CO_2$ and VP coinciding at 16.24 with the temperature at 23.3°C and RH at 70.3% towards the end of a sunny spring afternoon with ambient VP less than 1.0 kPa. In other words, the poor and moist air quality is due to the actions of the occupants rather than ambient influence. And this is not a brief surge. The $CO_2$ is above 4,000 ppm from 15.53 until 17.03, while the level is above 1,000 ppm from the morning at 11.15 until the early hours of the following morning at 04.36. It appears that there may have been some sort of social gathering on that particular day, as the overall average $CO_2$ is just below the 1,000 ppm mark. However, the potential for passive drying to exacerbate such high moisture levels in conjunction with poor air quality is clearly present, especially in winter when the tendency will be to open windows even more sparingly.

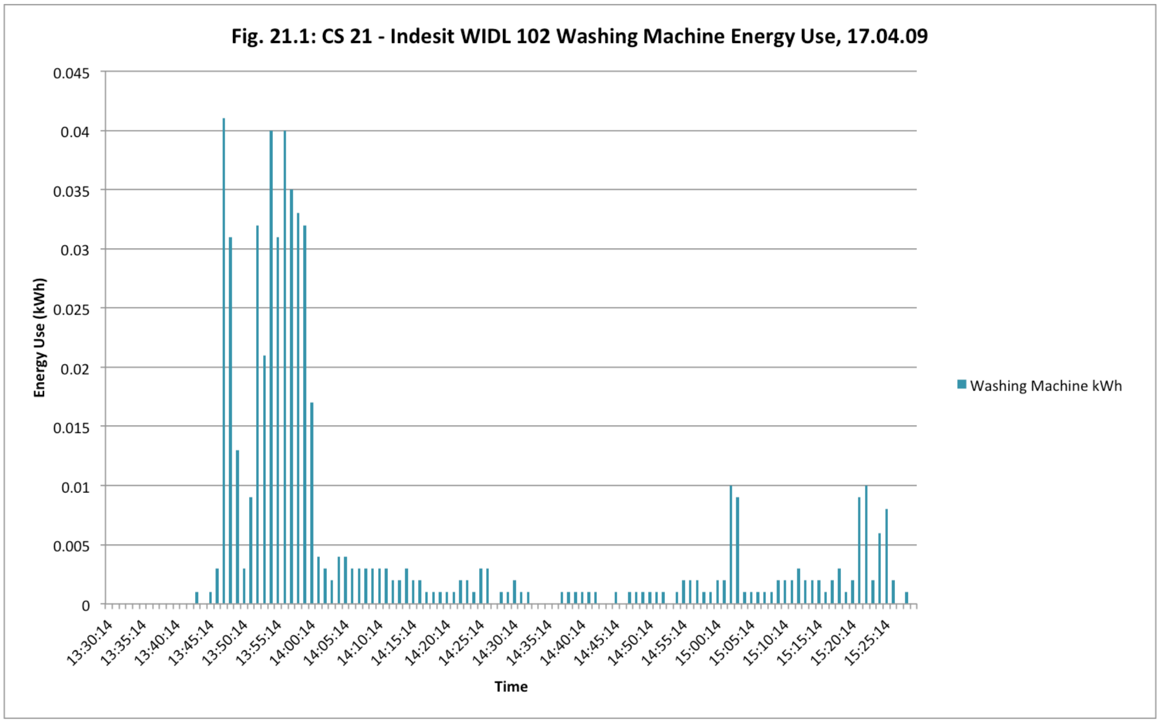
Table 20.4 Environmental conditions in Living room for 10th – 18th April 2009

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 926 | 4,983 | 450 | 19.8 | 23.4 | 18.1 | 1.14 | 2.01 | 0.92 | 49.2 | 78.8 | 39.7 |

Finally, as indicated above, the mould spore count is again relatively high and similar in many spaces to Case Study 19 (in parenthesis) on the same floor of the same block – living room: 1,125 (1,305), hall: 1,275 (1,185), kitchen 1,110 (1,700), bathroom: 1,020 (1,045), bedroom 1: 1,070 (1,115), bedroom 2: 3,055 (1,205) CFU/$m^3$. The last value for Case Study 20 is of interest since it is evident from $CO_2$ levels that the second bedroom is seldom used for overnight sleeping by the infant. However, it might well be used for ironing, as well as passive drying, and although this is partly conjectural (no particular bedroom specified for these activities), it might help to explain the high spore count. All in all, the overall count is commensurate with the theory of passive drying being associated with relatively high numbers of CFUs. Here, Aspergillus, Cladosporium and Penicillium are once again all present, and the overall list of mould species is longer than for Case Study 19.

MODERATE WASHING, ALL PASSIVE DRYING, HEATING TO ASSIST DRYING; SPRING MONITORING, FLAT IN TOWER BLOCK, 1970S 'NO-FINES' SEMI-HEAVY CONSTRUCTION, DRY-LINED INTERNALLY

Case study 21: This is a family of four, parents with two young children, living in the same type of 2-bedroom, 3-apartment flat as the previous two case studies, this time on the 16th floor of another tower in the Townhead area. Also the monitoring period is similar and much the same means of passive drying is adopted. A difference here is that the family own a washer/dryer, but during the monitored period do not appear to have used the drying programme. Again, although there is access available to a shared drying space on their landing, they seem to prefer drying within their own flat. Although windows are opened regularly in all main spaces, it appears that some heating was used (e.g. specific note of additional electric bar appliance used in living room on 19th April, and note in questionnaire conforms panel heater in second bedroom). The mould spore readings are high in all main rooms except Bedroom 1, which is at a moderate level.




The washing machine in this case was an Indesit WIDL 102, which has an integral dryer function. It has an A-rating for energy, a B for washing, and C for spin at 1,000 ppm. The normal wash temperature was indicated as 60$^{o}$C, which the manufacturers indicate should consume 0.95 kWh for a full load (washing only). There are some mixed messages regarding the use of the dryer cycle. Line 137 of the questionnaire indicates a 'no' to its use, while line 290 indicates 30-60 minute cycles were used. In any event, there is no evidence of its use during the monitored period, either from recorded power use, or from the diary notes. Hence no allowance for this is made for projected annual use. The average measured washing machine consumption over 5 cycles in eight days is 0.76 kWh/cycle, with a total of 3.8 kWh or 0.95 kWh/person. This extrapolates to 43 kWh/person over a year or 172 kWh for the household, and is 0.49 kWh for each hour of use. Fig. 21.1 shows a third fine-grained profile of a washing cycle, this time on the 17th April for 1 hour 40 minutes, with a more pronounced dip during the initial heating period, consuming a rather modest 0.56 kWh, and with the normal temperature stated as 60$^{o}$C.

The questionnaire also tells us that the portable airer is used in the living room, occasionally near heating appliances, but that these are not turned up to assist drying. In the diary for the monitored period, the passive drying is said to occur in a bedroom, assumed from measured data to be Bedroom 2 (see below). The questionnaire also tells us that windows are always open when drying, which means there will be a significant energy penalty while heating is used. On the other hand, the strategy acts as a pragmatic brake on excessive humidity levels.

The steam iron is a 1.8 kW Phillips Mistral (GC2220), which is estimated to use some 0.56 kWh per hour of use. Although the questionnaire indicates that half of the washing is ironed, there is only one day during the two weeks where the diary acknowledges that a half washing load was ironed. Assuming one hour every two weeks, annual consumption would be under 15 kWh.

In Tables 21.1–21.4 below two high maxima for RH are evident, both occurring in early afternoon of the 17$^{th}$ April. This is dry spring day when two full washes occurred, the first from 09.40-11.14 and the second from 13.43-15.28. It is tenable that the high RH of 74.5% Table 21.2 for Bedroom 2 is associated with the drying of the first of these washes. On the other hand similar surges occur on each of the other days at much the same time. It is perhaps more likely that at least some of the effect is due to a rest period for the two year old infant. There is correspondence between lifts in $CO_2$ on each day along with the moisture level, although not particularly so on the 17$^{th}$ - 521 ppm when RH is 74.5%, VP 1.46 kPa and temperature 17.2$^{o}$C. The other possibility is that at least some of the moisture in the bedroom has migrated from the kitchen, Table 21.3, which peaks at 95.4% at 14.22 on the 17$^{th}$ – this coinciding with 3.0 kPa, 825 ppm and 24.9$^{o}$C.

Table 21.1 Environmental conditions in Bedroom 1 for 9$^{th}$ – 17$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^{o}$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 640 | 1,326 | 371 | 20.5 | 27.1 | 18.3 | 1.02 | 1.34 | 0.71 | 47.4 | 62.9 | 28.7 |

Table 21.2 Environmental conditions in Bedroom 2 for 9$^{th}$ – 17$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^{o}$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 523 | 1,152 | 360 | 18.1 | 21.5 | 15.1 | 1.03 | 1.49 | 0.64 | 49.4 | 74.5 | 31.3 |

Table 21.3 Environmental conditions in Kitchen for 9$^{th}$ – 17$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^{o}$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 818 | 1,610 | 448 | 22.2 | 30.6 | 16.3 | 1.18 | 3.00 | 0.68 | 43.8 | 95.4 | 29.3 |

Overall, air quality is significantly better than that of Case Study 20, but the maximum in the living room, Table 21.4, is still twice the normal upper limit that coincides with 8 l/s fresh air per person. Although windows are open when drying, ambient vapour pressure during fine spring weather is typically low and moisture is evidently generated from within by domestic activity.

Table 21.4 Environmental conditions in Living room for 9$^{th}$ – 17$^{th}$ April 2009

| $CO_2$ (ppm) | | | Temperature ($^{o}$C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,092 | 2,121 | 466 | 23.0 | 28.3 | 19.9 | 1.18 | 1.66 | 0.89 | 41.9 | 62.1 | 29.4 |

Similar to Case Study 20, the mould spore count is again relatively high, in particular in the living room, kitchen and second bedroom. This time for comparison, Case Study 20 is shown in parenthesis – living room: 1,565 (1,125), hall: 995 (1,275), kitchen 1,260 (1,110), bathroom: 780 (1,020), bedroom 1: 665 (1,070), bedroom 2: 1,245 (3,055) CFU/m$^3$. The last value for Case Study 21 is of similar interest to that of 20, since environmental parameters are on the whole very reasonable. However, the data suggests that it is the children's bedroom that is used for passive drying, as the moisture values are consistently somewhat greater than for the parents' bedroom. Again, passive drying might help to explain the high spore count, bearing in mind that the questionnaire also cites the living room for this purpose. Here, the range and number of species is similar to previous case studies such as that of 20 above, but Cladosporium is absent.

LOW-FREQUENCY WASHING, ALL PASSIVE DRYING, OPEN WINDOWS TO ASSIST DRYING; WINTER MONITORING, FLAT IN TENEMENT, MODERN BRICK-CLAD CONSTRUCTION, DRY-LINED INTERNALLY

Case study 22: This is a household of two relatively young adults, who each use a bedroom in a 3-apartment modern pastiche tenement (circa late 1990s). The monitoring period is from the 6th to 21st January 2010, but data for the two bedrooms is only from the 6th to 9th. The diary only recorded two wash loads during the 2-week period, both on the same day, but the questionnaire indicates that a certain amount of hand washing occurs in the bathroom. The main washing appears to be dried on racks or airers on or close to the living room radiator, but these are apparently not turned up to assist drying. There is also a retractable 'pulley' in the bathroom that one may assume is used for the hand-washed items. The questionnaire indicates that the living room windows are always opened while drying takes place, but not at other times, and the recorded data supports this contention. The air quality in all main rooms is regularly very poor, and the moisture levels excessive in the living room and kitchen. However, this seems to coincide with intensity of occupation with closed windows, rather than from the passive drying – see below. The spore count is also high, generally well above the 1,000 CFU/$m^3$ level,

The washing machine in this case is a Whirlpool AWM 336, which is B-rated for energy and spin, and only C-rated for washing. 40$^oC$ is the normal wash setting, and the consumption total for the 2-weeks is recorded as 2.682 kWh for the two cycles – i.e. 1.31 kWh/cycle, which, if typical, would extrapolate to circa 66 kWh annually or 33 kWh/person. However, in this case the energy is recorded as a single total, rather than at I-minute or 10-minute intervals as other case studies. Therefore, it may not be reliable, and it is not possible to give a figure per hour of running time. Passive drying is reported as taking up to 48 hours, and the questionnaire states "makes the room feel damp". Regardless of this perception, with windows open, the drying process is bound to add to the heating consumption in cold weather. The questionnaire reports that heating is used for 6-8 months, with energy bills averaging from £30-39 weekly.

The 1.2 kW Tesco IR06 steam iron is also used in the living room, reportedly for about half of the total wash, and a note to this effect is included in the diary for the double-cycle day of washing on the 13th January. Over the year, this might total in the order of only about 14 kWh (7 kWh/person) if the relatively infrequent level of ironing were consistent. When it does occur, it will of course also add humidity. However, all this 'damp' activity appears to be well masked by the open window. The mean temperature in the 24 hours from midday on the 13th January is 20.8C, the RH 41% and VP 1.01 kPa. The maximum moisture values in this 24-hour slot are 47% RH and 1.2 kPa, which are well below the maxima in Table 22.4 below, and also that for the kitchen, Table 22.3, and comfortably below those for the two bedrooms, Tables 22.1 and 22.2. Therefore we may conclude that the environmental impact of passive drying lies more with energy consumption than with stressing the key moisture parameters, which in turn relate to air quality.

Table 22.1 Environmental conditions in Bedroom 1 for 6th – 9th January 2010

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,883 | 3,208 | 1,200 | 20.6 | 23.3 | 16.9 | 1.00 | 1.28 | 0.81 | 41.5 | 49.5 | 33.0 |

Table 22.2 Environmental conditions in Bedroom 2 for 6th – 9th January 2010

| $CO_2$ (ppm) | | | Temperature ($^oC$) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,875 | 3,269 | 1,198 | 20.2 | 22.0 | 16.5 | 1.02 | 1.29 | 0.81 | 43.2 | 53.7 | 35.4 |

Within the relatively short time-frame in the case of the two bedrooms, it is evident that poor air quality is the issue, rather than excessive humidity. The $CO_2$ averages are both more than 80% above the upper limit.

Table 22.3 Environmental conditions in Kitchen for 6th – 21st January 2010

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,391 | 4,550 | 517 | 21.3 | 32.2 | 16.8 | 1.07 | 2.95 | 0.75 | 41.6 | 75.8 | 23.2 |

In the kitchen, although there are spikes of high humidity and temperature that one might expect from cooking activity, it is the poor air quality that is again more concerning. However, the two issues are related. On the 6th January at 20.53, the maximum VP of 2.95 kPa coincides with RH of 67.2%, a temperature of 30.6°C and 3,760 ppm $CO_2$. This in turn coincides with cold and relatively dry ambient conditions – temperature –1.8ºC, RH 74% and VP circa 0.4 kPa. Similarly in the living room the maximum RH of 83.2% occurs on 20th January at 20.23, when the temperature is 24.3°C, VP 2.53 kPa and $CO_2$ 3,762 ppm. Again ambient conditions at this time are cold, but quite dry in terms of absolute moisture – temperature 0.1ºC, RH 89% and VP circa 0.55 kPa. It is apparently the presence of the occupants in a relatively airtight, heated environment that tends to generate such tropical, fuggy conditions.

Table 22.4 Environmental conditions in Living room for 6th – 21st January 2010

| $CO_2$ (ppm) | | | Temperature (°C) | | | Vapour Pressure (kPa) | | | Relative Humidity (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mean | max | min | mean | max | min | mean | max | min | mean | max | min |
| 1,545 | 4,374 | 757 | 20.6 | 26.6 | 16.4 | 1.18 | 1.66 | 0.89 | 41.9 | 62.1 | 29.4 |

Once again, in this household that passively dries washing, we have high spore count. Again, for comparison, the previous Case Study 21 is shown in parenthesis – living room: 1,265 (1,565), hall: 1,312 (995), kitchen: 1,245 (1,260), bathroom: 975 (780), bedroom 1: 1,290 (665), bedroom 2: 1,245 (1,245) CFU/$m^3$. Case Study 21 had better air quality than that of 22, but also had some high moisture readings. The question is can moisture in general stimulate high CFU levels, with or without passive drying? Alternatively, is there something specific in the nature of damp material in a room over relatively lengthy time frames that tend to be more potent in this regard? For example, Case Study 3 has similar construction to that of 22, and also has fairly high moisture levels; but it opens windows more freely, even though also inside the heating season, and importantly makes significant use of a tumble dryer in conjunction with passive drying. And 19 has a fairly low CFU count – living room: 550, hall: 630, kitchen: 510, bathroom: 540, bedroom 1: 595, bedroom 2: 540 CFU/$m^3$. More comparative analysis is required in this regard.

PART CSUMMARY TABLES FOR 22 CASE STUDIES AND OBSERVATIONS

SUMMARY TABLE 1.a: Air Quality and Moisture – qualitative relativities

| CS | Season | TD | OD | ID | CFU | M | AQ-L | AQ-B | VP-L | VP-B |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (e) | summer | ✔ | | | l-mod. | | good | good | high | high |
| 2 (g) | winter | | | ✔ | h-mod. | B | mod. | poor | high | high |
| 3 (g) | autumn | ✔✔ | | ✔ | l-mod. | K | good | mod. | high | high |
| 4 (e) | spring | ✔ | ✔ | ✔ | mod. | Ba | poor | poor | high | high. |
| 5 (e) | autumn | ✔ | | | low | B | mod. | poor | high | high |
| 6 (e) | autumn | ✔* | | | high | B | poor | poor | high | high |
| 7 (e) | spring | | | ✔ | high | B/Ba/K | poor | poor | high | high |
| 8 (g) | autumn | ✔✔ | | ✔ | l-mod. | K | good | poor | high | high |
| 9 (g) | summer | | | ✔ | high | Ba | good | good | high | high |
| 10 (e) | summer | ✔✔ | | ✔ | l-mod. | B | good | mod. | mod. | mod. |
| 11 (e) | summer | ✔✔ | | ✔ | h-mod. | B/Ba | good | poor | high | high |
| 12 (e) | summer | ✔ | | ✔ | h-mod. | | good | good | mod. | mod. |
| 13 (e) | summer | ✔ | | | l-mod. | | good | good | high | high |
| 14 (g) | summer | | | ✔ | h-mod. | | mod. | good | mod. | mod |
| 15 (g) | autumn | | ✔✔ | ✔ | l-mod. | | good | good | high | high |
| 16 (g) | spring | | ✔ | | l-mod. | B/Ba | poor | no d. | high | no d. |
| 17 (e) | spring | | ✔✔ | ✔ | h-mod. | | good | good | mod. | mod |
| 18 (e) | spring | | | ✔ | high | | good | good | low | mod |
| 19 (e) | spring | | | ✔ | high | | mod. | mod. | mod. | high |
| 20 (e) | spring | | | ✔ | high | K | poor | poor | high | high |
| 21 (e) | spring | | | ✔ | high | | poor | good | high | mod |
| 22 (g) | winter | | | ✔ | high | | poor | poor | high | low |

**Legend:**

CS = Case Study number, the sequence 1-22 of analysis of the 22 volunteers from the 100 households initially surveyed. This order was adopted to facilitate a coherent line of narrative research enquiry, and it is out of chronological sequence relative to the surveys (and the original numbering given at the time of data collection, which is used in the Chapter excerpt appended). Electric (e) and gas (g) heating in parenthesis after CS number.
TD = tumble drier, including where in laundrette or other communal facility; where double-ticked indicates the dominant strategy where there more than one drying technique is used.
OD = outside drying, whether using communal or private space.
ID = internal drying within the home, frequently employing more than one room or space.
CFU = colony forming unit (mould spores), expressed per $m^3$ from analysis of air samples; where high = > 1,000, h-mod/ l-mod. (high/low-moderate) 700-1,000/500-700, low <500.
M = mould – its visible presence at time of survey; B: bedroom, Ba: bathroom, K: kitchen.
AQ-L/AQ-B = air quality in living room and bedrooms; where good = $CO_2$ mean >1,000 and max. <2,000 ppm; mod. = mean <1,000, max. >2,000; poor = mean >1,000, max. >2,000.
VP-L/VP-B = vapour pressure in living room and bedrooms; where high = max. >1.6 kPa; mod. = mean <1.2 kPa, but max. >1.3 kPa; low = max < 1.2 kPa; noting 1.13 Kpa or 7 g/kg mixing ratio is dust mite threshold (Platts-Mills & De Weck), and 1.6 kPa or circa 10 g/kg gives RH levels above 70% for temperatures <19.7$^{o}$C.
no d. = no data available, in relation to AQ and VP above.

SUMMARY TABLE I.b: Air Quality and Moisture – numerical maxima

| CS | Season | CFU max /m$^3$ | M | AQ-L max ppm | AQ-B max ppm | VP-L max kPa | VP-B max kPa | RH-L max % | RH-B max % | RH-K max % |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (e) | summer | 710 | | 1,013 | 1,108 | 1.63 | 1.80 | 61.2 | 72.4 | 61.5 |
| 2 (g) | winter | 1,025 | B | 2,159 | 4,090 | 1.66 | 2.91 | 60.8 | 84.8 | 77.6 |
| 3 (g) | autumn | 595 | K | 1,402 | 2,124 | 1.74 | 1.88 | 67.1 | 75.9 | 77.1 |
| 4 (e) | spring | 865 | Ba | 2,058 | 4,281 | 1.79 | 1.63 | 67.9 | 73.8 | 84.5 |
| 5 (e) | autumn | 585 | B | 2,104 | 4,394 | 1.95 | 1.96 | 86.4 | 75.3 | 91.9 |
| 6 (e) | autumn | 1,610 | B | 5,000 | 5,000 | 2.00 | 2.24 | 85.6 | 93.9 | 91.7 |
| 7 (e) | spring | 2,875 | B/Ba/K | 4,247 | 4,165 | 1.90 | 1.72 | 72.6 | 63.7 | 95.7 |
| 8 (g) | autumn | 680 | K | 1,586 | 2,994 | 1.75 | 1.91 | 76.5 | 91.4 | 87.7 |
| 9 (g) | summer | 1,655 | Ba | 1,065 | 1,734 | 1.69 | 1.75 | 67.2 | 72.9 | 83.0 |
| 10 (e) | summer | 678 | B | 1,410 | 2,392 | 1.49 | 1.34 | 68.7 | 70.7 | 71.8 |
| 11 (e) | summer | 900 | B/Ba | 1,896 | 3,104 | 1.90 | 2.11 | 75.7 | 80.0 | 84.1 |
| 12 (e) | summer | 945 | | 964 | 1.174 | 1.49 | 1.50 | 83.1 | 62.0 | 68.7 |
| 13 (e) | summer | 570 | | 1,857 | 1,653 | 1.61 | 1.62 | 62.5 | 59.6 | 66.6 |
| 14 (g) | summer | 710 | | 2,341 | 1,089 | 1.51 | 1.57 | 69.8 | 68.9 | 81.5 |
| 15 (g) | autumn | 630 | | 1,244 | 1,878 | 1.61 | 1.75 | 76.4 | 85.6 | 82.7 |
| 16 (g) | spring | 770 | B/Ba | 4,815 | no d. | 2.20 | no d. | 65.5 | no d. | 85.8 |
| 17 (e) | spring | 1,005 | | 1,052 | 1,671 | 1.31 | 1.32 | 42.4 | 80.0 | 63.2 |
| 18 (e) | spring | 3,135 | | 1,559 | 801 | 1.22 | 1.50 | 54.5 | 77.2 | 76.0 |
| 19 (e) | spring | 1,700 | | 2,127 | 2,226 | 1.49 | 2.98 | 57.3 | 96.5 | 65.0 |
| 20 (e) | spring | 3,055 | K | 4,983 | 4,458 | 2.01 | 1.62 | 78.8 | 75.7 | 86.3 |
| 21 (e) | spring | 1,565 | | 2,121 | 1,326 | 1.66 | 1.49 | 62.1 | 74.5 | 95.4 |
| 22 (g) | winter | 1,312 | | 4,374 | 3,280 | 2.54 | 1.29 | 83.2 | 53.7 | 75.8 |

## Legend:

CFU max/m$^3$ = maximum number of 'colony forming units'* found in each of 5-6 spaces.
AQ-L/AQ-B max ppm = maximum $CO_2$ in living room and bedroom(s); noting that 5,000 ppm is the maximum instrument value; and where two bedrooms, highest value used.
VP-L/VP-B max kPa = maximum vapour pressure in living room and bedroom(s).
RH-L/RH-B/RH-K max % = maximum RH% in living room, bedroom(s) & kitchen.

