

Supplementary Information for

Development of formaldehyde flux sampler using a commercial DNPH cartridge

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Appendix A. Supplementary tables and figures from the chamber and research house test

Table A. 1. Dimensions of five PFS designs.

| | | PFS-D1 | PFS-D2 | PFS-D3 | PFS-D4 | PFS-D5 |
|-------------------------|------------------------|---|---------|---------|---------|---------|
| Upper part ^a | Height | 18.5 mm, including 11.3 mm silica gel with DNPH, two 1 mm polyethylene filters and 5.2 mm air phase | | | | |
| | Diameter | 11.7 mm for the DNPH phase; 4 mm ID and 6.35 mm OD for the DNPH cartridge tip | | | | |
| Lower part ^b | Height (mm) | 14.8 | 14.8 | 14.8 | 9.8 | 0 |
| | Diameter (mm) | 10 | 6.35 | 4 | 4 | 4 |
| Diff. part ^c | Height (mm) | 20 | 20 | 20 | 15 | 5.2 |
| | Area (m ²) | 7.9E-05 | 3.2E-05 | 1.3E-05 | 1.3E-05 | 1.3E-05 |

^a The upper part for a DNPH cartridge includes an air phase inside the large opening of the cartridge (4 mm inner diameter x 5.2 mm height), ^b The lower part (air phase, S1 in **Error! Reference source not found.**) is inside a stainless steel block below the air phase of a DNPH cartridge, ^c The diffusion part is combining the air phase inside a DNPH cartridge (S2) and a stainless steel block (S1) in **Error! Reference source not found.**

Table A. 2. Emission factors from PFS and chamber tests measured at 4 days.

| | Emission Factor Measured at 4 days | | | | | | |
|-------|---|------------|---|---|---|---|---|
| | Chamber | | PFS-D1 | PFS-D2 | PFS-D3 | PFS-D4 | PFS-D5 |
| | EF _{C,avg} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | RSD (%) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) |
| MDF1 | 206 | 5 | 182 | 330 | 570 | 612 | 1039 |
| MDF2 | 59 | 17 | 39 | 94 | 78 | 107 | 201 |
| MDF3 | 372 | 3 | 273 | 299 | 1035 | 476 | 1914 |
| MDF3b | 406 | 1 | 284 | 386 | 801 | 1050 | 2031 |
| PLY1 | 575 | 2 | 611 | 1010 | 1672 | 1836 | 3066 |
| PLY1r | 564 | 4 | 577 | 807 | 1753 | 1993 | 3049 |
| PLY2 | 17 | 20 | 34 | 47 | 54 | 105 | 133 |
| MOL1 | 38 | 7 | 45 | 82 | 102 | 163 | 102 |
| HDF1 | 187 | 9 | 122 | 198 | 291 | 344 | 653 |
| DR1 | 5 | 11 | 9 | 13 | 35 | 25 | 43 |

Note: EF_{C,avg}: emission factor (EF) from the chamber test (averaged over 4 days); RSD (relative standard deviation) > 20% in blue; and EF_{PFS}: EF from PFS tests, measured at 4 days.

Table A. 3. Emission factors from PFS and chamber tests measured at 6 days.

| | Emission Factor Measured at 6 days | | | | | | |
|-------|---|------------|---|---|---|---|---|
| | Chamber | | PFS-D1 | PFS-D2 | PFS-D3 | PFS-D4 | PFS-D5 |
| | EF _{C,avg} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | RSD (%) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) |
| MDF1 | 213 | 6 | 198 | 387 | 543 | 648 | 1039 |
| MDF2 | 60 | 13 | 36 | 63 | 156 | 105 | 201 |
| MDF3 | 372 | 2 | 340 | 471 | 1059 | 1062 | 1914 |
| MDF3b | 403 | 1 | 345 | 559 | 872 | 647 | 2031 |
| PLY1 | 562 | 4 | 524 | 863 | 1598 | 1937 | 3066 |
| PLY1r | 550 | 5 | 553 | 1057 | 1690 | 2136 | 3049 |
| PLY2 | 16 | 21 | 23 | 48 | 71 | 86 | 133 |
| MOL1 | 40 | 8 | 51 | 80 | 157 | 155 | 102 |
| HDF1 | 196 | 10 | 129 | 231 | 342 | 389 | 653 |
| DR1 | 5 | 11 | 8 | 18 | 32 | 25 | 43 |

Note: EF_{C,avg}: emission factor (EF) from the chamber test (averaged over 6 days); RSD (relative standard deviation) > 20% in blue; and EF_{PFS}: EF from PFS tests, measured at 6 days.