NB: the above Summary Table 1.b and 1.c (over) to be read in conjunction with Summary Table 1.a; the aim of 1.b to expand on insights into relationships between moisture peaks (VP & RH) and, respectively, CFUs and air quality ($CO_2$), already partly evident from 1.a. Note, however, that the CFU maxima represent the highest reading among the spaces sampled in any one home on the day that monitoring commenced. On the other hand, all other maxima occur over the entire period of monitoring. Hence relativity between CFU/m$^3$ and other variables may be misleading, and the same applies to means on Summary Table 1.c over.

*CFU/m$^3$ recovered from MEA (malt extract sugar) given in table; PDA (potato dextrose agar) also used, noting that the mean maxima for PDA was 1.265% higher than for MEA. Note also that a limiting value of 500 CFU/m$^3$ is used in Finland for indoor air in urban areas in winter (Ministry of Social Affairs and Health, 2003 (Finland); cited in 'WHO guidelines for indoor air quality: dampness and mould', 2009) and backed by ealier Danish research (Reponen et al, 1991).

**SUMMARY TABLE I.c: Air Quality and Moisture – numerical means (cf. Table 1.b)**

| CS | Season | CFU mean /m$^3$ | M | AQ-L mean ppm | AQ-B mean ppm | VP-L mean kPa | VP-B mean kPa | RH-L mean % | RH-B mean % | RH-K mean % |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (e) | summer | 644 | | 691 | 719 | 1.18 | 1.21 | 43.0 | 45.8 | 44.2 |
| 2 (g) | winter | 914 | B | 932 | 991 | 0.94 | 1.13 | 39.0 | 45.5 | 48.1 |
| 3 (g) | autumn | 561 | K | 715 | 747 | 1.34 | 1.32 | 52.3 | 60.0 | 57.1 |
| 4 (e) | spring | 751 | Ba | 1,097 | 1,385 | 1.22 | 1.31 | 44.7 | 58.0 | 58.0 |
| 5 (e) | autumn | 466 | B | 833 | 2,232 | 1.27 | 1.47 | 62.5 | 61.4 | 59.6 |
| 6 (e) | autumn | 1,013 | B | 2,390 | 1,824 | 1.59 | 1.58 | 74.6 | 71.9 | 75.4 |
| 7 (e) | spring | 2,186 | B/Ba/K | 965 | 1,701 | 1.42 | 1.35 | 55.8 | 51.5 | 60.6 |
| 8 (g) | autumn | 587 | K | 836 | 1,134 | 1.35 | 1.40 | 61.3 | 75.8 | 71.2 |
| 9 (g) | summer | 1,264 | Ba | 610 | 669 | 1.24 | 1.26 | 54.2 | 56.3 | 54.0 |
| 10 (e) | summer | 575 | B | 628 | 910 | 1.18 | 1.15 | 50.7 | 54.2 | 49.8 |
| 11 (e) | summer | 715 | B/Ba | 911 | 1,592 | 1.48 | 1.66 | 61.1 | 68.0 | 60.3 |
| 12 (e) | summer | 855 | | 488 | 601 | 1.31 | 1.14 | 56.9 | 60.8 | 51.1 |
| 13 (e) | summer | 526 | | 972 | 850 | 1.27 | 1.25 | 47.7 | 45.0 | 48.0 |
| 14 (g) | summer | 687 | | 709 | 699 | 1.17 | 1.19 | 56.9 | 53.1 | 48.6 |
| 15 (g) | autumn | 562 | | 785 | 996 | 1.28 | 1.40 | 68.5 | 71.8 | 70.5 |
| 16 (g) | spring | 685 | B/Ba | 1,478 | no d. | 1.26 | no d. | 47.3 | no d. | 48.7 |
| 17 (e) | spring | 752 | | 531 | 828 | 0.92 | 1.01 | 33.9 | 56.9 | 40.3 |
| 18 (e) | spring | 2,625 | | 586 | 561 | 0.91 | 0.93 | 40.3 | 50.9 | 48.8 |
| 19 (e) | spring | 1,259 | | 906 | 767 | 1.09 | 1.10 | 44.4 | 53.2 | 51.6 |
| 20 (e) | spring | 1,443 | K | 926 | 1,340 | 1.14 | 1.20 | 49.2 | 59.4 | 50.7 |
| 21 (e) | spring | 1,077 | | 1,092 | 640 | 1.18 | 1.03 | 41.9 | 49.4 | 43.8 |
| 22 (g) | winter | 1,222 | | 1,545 | 1,883 | 1.06 | 1.02 | 43.5 | 43.2 | 41.6 |

**Legend:**

CFU mean/m$^3$ = mean number of 'colony forming units' found by MEA in each of 5-6 spaces; the overall mean average of 849 being 1.26% more than that found by PDA (838)
AQ-L/AQ-B mean ppm = mean $CO_2$ in living room and bedroom(s); noting that 5,000 ppm is the maximum instrument value; and where two bedrooms, highest value used.
VP-L/VP-B mean kPa = mean vapour pressure in living room and bedroom(s).
RH-L/RH-B/RH-K mean % = mean RH% in living room, bedroom(s) & kitchen.
NB: the above Summary Table 1.c and 1.b (previous page) to be read in conjunction with Summary Table 1.a. The aim of 1.d below is to further explore seasonal differences between living/bedroom average moisture (RH) and air quality ($CO_2$), partly evident from 1.a to 1.c.

**SUMMARY TABLE I.d: Air Quality and Moisture – spot data averages in sample of 100**

| | AQ$^{Winter}$ | AQ$^{Spring}$ | AQ$^{Summer}$ | AQ$^{Autumn}$ | RH$^{Winter}$ | RH$^{Spring}$ | RH$^{Summer}$ | RH$^{Autumn}$ |
|---|---|---|---|---|---|---|---|---|
| Sample | 34$^{Dec-Feb}$ | 26$^{Mar-May}$ | 4$^{June-Aug}$ | 36$^{Sep-Nov}$ | 34$^{Dec-Feb}$ | 26$^{Mar-May}$ | 4$^{June-Aug}$ | 36$^{Sep-Nov}$ |
| Mean | 1,199 | 1,328 | 1,269 | 1,255(ppm) | 51.7 | 44.4 | 54.7 | 57.6(%) |
| Max | 2,847 | 1,675 | 1,607 | 1,630 | 74.1 | 66.8 | 55.4 | 76.9 |
| Min | 854 | 862 | 1,110 | 818 | 29.3 | 31.0 | 41.3 | 38.7 |

SUMMARY TABLE I.e: Air Quality and Moisture – 1st day numerical maxima (cf. 1.b)

| CS | Season | CFU max /$m^3$ | M | AQ-L max ppm | AQ-B max ppm | VP-L max kPa | VP-B max kPa | RH-L max % | RH-B max % | RH-K max % |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (e) | summer | 710 | | 937 | 867 | 0.95 | 0.95 | 34.6 | 35.8 | 36.5 |
| 2 (g) | winter | 1,025 | B | 1,467 | 4,031 | 0.87 | 2.50 | 39.3 | 84.8 | 51.6 |
| 3 (g) | autumn | 595 | K | 1,076 | 1,246 | 1.51 | 1.61 | 59.8 | 68.2 | 61.6 |
| 4 (e) | spring | 865 | Ba | 1,481 | 1,419 | 1.33 | 1.40 | 47.3 | 59.0 | 69.7 |
| 5 (e) | autumn | 585 | B | 1,178 | 3,178 | 1.17 | 1.37 | 57.2 | 57.3 | 53.3 |
| 6 (e) | autumn | 1,610 | B | 3,735 | 2,783 | 1.70 | 1.59 | 72.8 | 71.7 | 76.4 |
| 7 (e) | spring | 2,875 | B/Ba/K | 1,256 | 1,189 | 1.77 | 1.50 | 65.4 | 54.8 | 62.7 |
| 8 (g) | autumn | 680 | K | 1,342 | 1,350 | 1.35 | 1.32 | 56.6 | 70.7 | 67.6 |
| 9 (g) | summer | 1,655 | Ba | 640 | 622 | 0.98 | 0.96 | 43.6 | 45.1 | 52.1 |
| 10 (e) | summer | 678 | B | 1,034 | 1,262 | 1.24 | 1.19 | 59.1 | 63.3 | 59.0 |
| 11 (e) | summer | 900 | B/Ba | 1,896 | 1,990 | 1.81 | 1.91 | 75.7 | 76.7 | 78.1 |
| 12 (e) | summer | 945 | | 543 | 781 | 1.05 | 1.07 | 59.0 | 53.5 | 49.8 |
| 13 (e) | summer | 570 | | 1,323 | 1,218 | 1.39 | 1.37 | 58.8 | 52.4 | 61.7 |
| 14 (g) | summer | 710 | | 1,183 | 882 | 1.30 | 1.31 | 60.6 | 58.8 | 64.3 |
| 15 (g) | autumn | 630 | | 1,120 | 1,006 | 1.34 | 1.67 | 72.9 | 78.8 | 76.7 |
| 16 (g) | spring | 770 | B/Ba | 2,180 | no d. | 1.62 | no d. | 53.8 | no d. | 62.0 |
| 17 (e) | spring | 1,005 | | 1,033 | 1,431 | 1.06 | 1.10 | 40.0 | 71.1 | 63.2 |
| 18 (e) | spring | 3,135 | | 996 | 725 | 1.14 | 1.07 | 48.2 | 59.8 | 57.9 |
| 19 (e) | spring | 1,700 | | 1,652 | 1,415 | 1.40 | 2.03 | 49.9 | 73.2 | 60.1 |
| 20 (e) | spring | 3,055 | K | 1,327 | 1,612 | 1.43 | 1.18 | 59.4 | 58.4 | 61.4 |
| 21 (e) | spring | 1,565 | | 1,509 | 993 | 1.42 | 1.36 | 49.8 | 62.9 | 75.5 |
| 22 (g) | winter | 1,312 | | 4,209 | 3,175 | 2.51 | 1.27 | 80.8 | 49.5 | 67.2 |

## Legend:

CFU max/$m^3$ = maximum number of 'colony forming units' found in each of 5-6 spaces.
AQ-L/AQ-B max ppm = maximum $CO_2$ in living room and bedroom(s); noting that 5,000 ppm is the maximum instrument value; and where two bedrooms, highest value used.
VP-L/VP-B max kPa = maximum vapour pressure in living room and bedroom(s).
RH-L/RH-B/RH-K max % = maximum RH% in living room, bedroom(s) & kitchen.

NB: the above Summary Table 1.e and 1.f (over) to be read in conjunction with Summary Tables 1.b and 1.c respectively. Since 1.e and 1.f represent maxima and means in turn for the balance of the day that the instrumentation was installed and air sampling took place (up till midnight), the relationship between air quality ($CO_2$), moisture (VP and RH) and fungal spores (CFU/$m^3$) has greater relevance than for Summary Tables 1.b and 1.c. Note also that while maxima in the part-day 'snapshot' time period (1.e) cannot by definition be greater than for the full monitoring period (1.b), the means (1.f) may move up or down relative to 1.c.

SUMMARY TABLE I.f: Air Quality and Moisture – 1st day numerical means (cf. 1.c & 1.e)

| CS | Season | CFU mean /m³ | M | AQ-L mean ppm | AQ-B mean ppm | VP-L mean kPa | VP-B mean kPa | RH-L mean % | RH-B mean % | RH-K mean % |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 (e) | summer | 644 | | 725 | 675 | 0.86 | 0.98 | 31.6 | 33.7 | 33.5 |
| 2 (g) | winter | 914 | B | 990 | 1,081 | 0.70 | 0.99 | 34.7 | 45.2 | 42.4 |
| 3 (g) | autumn | 561 | K | 800 | 755 | 1.36 | 1.27 | 52.5 | 56.8 | 57.8 |
| 4 (e) | spring | 751 | Ba | 1,180 | 1,077 | 1.27 | 1.31 | 45.0 | 56.4 | 59.1 |
| 5 (e) | autumn | 466 | B | 878 | 1,404 | 1.04 | 1.09 | 50.8 | 48.3 | 47.4 |
| 6 (e) | autumn | 1,013 | B | 3,087 | 2,072 | 1.63 | 1.42 | 70.5 | 66.6 | 74.2 |
| 7 (e) | spring | 2,186 | B/Ba/K | 1.014 | 938 | 1.58 | 1.43 | 62.6 | 53.8 | 60.9 |
| 8 (g) | autumn | 587 | K | 859 | 794 | 1.19 | 1.20 | 49.1 | 64.7 | 64.3 |
| 9 (g) | summer | 1,264 | Ba | 570 | 521 | 0.86 | 0.87 | 38.4 | 39.6 | 38.6 |
| 10 (e) | summer | 575 | B | 528 | 526 | 1.15 | 1.10 | 52.6 | 56.6 | 49.5 |
| 11 (e) | summer | 715 | B/Ba | 1,317 | 1,243 | 1.65 | 1.77 | 69.4 | 73.3 | 71.0 |
| 12 (e) | summer | 855 | | 459 | 555 | 0.96 | 0.98 | 50.2 | 46.3 | 48.5 |
| 13 (e) | summer | 526 | | 1,143 | 1,052 | 1.33 | 1.32 | 54.6 | 51.1 | 52.9 |
| 14 (g) | summer | 687 | | 631 | 646 | 1.14 | 1.18 | 54.3 | 54.3 | 51.2 |
| 15 (g) | autumn | 562 | | 991 | 896 | 1.44 | 1.52 | 70.0 | 72.2 | 72.1 |
| 16 (g) | spring | 685 | B/Ba | 1,491 | no d. | 1.39 | no d. | 47.4 | no d. | 51.0 |
| 17 (e) | spring | 752 | | 639 | 674 | 0.96 | 0.96 | 37.3 | 58.0 | 44.9 |
| 18 (e) | spring | 2,625 | | 602 | 540 | 1.00 | 1.01 | 41.5 | 56.9 | 52.7 |
| 19 (e) | spring | 1,259 | | 1,138 | 895 | 1.17 | 1.19 | 44.7 | 50.8 | 49.7 |
| 20 (e) | spring | 1,443 | K | 970 | 911 | 1.25 | 1.08 | 53.7 | 53.7 | 53.7 |
| 21 (e) | spring | 1,077 | | 1,006 | 604 | 1.27 | 1.19 | 44.5 | 53.2 | 47.0 |
| 22 (g) | winter | 1,222 | | 2,553 | 2,178 | 1.40 | 1.06 | 49.3 | 41.6 | 45.7 |

## Legend:

CFU mean/m$^3$ = mean number of ‘colony forming units‘ found in each of 5-6 spaces.
AQ-L/AQ-B mean ppm = mean $CO_2$ in living room and bedroom(s); noting that 5,000 ppm is the maximum instrument value; and where two bedrooms, highest value used.
VP-L/VP-B mean kPa = mean vapour pressure in living room and bedroom(s).
RH-L/RH-B/RH-K mean % = mean RH% in living room, bedroom(s) & kitchen.
NB: the above Summary Table 1.f and 1.e (previous page) to be read in conjunction with Summary Tables 1.b and 1.c respectively.

SUMMARY TABLE I.g: drying methods and spore concentrations – variables (see 4.0-5.0)

| CS | Season + win:o/s/m | CFU$^{all}$ /m$^3$ | CFU$^{liv/bed}$ /m$^3$ | floor c/l/t | plants ✔ or ✘ | heat e or g | floor level | fan$^{kit'n}$ ✔ or ✘ | fan$^{bath}$ ✔ or ✘ | Ind. Var. 1 - 4 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | summer: o | 639 | 652 | c | ✘ | e | 13th | ✔ | ✔ | 1 |
| 2 | winter: m | 902 | 968 | c | ✘ | g | grd | ✔ | ✔ | 3 |
| 3 | autumn: o | 560 | 559 | l | ✘ | g | 1st | ✔ | ✔ | 1 |
| 4 | spring: m | 761 | 799 | l | ✔ | e | grd+ | ✘ | ✘ | 4 |
| 5 | autumn: o | 565 | 529 | c | ✘ | e | 1st | ✔ | ✘ | 1 |
| 6 | autumn: m | 990* | 1,088* | c | ✘ | g | 1st | ✔ | ✔ | 1 |
| 7 | spring: s | 2,110 | 2,772 | l | ✘ | e | grd | ✘ | ✘ | 3 |
| 8 | autumn: s | 594 | 592 | t | ✔ | g | 2nd | ✔ | ✘ | 1 |
| 9 | summer: o | 1,251 | 1,303 | c | ✔ | g | 3rd | ✘ | ✘ | 3 |
| 10 | summer: o | 587 | 623 | l | ✘ | e | 14th | ✘ | ✔ | 1 |
| 11 | summer: m | 696 | 704 | c/t | ✘ | e | grd+ | ✘ | ✘ | 1 |
| 12 | summer: m | 855 | 878 | c | ✔ | e | 4th | ✔ | ✔ | 4 |
| 13 | summer: s | 526 | 548 | c | ✘ | e | 1st | ✘ | ✔ | 1 |
| 14 | summer: o | 687** | 700** | c | ✘ | g | 3rd | ✘ | ✔ | 3 |
| 15 | autumn: m | 612 | 552 | l | ✔ | g | 3rd | ✘ | ✘ | 2 |
| 16 | spring: o | 681 | 735 | c | ✘ | g | grd+ | ✘ | ✔ | 2 |
| 17 | spring: o | 752 | 778 | c | ✘ | e | 7th | ✔ | ✔ | 2 |
| 18 | spring: o | 2.625 | 2,658 | l | ✔ | e | 2nd | ✔ | ✔ | 3 |
| 19 | spring: m | 1,279 | 1,233 | c | ✔ | e | 4th | ✘ | ✔ | 3 |
| 20 | spring: s | 1,317 | 1,594 | l | ✘ | e | 4th | ✘ | ✔ | 3 |
| 21 | spring: o | 1,111 | 1,260 | l | ✘ | e | 16th | ✘ | ✔ | 3 |
| 22 | winter: s | 1,213 | 1,267 | c | ✘ | g | 3rd | ✔ | ✔ | 3 |

## Legend:

Season + win: o/s/m = relationship of window opening habits to survey season, whereby 'o' signifies frequent opening, 's' generally shut and 'm' moderate opening according to need.
CFU/m$^3$ = main dependent variable, 'colony forming units' found in living rooms, bedrooms (mean of two where applicable), kitchens, bathrooms and halls; abbreviated suffixes.
floor c/l/t = main floor finishes where initials c/l/t represent carpet, laminate and timber.
plants = presence ✔ or absence ✘ of house plants.
heat = space heating by either electrical 'e' or gas 'g'.
floor level = flat location where grd = ground floor, grd+ = ground+1st floor maisonette etc.
fan = presence ✔ or absence ✘ of mechanical extract fan in kitchens and bathrooms.
Ind. Var.= independent variable: drying methods, where 1 = tumble drying is the dominant or only method used, 2 = outside drying is the only or dominant method used (during monitoring); 3 = inside drying passively is only method or dominant method used, 4 = mixture of methods used.
* = an exception, where there is a tumble drier as the sole means of drying, but the CFU count is near or above 1,000; thought to be due to mean RH >70% and mean VP >1.5 kPa.
** = an exception – passive indoor drying together with very liberal summer window opening.

SUMMARY TABLES 1.a, 1.b, 1.c, 1.d, 1.e, 1.f and 1.g: Preliminary Observations

1.0 There are certain seasonal relativity characteristics between key variables that are evident from analysis of Tables 1.a, 1.b and 1.c for the 22 monitored case studies, all volunteers from 100 surveyed dwellings, with an overview of spot data in Table 1.d.

1.1 For example the respective living room and bedroom means of $CO_2$ step upwards with summer lowest (716 and 813 ppm), spring (948 and 1,032 ppm), autumn (1,058 and 1,286 ppm), and winter (1,239 and 1,437 ppm); with annual means closest to spring (971 and 1,099 ppm). One would of course expect summer to have low values in terms of the likelihood of occupants opening windows relatively frequently. By the same token, spring is a time of opening up after the long winter, while autumn tends to be a time of 'battening down the hatches' in expectation of worse to come in winter. What is also of interest is that in both spring and autumn the range of values is much greater than in summer or winter. These are respectively 997 and 1,140 ppm from lowest to highest in living room and kitchen in spring (greater than the means), and 2,404 and 1,485 ppm in autumn; compared with 362 and 991 ppm in summer and 613 and 892 ppm in winter. The mean annual maxima are also disturbingly high – 2,334 ppm for living rooms and 2,616 ppm for bedrooms. Although, some caution is required relative to the winter set of only two out of 22, the implication of less predictable behaviour with respect to window opening in the two transitional seasons chimes with expectations based on findings from other studies.

1.2 The VP means also have a ranking, this time in seasonal sequence from winter to autumn. Respectively the living room and bedroom pairs starting in winter are: 1.00 and 1.08; 1.14 and 1.13 in spring; 1.26 and 1.27 in summer; 1.37 and 1.43 in autumn (kPa); with the annual means now closest to summer at 1.22 and 1.24 kPa. Again the range is significant with the mean annual maxima 1.73 kPa for living rooms and 1.80 kPa for bedrooms.  This time the sequence runs partly contra to $CO_2$'s seasonal irregularity, which stepped up from summer to spring to autumn to winter. This tells us that $CO_2$ levels do not rigidly correspond with moisture levels, although this is a common cyclical occurrence. Leaving aside winter as too small a sample, the respective $CO_2$ and VP seasonal orders from low to high are; summer, spring, autumn and spring, summer autumn. This implies that some of the moisture fluctuations are attributable to something other than simply human presence, the likely causes being cooking, showering/bathing and laundering. Although the detailed analysis suggests that the first two are more potent than the third in their own domains, migration to living rooms and bedrooms is quite possible. Also bedrooms in particular may host other moist activities such as electric blow-drying of hair. Nevertheless the analysis did also mange to isolate the moisture impact from passive drying in certain cases and steam-ironing is bound to have an impact in whatever room hosts this activity.

1.3 When moisture is expressed as RH, the ranking is the same as for VP for living rooms and autumn is still highest for both living rooms and bedrooms: 41.3, 44.4 winter; 44.7, 54.9, spring; 47.4, 47.8, summer; 63.8, 68.2 (%), autumn. Although the spring to summer bedroom relativity has changed order compared with VP, the autumn tendency to have higher humidity levels is marked, the more so when expressed as RH rather than VP. This may be partly due to autumn not having favourable weather for outdoor passive drying, and partly due to open windows not helping to reduce moisture when ambient levels are high.

1.4 With respect to the CFU count, if outdoor levels were to be a strong influence indoors, one would anticipate the highest values in summer and autumn. However the respective summer and autumn means were 752 and 638 CFU/$m^3$, while those for winter and spring were 1,068 and 1,347. This indicates that levels of moisture indoors were the most likely contributor to these higher levels. However, no such simple correspondence exists, both VP and RH being highest in autumn (VP levels are higher by 20% and 27% in living rooms and bedrooms in autumn cf. spring), when the mean CFU count is roughly half that of spring. This issue will be explored further in observation 3 below.

1.5 For the sample of 100 dwellings where spot measurements were recorded on a single day, 1.d indicates highest mean and maximum RH in autumn, while mean $CO_2$ remains more consistent (+/- 5% about annual mean). Note that the seasonal spot averages of $CO_2$ and RH for the larger sample are not all consistent with the 22 monitored case studies, with only two winter examples; but the autumnal RH maximum is common to both sets.

2.0 Bearing in mind the seasonal observations 1.1 to 1.3 above, there is an evident association between air quality and moisture, often high $CO_2$ levels cyclically tracking high VP and RH on a day to day basis in the 22 monitored case studies. In other words, it is most apparent when examining respective profiles on a daily basis, rather than averages.

2.1 However, in addition to the lack of alignment in respective spring-summer averages between moisture and air quality addressed in 1.2 above, there are specific exceptions. For example, comparing CS 9, summer, and CS 15, autumn, where air quality, as defined in the notes is 'good', but VP and RH levels are 'high'. In these exceptions, it would seem that it is the activities and habits of the occupants that are generating moisture without adequate ventilation, rather than simply their presence being a dominant factor, again without adequate ventilation. This is particularly the case with maxima (Table 1.b), where short high spikes of moisture are common; but it may prevail for comparative mean averages (Table 1.c). It should also be noted with regard to exceptions that the spot means of $CO_2$ for the larger sample of 99 dwellings do not necessarily correspond proportionately with the spot means of RH – e.g. the spring $CO_2$ mean is the highest, while the spring RH is the lowest, of the four seasonal groups (Table 1.d, noting that sample numbers vary between seasons in different proportions compared with the 22 monitored case studies).

2.2 Having established that the respective $CO_2$ and VP mean averages are out of kilter between spring and summer in 1.2 above, when the same comparison is made for the respective maxima the corresponding seasonal means are now aligned, with spring values greater than those of summer in each case: $CO_2$ 2,870 ppm living rooms, 2,704 bedrooms in spring, and 1,507 and 1,608 in summer, VP 1.70 kPa living rooms, 1.75 bedrooms in spring, and 1.62 and 1.67 in summer. The conclusion to be drawn is that it is in the surges of moisture due mainly to the presence of people where the air quality and moisture correspondence is greatest. Drying wash-loads does not necessarily correspond with the presence of people, and such contra-influences can be reflected in lack of correspondence in the mean averages – i.e. reinforcing the explanations mooted in 1.2 and 2.1 above.

2.3 The analysis of passive indoor drying in CS 4 indicated that a substantial amount of moisture released was either absorbed by fabric and furnishings, dissipated via ventilation, or migrated to other parts of the house; with the increase in the absolute moisture profile a relatively gentle surge rather than a spike. Further 'what if?' analysis in relation to CS 5, showed that passive indoor drying of two wash-loads could have contributed approximately 45% of the daily moisture total, and 30% for one load – proportions that would have been of great significance to CS 5, which was very humid in the absence of such injections.

2.4 Apart from its role as an indicator of 'bad company' such as high moisture (related to dust mites, mould spore concentration and surface mould/mildew) and VOCs (water soluble VOCs such as aldehydes in turn related to moisture), high $CO_2$ is also associated with a feeling of stuffiness and lethargy that can lead to window opening, and hence loss of heat. It also has a relationship to the UK standard for fresh air supply of 8 l/s for each person. This corresponds with 1,000 ppm (parts per million) of $CO_2$, the recognized maximum limit for good air quality. The relationship between progressively lower values than 8 l/s and $CO_2$ is non-linear – i.e. an exponential curve results in rapidly rising $CO_2$ levels. To give some indication of this in practice in the case of the Glasgow survey, the maximum instrument value of 5,000 ppm was reached on several occasions. Moreover, the arithmetic mean value in the living rooms of the 22 case studies was above 1,000 ppm in over 40% of the sample, and the mean for the entire group of 22 homes was still over 1,000 ppm (1,026 ppm). This poor standard occurred with only two homes surveyed in the winter months from December to February, while seven were in the summer months from June to August and the remainder in autumn and spring – i.e. most were measured when we would anticipate windows being regularly opened depending on the prevailing weather.

2.5 It is also worth commenting on the reliability of the $CO_2$ measurements in the 22 case studies. It is known that there may be significant variations within a room – e.g. up to 400 ppm during a build-up due to occupancy in one field study (Naydenov et al, 2004); and even more in a controlled experiment in a naturally ventilated room, particularly vertically (Steiger et al, 2008). However, there was generally a high level of consistency between $CO_2$ levels in different rooms of dwellings – i.e. a dwelling with inadequate ventilation tended to have fairly uniformly high $CO_2$. Moreover, as already stated there was also a general correspondence between $CO_2$ and moisture levels reflecting periods of occupancy. And since the emphasis is on $CO_2$ as an indicator of 'bad company' as in 2.4 above, rather than for stuffiness, and since occupancy surges during daily cyclical measurements over 2-week periods conform to expectations from field measurements such as that by Naydenov et al, any variations of $CO_2$ within rooms above and below the measured values are not likely to be misleading in terms of inferences.

3.0 The presence of mould is usually associated with high moisture levels; but that does not mean that high moisture levels will necessarily result in mould, although high moisture levels do indicate a failure of adequate moisture control by means of ventilation, with a consequent risk of excess dust mite growth – and hence asthma risk.

3.1 It may also be that where there are high moisture levels and no evident mould, temperature regimes may vary significantly, while the air quality is consistently reasonably good. For example, in CS's 1, 13 and 15 the VP in both living rooms and bedrooms is high, with 15 the highest and with significantly lower temperatures than 1 or 13 (by >5 K), there is no mould anywhere and air quality is also good in both bedrooms and living rooms. For CS 15 air movement may have been critical for mould avoidance. However, high moisture levels >7 g/kg mixing ratio, or 1.13 kPa (Platts-Mills and De Weck, 1989; Niven et al, 1999), temperature not falling below 17.5ºC while RH above 53.3% at 7 g/kg, aligned with 'critical equilibrium humidity' (Cunningham, 1998; Arlian and Veselica, 1981; Arlian, 1992), will promote excess dust mite growth, and indoor drying will contribute to this. Tables 1.b and 1.d respectively show that all VP maxima for living rooms and bedrooms, and more than 70% of the means, are greater than 1.13 kPa. Unlike mould, dust mites are evidenced as causally linked to asthma in sensitized individuals (Institute of Medicine, 2000).

3.2 Adding further detail in terms of conditions likely to cause excess dust mite growth, investigation of specific cases reveals that exceeding the 1.13 kPa threshold often also breaches the curve derived for 'critical equilibrium humidity' (CEH) expressed as a function of temperature. The mean for bedrooms is still above (CEH) with regard to excess dust mite growth (mean RH 57%, mean temperature 17.7ºC), while that for living rooms is slightly below this level (mean RH 51.4%, mean temperature 19.4ºC). Looked at individually more than half of the monitored bedrooms were above CEH, with autumn predominating; while for those below CEH, summer and spring predominated. This compares with sixteen above the 1.13 kPa limit, but three of these were only slightly above. In other words, the absolute moisture criterion Platts-Mills and Niven et al compares reasonably well with that of RH as a function of temperature cited by Cunningham (Arlian and Veselica, 1981). Eight of the living rooms were also above the CEH, again with autumn cases dominant; but in this case twice as many were above the 1.13 kPa threshold. The reason for this disparity is that living rooms averaged higher temperatures, but as most of those that were below CEH were monitored either in spring or summer, it does not invite complacency for living rooms in terms of being prone to high populations of dust mites. Overall, data suggests that if all surveys had occurred in autumn or winter, the problem of excessive humidity relative to dust mite populations would have been even worse (noting that only two of the case studies were monitored during winter).

3.3 If we look at specific case studies where the mean RH and temperature fall comfortably below CEH, we also find that there are tendencies for the situation to significantly reverse – say in evenings when living rooms are occupied intensively, or bedrooms overnight. For example, CS 22 in January had a fairly low mean value for RH and temperature in the living room (43.5%, 20.6ºC), but examination of evenings finds very different conditions. For three and a half hours in one evening for example, mean RH was 70.2% and temperature 23.5ºC, mean $CO_2$ 2,846 ppm, and above CEH for dust mites at all times during this period with RH peaking at 83.2%. Similarly a bedroom in CS 7 overnight in April averaged 58.8% RH, temperature 21.3ºC and $CO_2$ 2,328 ppm, putting it well above CEH when its 24-hour average was below. On the other hand, the living room of CS 17, where the bedroom mean is well above CEH, never falls below it. However, this is at the cost of heating while windows are liberally opened, the maximum CEH occurring when the temperature drops from its average of 22.4ºC to 18.5ºC in the late evening.

3.4 Of the group where there is evidence of mould in bedrooms only, CS's 2, 5, 6 and 10, only the last has moderate vapour pressure recorded for bedrooms; but it was also the only one out of that set of four monitored in summer. Therefore it is reasonable to conclude that the mould may well be symptomatic of conditions in colder weather. Of a group with mould in bedrooms plus at least one other space, CS's 3,7 and 11, the VP is high in the bedrooms in the latter two cases and, while no data is available in the first one, the living room VP is high.

3.5 Although we know that passive drying will add a particular amount of moisture, depending on the type of washing as well as level of heat and ventilation (0.38 kPa for CS 4 – refer to observation 2.3 above), there is no consistent association between indoor passive drying and high moisture levels. The impact of the added moisture due to internal drying is frequently masked by more potent moisture generating activities. As in 3.1 above, the air quality can provide clues as to likely impact. For example CS 18, with internal drying as the only method, has good air quality and low to moderate moisture. On the other hand, CS 9 has good air quality but high moisture levels, even though it was monitored in summer. Multiple drying techniques can be helpful relative to moisture, but, again, other activities can result in high moisture levels while air quality is good – e.g. CS 3 has good and moderate air quality, but high moisture in autumn. Equally, multiple techniques for drying may correspond with poor air quality and high moisture – e.g. CS 4 in spring.

3.6 Following from observation 3.3, passive drying inside is rather less associated with presence of mould than when other methods of drying are adopted. Out of 9 case studies where passive drying is the only or dominant method, less than half also have visible mould present in at least one space; whereas of the remaining 13, more than half also have visible mould present in at least one space.

3.7 With respect to the issue of inadequacy of ventilation control, there are two key issues – the means available, and awareness of the means. Of the eight case studies in high-rise towers, half gave a correct return in relation to mechanical provision and the other half gave an incorrect return, stating 'no fans' when in two cases there was mechanical extract to both kitchens and bathrooms and two cases to bathrooms only. The four in tower blocks who did give a correct return also seemed aware of the controls in terms of the degree of automation, as did the remaining nine with correct returns for presence of fans, with only one exception. Overall the four households with one or more extracts, but unaware of this facility, represented just under a quarter (23.5%) of the number with them (17 ex 22).

3.8 With respect to trickle vents, almost half (10 No.) never used them, of which four were unsure how (not surprising in one case as there were no trickle vents fitted to replacement uPVC windows), three did not know how or gave no reason, two stated that they were not functional, and one gave obstruction as the reason for non-use. Of the twelve who used trickle vents, three never adjusted (one case had no trickle vents to adjust) and two occasionally adjusted them. Thus we may conclude that trickle vents are a poor provision.

3.9 The combination of the total reliance on trickle vents and window opening in five of the 22 case studies (23%), together with trickle vents and mechanical extraction in sixteen cases, absence of trickle vents in one case, and overall poor awareness, convenience or use of trickle vents, and finally unknown or indeterminate use of manual fan control and window opening, is a recipé for poor standards of ventilation and hence poor air quality. Moisture inputs from passive drying and ironing indoors can only add to this problem.

4.0 There is no consistent association between visible presence of mould and the CFU count, with twelve of the 22 case studies having mould present and ten having none; but of those with mould, a greater number were surveyed in autumn.

4.1 The cases with no mould included four in spring, four in summer, one in autumn and one in winter; while those with mould had four in spring, three in summer, four in autumn and one in winter. However, there is no evident consistent association between absence or presence of visible mould and CFU count – see Summary Tables 1.a-1.g; and this finding accords with earlier work by others (Garrett et al, 1998): "It is very difficult to explain why significantly smaller viable spore concentrations would be found in rooms with visible mould growth." However, Garrett et al found that visible mould or evidence of condensation did correspond with Cladosporium spores.

4.2 In relation to absence of visible mould and Cladosporium, the following was found from 20 of the 22 case studies (CS), where air samples were analysed for spore type:

| | | |
|---|---|---|
| CS 1 (summer), 14 (summer) &17 (spring) | 2 types Cladosporium | no visible mould |
| CS 13 (summer), 15 (autumn),18 & 19 (spring) | 1 type Cladosporium | no visible mould |
| CS 12 (summer) & 21 (spring) | no Cladosporium | no visible mould |

4.3 In relation to presence of visible mould and Cladosporium, the following was found:

| | | |
|---|---|---|
| CS 6, 7 (spring) &11 (summer) | 2 types Cladosporium | mould in >1 room |
| CS 20 (spring) | 2 types Cladosporium | mould in 1 room |
| CS 16 (spring) | 1 type Cladosporium | mould in >1 room |
| CS 3, 5, 8 (autumn), 4 (spring), 9-10 (summer) | 1 type Cladosporium | mould in 1 room |

4.4 The summarised data in 4.2 and 4.3 above do not provide a convincing association between presence of Cladosporium and presence of mould, although there are four more case studies with both Cladosporium and mould present (11 No.) than there are with Cladosporium present, but no visible mould (7 No.); and there are also two cases where neither Cladosporium nor mould are present. Moreover, seasonal variations do not appear to signify in this regard.

4.5 Both Aspergillus, present in all the dwellings sampled and Penicillium, present in all but one (95%) "contaminate indoor spaces biologically" and "are important sources of allergens". (Haas et al, 2007), Perhaps more importantly, Aspergillus fumigatus was found in 25% of the sample. This "causes invasive allergenic disease" where immune systems are vulnerable (Cramer et al, 2011); and "can be very dangerous". (University of Cambridge, 2011).

5.0 There is an apparent association between absence of indoor passive drying and the CFU count, which consistently tends to be lower when it is absent than when it is present.

5.1 Although it may seem entirely logical, even self-evident, that the presence of damp material inside relatively confined spaces should lead to higher spore counts, since fungal growth can only occur when moisture is present, there are several confounding variables. One is the level to which windows and doors are opened to admit spores from outside, this in turn varying considerably with season – highest in summer and autumn. Also, people and pets entering dwellings can bring in spores from outside. Inside the dwelling, in addition to the production and migration of moisture from laundering activities (mainly passive drying and ironing, but also hand washing and even the reservoirs of water in certain condensing tumble dryers), cooking and personal hygiene will be influential. In one respect the latter generates equivalent moisture by evaporation to passive drying of washing – the drying of damp towels after baths or showers; but generally such activities tend to be of shorter duration of a more rapid moisture generation – for example, blow-drying of wet hair. The means of controlling ventilation, particularly mechanically from 'wet' areas may be expected to exert influence in this regard. Growth of spores from all moisture-producing activities will occur on surfaces, the presence of dust and other larger organic matter being additionally influential. Thus differences in standards of housework associated with cleanliness constitute another confounding variable. This in turn raises the issue of different surface finishes – for example, textured wallpapers compared with painted plaster or plasterboard; carpets compared with laminate floors. The soil in which house-plants are set could also promote growth of mould spores; moist vegetable matter in waste bins could be another source etc. Finally a recent survey in France included heating mode as a variable (Roussel et al, 2008), and one may assume either that the degree of convective air agitation in delivery of heat should be relevant in this regard for CFUs, or that electric heating signifies the potential for greater airtightness compared with at least some other heated options – e.g solid fuel appliances or radiant gas fires.

5.2 Taking the above into account, the tentative hypothesis is that the presence of damp material drying slowly over a period of several hours tends to be more potent in terms of fostering fungal spores, compared with other producers of moisture that are more concentrated but in shorter durations; the latter, as noted in 4.1 above, are generally more air-borne in nature and often exhausted rapidly at source either by extract fans or by opening windows. This is supported by Summary Table 1.g, which is discussed further below. For the eight case studies, which either tumble dry exclusively or predominantly, the geometric mean spore count for living rooms and bedrooms is 644 CFU/$m^3$ (cf. arthmetic mean 662) and for the three where outside drying is the only or dominant means, the average is very similar at 680 CFU/$m^3$ (cf. arthmetic mean 688). But for the nine where most washing is dried passively indoors, the average rises to 1,398 CFU/$m^3$ (cf. arthmetic mean 1,528); and for the remaining two (4 and 12), where there is a relatively even mix of methods including active and passive drying, the score is 837 CFU/$m^3$ (cf. arthmetic mean 838). Statistical anlaysis confirms that such differences are highly significant for the respective sets of drying methods, the independent variables, relative to the spore concentrations as the dependent variable, whether for all spaces or just living rooms and bedrooms. Multiple regression also indicated that none of the potentially confounding variables were significant. Appendix 3 fleshes out the statistical data, including p-values.

5.3 To summarise the key findings, if the mainly tumble-dried set is independent variable 1 or IV1, the mainly externally dried group IV2, the mainly passive indoor dried group IV3 and fairly mixed modes IV4, F-tests show that IV3 has a p-value of 0.009 relative to the mean CFU/$m^3$ for all spaces and 0.010 for the mean CFU/$m^3$ for living room and bedrooms. If IV1,IV2 and IV4 are lumped together, t-tests show even lower p-values for IV3 – 0.001 if equal variances are assumed and 0.008 if equal variances are not assumed. Multiple regression with a set of confounding variables gives a p-value of 0.002 for IV3 relative to CFU/$m^3$ for all spaces; whereas p-values for other variables all exeed 0.05, some by a factor of more than 10. In other words IV3 stands out as highly significant relative to spore concentrations, whereas confounding variables found by multiople regression do not – some p-values of such variables included in observations below as well as in Appendix 3.

5.4 However, although this theory, as well as the CFU data, accords with the expectations of the French survey cited in 5.1 above, its findings for a significantly larger group of dwellings (128 in France cf. 22 in Scotland) suggested otherwise. Roussel et al found that both density of occupation relative to volume (indicated by $CO_2$ in Summary Tables 1.a-1.f above for Glasgow, and discussed further below in 5.9) and presence of mechanical air extraction were influential, but not whether a room was used to dry laundry. It is possible that the French study had a relatively strong association between mechanical extract and spaces used for drying (further information unavailable). In Glasgow, presence of mechanical extract from kitchens had a p-value of 0.091 – i.e. still nearly double the normal 0.05 threshold of significance; while presence of bathroom extracts was very insignificant – p-value 0.592. This potentially significant variable may to some extent justify the use of the word ‘tentative’ in relation to the contra hypothesis mooted for Glasgow, despite the strong statistical association between IV3 and CFU/$m^3$.

5.5 Specific examples concerning ventilation, mechanical and natural, help to indicate the level of complexity concerning variables, and ultimately justifies the need for multiple regression analysis. Even that, however, may not be sufficiently fine-grained – e.g. judgments as to what constitues a ‘open’ window regime as opposed to ‘moderately open’? Comparing firstly CS 2 with 22, both have extract fans in kitchen and bathroom and all drying is passively done inside, 2 has a CFU count just below 1,000 while that of 22 is well above; while the other potential influence is windows – opened according to need in the former case and mainly shut in the latter. The Austrian survey by Haas et al (2007) shows that median outdoor concentration of spores is significantly higher in summer than other seasons: 1,000 CFU/$m^3$ (MEA: malt extract agar) and 1,200 CFU/$m^3$ (DG: Dichloran Glycerol) being 2.8-3.0 times the respective values in autumn, 4.0-4.6 times in spring and 12.5-12.0 times in winter. The question then arises as to whether either the fans or the natural ventilation has influenced either of the respective CFU counts. But CS 18 also has two fans, dries entirely passively indoors, and has a much higher presence of spores. In this instance the season is spring and windows are mainly open. By contrast, CS 17 is also in spring, has open windows and much lower spore counts; the main difference compared with 18 being the absence of indoor drying. Summer 'window-open' CS 9 and 14 also have widely varying CFU counts from 700 to over 1,300, and again it is presence or absence of indoor passive drying that seems to be most significant. The nonconformist in this regard is CS 14, where particularly liberal window opening in early summer may have modified CFU count downwards, rather than upwards; noting also that CS 14 recorded "windows open all day and night" compared with CS 9's "windows open most of day"; and where CS 9 has significantly higher CFU counts. Both CS 9 and 14 had a washing drying indoors on the day that the air sample was taken. The specific high to low contrasts of spore concentration relative to regimes of regularly open windows correspond with a very high p-value from multiple regression analysis – 0.769 – ie. not at all significant.

5.6 The instance of CS 14 is also mirrored in Australia (Garrett et al, 1998), where results suggested that "... regular ventilation through open windows can significantly reduce Cladosporium concentrations, despite outdoor concentrations being larger." In other words this survey indicates that 'wet' activity within the home could be more potent in terms of spore concentrations, than potential influx from outside; taking samples from each dwelling at 2-month intervals over an entire year, and also finding a correspondence between presence of mould and Cladosporium concentrations.

5.7 Indeed an aspect that is in accord with the results of the French study cited above is the apparent lack of identifiable impact of window opening habits on spore counts, accepting that no French surveys were carried out from June to September. Taking another example, comparing CS 5 and 8, both in autumn, but one with windows predominantly open and the other shut, and both with an extract fan in the kitchen only, it is the use of tumble drying and the absence of passive drying indoors that appears to be significant relative to the modest CFU counts; noting that those in CS 5 are somewhat lower than those in CS 8, the former doing all drying by machine, while some auxiliary drying occurs in the latter case. Neither does a tendency towards open windows appear to adversely affect the case studies where passive internal drying is absent or not dominant. Of the 13 such cases, six liberally open, five moderately open, and two shut windows, the six in the 'open' category average 621 CFU/m$^3$ in all spaces compared with 779 for the 'moderate' and 568 in the two 'shut' cases. Only one of the 'open' cases, 10, has Alternaria present amongst the species, which is known to cause allergies, but the spore count is modest at 584 CFU/m$^3$. However, there are five instances of Aspergillus fumigatus, which is known to cause lung infections in people with weakened immune systems, and indeed "causes invasive and alllergenic disease" (Cramer et al, 2011). The University of Cambridge's 'Map of Life' also claims "it can be very dangerous" (2011). These include CS 10, and four others, three having quite high counts – a mean of 995 CFU/m$^3$ for 6, 1,321 for 9, and 1,140 for 21; and two of these, 9 and 21 passively dry all washing inside the home.

5.8 Further comparisons regarding any combined influence of fans or natural ventilation are also not convincing in comparison with the evident associations attributable to presence or absence of indoor drying. If we compare the two dwellings with the highest spore counts CS 7 and 18 (living room/bedroom means respectively 2,772 and 2,658 CFU/m$^3$), the former keeps windows closed and the latter open, both monitored in spring, and the former has no extract fans while the latter has two. The common factor is indoor passive drying, but the spore counts are well over the average of 1,528 CFU/m$^3$ for indoor drying households, and moisture and $CO_2$ levels differ between the two case studies. In the one significant exception to the 5.2 hypothesis, CS 6, where tumble-drying is the only method used and there are extract fans in both kitchen and bathroom, spore counts are above 1,000 CFU/m$^3$ in all spaces apart from the kitchen. It was suspected that part of the reason for this is that the tumble dryer, located in a bedroom, may have back-vented via the window left ajar to feed out the dryer's exhaust-tube; but that there is also migration of humid air within the flat coupled with inadequate ventilation and high humidity, with RH generally above 70%. The notes in Part B for CS 6 concluded: "Overall, the data suggests a possible moisture threshold, say above 70% mean RH, in turn linked to poor air quality, above which a high spore concentration is more likely." High RH combined with fairly modest mean temperatures are also likely to increase risk of mould growth – 18.5ºC at 70% also has a high absolute moisture content of approximately 1.5 kPa; noting that CS 6's living room averaged 18.4ºC at 74.6%. Used properly, tumble-drying is simply one means of facilitating the absence of prolonged periods where damp fabric is present, while fans help to exhaust humid air directly when generated by other 'wet' activities. Nevertheless, the range of CFU counts within the indoor passive drying set leads on to consideration of other potential confounding variables.