Table A. 4. Emission factors from PFS and chamber tests measured at 7 days.

| | Emission Factor Measured at 7 days | | | | | | |
|-------|---|------------|---|---|---|---|---|
| | Chamber | | PFS-D1 | PFS-D2 | PFS-D3 | PFS-D4 | PFS-D5 |
| | EF _{C,avg} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | RSD (%) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) | EF _{PFS} ($\mu\text{g m}^{-2} \text{h}^{-1}$) |
| MDF1 | 213 | 5 | 190 | 362 | 644 | 647 | 1039 |
| MDF2 | 60 | 12 | 44 | 65 | 112 | 145 | 201 |
| MDF3 | 370 | 2 | 373 | 520 | 1264 | 1409 | 1914 |
| MDF3b | 401 | 2 | 350 | 640 | 886 | 692 | 2031 |
| PLY1 | 556 | 5 | 643 | 871 | 1564 | 2223 | 3066 |
| PLY1r | 545 | 5 | 595 | 970 | 1576 | 1723 | 3049 |
| PLY2 | 16 | 21 | 23 | 39 | 118 | 56 | 133 |
| MOL1 | 40 | 8 | 47 | 92 | 141 | 156 | 102 |
| HDF1 | 199 | 10 | 133 | 234 | 374 | 393 | 653 |
| DR1 | 5 | 11 | 8 | 14 | 24 | 22 | 43 |

Note: EF_{C,avg}: emission factor (EF) from the chamber test (averaged over 7 days); RSD (relative standard deviation) > 20% in blue; and EF_{PFS}: EF from PFS tests, measured at 7 days.

Table A. 5. Temperature and RH measured in the duplex research house for 7 days at 3 months (June 2017) and 8 months (November 2017).

| Test ID | Duplex ID | Temperature (°C) | | | RH (%) | | |
|---------|-----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| | | BM | F1 | F2 | BM | F1 | F2 |
| 3M | Unit E | 21.0 (± 0.2) | 21.7 (± 0.3) | 23.1 (± 0.5) | 65.6 (± 3.1) | 62.2 (± 0.7) | 62.2 (± 0.6) |
| | Unit F | 19.9 (± 0.1) | 21.8 (± 0.2) | 23.4 (± 0.6) | 70.8 (± 0.5) | 61.3 (± 0.8) | 64.0 (± 0.5) |
| 8M | Unit E | 20.0 (± 0.1) | 19.9 (± 0.2) | 19.4 (± 0.2) | 33.0 (± 1.6) | 40.3 (± 1.1) | 42.2 (± 1.2) |
| | Unit F | 19.9 (± 0.1) | 20.0 (± 0.1) | 19.8 (± 0.2) | 51.9 (± 0.6) | 46.5 (± 0.6) | 54.0 (± 0.6) |

Mean (± Standard Deviation)

Table A. 6. Ventilation rates calculated from the measured emission rates and concentrations of perfluoro-carbon tracer (PFT) gases in the duplex research house.

| Test ID | Duplex ID | PFT | PFT emission rate (mg h ⁻¹) | Concentration (µg m ⁻³) | | | | Ventilation rate (m ³ h ⁻¹) | ACH (h ⁻¹) |
|---------|-----------|---------------------|---|-------------------------------------|-------|-------|-------|--|------------------------|
| | | | | BM | F1 | F2 | Mean | | |
| 3M | Unit E | 3 PFTs ^a | 7.73 | 34.0 | 31.4 | 44.2 | 36.6 | 211.5 | 0.505 |
| | Unit F | 3 PFTs ^b | 8.94 | 369.5 | 418.2 | 438.4 | 408.7 | 21.9 | 0.052 |
| 8M | Unit E | mPDCH | 7.33 | 34.6 | 33.7 | 35.4 | 34.6 | 211.9 | 0.506 |
| | Unit F | PMCH | 9.82 | 245.9 | 317.1 | 352.5 | 305.2 | 32.2 | 0.077 |

^a Mean of octafluorotoluene (OFT), perfluorodimethyl cyclobutane (PDCB), and m-perfluorodimethyl cyclohexane (mPDCH); and ^b Mean of hexafluorobenzene (HFB), perfluoromethyl cyclohexane (PMCH) and perfluorotrimethyl cyclohexane (PTCH).