5.9 As noted above in 5.4, the French survey had one apparently important finding that runs counter to the Glasgow analysis: "The total concentration of fungi increased with the number of inhabitants per cubic metre." Although the Glasgow monitoring indicated consistent, and anticipated, associations between intensity of occupation ($CO_2$ readings) and moisture (VP in particular), the relationship of both to CFU/m$^3$ is quite erratic. Importantly, the statistical regression analysis found that density of occupation (number of occupants ÷ number of apartments [bedrooms + living rooms]) gives a p-value of 0.093 – i.e. only relevent at a 10% level. Also, despite a close relationship between $CO_2$ profiles and VP profiles, there was no statistical association between IV3 and VP – i.e. occupant related absolute moisture levels. Aside from p-values, summary Tables 1.e and 1.f provide the most convincing picture in this regard. It is also probable, although not known, that the cubic content of the Scottish sample was less than the French ones – Scottish space standards are not generous. Taking specific examples once again, CS 2, 6, 7, 20 and 22 all have spore counts greater than 1,000 CFU/m$^3$, poor air quality and mainly rather high moisture levels (living room of CS 2 the exception). On the other hand, there are those with high spore counts, but with good air quality ($CO_2$ below 1,000 ppm) and reasonably low moisture levels (VP maxima mainly below the Platts-Mills and De Weck dust mite benchmark), for example CS 9 and 18. There are also others with low spore counts, and relatively poor air quality and high moisture levels such as CS 5 and 13. Summary Table 1.f confirms that these disparities are still in evidence when considering the mean averages rather than maxima. Moreover, although the long term maxima and means on Summary Tables 1.b and 1.c should be treated with some caution relative to the spore counts on the first day of monitoring, the same disparities are again evident. Neither, as has been previously observed, do the instances of visible mould necessarily correspond with high spore counts. Therefore, in this particular set of 22 households, there is no consistent relationship between intensity of occupation and concentration of fungi.

5.10 This then poses the question as to how these apparently contradictory findings regarding the density of occupation, presence of mechanical extraction and presence of passive indoor drying can be reconciled. The measure for occupant density in the French case is relatively blunt, as is the ratio of occupants to habitable rooms used for Glasgow. But the use of $CO_2$ monitoring in Glasgow gives a fine grain to the measure of occupancy and this did not yield significance relative to spore concentration. On the other hand, a measure of persons/m$^3$ could indirectly convey a higher level of washing and drying demand, in which case one could reasonably expect both density and indoor drying to be statistically aligned relative to CFU/m$^3$. However, much would depend on the variety of methods used for drying relative to persons/m$^3$. For example, the indoor drying in the French case studies may have been relatively rare or for smaller washing loads compared with Glasgow; or the proportionate use of tumble-drying might have been higher in the French study; or the density of occupation may have related more strongly to high levels of indoor humidity in the French study, noting that it excluded the summer months. Unfortunately, that level of comparative detail is not available.

5.11 Other potential confounding variables included in Table 1.g, different floor finishes and presence/absence of house plants are evidenced as inconsequential (respective p-values 0.492 and 0.430) as the opening or shutting of windows ($p = 0.769$, see observation 5.5 above). This finding is in conformity with the large French study despite contrary expectations. In the smaller Scottish set, of the thirteen case studies where passive internal drying is absent or not dominant, there are six with carpets (ignoring CS 6 – see 5.7 above) averaging 662 CFU/m$^3$, five laminate or timber averaging 616 and one carpet/timber of 645. Similarly, there is no significant difference attributable to the presence of house plants – 699 CFU/m$^3$ for the four out of thirteen with house plants (2 with one extract fan and 2 without any) and 612 without (with random presence or absence of fans). Hannah Cunniffe in a study at Worcester (2006) found differences between carpets of various ages in bedrooms and living rooms, the former being relatively stable in terms of CFUs, while the latter showed significant increases over time. Cunniffe also found statistically significant differences between spores present in dust (CFU/g) between spring and autumn, the latter greater than the latter; and further that ‘smooth’ finishes such as wood laminates had lower spore counts than carpets – varing by factors <2.0 before vacuuming (1.8 Alternaria; 1.6 Cladosporium; 1.3 Aspergillus/Penicillium), and by <5.0 after (4.6 Alternaria; 4.4 Cladosporium; 4.9 Aspergillus/Penicillium). However the case studies in Glasgow were randomised in this regard, and carpets occurred with both low and high CFU counts, as did laminate finishes. Also, the level of hygiene, particularly in relation to dust levels, may be considered to be relatively random. On the other hand, a circular interaction between damp material suspended for several hours while gradually losing moisture, and ambient dust may help to increase the fungal activity within it. In this case, it is the presence of the damp material that has potency rather than dry dust in the absence of prolonged moisture.

5.12 Overall, the absence of indoor passive drying, or where it is not the dominant method, also corresponds with reasonable air quality in the majority of cases – nine good/moderate in the living room compared with three poor. There is no reason why passive indoor drying (IV3) and $CO_2$ should relate, unless occupants always keep their drying washing company.  On  the other hand, there could be underlying reasons for lower intensities of occupation coinciding with tumble drying (IV1). For example busier lifestyles, with lower intensity of occupation and so lower $CO_2$ counts, might correspond with greater use of tumble drying. Regardless of indoor air qaulity (IAQ) measured by $CO_2$, a key aspect is that lower CFU counts, which tend to correspond to internal drying being absent or not dominant, has potentially positive implications for health; while the opposite is true for the higher counts. This is particularly so for the atopically sensitized group who are vulnerable to asthma. It is the combination of high CFU counts with high moisture levels that is concerning for health. Table 1.a shows that, of the 8 case studies where the CFU count are classified as ‘high’, 6 of the living room and 5 of the bedroom VPs are also ‘high’. This means that sensitized individuals are at risk from two sources – mites and fungal spores. Risks associated with specific fungi such as Aspergillus fumigatus have been highlighted in 4.5 and 5.7 above,

5.13 It may also have significance, in terms of assisting the process of passive drying to a degree, that all nine of the case studies where this was the only or dominant method used had “good access to sunshine” in the rooms used; and further that in seven of these cases the weather was sunny on the first day of the monitoring when the air samples were taken. Four out of five other cases where passive indoor drying was employed to some extent also enjoyed good access to sunshine and had sunny weather on the first day. However, as one might expect, there is no correspondence between sunny weather on the day of air sampling and high or low spore count. However, this information does suggest a positive role for exploiting solar heat to help with drying in ways that do not involve risk to health.

5.14 Having introduced the issue of passive solar thermal gain, another potential variable explored in the French survey by Roussel et al was method of heating (see 5.1 above). In this regard, there appears to be a conflict between one part of the text, which claims that spore concentrations were ‘significantly‘ higher in electrically heated dwellings ($p = 0.04$), and a later part  which asserts that ‘heating mode’ was “not associated with a significant change in the total concentration of fungi”. Both statements have possible validity in that the geometric mean for electric (less than one fifth of the total sample) was significantly higher than either gas, or centrally heated categories, but it was nevertheless still just under 500 CFU/$m^3$. This value is regarded as low in the Glasgow sample, where there are 13 electrically heated and 9 gas-heated dwellings, all of the latter group by modern gas central heating, and a p-value of 0.326. It may be that the water-filled radiators promote a slightly more active convective environment compared with the electric appliances, mainly storage heaters, but the intrinsic airtightness, with windows a significant influence, is fairly similar for the entire sample. The main convective variable is use of the means of ventilation control, that is windows and extract fans. In terms of electric versus gas heating in the Glasgow set, there is a similar breakdown of high, low and medium spore concentrations: gas – 4 high, 3 low, 2 medium; electric – 5 high, 4 low, 4 medium.

5.15 Finally, the French survey of Roussel et al finds that ground floor apartments had higher concentrations than those above this level or individual houses, but again the geometric mean for the ground floor category was not excessively high at 574 CFU/m$^3$. This equates to the low range for the Glasgow sample, where there were only a small number of ground floor situations, and three of these were maisonettes. In any case, there was no consistent trend with regard to height above ground level – e.g. a 16th floor living room having 1,565 and a 14th floor one 678 CFU/m$^3$, both with open windows and the lower of the two values occurring in summer as opposed to spring in the higher case. On the other hand, the 16th floor flat dried entirely passively indoors, while the 14th floor flat predominantly used a tumbler dryer.

5.16 In summary, the position stated in 5.0 appears to hold good, despite many potential confounding variables, and statistical analysis strongly supports this contention. It is for health experts to judge how serious an issue consistently high spore counts, and prevalence of particular fungi, mught be for atopic inhabitants, and children in particular. There is the added issue of adding additional moisture to an already over-humid indoor climate, and the risk this carries of increasing numbers of dust mites (see 3.1-3.3), or at the least increasing their rate of survival – with an established association between dust mite population and asthma. There is a further issue brought up in relation to CS 2 in Part B – that of water soluble VOCs increasing with increased humidity (Arundel et al), and in particular acetaldehyde associated with fabric softeners (see research by Steinemann et al discussed under CS 2 notes in Part B). Of the 22 case studies, 14 used softeners, 6 did not (no data for 2). Of those that used softeners, 9, roughly two thirds of this sub-set, had mean VP greater than the 1.13 kPa dust mite threshold set by Platts-Mills and De Weck (1989), and Niven et al (1999) in both living rooms and bedrooms. However, of that set of 9, only one used PID as the predominant method (i.e. IV 3), and another five used PID on a more occasional basis along with a tumble dryer or outdoor drying. The entire set of 100 gives less reason for complacency, however (see Part D). Again it is for health experts to weigh up the risk associated with a hazardous and potentially carcinogenic VOC such as acetaldehyde, particularly in the humid environments found; as it is to assess the asthma risk, particularly for children, attributable to dust mites – in turn high moisture resulting from poor control of ventilation.

6.0 Since tumble-drying carries an energy penalty of which users are well aware, it seems logical to promote the use of discrete, fortuitously heated passive drying spaces (cupboard, sun-room) inside dwellings and solar-enhanced, weather-sheltered spaces outside.

6.1 In the set of 22 case studies monitored, only CS 16 had a walk-in drying cupboard in use. However, at the time of the spring monitoring all drying was done passively outside. If the hypothesis of 4.0 and 4.2 above is correct, the isolation of drying from the main spaces within a heated and ventilated cupboard must be a crucial factor, and one would expect this case study to match others where the low CFU count corresponds with tumble drying.

6.2 There is therefore a case for requiring such isolated spaces inside all homes, and to accommodate a typical washing load, a minimum of 1.75 m$^3$ to accommodate a hanging length of at least 7.2 m of would be necessary (e.g two rows of four 0.9 m long slats, dowels of cords). This is 75% greater than the current minimum in the Scottish statutory standards, which do not require a discrete space for this purpose. There is also a case for passive solar enhancement of such spaces where possible, as well as providing covered passive solar spaces externally – e.g. a lean-to transparent canopy above a pulley.

SUMMARY TABLE 2.a: Appliances – estimates of energy consumed

| CS | Machine Washing [estimate for ironing] | | | | | | Tumble Drying | |
|---|---|---|---|---|---|---|---|---|
| | T-norm | Feed | E-rat | kWh/p-y | kWh/h-rt | kWh/c | m-est/site-d | kWh/p-y |
| 1 | 30$^{o}$C | cold | A | 40 [44] | 0.48 | 0.52 | m-est/com | 580 |
| 2 | 30$^{o}$C | cold | B | 48 [5] | 0.50 | 0.92 | n.a. | n.a. |
| 3 | 30$^{o}$C | cold | A | 115 [22] | 0.42 | 0.57 | site-d/home | 130 |
| 4 | 30$^{o}$C | cold | A | 84 [no d.] | 0.88 | 0.72 | m-est /home | 78 |
| 5 | 40$^{o}$C | cold | A | 238 [5] | 1.00 | n.r. | m-est/home | 212 |
| 6 | 30$^{o}$C | cold | B | 16 [7] | 0.51 | 0.60 | site-d/home | 120 |
| 7 | 40$^{o}$C | cold | C | 33 [5] | 0.68 | 0.94 | n.a. | n.a. |
| 8 | 80$^{o}$C? | cold | A | 148 [30] | 0.82 | 0.81 | m-est/home | 228 |
| 9 | 30$^{o}$C | hot | B | 21 [9] | 0.21 | 0.33 | n.a. | n.a. |
| 10 | 30$^{o}$C | hot | A | 63 [6] | 0.31 | 0.47 | m-est/com | 390 |
| 11 | 30$^{o}$C | cold | A | 64 [10] | 0.83 | 1.23 | m-est/home | 162 |
| 12 | n.a | n.a. | n.a. | n.a. [4] | n.a. | n.a. | site-d/home | 57 |
| 13 | n.a. | n.a. | n.a. | 58 [15] | n.a. | n.a. | m-est/com | 112 |
| 14 | 30$^{o}$C | cold | B | 64 [n.a.] | 1.05 | 1.38 | n.a. | n.a. |
| 15 | 30$^{o}$C | cold | A | 25 [7] | 0.53 | 0.98 | n.a. | n.a. |
| 16 | 30$^{o}$C | cold | A | 95 [15] | 0.44 | 0.70 | n.a. | n.a. |
| 17 | 30$^{o}$C | hot? | A | 21 [13] | 0.40 | 0.46 | n.a. | n.a. |
| 18 | 40$^{o}$C | cold | A | 90 [15] | 0.55 | 0.65 | n.a. | n.a. |
| 19 | 30$^{o}$C | cold? | B | 50 [14] | 0.47 | 0.76 | n.a. | n.a. |
| 20 | 30$^{o}$C | cold | A | no d. [no d.] | no d. | no d. | n.a. | n.a. |
| 21 | 60$^{o}$C | hot? | A | 43 [4] | 0.49 | 0.76 | n.a. | n.a. |
| 22 | 40$^{o}$C | hot? | B | 33? [7] | n.a. | n.a. | n.a. | n.a. |
| mean | | | | 67 [12.5] | 0.59 | 0.75 | | 207 |

Legend:

T-norm = normal temperature for was cycle given on questionnaire.
Feed = hot or cold water supply to washing machine – questionnaire cross-checked with recorded survey data. Use of ? indicates some dubiety on this issue.
E-rat = manufacturer's energy rating for washing machine.
kWh/p-y = estimate of annual consumption per person in household extrapolated from monitored data, diary notes and questionnaire responses. Equivalent estimate in square brackets for ironing is based solely on power of specific iron used and diary/questionnaire.
kWh/h-rt = consumption of washing machine per hour of running time (recorded data).
kWh/c = consumption of washing machine per cycle evident from recorded data and diary.
m-est/site-d – tumble drying based either manufacturer's estimate of standard full load of cottons, or on recorded site data where available (site-d/home); m-est/com = tumble dryer located in communal facility, either within project or commercial laundrette. Tumble drying energy per cycle from manufacturers' data (md) or from site measurement (sm) as follows:

| CS | 1 | 3 | 4 | 5 | 6 | 8 | 10 | 11 | 12 | 13 kWh/c |
|---|---|---|---|---|---|---|---|---|---|---|
| | md | sm | md | md | sm | md | md | md | sm | md |
| | 3.50 | 0.88 | 3.96 | 3.50 | 4.62 | 4.38 | 4.25* | 3.73 | 0.55 | 4.25* |

* half of manufacturer's estimate for 16 kg full load of 8.5 kWh/cycle for commercial appliance

SUMMARY TABLE 2.b: Appliances – consumed & primary totals plus $CO_2$ emissions

| CS | Season | wm+td+i consumed kWh/p-y | wm+td+i primary kWh/p-y | wm+td+i emissions kg $CO_2$/p-y | ID: env'l implications none/some/significant |
|---|---|---|---|---|---|
| 1 | summer | 664 | 1,819 | 357 | none: all td |
| 2 | winter | 53^-td | 145^-td | 29^-td | significant: see note 6.3 |
| 3 | autumn | 267 | 732 | 144 | significant: as for CS 2 |
| 4 | spring | 162^-iron | 444^-iron | 87^-iron | none: night charge aids |
| 5 | autumn | 455 | 1,247 | 246 | none: all td |
| 6 | autumn | 143 | 392 | 77 | some: non-vented td? |
| 7 | spring | 38^-td | 104^-td | 21^-td | significant: htg boosted |
| 8 | autumn | 406 | 1,112 | 219 | some: htg + low vent'n |
| 9 | summer | 30^-td | 82^-td | 16^-td | some: for winter regime |
| 10 | summer | 459 | 1,258 | 248 | some: htg boosted |
| 11 | summer | 236 | 647 | 126 | none: mainly td |
| 12 | summer | 61^-wm | 167^-wm | 35^-wm | some: part ID on htg/v'n |
| 13 | summer | 185 | 507 | 100 | some: ID boosts ba RH |
| 14 | summer | 64^-iron-td | 175^-iron-td | 35^-iron-td | some: winter htg boost? |
| 15 | autumn | 32^-td | 88^-td | 17^-td | some: htg boosted |
| 16 | spring | 110^-td | 301^-td | 59^-td | some: ID in hall/cup'd |
| 17 | spring | 34^-td | 93^-td | 18^-td | some: part ID on htg/v'n |
| 18 | spring | 105^-td | 288^-td | 57^-td | significant: htg boosted |
| 19 | spring | 64^-td | 175^-td | 35^-td | significant: htg boosted |
| 20 | spring | no d. | no d. | no d. | significant: htg boosted |
| 21 | spring | 47^-td | 129^-td | 25^-td | significant: htg boosted |
| 22 | winter | 40^-td | 110^-td | 22^-td | significant: htg boosted |
| | mean | 174 | 477 | 94 | |

Legend:

wm+td+i = combined totals for washing machine, tumble dryer and iron from Table 2.a.
consumed kWh/p-y = energy used (measurement/estimate) extrapolated per person-year.
primary = ditto consumed, divided by grid coefficient 0.325 (all power useful at end point).
emissions kg $CO_2$/kWh = mass $CO_2$ emitted – multiply consumed by grid coefficient 0.54.
^-td/-wm/-iron = suffixes where household does not own tumble dryer/washing machine/iron.
no d. = no usable data in terms of estimating energy/carbon use (see case study notes).
ID: env'l implications = implications of internal passive drying for heat demand or moisture.
none = no evidence that drying habits (diary/questionnaire/monitoring) will have impact.
some = indications that drying habits (ditto diary etc.) will impact to a moderate extent.
significant = evidence that drying habits (ditto diary etc.) will impact to a major extent.
all td = all drying by tumble dryer in home or off-site – therefore no impact on sp htg.
see note 6.3 = reference to observation 6.3 below with regard to analysis of CS 2.
night charge aids = passive drying overnight assisted by electric off-peak storage charge.
htg boosted = space heating demand up due to open windows/thermostat raised for ID.
part ID on htg/v'n = partial ID assumed to impact on heating/ventilation/moisture.
ID boosts ba RH = specific case of light hand washing dried in unheated bathroom (ba).
ID in hall/cup'd = specific case of both hall and adjacent drying cupboard used for drying.
NB: all brief explanatory notes should be correlated with extended analytical CS notes.

SUMMARY TABLES 2.a and 2.b: Preliminary Observations (following from 1.a-1.g)

7.0 There is large range of energy consumption values for all three appliances, washing machine, tumble dryer and steam iron, differences in typical usage during monitoring accounting for the largest factorial differences. (The figures in Table 2.a are based partly on site measurement, partly on manufacturer's data, and partly on extrapolation of frequency determined from 2-week monitoring.)

7.1 The mean average estimate for tumble-drying based on available evidence, 207 kWh annually for each person in a household (infants counted equally), is just over three times greater than that for washing, 67 kWh, and 16.6 times that for ironing at 12.5 kWh. It should be born in mind in making this comparison, that the majority of tumble drying estimates were based on diary information with respect to frequency of use together with manufacturers' estimates of energy consumption for full cotton loads. The estimates for ironing are based on questionnaire information concerning the appliance and frequency of use, together with diary notes, and a controlled test for consumption using different irons. Values are therefore more approximate than those for tumble-drying. On the other hand those for the washing machine are taken directly from measurements during monitoring, only the extrapolation of the 2-week monitoring period introducing scope for error.

7.2 The median value for tumble-drying is lower than the arithmetic mean, lying between 162 (CS 30) and 130 kWh (CS 3); the geometric mean also lower at 163.6; and with the range varying by a factor of over 10 from 580 (CS 1, making use of an effectively 'free' communal facility) down to 57 kWh (CS 12, where tumble drying used to finish of after passive drying). Similarly, when expressed in kWh/cycle, the range from maximum to minimum is 8.4, noting that both are site measurements – CS 6 at 4.62 and CS 12 at 0.55 kWh. It may also be noted that the former was the only one occupant of the three where tumble drying consumption was measured on site, and who consumed as much as manufacturers' predictions for full cotton loads; and, even then, the relative infrequency of usage during monitoring indicated a correspondingly modest annual total of 120 kWh/person or 360 kWh for the household of three. In the other two cases that were measured on site (3 and 12) the consumption for brief cycles was significantly less than that predicted by manufacturers for full drying of cotton loads, averaging 3.8 kWh/cycle for Case Studies 1, 4, 5, 8 and 11 (4.25* value for both CS 10 and 13 is half of manufacturer's estimate for 16 kg full load of 8.5 kWh/cycle for commercial appliance in communal laundry as in 10). In other words, it seems that awareness of the expense of operating tumble dryers was responsible for economy, either by drying partial loads or by not fully drying.

7.3 If CS 6 is taken as a norm for full-load and full-cycle tumble-drying, its estimate of 360 kWh annually for the household closely matches the 354 kWh estimated by the DEFRA Market Transformation Programme, Briefing Note BNW06 (2008a). However, in making this comparison, one must bear in mind that this household only had three washing and drying cycles in the 2-week period, which is less than typical. Nevertheless, since this value appears to approximate to a government benchmark, it is of interest to compare it with the additional thermal energy implicit in passive drying households. PM3 simulations based on the rather extreme scenario of CS 2 indicate that its number of wash cycles dried passively in 7-hour periods with open windows (air change increased by 3.6 ac/h) and raised temperatures (by 3K) would add an annual energy load of almost exactly ten times that of the 360 kWh CS 6 value. Proportionately this corresponds with a rise of over 50% over the year, but only 38.5% from October to April, and adds 40 kWh/m$^2$ to the space heating load. Although one would expect the internal base temperature to be frequently not far above, and also below, ambient temperature, modelling nevertheless indicated increases for each month of the year – i.e. suggesting relatively small ratios of free gains to losses.

7.4 The same simulation worked out that this extreme rate of washing, averaging more than one load daily, would entail a tumble drying consumption nearly four times greater than 360 kWh. Although in primary energy terms this would be some 8% greater than the equivalent for extra gas heating for this scenario, the emissions for the tumble drying would be less than that for the extra gas heating. On the other hand, PM3 simulations for an enclosed, heated and ventilated drying cupboard with MHRV, indicated lower energy consumption compared with 1,400 kWh for the extreme CS 2 scenario (without alowing for added space heating demand due to venting practice found in most of the case studies with tumble dryers). In primary energy terms the contrast would be considerably greater if the drying cupboard's heat came from gas, particularly if it were 'borrowed' from a source such as boiler; in which case the $CO_2$ emissions for the drying cupboard would also be significantly less than that for relatively infrequently used tumble drying.

7.5 For washing machines, the mean of 0.75 kWh/cycle (Summary Table 2.a) may be compared with that given by BNW05 for a 2 kg load at 40ºC of 0.63 kWh/cycle (DEFRA, 2008b). The range per hour of running time also expresses the efficiency of operation. The highest (CS 14) at 1.05 kWh is B-rated for energy, compared to the lowest (CS 9) at 0.21, also B-rated, gives a factorial range of 5.0. The next highest (CS 5) is A-rated for energy, and is almost as high as that of CS 14 at 1.00 kWh. However, the high examples tend to be the exception. The median value sits between 0.50 (CS 2) and 0.41 (CS 6); the geometric mean is 0.54; while the arithmetic mean is somewhat higher at 0.59 kWh. Another variable is temperature setting, given as a norm on questionnaires, and in diaries for specific washes. The lowest value of 0.21 kWh for A-rated CS 9 is for hot fill at 30$^{o}$C, and the highest of 1.05 kWh for B-rated CS 14 is cold fill at 30$^{o}$C. Both CS 2 and 6 representing the median are B-rated for energy and used cold fill with 30$^{o}$C stated the norm. Note that low-temperature settings and cool-water detergents to wash bedding do not harm live mites (Platts-Mills & de Weck, 1989). Predictably, the respective range of lowest to highest values extrapolated annually per person is greater than that per hour of use – lowest at 16 (CS 6), highest at 238 kWh (CS 5), a factorial difference of nearly 15. In the same way as for tumble drying, the median is lower than the mean of 67, occurring between 50 (CS 19) and 58 (CS 13); and the geometric mean is 53.3 kWh/p-y. The three lowest (CS 6, 9 and 17) state 30$^{o}$C as the norm, and the latter two also claim hot fill; but respective energy ratings run counter to expectations – B for both 6 and 9, only 17 A-rated. CS 6 and 9 doing some washing by hand, and though this complicates direct comparison, it may explain the low consumption figures relative to the B energy rating. The highest, CS 5, with cold fill, 40$^{o}$C normal and A-rated for energy efficiency is undoubtedly in part due to the lengthy cycles, a recognized 'feature' of the particular appliance. The household also adopted a fairly intensive regime of use and had the second highest consumption per hour of use. All these circumstances must contribute to the unusually high extrapolation.

7.6 The range for the estimated consumption per person for annual use of steam irons follows a similar pattern with a factorial difference of 11.0. Again the median at 7.0 kWh/p-y is considerably (44%) less than the arithmetic mean average of 12.5 kWh/p-y, with the geometric mean between these two values at 9.8 kWh/p-y; indicating a general trend towards partial ironing with a correspondingly moderate energy burden.

7.7 There is a significant difference between households where tumble drying was the only or dominant method and those drying mainly passively inside or outside. Summary Table 2.c below demonstrates increases in the 30-40% range comparing the tumble dryers (sole or dominant method, per person and household) with the entire set from Summary Table 2.a; and significantly more when tumble dryers are compared with non-tumble dryers.

SUMMARY TABLE 2.c Ironing consumption relative to drying method

| Sample | households | average | kWh/p-y | % increase | kWh/h-y | % increase |
|---|---|---|---|---|---|---|
| TD set | 8 No. | arithmetic | 17.4 | 39% | 32.9 | 31% |
| All set | 19 No. | arithmetic | 12.5 (100%) | | 25.1 (100%) | |
| TD set | 8 No. | geometric | 13.2 | 35% | 27.2 | 31% |
| All set | 19 No. | geometric | 9.8 (100%) | | 20.8 (100%) | |
| TD set | 8 No. | geometric | 13.2 | 67% | 27.2 | 58% |
| non-TD set | 11 No. | geometric | 7.9 (100%) | | 17.2 (100%) | |

kWh/p-y = annual consumption per person; kWh/h-y = annual consumption per household

7.8 The use of fabric softeners, especially for those who vent tumble dryers via a hose through an open window or even fail to vent outside (see detailed notes for CS 3, 5, 6 and 8 in Part B), or who iron in an over-humid setting as CS 11 (see also Part B notes), are also running a potential risk of exacerbated off-gassing of water-soluble VOCs such as acetaldehyde (Steinemann et al, 2008). Even though some of the chemical output may have been ventilated outside or absorbed in condensate, depending on type of dryer, or already emitted to the host room in the case of passive indoor drying, the effect of the steam-ironing is likely to facilitate the release of residual chemical content. The additional moisture from the iron and the ironer will in any case add some extra humidity to a potentially already fragile environment (see Appendix 1).

8.0 Bearing in mind the scope for inaccuracy in observation 7.0, in particular when data from 2-weeks of monitoring are extrapolated to a year per person, there is an even larger range of total delivered energy, primary energy and carbon emissions for all three appliances – the factorial difference in each case comfortably over 20. Nevertheless, the data provide a useful basis for comparison with typical total domestic power consumption.

8.1 The median values in each case are again significantly lower than the arithmetic means – respectively 105 kWh/p-y (consumed); 288 kWh/p-y (primary); 57 kg $CO_2$/p-y; and similary geometric means 108 kWh/p-y (consumed); 297 kWh/p-y (primary); 59 kg $CO_2$/p-y. With an average of 2.41 persons per household among the case studies respective 'house' median values rise to 253 kWh/y (consumed); 693 kWh/y (primary); 137 kg $CO_2$/y; and geometric means to 260 kWh/y (consumed); 716 kWh/y (primary); 142 kg $CO_2$/y. The equivalent 'house' arithmetic means are: 419 kWh/y (consumed); 1,150 kWh/y (primary); 227 kg $CO_2$/y. It is possible to estimate ballpark percentages for the median and arithmetic mean relative to typical total power consumption for lighting and appliances. The typical floor area for all 22 case studies is approx. 65 $m^2$, and the average household size is 2.41 persons. Thus median consumed energy demand per average household divided by 65 gives a value in kWh/$m^2$, which is 11.1% of typical total power consumption of 35 kWh/$m^2$.* Repeating this process for the geometric means (energy and carbon), the proportion rises slightly to 11.4%; and for the significantly higher arithmetic mean it increases to 18.4%.
[*Note: 35 kWh/$m^2$ is a pragmatic benchmark based on the UK mean floor area for a household of 2.41 persons (Boardman et al, 2005; citing work published by the Office of the Deputy Prime Minister or OPDM, 2003); where DEFRA 'reference' values for all power use total approximately 39 kWh/$m^2$ and those for 'Earliest Best Practice' or EBP, including maximum energy ratings, total approximately 27 kWh/$m^2$.]

8.2 It may also be noted in this regard that the typical power use figure of 35 kWh/$m^2$ is likely to fall for larger dwellings, where key appliances are not duplicated; and, similarly, likely to rise for smaller dwellings. A recent 2-week monitoring exercise, where a 123 $m^2$, five-apartment dwelling was occupied by four volunteers, halved the value to 17 kWh/$m^2$. However, the occupants did not use as many appliances as one would expect in a permanent residence, and a relatively large Canadian house of 230 $m^2$ recently reported an annual figure of 21.6 kWh/$m^2$ for lighting and appliances (4,962 kWh). By contrast, a set of smaller dwellings of 56.5 $m^2$ in Glasgow averaged 37.2 kWh/$m^2$, a somewhat higher figure than the benchmark of 35 kWh/$m^2$.

8.3 Returning to the proportional median and arithmetic mean estimates of power use associated with domestic laundering as a percentage of typical total power use, 11.1% and 18.4% respectively, we must bear in mind that these takes no account of additional impacts on space heating attributable to indoor drying, as indicated in Summary Table 2.b – with 8 dwellings categorised as 'significant', 10 as 'some' and only 4 as 'none'. Neither does it take account of the impact on space heating when windows are opened to allow the flexible venting hose of tumble dryers to exhaust their warm and humid air.

9.0 It is also of interest to compare the primary median and arithmetic mean kWh values with the equivalent for the German Passivhaus space heating and total primary energy limits, where the more energy-efficient targets will cause percentages to rise significantly.

9.1 If we firstly take the Passivhaus space heating maximum of 15 kWh/$m^2$, divide by 0.91 for efficiency of a gas condensing 'combi' boiler to give 16.5 kWh/$m^2$ delivered; and divide this by a 'primary to delivered' coefficient of 0.9, the demand of 15 kWh/$m^2$ rises to 18.3 kWh/$m^2$. If we assume delivered hot water for 2.41 persons at 85% efficiency is 2,300 kWh, we might assume 40% is met by solar thermal collection; dividing the balance by 65 $m^2$, we get 21.23 kWh/$m^2$; in turn dividing this by a 'primary to delivered' gas coefficient of 0.9, the primary hot water by fossil fuel comes to 23.6 kWh/m$^2$. The primary energy total for space heating and hot water is therefore approximately 42 kWh/m$^2$. Subtracted from the Passivhaus limit of 120 kWh/m$^2$ for total primary consumption, this leaves 78 kWh/m$^2$. However, to allow a margin for fans, pumps and efficiency loss, the balance is reduced to 76 kWh/m$^2$. The median laundering consumption of 105 kWh/p-y (8.1 above) divided by 0.365 primary electrical efficiency gives 288 kWh/p-y; and this multiplied by 2.41 persons = 693 kWh/y; thence divided by 65 m$^2$ = 10.7 kWh/m$^2$; which is 14.0% of the 76 kWh/m$^2$ Passivhaus balance for lighting and appliances. Repeating for the mean average of 174 kWh/p-y, the primary value for laundering rises to 17.7 kWh/m$^2$, which increases the proportionate share of total lighting and appliances to 23.3% of the 76 kWh/m$^2$ allowance.

9.2 However, it seems likely from recent monitoring studies – e.g. that for Elm Tree Mews, (Wingfield et al, 2011) – that actual boiler efficiencies for A-rated condensing boilers will be lower for heating – approximately 85%, not over 90%; and hot water may be subject to the vagaries of intermittency and distance from boiler to supply point; noting that the 2006 SAP rating for a condensing gas boiler was 85% for heating and 83% for hot water. If we pragmatically assume 85% heating efficiency and 80% hot water efficiency, and then omit a solar thermal system, the net rise in primary delivered energy will reduce the balance available for lighting and appliances to circa 56.6 kWh/m$^2$. Respective median and mean proportions for domestic laundering activities would then rise to 19% and 31%.

9.3 Comparing respective median and mean proportions of 14.0% and 23.3% in 9.1 above, and 19% and 31% in 9.2 above, with those in 8.1 – 11.1% and 18.4%, the tightening of overall energy efficiency implied by the Passivhaus standard is evident. In other words, if laundering activity maintains a status quo, other energy economies with regard to lighting and appliances are required – acknowledging the sensitivity of the analysis to floor area.

9.4 Furthermore, if the Passivhaus standard is to be achieved as in 9.1/9.2 above, the other laundering impacts on space heating, as alluded to in 8.3 above, must be eliminated.

9.5 In regard to 9.4, and using the optimistic figures derived in 9.1, comparisons with the Passivhaus primary value for space heating is of interest. Median primary consumption of 10.67 kWh/m$^2$ for laundering (105 x 2.41 / 0.365 x 65) is 58% of a Passivhaus space heating value of 18.3 kWh/m$^2$. Secondly, the mean laundering equivalent of 17.7 kWh/m$^2$, is 96.5% of that required for space heating. For average laundering in a varied sample of house types and demographics to almost match modern expectations for space heating seems remarkable. Athough it is technically easier to reduce space-heating loads, and they would reduce further if renewable fuel is used to meet thermal demand, some effort is required to curtail the laundering consumption of electricity. Additional effort is required, as noted in 9.3, to curtail laundering impacts on space heating demand. The evident risk in this regard from the survey and analysis is that electrical savings on tumble drying tend to generate a ‘catch 22’ by increasing thermal loads, as well as reducing the quality of the indoor environment in such a way that has health implications for the occupants.

9.6 Looking again at a specific case study, that of CS 6 (see 7.3 above), where a tumble dryer was used for full loads and measured, there is less risk of inaccuracy compared with using means or medians, and the relationship to Passivhaus standards is stark. Taking the total primary energy figure of 392 kWh/p-y, multiplying by the household of 3 and dividing by the area of 65 m$^2$ (approximately correct for CS 6), we get 18.1 kWh/m$^2$, which is 99% of the 18.3 kWh/m$^2$ Passivhaus equivalent for maximum space heating. It is also 24% of the 76 kWh/m$^2$ arrived at in 8.1 above, or 32% of the 57 kWh/m$^2$ estimated in 9.2, as the total available for lighting and appliances. This serves to emphasize the ‘catch 22’ point made in 9.5 above – tumble drying has a large primary energy penalty, often made worse by venting practice via open windows, but normal passive drying carries other hazards.

9.7 Summarising the ‘what if?’ scenarios examined in terms of values for laundering appliances:
a) mean where space heating is 91% efficient, water heating 85% and 40% met by solar thermal;
b) median where space heating is 91% efficient, water heating as a);
c) mean where space heating is 85% efficient, water heating 80% and there is no solar thermal.

9.8 Estimated Glasgow values for laundering appliances are used alongside UK averages* for other appliances and expressed firstly for a floor area of 65 m$^2$ and secondly for 90 m$^2$:

Lighting (EBP) 4.6; 3.32 kWh/m$^2$ (DEFRA, 2008c); fridge ('best available technologies' 2008) 2.4; 1.73 kWh/m$^2$ (DEFRA, 2010a); upright freezer ('best available technologies' 2008) 2.7; 1.95 kWh/m$^2$ (DEFRA, 2010a); dishwasher (A-rated, 9-place setting capacity) 4.6; 3.32 kWh/m$^2$ (DEFRA, 2008d); PCs and laptops 2.65; 1.91 kWh/m$^2$ (DEFRA, 2010b); TVs 4.6; 3.32 kWh/m$^2$ (Chobanova, McNeil and Letschert, 2009)**; Kettles 1.9; 1.37 kWh/m$^2$; hobs 3.3; 2.28 kWh/m$^2$; ovens 1.5; 1.08 kWh/m$^2$; microwave 1.4; 1.01 kWh/m$^2$ (DEFRA, 2008e) – total 29.65; 21.29 kWh/m$^2$. [Notes: *DEFRA population and household statistics (2010c); **interpolating values given for Western Europe of 39.6 TWh in 2005 to 103.6 TWh in 2030 to 52.4 TWh in 2010; and assuming 174.91 x $10^6$ households = 300.0 kWh/household ÷ 65 m$^2$ = 4.6 kWh/m$^2$.]

9.9 The analysis reveals a significant underlying problem for scenarios a-c) for 65 m$^2$ floor area, but suggest that scenario a) and 90 m$^2$ should be feasible within the Passivhaus standard, providing the relatively low values for laundering appliances in Glasgow prevail. Although the analysis omits miscellaneous electrical items such as electric toasters common in most homes, the balance of 25.5 kWh/m$^2$ gives some leeway relative to 21.3 kWh/m$^2$; this assuming maximum efficiency ratings and 'earliest best practice' (EBP). Scenario c) at 90 m$^2$ is borderline in this regard – see summarised data in Table 10 below.

SUMMARY TABLE 2.d Testing viability of Passivhaus standard relative to laundering data

| Scenario | hw + sh (PE) (kWh/m$^2$) | net el'y (PE) (kWh/m$^2$) | laundry (PE) (kWh/m$^2$) | balance (PE) (kWh/m$^2$) | balance (UE) (kWh/m$^2$) | UK cf. (UE) (kWh/m$^2$) |
|---|---|---|---|---|---|---|
| a) 65 m$^2$ | 42.0 | 76.0 | 17.7 | 58.3 | 21.3 | 29.65 |
| a) 90 m$^2$ | 35.3 | 82.7 | 12.8 | 69.9 | 25.5 | 21.29 |
| b) 65 m$^2$ | 42.0 | 76.0 | 10.7 | 65.3 | 23.8 | 29.65 |
| c) 65 m$^2$ | 61.4 | 56.6 | 17.7 | 38.9 | 14.2 | 21.29 |
| c) 90 m$^2$ | 44.3 | 73.7 | 12.8 | 60.9 | 22.2 | 21.29 |

Legend:
hw + sh (PE) = hot water plus space heating (Primary Energy)
net el'y (PE) = net electric power available having deducted fans/pumps (Primary Energy)
laundry (PE) = power estimated for laundering appliances in Glasgow (Primary Energy)
balance (PE) = balance electric power available for lighting + appliances (Primary Energy)
balance (UE) = balance electric power available for lighting + appliances (Used Energy)
UK cf. (PE) = UK comparator (official estimates) for lighting + appliances (Used Energy)

9.10 What this means is that unless the primary to useful delivered grid efficiency in the UK improves significantly, Passivhaus standards will be hard to achieve, especially when or where house areas are small. Even if all appliances, including those relating to laundering activity in the home, move to maximum achievable efficiency and consumers become more frugal in their use of such commodities, in the normal constrained 'social' and competitive private housing sectors, low- and zero-carbon standards will remain illusory.

10.0 The above observations imply a direction that welcomes an improvement to appliance efficiency as well as more appropriate passive laundering strategies, in particular for the drying of washing loads, but also to accommodate the moisture impacts of steam irons.

10.1 For example, ambient-temperature ozone washing technology might penetrate the domestic market; recovered heat from waste water (washing machines) and air (tumble dryers) could preheat water; better market penetration of improved heat-pump tumble dryers, with typical consumption less than 2.0 kWh full cotton cycle could potentially be improved further by sourcing warm ambient air from fridge/freezers. Such technical improvements would require to be both simple and economic to gain traction.

10.2 However, the observations also imply that much more is required to make use of appliances unnecessary, in particular tumble dryers, but also steam irons. If adequately 'quarantined', heated and ventilated indoor spaces and semi-outdoor spaces were provided for drying, much ironing could be deemed redundant, as well as drying with an inherently energy-intensive appliance. In this regard, passive solar gain may be exploited to accelerate drying in indoor or semi-outdoor spaces. Furthermore, moisture buffering of the bounding surfaces of a dedicated drying space, may assist in reducing the rate of ventilation required, as well as potentially mitigate sudden inputs of moisture from other activities if used stragically in other 'wet' areas of a dwelling. Hence the moisture absorption properties of various materials have been an important part of the laboratory investigations by RICH (PM 2) in parallel with the field surveys and subsequent analysis by MEARU. This in turn feed in to the advanced modelling process by ESRU (PM 3).

11.0 As washing clothing and other fabric represents some 12% of total domestic use indoors at 50 l/cycle (DEFRA, 2008b) and approximately 21% of 'grey' waste water*, with a total average annual water use per household for the case studies of circa 120,000 litres per dwelling (150 l/person daily), the opportunities for saving energy and carbon emissions from this alone is very limited. However, in tandem with other domestic 'grey' water, although there is limited carbon-saving potential for recycling for flushing WCs, there is potential for contributing to thermal demand via a water-source heat pump.

*Note: 21% from all key washing activities – clothes/bedding, dishes and personal hygiene (Environment Agency, 2011).

11.1 If we take a Scottish $CO_2$ emissions value of 0.17 g/l for supply and 0.81 g/l for waste (Scottish Water, 2011), we could potentially save approximately 1.0 g/l by grey-water recycling to flush WCs – possibly a net saving of 0.9 g/l, allowing for emissions arising from this process. But since a typical household might use from 30,000-40,000 litres for flushing annually, the annual $CO_2$ saving potential is only of the order of 27-36 kg/house; and the proportion attributable to domestic laundering a part of this. Nevertheless, the saving on $H_2O$ use, rather than $CO_2$, would be valuable. Even though it might seem that rainwater is a plentiful commodity in Glasgow, harvesting it from Loch Katrine or the Renfrew Hills and getting it to its urban dwellings is an expensive business, and WCs do not require to flush with potable water. Having said that, capturing rainwater on site is simpler than utilising grey water for this purpose, given that only basic filtration is required.

11.2 On the other hand, grey water embodies thermal potential. If all of it is passed through a holding tank of 300 l/house, (1.2 x 0.5 x 0.5 m) allowing for a daily throughput of 'grey' water of 70% of a net capacity of 270 litres or approximately 185 l (Environment Agency, 2011), the mean temperature in the tank is 20$^o$C, and this is reduced by 15 K to 5$^o$C by a heat pump of 2.5 COP, the tank should give a daily yield of circa 12 kWh (0.001163 kWh x 270 l x 15 K x 2.5 = 11.8 kWh, where 1.163 Wh raises 1 litre water by 1 K). Even a temperature difference of 7 K would yield 5.5 kWh on a daily basis. Since hot water demand for this size of household is likely to be in the range 5.0-5.5 kWh/day, such a system should be viable, with additional benefits for larger systems for groups of houses. To fund 5.5 kWh/day from solar PV net over a year, with a COP of 2.5 implies approximately 10 $m^2$ PV averaging 80 kWh/$m^2$; and to fund 12.0 kWh/day output would require approximately 22 $m^2$ PV, and provide at least 6.5 kWh/day to meet space-heating demand. But a solar thermal array in tandem with a heat pump and PV of 10 $m^2$ could also facilitate tackling space heating demand renewably.

11.3 In order to establish the viability of such a system, a live demonstration project would be required, with funding to include a detailed research and development (R&D) stage as well as capital costs of installation and those for detailed monitoring over at least one year. The three technical key risks would be: a) inadequate average outflow temperature for all grey water to fund a suitable temperature difference as indicated in the ballpark estimate above: b) a COP significantly less than the assumed 2.5 value; c) too low a supply of grey water on a daily cyclical basis. A fourth risk would be that the initial cost of the holding tank and associated extra plumbing would not compare favourably with equivalent costs of other ambient sources for a heat pump.

## PART D ADDITIONAL OBSERVATIONS FROM SURVEY OF 100 HOUSEHOLDS

12.0 In terms of washing machine and detergent/softener usage, means of drying, ironing and ventilation, all with relevance in terms of air quality and/or humidity, the sample of 100 is reasonably representative of the set of 22 that were monitored.

12.1 The following table summarises the key data with regard to washing machines. 46 of the 100 dwellings surveyed both used fabric softeners and passive indoor drying, 32 of which did not own a tumble dryer and all but one of these used indoor passive drying, 29 in rooms, 2 in dryng cupboards. It may also be noted relative to those that used softeners and a tumble dryer (18 of the 100 households in Glasgow), work in USA has also established a level of reported irritation to scented laundry products vented outside by tumble dryers, 10.9% from two samples of over 1,000 people (Caress and Steinemann, 2009). Logically, this would suggest expectancy for higher numbers to experience irritation, if not adverse health effects, from the VOCs from fabric softeners within the confines of their homes. Note that the US Environmental Protection Agency (EPA) published a list in 1995 of nine chemicals and associated health risks found in fabric softeners and/or drying sheets for tumble driers (authored by Julia Kendall); and Steinemann et al (2008, 2011) has ranked concentrations of chemicals in fabric softeners and detergents, including acetaldehyde, a 'hazardous air pollutant' classed by EPA as a probable carcinogen. However, this study did not attempt to relate use of softeners or detergents to the health of occupants.

SUMMARY TABLE 3.1 Washing machine energy rating, detergents and softeners

| Sample | A-rated | B-rated | C-rated | D-rated | unknown | n.a |
|---|---|---|---|---|---|---|
| 100 No. | 56% | 27% | 9% | 1% | 1% | 6% |
| 22 No. | 59% | 27% | 5% | 0% | 0% | 9% |
| | bio | non-bio | variable | softener | no softener | n.a. |
| 100 No. | 49% | 32% | 13% | 51% | 43% | 6% both sets |
| 22 No. | 50% | 23% | 18% | 64% | 27% | 9% both sets |

12.2 With regard to tumble dryers, 33% of the 100 surveyed households used one, 24% individual appliances within the home and 9% communal (slightly more than those making use of communal/commercial washing). This compares with 45% of the 22 case studies, or ten dryers of which seven were within the home and three were communal. However, of the 33% in the 100 sample, only 5% used tumble drying exclusively for drying, and 1% used a dryer in conjunction with a dedicated drying cupboard; so that 27 of the 33% used tumble dryers in association with other forms of drying that included passive drying inside other spaces within the homes. Of the 24% (24 households) with their own appliances, 11 used some form of internal airer to supplement the drying process, and another 10 some other means. Of the 22 case studies, the proportion that used tumble-drying exclusively was greater at 14% (3 No.), although still numerically very much a minority at less than one third of the total used.

12.3 With 99% ownership, and 4% unknown makes, the mean power rating of 95 steam irons was 1.71 kW, ranging from 1.0-2.4 kW. (See 13.32 below for details of usage.)

12.4 In the case of presence versus absence of at least one extract fan, the sample of 100 has marginally fewer – 72% with compared with 77% (17 No.) in the smaller sample of 22 dwellings. The presence of at least one fan may assist in the dispersal of water vapour and odours from drying, but 22 of the 100 dwellings employ passive drying indoors with no mechanical assistance in terms of exhausting water vapour. There are also 4 households without mechanical extraction who claim to undertake no passive drying indoors. Indoor passive drying undoubtedly influences habits with respect to window opening while drying takes place, the impact of which during the heating season will be reviewed below.

13.0 The preponderance of surveys during winter (34 ex 100), compared with the 22 case studies, allows the issue of passive drying relative to window opening and heating to be further examined, albeit without the benefit of durational measured data.

13.1 Out of 34 households interviewed in winter (between December to February) 28 (82%) passively dried with their homes, often in more than one space. Of these, 19 (68% of 28) located airers on/near heat emitters, and 6 (21% of 28) of these admitted to turning heat up to speed the drying process. In terms of moisture mitigation, 8 (31% of 26 applicable cases) said that a window was always open while drying, and a further 13 (50% of 26) occasionally opened windows. Some 'occasional' window openers coincided with heat-to-dry boosters, but none of those that 'always' opened windows also boosted heat.

13.2 Of the 28 households, 12 (43% of 28; 35% of 34) owned tumble dryers. Of these, 2 (7% of 28; 6% of 34) used it as the sole means of inside drying, 10 used an external method, and 10, including 9 of that 10 (32% of 28), dried inside to augment the machine.

13.3 In addition to heated indoor spaces, 5 (15%) of the winter cohort of 34 had some form of conservatory or sunspace that offered potential for drying. As it happened, this was the only seasonal group out of the entire set of 100 to have this facility (i.e. 5% of total). There were also 3 with a shared backcourt drying area, 1 with a rooftop drying area, 2 with a balcony, 5 with other communal drying facilities such as semi-enclosed rooms and 8 with a garden. One of the gardens was the only auxiliary drying system used apart from a tumble dryer. The other seven shared passive drying facilities outside the home constituted one of a palette of methods used, including passive drying within the home itself.

13.4 Since many of the dwellings surveyed in winter were monitored over two weeks in spring or summer (end of monitoring in June taken as summer), it is to be expected that significant variability will occur between spot and durational measurements. Summary Table 3.2 summarises $CO_2$ and RH, averaged for living rooms and bedrooms in each case.

SUMMARY TABLE 3.2 Spot data for winter cohort cf. spring/summer monitored data

| Date | $CO_2$ (L & B) | RH (L & B) | Case Study | season | $CO_2$ (L & B) | RH (L & B) |
|---|---|---|---|---|---|---|
| 08/01/09. | 1,301 ppm | 39.3% | 17 | spring | 680 ppm | 45.4% |
| 09/01/09 | 994 ppm | 58.5% | 11 | summer | 1,306 ppm | 64.5% |
| 12/01/09 | 1,761 ppm | 59.7% | 10 | summer | 711 ppm | 52.7% |
| 13/01/09 | 1,020 ppm | 40.7% | 1 | summer | 689 ppm | 44.7% |
| 13/01/09 | 1,096 ppm | 40.0% | 4 | spring | 1,259 ppm | 52.7% |
| 20/01/09 | 1,090 ppm | 45.1% | 18 | spring | 584 ppm | 45.6% |
| 03/02/09 | 883 ppm | 45.1% | 19 | spring | 801 ppm | 47.5% |
| 03/02/09 | 950 ppm | 38.4% | 21 | spring | 925 ppm | 42.2% |
| 05/02/09 | 1,215 ppm | 41.2% | 7 | spring | 1,260 ppm | 54.6% |
| mean 9 No. | 1,146 ppm | 45.3% | 9 No. | | 913 ppm | 50.0% |

Note that the RH in all except Case Study 10 moved upwards from winter to spring and summer, and some of these significantly so (CS 4, 7 and 11). Rather lower temperatures with the heating off and/or windows more frequently opened could be the explanation for this. The majority of $CO_2$ levels also moved down, again some significantly (CS 1,10, 17 and 18) and more liberal ventilation coupled with less intensive occupation could explain this tendency. However, the durational $CO_2$ for three case studied are higher than the winter spot measurements, the explanation in these instances (CS 4, 7 and 11) likely to be higher evening and overnight intensity of occupation, with relatively little window opening.

14.0 There was a reasonable proportion of households surveyed in spring and autumn, both in the initial cohort of 100 and the 22 case studies drawn from that number; and since these 'fringe' seasons still involve significant use of space heating, passive indoor drying is again (as in winter) likely to impact on energy consumption and ventilation control.

14.1 Of the 26 households interviewed in spring (between March and May), 25 (96%) passively dried within their homes, again often in more than one space. In this case 15 (60% of 25; 8% less than in winter) stated that they located airers close to sources of heat, and 8 (32% of 25; 11% more than in winter) to turning heat up to assist drying. Two of these coincided with one of a slightly smaller number, 7 (28% of 25; 1% less than in winter), who declared a window always to be open when drying, while 12 (48% of 25; 2% more than in winter) stated that they occasionally opened windows when drying.

14.2 Of the 25 households using some form of airing device within the home, 5 (20% of 25; 19% of 26) owned tumble dryers, and 4 of these also used an external method of passive drying to augment that of the machine. In other words, there were relatively far fewer owners of tumble dryers in the spring set compared with winter. Only one of this set made use of a communal tumble-drying facility, but that household was also one that dried passively on airers within the home and always opened windows while doing so.

14.3 Of the 26 in the spring set, 4 (15%) had access to a backcourt for communal drying, there was 1 additional communal drying facility, 3 balconies and 3 gardens, all of which were used in addition to internal drying within the home. Proportionately somewhat fewer in the spring cohort used more than one room or space to passively dry indoors – 13 ex 25 or 52%, compared with 18 ex 28 or 64% for the winter set.

14.4 Only three of the original spring cohort became durational case studies, the season in each case shifting to summer. Again the durational measurements, in particular those for $CO_2$, were at some variance from the original daytime spot measurements, and it seems likely that the lower $CO_2$ values can be explained by opening windows and/or lower intensity of occupancy inside the home. However, given the small number monitored over two weeks in this case, the comparisons may be misleading. For example, households that occupied their homes intensively during evenings and overnight would not conform.

SUMMARY TABLE 3.3 Spot data for spring cohort cf. summer monitored data

| Date | $CO_2$ (L & B) | RH (L & B) | Case Study | season | $CO_2$ (L & B) | RH (L & B) |
|---|---|---|---|---|---|---|
| 07/04/09. | 1,440 ppm | 40.9% | 13 | summer | 911 ppm | 46.4% |
| 27/04/09 | 1,420 ppm | 45.2% | 12 | summer | 540 ppm | 53.2% |
| 20/05/09 | 1,400 ppm | 55.9% | 14 | summer | 704 ppm | 55.0% |
| mean 3 No. | 1,420 ppm | 47.3% | 3 No. | | 718 ppm | 51.5% |

14.5 Of the 36 households interviewed in autumn (September - November), 30 (83%) passively dried indoors, again often in more than one space. In this case 19 (63% of 30; 2% less than in winter) located airers close to sources of heat, and 5 (17% of 30; 4% less than in winter) turned heat up to assist drying. Two of these coincided with one of a proportionally larger number, 14 (50% of 28 applicable cases), who declared a window always to be open when drying, and 12 (43% of 28 applicable cases) recorded windows opened occasionally when drying. The most potent addition to energy loads would be from the number that turned up their heat to assist drying, especially if it coincided with opening windows. In this case the greater proportion of the ‘heat boosted’ category occurred in spring, when average ambient temperatures tend to be lower (by 1.64 K in Glasgow); while the greater proportion of the ‘window always open’ category were in autumn.

14.6 Of the 30 households using some form of airing device within the home, 4 (13% of 30) owned tumble dryers, and two of these also used an external method of passive drying to augment that of the machine. There were 3 other owners of tumble dryers in the autumn set that did not passively dry inside their dwellings, but one of these also used a backcourt for passive drying. There were 2 who used tumble dryers in facilities outside the home, both of these also using an external line on their own private balcony, but not drying inside.

14.7 Of the 36 in the autumn set, 14 (39%) declared access to a backcourt or communal covered drying space for drying, 1 of whom used this as the sole means of drying. There were also 4 private gardens and 2 balconies, both of the latter used as the sole means of augmenting active communal laundering facilities. In this autumn cohort proportionately somewhat more used more than one room or space to passively dry indoors – 22 ex 30 or 73%, compared with 18 ex 28 or 64% for the winter set.

14.8 A reasonable proportion of the autumn cohort (7 ex 36 or 19%) was represented in the monitored case studies, and for all but one this phase of the research also occurred during autumn. Hence, the likely reason(s) for differences are more evident in some cases.

14.9 For example (Summary Table 3.4 below), the large increases in $CO_2$ for CS 5, 6 and 22 are likely to be due to nocturnal intensity of occupation with closed windows, all three spot measurements occurring from morning to early afternoon. However, significant falls in $CO_2$ averages compared with spot data in CS 2 and 3 are less easy to rationalise. Perhaps the time of spot measurements in early evening between 7.00-8.00 p.m. coincided with a period of intense occupation. It should also be noted that some of the durational averages are very high in absolute terms – e.g. CS 6 for both $CO_2$ and RH (refer to detailed case study notes in Part B above); and that RH levels are generally of a higher order than those in Summary Tables 3.2 and 3.3. Furthermore, six of the seven spot $CO_2$ levels are above the recommended maximum of 1,000 ppm that corresponds with a fresh air supply of 8 l/s for each person present. This suggests a greater need for fresh air at a time when ambient humidity tends to be high, thus providing an environmental context whereby additional moisture from passive drying would not be welcome.

SUMMARY TABLE 3.4 Spot data for autumn cohort cf. autumn/winter monitored data

| Date | $CO_2$ (L & B) | RH (L & B) | Case Study | season | $CO_2$ (L & B) | RH (L & B) |
|---|---|---|---|---|---|---|
| 23/09/09 | 1,190 ppm | 41.8% | 5 | autumn | 1,630 ppm | 60.6% |
| 30/09/09 | 1,198 ppm | 64.1% | 8 | autumn | 982 ppm | 70.0% |
| 14/10/09 | 818 ppm | 74.5% | 15 | autumn | 875 ppm | 70.3% |
| 14/10/09 | 1,290 ppm | 53.8% | 3 | autumn | 719 ppm | 54.7% |
| 15/10/09 | 1,297 ppm | 50.9% | 6 | autumn | 2,174 ppm | 73.2% |
| 23/10/09 | 1,379 ppm | 55.1% | 22 | winter | 1,768 ppm | 42.7% |
| 16/11/09 | 1,504 ppm | 52.5% | 2 | autumn | 962 ppm | 42.3% |
| mean 7 no. | 1,242 ppm | 56.1% | 7 no. | | 1,301 ppm | 59.1% |

14.10 In terms of fine-tuning passive ventilation control, whether related to passive drying or not, nearly half (49 ex 100) reported that they never used trickle vents, although it is conceivable in some of these cases that they remained permanently open, rather than permanently closed. Of the remainder, the majority, 31, claimed to regularly adjust the vents, while 20 said they did this occasionally. Just over one fifth of the total cohort (21) said that they were not sure how to operate the vents and a larger number (28) gave other reasons for non-use including obstructions to accessibility and non-functionality.

14.11 In terms of mechanical exhaust, of the 64 with this facility in bathrooms, 17 declared the control to be manual and 13 automatic. Lack of knowledge regarding the remaining 34 again highlights the poor overall level of awareness in this regard. For kitchens the proportion aware of whether a fan was manual or automatic was greater – of a total of 42 fans, 27 declared manual use and only one automatic. The low response in the latter regard can be explained by the number that were linked to vertical bathroom 'shunt' exhausts in high-rise towers.

15.0 Even though the spot readings cannot be considered representative of longer data collected over successive 24-hour cycles, they may be regarded as indicators of a set of 'snapshot' environmental contexts, and this is relevant for both drying and ironing.

15.1 Accepting the limitations of 'snapshots' and averages, we may note that the mean for three rooms in the entire set, the living room and two bedrooms, is 1,251 ppm $CO_2$ (some 25% above the desired maximum value), while mean of temperatures in the same room is 19.3ºC and RH 53.4%. This gives a mean average mixing ratio above 7.3 g/kg (1.17 kPa), which is approximately 4% above the maximum recommended by Platts-Mills and De Weck (1989) relative to inhibiting dust mites; dust mites in turn causally linked to incidence of asthma. On the other hand, this lies just within the 'critical equilibrium humidity' curve for mite growth, expressed as a function of temperature and derived from values given by Cunningham (1998). It therefore implies a borderline average in terms of the spot readings. Axiomatically, if an average is at a maximum limit, it means that there will be frequent occurrences above that limit, and armed with the knowledge of the preponderance of passive indoor drying, we may conclude that this plays an undesirable part.

15.2 Ironing will also have a role in this regard. Of the 100 households surveyed, 99% climed to use their iron, 26 said that they ironed all their washing, 51 approximately half and 22 less than half. One experiment with a complete load of washing ironed over a 2-hour period was found to raise the moisture level by approximately 1 g/kg (0.17 kPa), this in the living room of the same flat type as Case Studies 19 and 20 (see also Appendix 1 for a range of VP increases). The significance of this would of course depend on the environmental starting point in terms of temperature and humidity. In this case the temperature remained stable with an increase of only 0.4 K from start to maximum; while the RH rose by 6.4%. The $CO_2$ also rose by 169 ppm, but not so as to affect air quality adversely, with a maximum at 774 ppm.

15.3 To expand on 14.1 and 14.2, the overall context from daytime 'snapshot' readings, which are likely to be considerably lower than 24-hour averages once evenings and bedrooms overnight are included, is of concern. It is one where air quality is poor, above the accepted 1,000 ppm maximum by some 20-30%, and humidity is above the Platts-Mills and De Weck (1989) dust-mite threshold by some 2-10%. However, the averages of spot readings for all 100 dwellings only indicate bedrooms and bathrooms as being over the 'critical equilibrium moisture' per temperature curve for dust mites as given by Cunningham (1998). Hence the prospect of dust mite excess sounds less serious than for air quality, but once the inevitable peaks are taken into account respectively, it indicates an environmental context redolent of poor ventilation control, whereby passive drying and steam-ironing are bound to exacerbate matters. Summary Table 3.5 illustrates the point.

SUMMARY TABLE 3.5 Spot data averages for 100 dwellings

| Room | $CO_2$ (ppm) | %>1,000ppm | Temp. ($^oC$) | RH (%) | VP (kPa) | %>1.13 kPa |
|---|---|---|---|---|---|---|
| Living Rm | 1,248 | 25% (24%<) | 19.6 | 51.5 | 1.16 | 3% |
| Bedroom 1 | 1,314 | 31% (21%<) | 19.1 | 52.4 | 1.15 | 2% |
| Bedroom 2 | 1,192 | 19% (31%<) | 19.3 | 56.2 | 1.24 | 10% |
| Kitchen | 1,245 | 25% (26%<) | 19.2 | 52.5 | 1.16 | 3% |
| Bathroom | 1,297 | 30% (21%<) | 18.3 | 56.8 | 1.17 | 4% |
| Hall | 1,314 | 31% (20%<) | 18.9 | 53.3 | 1.15 | 2% |

Note: 3rd column values in parenthesis, e.g. (24%<) for living room, indicate % dwellings where $CO_2$ spot values <1,000 ppm – i.e remaining 76% living rooms > 25% above 1,000 ppm; averaging 1,355 ppm or 36% above the accepted maximum level in this instance.

15.4 None of the 100 dwellings were of an age and standard that could be regarded as 'sealed tight' (i.e. they are not intrinsically airtight), but neither are they 'ventilated right'.

15.5 When we look at spot maxima for the 100 dwellings, the respective values for temperature and RH are not coincident, and the highest moisture levels (VP) occur consistently at maximum RH values rather than those of temperature. For example, in Summary Table 3.6 below the living room maximum VP of 1.94 kPa corresponds with the maximum RH of 77.9% when temperature is at 21.2C; 3.7 K lower than the maximum of 24.9 C, which occurs in another dwelling with a VP level considerably lower at 1.27 kPa.

Note in Summary Table 3.6, however, that both VP values are above the Platts-Mills and De Weck dust mite limit of 1.13 kPa, and that all spot readings were taken at a time when they were unlikely to be at their highest for a 24-hour period. The VP values for other rooms associated with maximum RH are also well above 1.13 kPa, the range varying from 17-72% in excess.

SUMMARY TABLE 3.6 Spot data maxima for 100 dwellings

| Room | $CO_2$ (ppm) | Temp. (°C) | $VP^{T\text{-}max}$ (kPa) | RH (%) | $Temp.^{RH\text{-}max}$ (°C) | $VP^{RH\text{-}max}$ (kPa) |
|---|---|---|---|---|---|---|
| Living Rm | 1,940 | 24.9 | 1.27 | 77.9 | 21.2 | 1.94 |
| Bedroom 1 | 3,790 | 25.4 | 0.86 | 78.2 | 19.1 | 1.72 |
| Bedroom 2 | 3,291 | 25.2 | 0.92 | 76.6 | 18.6 | 1.64 |
| Kitchen | 1,790 | 24.1 | 1.31 | 76.2 | 15.2 | 1.32 |
| Bathroom | 3,480 | 28.0 | 0.88 | 80.2 | 15.2 | 1.39 |
| Hall | 3,510 | 28.3 | 0.88 | 77.3 | 16.2 | 1.41 |

Legend:
$VP^{T\text{-}max}$ = maximum vapour pressure corresponding with maximum temperature (Temp.)
$Temp.^{RH\text{-}max}$ = maximum temperature corresponding with maximum RH (column to left)
$VP^{RH\text{-}max}$ = maximum vapour pressure corresponding with maximum RH and $Temp.^{RH\text{-}max}$

15.6 The picture for the spot minima is rather different, with much greater parity between VP levels that correspond with lowest temperatures and those that correspond with lowest RH, and all these values comfortably below 1.13 kPa. On the other hand, the minimum temperatures are all well below comfort level at a time when the particular dwellings involved were occupied. This in turn raises the issue of poor thermal comfort and fuel poverty, with attendant high risk of mould and mildew. In fact a single dwelling is responsible for all the temperature minima apart from the second bedroom (it only had one), and it had both visible mould in the bathroom and hall, as well as mildewed clothing. In the other dwelling with the coldest temperature of the set of 100 in the second bedroom, the warmth in other rooms was significantly higher and there was no mould or mildew. Note also in Summary Table 3.7 below that the unusually low value of 210 ppm $CO_2$ in Bedroom 2 occurs in another dwelling, but it is low enough to suggest a transcription error.

15.7 In fact a single dwelling is responsible for all the temperature minima apart from the second bedroom (it only had one), and it had both visible mould in the bathroom and hall, as well as mildewed clothing. In the other dwelling with the coldest temperature of the set of 100 in the second bedroom, the warmth in other rooms was significantly higher and there was no mould or mildew. Note also in Summary Table 3.7 below that the unusually low value of 210 ppm $CO_2$ in Bedroom 2 occurs in another dwelling, but it is low enough to suggest a transcription error.

SUMMARY TABLE 3.7 Spot data minima for 100 dwellings

| Room | $CO_2$ (ppm) | Temp. (°C) | $VP^{T\text{-}min}$ (kPa) | RH (%) | $Temp.^{RH\text{-}min}$ (°C) | $VP^{RH\text{-}min}$ (kPa) |
|---|---|---|---|---|---|---|
| Living Rm | 740 | 10.9 | 0.89 | 29.7 | 22.9 | 0.82 |
| Bedroom 1 | 810 | 10.4 | 0.92 | 26.8 | 25.4 | 0.85 |
| Bedroom 2 | 210? | 14.1 | 0.85 | 29.4 | 25.2 | 0.93 |
| Kitchen | 720 | 11.1 | 1.91 | 31.0 | 23.9 | 0.90 |
| Bathroom | 800 | 9.8 | 0.92 | 23.8 | 28.0 | 0.88 |
| Hall | 700 | 11.2 | 0.97 | 30.6 | 23.3 | 0.87 |

Legend:
$VP^{T\text{-}min}$ = minimum vapour pressure corresponding with minimum temperature (Temp.)
$Temp.^{RH\text{-}min}$ = minimum temperature corresponding with minimum RH (column to left)
$VP^{RH\text{-}min}$ = minimum vapour pressure corresponding with minimum RH and $Temp.^{RH\text{-}min}$

16.0 Aside from the hidden or indirect energy impacts, a considerable number of respondents associated the drying part of domestic laundering as a problem or issue.

16.1 A very high proportion, 95% of the overall 100 dwellings surveyed used some form of passive drying indoors, and 49 of these (over half) had some criticism of the practice –

impediment to space, unsightliness, safety issue (over heat emitters), staining (associated with drying on radiators), adding dampness to the air, time to dry etc. 12 households out of 70 who observed surface condensation on windows, mainly after cold nights, associated this with laundering, although most also cited other potential causes such as cooking.

16.2 A relatively low proportion (24 households as noted in 10.2 above) had their own tumble dryers, and of these, 21 augmented their use, overwhelmingly citing expensive running costs as a reason for not purchasing the appliance in the first instance, or limiting use once purchased. A small number also cited lack of space as an issue, and others mentioned that not all washed fabric was suitable for tumble dryers.

16.3 Only five households declared use of drying cupboards, although more were probably built with this facility, especially those of the 1960s (e.g. CS 4), and the small number in use may not have been designed for this purpose. As previously mentioned five dwellings had a conservatory or sunspace that offered potential for solar-assisted passive drying. Only one dwelling had a utility room, although 82 others said they would like one. Surprisingly, 17 said they would not like one.

16.4 A relatively small number, 18 (19%) of the 95 who passively dried indoors, perceived a 'smell' of dampness, and 11 of these also observed visible mould. Altogether there were 53 households with visible mould, but 8 of these were confined to the window sealant, and it was not possible to link the incidence of mould specifically with laundering activities.

16.5 Of the 53 with visible mould, although poor ventilation and/or inadequate heating would play a part in all cases, there was no convincing evidence that the presence of mechanical extract fans assisted or ameliorated. A large proportion, 42, had at least one extract, 14 of these in both bathrooms and kitchen, 21 in the bathroom only and 7 in the kitchen only. More than half of the 53 with mould had no fan reported. However, many of these (16 No) were in tower blocks, which have a vertical 'shunt' mechanical extract system for bathrooms, often also linked to kitchens. On one hand this implies residents tend to perceive mechanical extraction when clearly visible and audible (as a fan set into a window or wall), but not remotely located up a service shaft with only a small register evident. On the other hand, the provision of mechanical extracts means that nearly 80% of those with visible mould had at least one mechanical extract. This should at least limit migration of moist air. Thus where there was a fan or fans, and where mould existed in rooms without fans, it was likely to be due to excess moisture production within that room, or migration of moisture to that room, relative to rate of ventilation and to temperature.

16.6 A BBC TV programme recently showed a significant mould problem above a drying pulley located in the bathroom of a Tracoba tower block in Glasgow (BBC1 'Poor Kids' 07/06/11), this in spite of the mechanical extract system. This same type of tower block was included in both the 100 households initially surveyed and in the 22 case studies. However, of the 100, just under 10% (9 No.) reported using a 'pulley' or retractable airer in bathrooms. On the other hand 25% hand-washed some clothing in their bathroom.

16.7 Despite the lack of perception of dampness as an issue in terms of smell (15.4 above), the survey clearly indicates that the drying part of the laundering cycle represents a problem or issue for many of the users, economically and/or with contingent detriment to the quality of life inside their homes. The other point to note in this regard is that the environmental context for indoor passive drying, and ironing, is already stressed by poor air quality and high moisture levels coinciding with the main peaks of occupancy.

16.8 Exactly half of the 100 dwellings surveyed had access to some form of outdoor or covered semi-indoor drying, but almost half of that number saw some drawback in using these – ranging from unpredictable weather in the case of completely outdoor spaces to lack of security and competition for limited line-space. Therefore, although this facility may have relieved some of the detriment associated with the cost of tumble dryers or alternative passive indoor means adopted, it was by no means a trouble-free solution.

16.9 Only 6 respondents had a communal laundry facility within their block other than passive drying spaces noted in 15.8. Another 4 declared a commercial one nearby. Where they existed, they seem well used and hence to indicate a need for greater such provision.

17.0 Countering the prevalence of viewing drying as a problem or issue, where passive drying occurred, there were optimistic perceptions of ‘good access to sunshine’ in rooms used for this purpose.

17.1 Of the 70 households who responded to questions about rooms ‘having natural sunlight’ relative to the issue of drying on or near radiators, 67 or 96% responded ‘yes’.

17.2 Of 68 households who responded to questions about rooms having ‘good access to sunshine’ and the issue was the use of portable airers, 57 or 84% responded ‘yes’.

# APPENDIX 1

## TEST OF DOMESTIC IRONING PRACTICE AND EFFICIENCIES

### Context:

As the monitoring and analysis of the EPSRC Domestic Laundering project continues specific values are being identified, based on recorded data, for occupant energy uses in relation to their domestic laundering practice.

One such measured value appears to have identified that the energy use created by the use of domestic tumble dryers is significantly less than could be expected based on assumed values of operational duration and manufacturers values for electrical efficiency. With a measured value of electrical consumption lower than the predicted value it raises a question over whether all electrical appliances involved in the process of domestic laundering could exhibit a similar disparity between predicted and measured values.

As such, and in order to reduce the degree of assumption put against electrical consumption values for each dwelling, the undernoted is an attempt to provide 'in use' values of electrical consumption for domestic ironing.

Values for ironing duration, in relation to load size, and impact on VP/ RH during the ironing process will also be investigated during this experiment.

### Methodology:

Below is a collation of the factors which could influence rate of ironing and the efficiency of the process along with a description of how they have been considered or standardised to ensure the validity of the obtained results.

| No. | Garment | Material | Size | Ironing req'd? |
|---|---|---|---|---|
| 01 | Jeans | Denim | 30"w, 32"l | Y |
| 02 | Jeans | Denim | 30"w, 32"l | Y |
| 03 | Shirt | Cotton | S | Y |
| 04 | Shirt | Cotton | S | Y |
| 05 | Shirt | Cotton | S | Y |
| 06 | T-shirt | Cotton | S | Y |
| 07 | T-shirt | Cotton | M | Y |
| 08 | Shorts | Cotton | 30"w | N |

To ensure continuity of results for comparison this laundry load remained constant throughout the ironing phase.

Drying method:

The full load was allowed to dry on an internal clothes horse for 48 hours prior to the commencement of the ironing phase of the experiment. This ensured that there was no latent moisture which could affect the results of the ironing. This was of particular relevance to the first instance of ironing as the clothes were only washed at the start of the experiment and therefore any retained moisture would have impacted on the results of the first ironing procedure compared to those later in the experiment.

It should be noted that this drying methodology provides a fair representation of the main body of 22 case studies as the majority of case study respondents exhibited this type of drying behaviour.

Prior to each ironing phase, the dry garments were mixed, placed in a laundry basket and compressed, by body weight, to ensure that a random and even creasing was maintained as best as possible throughout the process – it was essential to endeavour to maintain a parity of the volume and complexity of ironing which was required at each phase.

Ironing Method:

3 no. different irons (see tables 1.1 and 1.2 below) were tested with measurements taken for, duration to iron identified load, electric energy used over this duration, relative humidity, temperature and $CO_2$ concentration of the room during the ironing period.

The true electrical draw of each appliance was monitored using a Grant instruments kWh meter and recorded on an Eltek Squirrel 1000 data logger at 1 minute logging and 3 second measurement intervals.

The relative humidity, temperature and $CO_2$ concentration of the room over the duration of the ironing was monitored using 2no. Eltek transmitters and recorded, again, on the Eltek Squirrel 1000 data logger (see tables 1.3). The monitors were placed at approximately 600mm and 3500mm from the ironing activity, at an altitude of 1000mm and 400mm respectively and outwith the path of any direct solar radiation.

During this phase all parameters, room temp, iron setting ironing board, etc, remained as constant as was reasonably practicable with the model of iron being the only variable. Results for the monitored data along with manufacturers specifications are noted below.

Table 1.1 – Irons Tested

| Iron | Manufacturer | Model | Power (W) |
|---|---|---|---|
| 01 | Tesco | Steam Iron IRS04B | 1200 |
| 02 | Philips | Comfort 226 | 1200 - 1450 |
| 03 | Tefal | Superglide 30 | 1680 - 2000 |

## Results:

Table 1.2 – Energy Use results

| Iron | Ironing Duration | Total Energy Use | Equiv. Energy per hour |
|---|---|---|---|
| 01 | 29 mins | 0.225kWh | 0.465kWh |
| 02 | 26 mins | 0.231kWh | 0.533kWh |
| 03 | 21 mins | 0.196kWh | 0.560kWh |

Table 1.3 – Monitored results

| Parameters | Monitor 1 (Bedside Table) | Monitor 2 (Chest of Drawers) |
|---|---|---|
| Temp Min | 17.60°C | 17.40°C |
| Temp Max | 19.40°C | 20.30°C |
| Temp Mean | 18.64°C | 19.10°C |
| VP Min | 14.60 haPa | 14.73 haPa |
| VP Max | 18.50 haPa | 19.00 haPa |
| VP Mean | 16.80 haPa | 16.95 haPa |
| $CO_2$ Min | 1181 ppm | 827 ppm |
| $CO_2$ Max | 1892 ppm | 1465 ppm |
| $CO_2$ Mean | 1538 ppm | 1192 ppm |

Fig 1.1 – Monitored data from 'Bedside Table' position

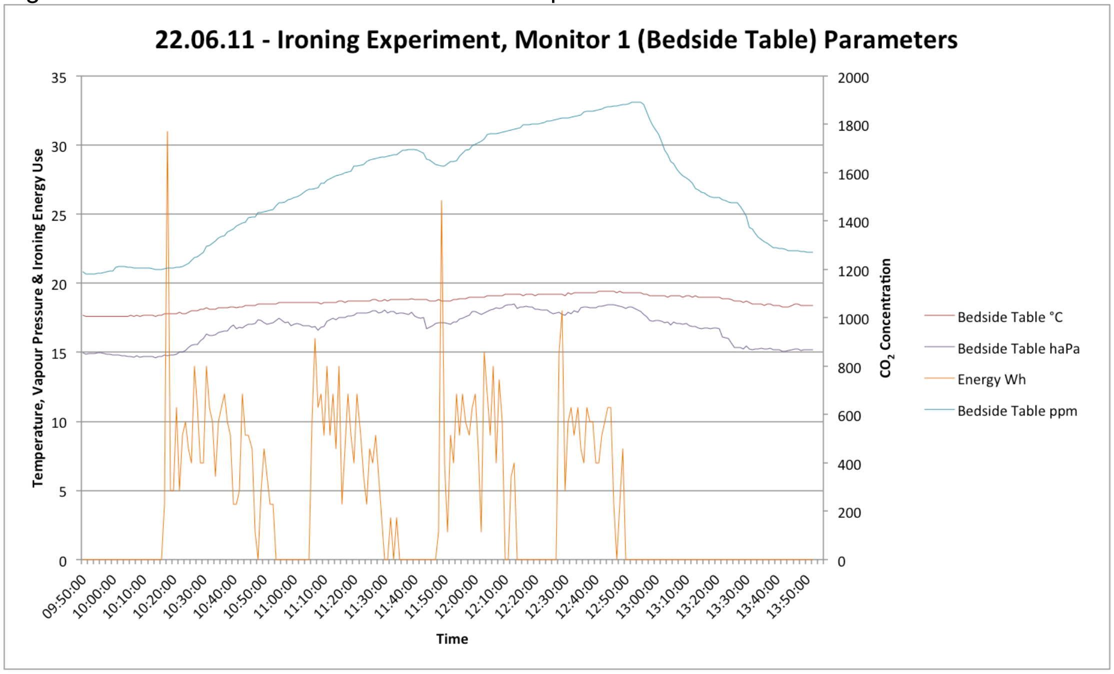
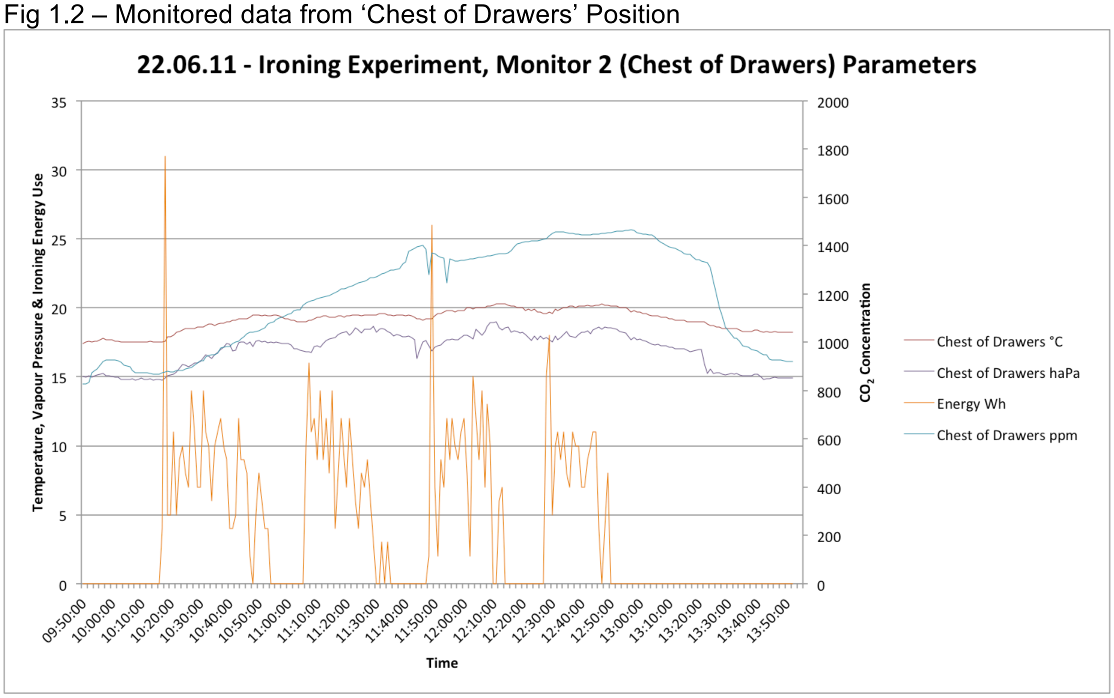



Fig 1.2 – Monitored data from 'Chest of Drawers' Position




### Notes:

- Room volume 41.3 $m^3$
- (tenement bedroom, with reasonable volumetric equivalence to modern living room)
- Experiment conducted in bedroom with door closed for duration. Door was briefly opened at 10.57, 11.45 and 12.50.

- Room trickle vent was open throughout duration.
- Irons used on maximum heat for majority of experiment but in each instance turned down to medium heat for last two items (2 t-shirts). The results show that consumption does not increase proportionally to maximum power output. Respective iron 1 (1.2 kW), 2 (1.45 kW) and 3 (2.0 kW) consumption translated to 30 minutes in all cases was 0.233, 0.267 and 0.280 kWh; this implying a flattening curve as the power increases.
- Initial energy draw (as graphed) represents a test ironing undertaken to check equipment and to create the 'control' start condition for the clothing.
- After the last phase of ironing the room was left for 30 minutes with door closed to allow decay of parameters to be monitored under these conditions. Following this time period the room was then left with door open to allow decay to be monitored under these varying conditions.
- It was noted the initial test phase was longer than the three trials and resulted in the largest rise in vapour pressure – 0.274 kPa in 39 minutes. The first two ironing cycles each resulted in another 0.145 kPa increase in 22 and 21 minutes respectively, and the third only a further 0.076 kPa rise in 15 minutes; this data from the sensor located on the bedside table some distance away from the ironing board (but similar effects found with the nearer sensor). Although decreasing times spent from minimum to maximum are clearly relevant, this does not proportionally account for all of the respective reductions. For example, direct proportionality relative to time for the 3rd ironing session would have given a rise of 0.105 kPa, whereas the actual rise of 0.076 kPa is only 72% of this; while the rise of the 1st and 2nd readings would have been 0.151 kPa and the actual rise of 0.145 kPa is 96% of this – a much lower relative reduction in comparison with the 3rd ironing cycle. It is possible that variable air flow via the trickle vent accounted for some of the diminishing impact, but it is more likely to be due to a delayed timescale in terms of absorbent materials accumulating some of the water vapour from the iron – e.g. bedding.
- $CO_2$ concentration figures should be viewed with a degree of caution as the two transmitters used appear to be giving different readings for the same monitored conditions (an absolute difference of approximately 340ppm is apparent even though respective ranges are similar).
- However, experiments in a room of similar volume – 39.3 $m^3$ cf. 41.3 $m^3$ in the ironing test – also found considerable variations in $CO_2$ readings (Steiger, Hellwig and Junker, 2008). For example, a sensor at 2.7 m from floor level peaked at approximately 3,750 ppm, while just over 2,000 ppm at 1.2 m and some 1,500 ppm at floor level; the sensor located centrally within the space on plan, and the room occupied by six dummies emitting $CO_2$ at the rate of 0.216 $m^3$/h or 0.006 l/s (normal for adult male). Similarly horizontal variations in sensor locations all at 1.2 m from floor level gave widely different values. While $CO_2$ is being emitted – i.e. people present – the opening of windows was noted as particularly influential with respect to such $CO_2$ variance. Field studies by another team give similar results with varaitions of up to 400 ppm during a build-up period (Naydenov, Barankova, Sundell and Melikov, 2004); this work supported by laboratory studies (Barankova, Naydenov, Melikov and Sundell, 2004). Other work concerning larger lecture rooms that were air-conditioned also found variations btween front, middle and rear (Halgamuge, Chan and Mendis, 2009). In one case, with an older AC system and 100 students (250 seat maximum), and sensors all at desk height, the differences between each location were of the order of 200 ppm – the lowest in the middle, the middling values at the rear and the highest at the front; and the highest values approximately 900 ppm. In another case, with a newer AC system, a smaller room and 30 students (120 set maximum), the gradation of low to high $CO_2$ was from front to rear – approximately 200 ppm in all, the highest values approximately 800 ppm. Note that the contrasts in absolute values between the two experiments does indicate that small naturally ventilated rooms can be problematic compared with larger AC spaces. On the other hand, the lecture theatres were lightly occupied, while the experimental room had 6.9 $m^3$/person – i.e. less than two thirds of the minimum of 11 $m^3$/person required by Regulation 10 of the Workplace (Health, Safety and Welfare) Regulations 1992.

## APPENDIX 2

Excerpt from draft of book chapter 'Sensing a historic low-$CO_2$ future' by Colin D A Porteous in 'Chemistry, Emission Control, Radioactive Pollution and Indoor Air Quality' published June 2011 by Intechweb.org; pp 213-246

Olaf Adan has shown that short-term peaks of high humidity can support fungal growth[95]. This characteristic has been shown to be common in a series of 2-week surveys carried out as part of a Glasgow project 'Environmental Assessment of Domestic Laundering' led by the present author. In most cases $CO_2$ peaks coincide with vapour pressure peaks, indicating that both are due to relatively intensive occupation with closed windows, but not with particularly airtight construction. Fig. 5 illustrates this situation, where vapour pressure rises steeply to over 2.0 kPa (nearly 100% above the 7 g/kg threshold) from less than 1.0 kPa (well below the 7 g/kg threshold); and contrasts it with a situation whereby drying a washing load overnight gives a gradual increase of vapour pressure, while $CO_2$ levels fall in the absence of occupants. In the second case, however, the mixing ratio rose above 7 g/kg to approximately 11 g/kg (1.78 kPa) by 0830; while $CO_2$ fell from a peak of 2,007 ppm in late evening. Therefore, although $CO_2$ and vapour pressure maxima were more severe in the first instance, they are a cause for concern in both instances. Neither were these particular two case studies unusual. Table 9 below summarises key data seasonally for 23 households, all monitored for approximately two weeks at different times of the year.

Table 9 Comparative $CO_2$ and RH for living rooms in domestic laundering study, Glasgow

| Description ($CO_2$ ppm & RH%) | Spring (10) | Summer (5) | Autumn (5) | Winter (2) |
|---|---|---|---|---|
| 1. $CO_2$ ppm: mean | 953 | 762 | 1,112 | 1,178 |
| 2. $CO_2$ ppm: mean maximum | 2,630 | 1,448 | 2,267 | 3,844 |
| 3. $CO_2$ ppm: maximum | 4,983 | 1,896 | 5,000* | 5,000* |
| 4. $CO_2$ ppm: mean minimum | 448 | 495 | 505 | 560 |
| 5. $CO_2$ ppm: minimum | 299 | 431 | 434 | 380 |
| 6. RH: mean | 47 | 51 | 64 | 41 |
| 7. RH: mean maximum | 65 | 67 | 78 | 70 |
| 8. RH: maximum | 83 | 76 | 86 | 83 |
| 9. RH: mean minimum | 32 | 29 | 47 | 26 |
| 10. RH: minimum | 20 | 21 | 36 | 22 |

Note*: 5,000 ppm is the maximum possible reading on the instrument used

Table 9 indicates a distinct tendency for the lowest $CO_2$ levels in summer and highest in winter, suggesting linkage with ventilation regimes relative to intensity of occupation. The considerable range of RH values reflect a similar range of temperatures. In this regard some aberrant values due to the location of sensors in direct radiant view of the sun have been omitted from the analysis. Even so, passive solar gain in the absence of occupants during the daytime has given some very high absolute values – see Table 10 below.

Table 10: Range of temperatures for living rooms in domestic laundering study, Glasgow

| Description ($^oC$) | Spring (10) | Summer (5) | Autumn (5) | Winter (2) |
|---|---|---|---|---|
| 1. Temp: mean | 20.7 | 21.0 | 18.6 | 21.0 |
| 2. Temp: mean maximum | 24.3 | 23.2 | 22.8 | 24.8 |
| 3. Temp: maximum | 34.6 | 33.3 | 27.8 | 26.6 |
| 4. Temp: mean maximum | 16.2 | 18.2 | 15.7 | 12.7 |
| 5. Temp: minimum | 12.1 | 16.2 | 13.1 | 14.0 |

In general, the values in Table 9 are concerning. For example, the mean maximum in winter of 3,844 ppm is 20% greater than the absolute maximum of the 19$^{th}$ C Scottish survey for single-room dwellings of 3,210 ppm, the smaller figure at a time when overcrowding and fetid air was a major health concern. Given some of the high $CO_2$ and RH values, one might reasonably anticipate problems with condensation and mould growth. However, although the colony forming units (CFUs) vary considerably there is no evident seasonal effect – see Table 11 below. Nor is there any consistency when taking individual cases and comparing the CFU value with $CO_2$, vapour pressure and presence of mould itself – see Table 12 below. Nevertheless, the CFU level is generally of some concern. Vivienne Ryan of Belfast City Council[96] has usefully categorized approximate low, moderate and high levels, respectively <500, from 500-1,300 and from 1,300-5,000+.

Table 11: Comparative CFU/m$^3$ for living rooms in domestic laundering study, Glasgow

| Description (CFU/ m$^3$) | Spring (10) | Summer (5) | Autumn (5) | Winter (2) |
|---|---|---|---|---|
| 1. Mould count: mean | 1,352 | 809 | 672 | 1,115 |
| 2. Mould count: maximum | 2,975 | 1,275 | 1,045 | 1,265 |
| 3. Mould count: minimum | 545 | 595 | 548 | 965 |

Table 12 CFU/m$^3$ cf. $CO_2$ and vapour pressure in domestic laundering study, Glasgow

| CS | Date | CFU/m$^3$ | $CO_2$ (ppm) | VP (kPa) | Notes |
|---|---|---|---|---|---|
| 18 | 14/04/09 | 2,960 (liv) | 996 (1212) | 1.13 (1210) | no mould |
| 17 | 14/04/09 | 735 (liv) | 948 (1811) | 1.04 (1812) | no mould |
| 21 | 13/04/09 | 1,565 (liv) | 1,139 (1104) | 1.24 (1105) | no mould |
| | | | 1,068 (1117) | 1.37 (1117) | |
| | | | 1,278 (2245) | 1.12 (2245) | |
| 7 | 07/04/09 | 2,975 (liv) | 1,239 (1824) | 1.79 (1824) | no mould |
| | | 2,900 (Br2) | 2,990 (0724) | 1.64 (0934) | Mould + K & Ba |
| 13 | 26/05/09 | 545 (liv) | 1,323 (1810) | 1.42 (1820) | no mould |
| 9 | 11/06/09 | 1,275 (liv) | 640 (1234) | 1.04 (1214) | no mould, Ba only |
| 22 | 06/01/10 | 1,265 (liv) | 4,209 (2113) | 2.42 (2053) | no mould |

Legend: $CO_2$ peaks in ppm; VP = vapour pressure in kPa; K = Kitchen; Ba = Bathroom

In the 22 case studies where CFU/m$^3$ values were obtained from air samples, none were in the 'low' category as defined above; 19 were in the 'moderate' range, but with 4 of these close to the upper limit; and 3 were in the 'high' range. Also some of the 'moderate' category that are not listed in Table 12 above had mould reported – see Table 13 below.

Table 13: CFU/m$^3$ cf. $CO_2$ and mould presence in domestic laundering study, Glasgow

| CS | Date | CFU/m$^3$ | $CO_2$ (ppm) | Notes |
|---|---|---|---|---|
| 20 | 17/04/09 | 1,110 (K) | 1,093 (1800) | 1.32 kPa, mould K + drying *pulley* |
| 10 | 27/05/09 | 595 (Br1) | 1,646 (2316) | 16.4$^o$C, 62.8% RH, mould; drying? |
| 11 | 29/05/09 | 875 (Br1) | 1,157 (1408) | 20.5$^o$C, 75.5% RH, mould; drying? |
| 5 | 15/10/09 | 515 (Br2) | 4,217 (2355) | 1.47 kPa, 23.8$^o$C, mould; ironing? |
| 3 | 19/10/09 | 510 (K) | 723 (2233) | 1.47 kPa, 19.4$^o$C, mould; drying? |
| 2 | 06/01/10 | 1,025 (Br1) | 4,031 (1853) | 23.8 $^o$C, 84.8% RH, mould; drying? |

The association with some aspect of domestic laundering, usually drying and/or ironing, is somewhat tentative, although there are notes in diaries kept by occupants to support this contention. The $CO_2$ peaks are also variable, and this may suggest a liberal or frugal ventilation regime. But it is possible that peaks of vapour from occupants play a role in tandem with a laundering activity such as ironing. Although the mean maximum of vapour pressures in each of the six cases in Table 13 is 1.69 KPa on the date when the air sampling was carried out, the mean maximum for the whole period of measurement is 2.07; and absolute maxima for Case 21, the highest, are respectively 2.46 kPa and 2.69 kPa. In this instance the high RH value of 84.8% in Table 13 for the first day of measurement is not typical of the monitored period, the average dropping to 45.5%. Therefore, one has to be careful about expectations with regard to cause and effect. The overall lack of consistent association between mould indicators (CFUs), presence of mould, and $CO_2$ or humidity is in accord with the findings of the Scottish survey of the 1880s. In any case, given that mould was a relatively frequent occurrence, the guideline of keeping RH below 70%, which corresponds approximately with 1.4 kPa at 20$^{o}$C air temperature and dew point of 12$^{o}$C, is generally accepted as 'good practice'.

In summary, the above findings suggest a case firstly for better control of ventilation, and secondly for improved drying facilities for domestic laundering. In the first regard, MHRV will undoubtedly have a role to play. However, there is presently an attitude of undue complacence in the ability of MHRV to resolve all conditions of ventilation control satisfactorily. For example, automated changes in volume flow rate switched by moisture level and $CO_2$ should become the norm in domestic systems. Also filters should always be readily accessible, materiality of ducts should receive greater consideration, and thermal insulation of ducts, as well as sound reduction through ducts, should be more effective. Since even a low background noise at the lowest flow rate can be disturbing in a bedroom, consideration could be given for a facility to isolate parts of a system manually. Bedrooms should not require to be heated overnight in a well-insulated envelope, so that open windows rather than MHRV overnight should be feasible without compromising energy efficiency. With regard to dedicated drying facilities, both passive and active solar systems have been shown to be capable of playing a part[97]. However, it seems a dubious tactic to employ photovoltaic (PV) arrays to displace thermal energy for tumble dryers. For example, small-scale renewable combined heat and power (RCHP), with the waste heat from electrical generation used directly for communal dryers could be more effective.

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***Footnote:*** *Case Study (CS) numbers in Tables 12 and 13 have been changed to align with those used in the main text of this report, which follow a narrative order; with dates in 2nd column remaining chronological.*

## APPENDIX 3

### Statistical Analysis of mould spore concentration (dependent variable) relative to drying methods (independent variable)

This appendix relates to observations in Part C, 5.0-5.16, summarising specific aspects of the statistical analysis that support the hypothesis of passive indoor drying (PID) being generally more potent in terms of mould spore concentrations than other 'wet' activities in the home.

Significantly, in the Glasgow study, there is a marked association between presence of passive indoor drying (PID) and the CFU count, which consistently tends to be higher when it is present than when it is absent. Fig. 3 below shows the 'boxplot' for 4 independent variables, predominantly: 1) tumble drying (TD); 2) passive outdoor drying (POD); 3) passive indoor drying (PID); 4) mixed methods. The statistical analysis indicates a strong association between PID and spore concentration. Independent variable 3 for CFU in all spaces stands out from the rest (box is the interquartile range, heavy line the median, and case numbers of outliers are shown).

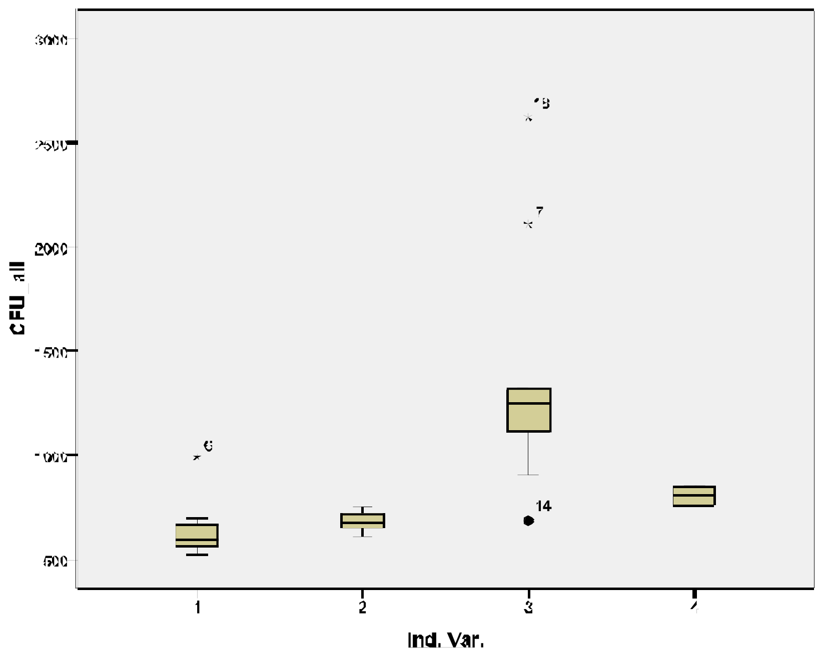


Fig. 1 Boxplot

Tables 1 and 2 below gives means (Standard Deviation) respectively for CFU for all rooms and the means for living and bedrooms in each of the four categories of independent variable.

**Table 1: means and standard deviations**

CFU_all spaces (geometric mean)

| Ind. Var. | Mean | N | Std. Deviation |
|---|---|---|---|
| 1 | 644.63 | 8 | 149.002 |
| 2 | 681.67 | 3 | 70.002 |
| 3 | 1388.33 | 9 | 604.369 |
| 4 | 808.00 | 2 | 66.468 |
| Total | 968.77 | 22 | 526.243 |

**Table 2: means and standard deviations**

CFU_living/bedrooms (geometric mean)

| Ind. Var. | Mean | N | Std. Deviation |
|---|---|---|---|
| 1 | 661.88 | 8 | 181.681 |
| 2 | 688.33 | 3 | 120.010 |
| 3 | 1528.33 | 9 | 716.378 |
| 4 | 838.50 | 2 | 55.861 |
| Total | 1036.00 | 22 | 621.460 |

The difference between drying methods is statistically significant overall for both as per Table 3 below (F (3,18) = 5.29, p=.009) and F(3,18) = 5.14, p=.01).

**Table 3: F tests comparing drying methods**

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Cfu_all | Between Groups | 2723839.322 | 3 | 907946.441 | 5.286 | .009 |
| | Within Groups | 3091724.542 | 18 | 171762.475 | | |
| | Total | 5815563.864 | 21 | | | |
| Cfu_liv/bed | Between Groups | 3741913.958 | 3 | 1247304.653 | 5.139 | .010 |
| | Within Groups | 4368550.042 | 18 | 242697.225 | | |
| | Total | 8110464.000 | 21 | | | |

Grouping everything that is not Independent Variable (IV) = 3 together, with a new variable IV3 =1 and IV = 0 otherwise, means and t-test, Tables 4-5, show that the difference is highly significant.

**Table 4: means and the t-test for former IV1, 2 & 4 as O and IV3 as 1.00**

| | IV3 | N | Mean | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| CFU_all | .00 | 13 | 678.31 | 133.035 | 36.897 |
| | 1.00 | 9 | 1388.33 | 604.369 | 201.456 |

| CFU_all | Table 5: t-test for Equality of Means | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | 95% Confidence Interval of Difference | |
| | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference | Lower | Upper |
| Equal variances assumed | -4.136 | 20 | **.001** | -710.026 | 171.667 | -1068.116 | -351.935 |
| Equal variances not assumed | -3.467 | 8.539 | **.008** | -710.026 | 204.807 | -1177.170 | -242.881 |

Multiple regression for seven potential confounding variables indicated nothing of significance, Table 6: season (spring most significant), floor covering (laminate/timber or carpet), house plants (present or absent), heating (gas or electricity), fan in kitchen (present or absent), fan in bathroom (present or absent), windows (open or closed … no difference between wide open and ajar).

None of the p-values (Sig. In right hand column) have high significance other than IV3, with that for the kitchen fan coming closest to the 10% range. Note that detailed investigations into different floor coverings of different ages and dust in different seasons indicated differences in spore concentrations (Cunniffe, 2006) although evidently not of significance in the Glasgow study.

**Table 6: Multiple regression of 7 potential confounding variables**

| Model: CFU-all | | Unstandardized Coefficients B | Std. Error | Standardized Coefficients Beta | T | Sig. |
|---|---|---|---|---|---|---|
| 1 | (Constant) | 524.483 | 262.355 | | 1.999 | .067 |
| | IV3 | 682.856 | 182.845 | .653 | 3.735 | .002 |
| | spring | 307.786 | 212.910 | .288 | 1.446 | .172 |
| | Floor Cover | 127.343 | 179.971 | .122 | .708 | .492 |
| | Plants | 154.671 | 189.903 | .140 | .814 | .430 |
| | Heat | -184.802 | 181.198 | -.177 | -1.020 | .326 |
| | Fan_kit | 318.247 | 174.626 | .308 | 1.822 | .091 |
| | Fan_bath | -110.047 | 200.079 | -.100 | -.550 | .592 |
| | Window open | -54.761 | 200.867 | -.045 | -.273 | .789 |

Looking specifically at the issue of window opening, averaging the residuals from the regression of CFU_all with IV3 (i.e. dries clothes indoors) as before for each window opening category gives:

**Table 7: Window opening means and standard deviation for 3 modes**

| Window | Mean | N | Std. Deviation |
|---|---|---|---|
| m | -10.4578755 | 7 | 2.54174589E2 |
| o | -16.5179487 | 10 | 4.89491121E2 |
| s | 47.6769231 | 5 | 3.79332629E2 |
| Total | .0000000 | 22 | 3.86342728E2 |

Window opening ‘s’ appears different from the other two categories, so lumping ‘m’ and ‘o’ together, Table 8, to give a new variable windowopen =0 if window = ‘s’, 1 otherwise gives:

Table 8: Window opening with 2 modes - ‘open’ and ‘shut’

| | windowopen | N | Mean | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| Unstandardized Residual | .00 | 5 | 47.6769231 | 3.7933269E2 | 1.6964209E2 |
| | 1.00 | 17 | -14.0226244 | 3.9876311E2 | 96.71428455 |

The t-test shows the significance of the difference is 0.769, i.e. not significant at all, and the box plot below shows that it is only case 7 that is pulling the mean with windowopen = 0 positive.

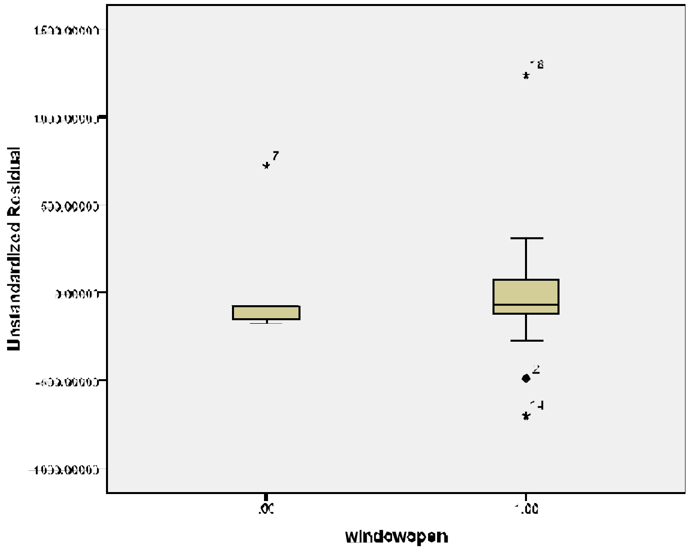


Fig. 2 Boxplot

Including 'windowopen' in the full regression equation shows it is not significant.

Various tests were also done to establish whether intensity of occupation might be significant: firstly, CFU-all against the number of occupants; secondly comparing dwellings with adults only to those with children; thirdly, the density of occupation taken as the ratio of all occupants to number of apartments (bedrooms + living room). Again this showed no significance for occupation factors, relative to IV1-4, but regression showed IV3 to be highly significant with p-value = 0.001, while that for density was negative at p = 0.093 – i.e. higher densities implied fewer mould spores. There is no evident logic for this other than a statistically insignificant random paradox, but it runs counter to a French survey (Roussel et al, 2008, 727), where concentration of spores increased with the number of inhabitants per cubic metre (e.g. Penicillium, p = 0.048 – just within the normal 5% margin of significance).

**Household size:** CFU_all against number of occupants does not show anything significant.

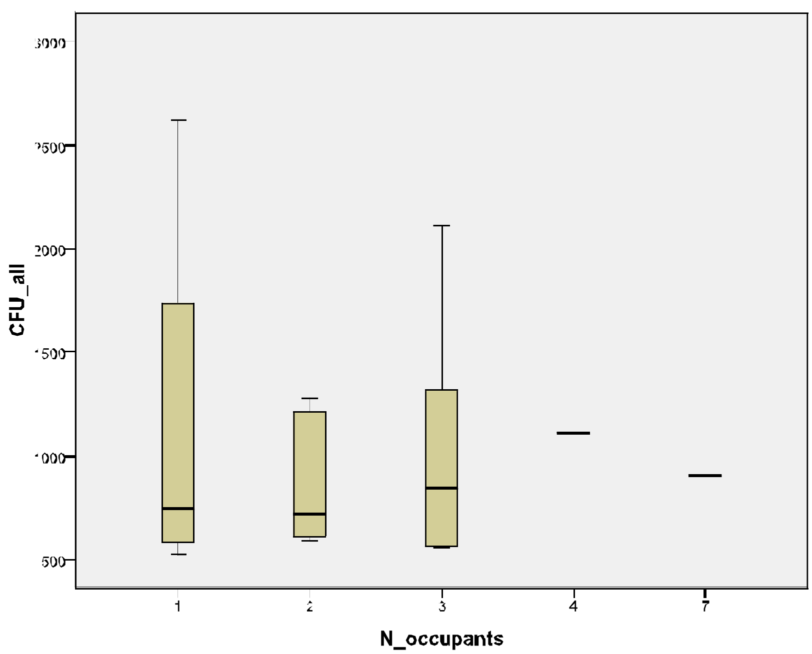


Fig. 3 Boxplot

Separating the households into those with adults alone (kids=0) and those with children or infants (kids = 1) does not show anything

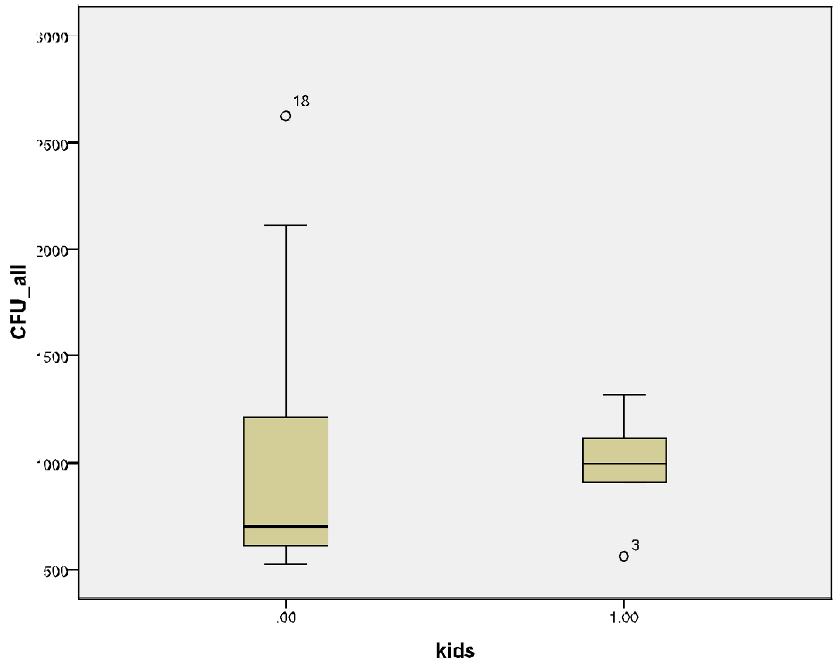


Fig. 4 Boxplot

The means of the two groups are not significantly different , Tables 9a-9b

**Table 9a: 'Kids' means and standard deviation**

| | kids | N | Mean | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|---|
| CFU_all | .00 | 17 | 966.65 | 586.408 | 142.225 |
| | 1.00 | 5 | 976.00 | 279.837 | 125.147 |

**Table 9b: 'Kids' means and standard deviation - significance**

| | | t | df | Sig. (2-tailed) | Mean Difference | Std. Error Difference |
|---|---|---|---|---|---|---|
| CFU_all | Equal variances assumed | -.034 | 20 | .973 | -9.353 | 274.328 |
| | Equal variances not assumed | -.049 | 14.823 | .961 | -9.353 | 189.446 |

Plotting CFU_all against density of occupation (no of occupants / (no. of bedrooms + 1)) does not show anything of significance – see Fig. 1 below; and regression of CFU-all against IV3 (=1 when Ind Var = 3, 0 otherwise) as before gives $R^2$ =0.461 and a highly significant coefficient.

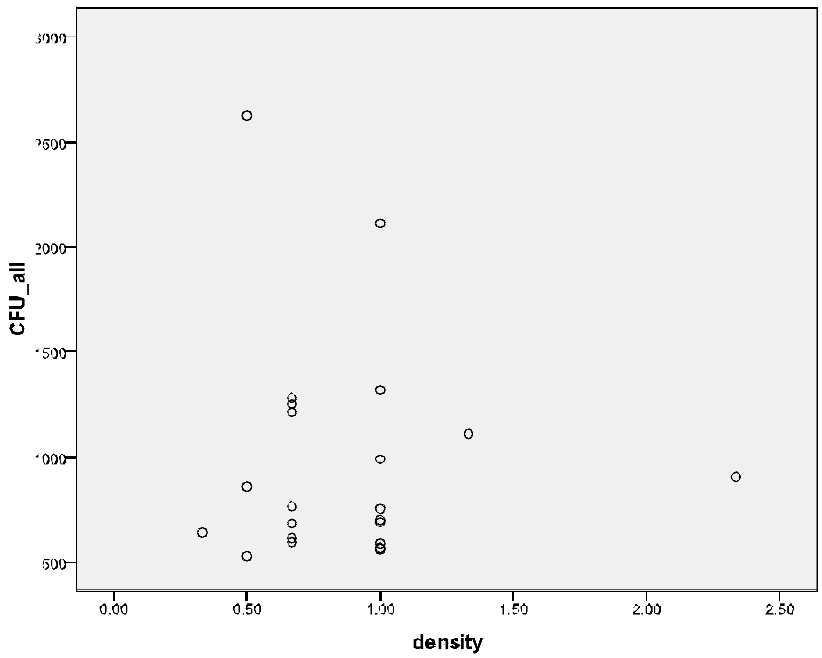


Fig. 1 Density

**Table 10**: Regression of CFU-all against IV3

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 678.308 | 109.798 | | 6.178 | .000 |
| | IV3 | 710.026 | 171.667 | .679 | 4.136 | .001 |

Looking at the residuals of this against No of occupants suggests a decrease with higher occupancy?

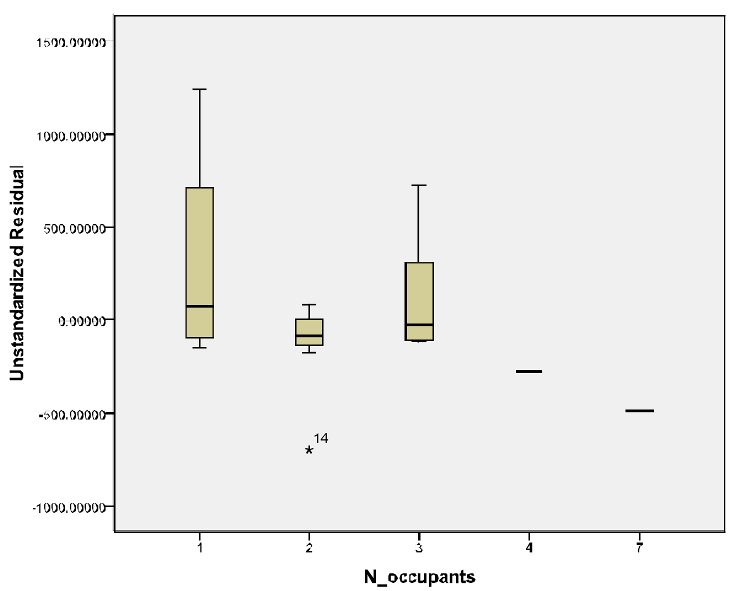


Fig. 5 Boxplot

Similarly with density of occupation:

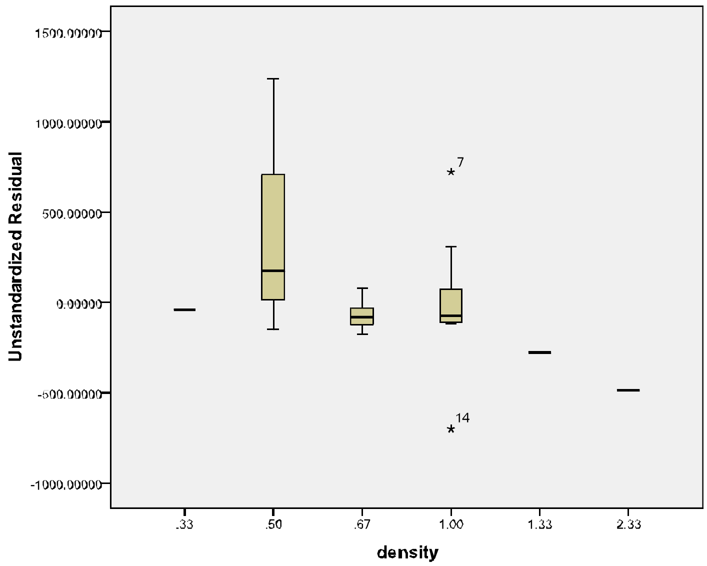


Fig. 6 Boxplot

Including density of occupation in the regression equation raises the $R^2$ to 0.537, and produces a coefficient which is significant at 10% level. However the coefficient is negative.

**Table 10: Regression of density coefficients[a] against IV3**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 965.714 | 193.363 | | 4.994 | .000 |
| | IV3 | 803.166 | 171.548 | .768 | 4.682 | .000 |
| | density | -373.628 | 211.577 | -.290 | -1.766 | .093 |

a. Dependent Variable: CFU_all

Residuals from this equation against the other variables does not show anything of interest.

**Measured conditions:** Nothing of interest was found from these: Plotting the residuals from the IV3 equation above against VP or RH in the bedroom or living room does not show anything.

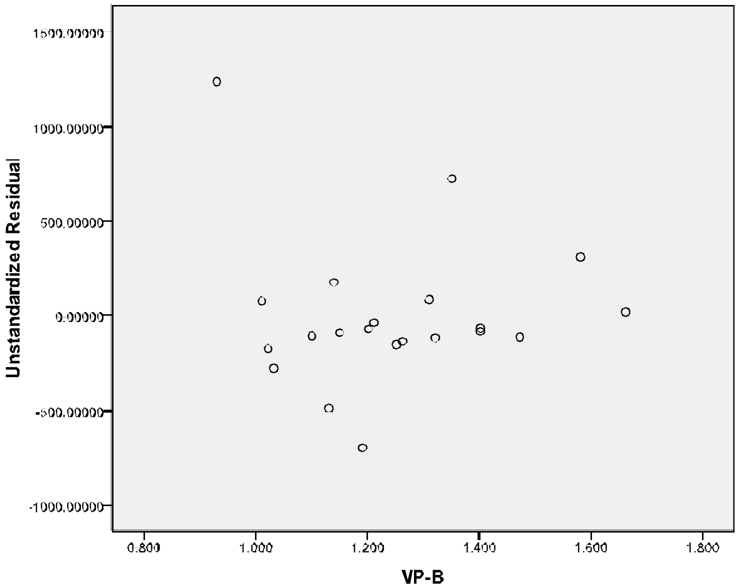


Fig. 2 Bedroom VP

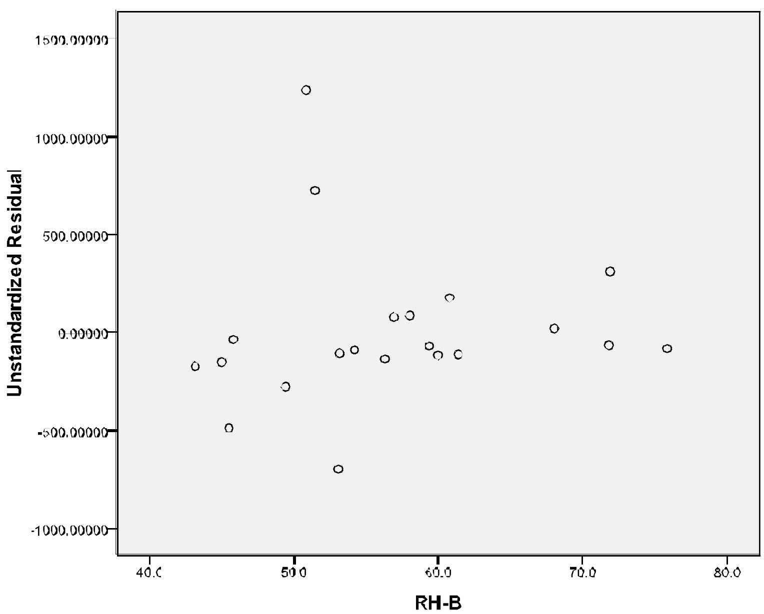


Fig. 2 Bedroom RH

Dividing in the sample into those cases where kitchen fan is not used (Fan_kit = 0) and those where it is (fan_Kit = 1) and then comparing the VPs and RHs with and without indoor clothes drying, suggests that where clothes are dried indoors, the VP and RH is lower. This could mean there is other ventilation when clothes are dried indoors – e.g. tendency to open windows.

Conclusion: There is convincing statistical evidence that only absence or presence of PID with its slow-drying damp material is significant relative to spore concentrations despite analysis of potentially confounding variables as noted above. The range of values of spore counts associated with the presence of PID is also of a level whereby the health of atopic occupants (those vulnerable to hay fever, asthma and eczema) could be adversely affected, the arithmetic mean over three times the Finnish health limit of 500 CFU/m$^3$ (Ministry of Social Affairs and Health (Finland), 2003), which is in turn supported by earlier Danish research (Reponen et al, 1991). Further, it is estimated that 6-10% of the population and 15-55% of atopics are sensitized to fungal allergens (Institute of Medicine, 2000, 165). lthough $CO_2$ is long known as a useful indicator of 'bad company' with regard to IAQ (Porteous, 2011), here CFU concentration is the 'bad company', but unrecognised by $CO_2$ since PID may occur in the absence of the occupants.

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*[Prefacing note: DEFRA will appear as author in lieu of full name Department of Environment, Food and Rural Affairs or adopted logo versions such as 'defra' or 'Defra']*


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