Table A. 7. Formaldehyde emission factors and concentrations measured in Unit E of the duplex research house.

| Unit E | | 3 Months (June 19 - 26, 2017) | | | | 8 Months (Nov 16 - 23, 2017) | | | |
|---------------------------------|-------------------------------------|--|---|--|------------------|--|---|--|------------------|
| Ventilation | | Q (m ³ h ⁻¹) | ACH (h ⁻¹) ^a | | | Q (m ³ h ⁻¹) | ACH (h ⁻¹) ^a | | |
| Air flow rate to/from outdoor | | 211.5 | 0.505 | | | 211.9 | 0.506 | | |
| Source | A _i (m ²) | EF _i (μg m ⁻² h ⁻¹) | EF _i *A _i (μg h ⁻¹) | EF _i *A _i /Q = C _i (μg m ⁻³) | Contribution (%) | EF _i (μg m ⁻² h ⁻¹) | EF _i *A _i (μg h ⁻¹) | EF _i *A _i /Q = C _i (μg m ⁻³) | Contribution (%) |
| Trim & sill (window) | 2.4 | 11.2 | 26.9 | 0.1 | 1 | 2.2 ^e | 5.3 | 0.0 | 0 |
| Trim (baseboard) | 12.1 | 11.2 ^b | 135.5 | 0.6 | 3 | 2.6 ^e | 31.5 | 0.1 | 2 |
| Trim & jamb (door) | 11.2 | 11.2 ^b | 125.4 | 0.6 | 3 | 2.6 ^e | 29.1 | 0.1 | 2 |
| Interior door | 42.0 | 14.6 | 613.2 | 2.9 | 13 | 14.2 ^e | 596.4 | 2.8 | 34 |
| Closet door (inside) | 12.6 | 14.6 ^c | 184.0 | 0.9 | 4 | 7.8 ^e | 98.3 | 0.5 | 6 |
| Closet door (outside) | 12.6 | 14.6 ^c | 184.0 | 0.9 | 4 | 2.3 ^e | 29.0 | 0.1 | 2 |
| Laminated floor | 68.8 | 36.8 | 2531.8 | 12.0 | 55 | 10.4 ^e | 715.5 | 3.4 | 40 |
| Cabinet | 11.5 | 16.7 | 192.1 | 0.9 | 4 | 1.4 ^e | 16.1 | 0.1 | 1 |
| Countertop | 3.3 | 2.6 ^d | 8.6 | 0.0 | 0 | 1.2 | 4.0 | 0.0 | 0 |
| Outdoor air (C _{out}) | | | | 3.0 | 14 | | | 1.1 | 14 |
| Sink | A _w (m ²) | k _w (m h ⁻¹) | k _w *A _w (m ³ h ⁻¹) | k _w *A _w /Q (unitless) | | k _w (m h ⁻¹) | k _w *A _w (m ³ h ⁻¹) | k _w *A _w /Q (unitless) | |
| Removal by walls | 323.2 | 0.00 | 0.0 | 0.0 | | 0.00 | 0.0 | 0.0 | |
| Concentration | | | | C _{ss} (μg m ⁻³) | Diff (%) | | | C _{ss} (μg m ⁻³) | Diff (%) |
| Predicted conc. | | | | 21.9 | -22 | | | 8.3 | -17 |
| Measured conc. | | | | 28.0 | | | | 10.1 | |

Note: ^a The air change rate per house (ACH) was calculated based on the house volume of 418.5 m³; ^b The EF for baseboard and door trim was not measured and, therefore, the window trim data was used; ^c The closet door was not measured for EF and, therefore, the interior door data was used. ^d The mean value of two countertops in the kitchen and bathroom was used; and ^e The mean value of two materials (1st and 2nd floor) was used.

Table A. 8. Formaldehyde emission factors and concentrations measured in Unit F of the duplex research house.

| Unit F | | 3 Months (June 19 - 26, 2017) | | | | 8 Months (Nov 16 - 23, 2017) | | | |
|---------------------------------|-------------------------------------|--|---|--|------------------|--|---|--|------------------|
| Ventilation | | Q (m ³ h ⁻¹) | ACH (h ⁻¹) ^a | | | Q (m ³ h ⁻¹) | ACH (h ⁻¹) ^a | | |
| Air flow rate to/from outdoor | | 21.9 | 0.052 | | | 32.2 | 0.077 | | |
| Source | A _i (m ²) | EF _i (μg m ⁻² h ⁻¹) | EF _i *A _i (μg h ⁻¹) | EF _i *A _i /Q = C _i (μg m ⁻³) | Contribution (%) | EF _i (μg m ⁻² h ⁻¹) | EF _i *A _i (μg h ⁻¹) | EF _i *A _i /Q = C _i (μg m ⁻³) | Contribution (%) |
| Trim & sill (window) | 2.4 | 9.5 | 22.8 | 1.0 | 1 | 2.2 ^e | 5.3 | 0.2 | 0 |
| Trim (baseboard) | 12.1 | 9.5 ^b | 115.0 | 5.3 | 3 | 2.6 ^e | 31.5 | 1.0 | 2 |
| Trim & jamb (door) | 11.2 | 9.5 ^b | 106.4 | 4.9 | 2 | 2.6 ^e | 29.1 | 0.9 | 2 |
| Interior door | 42.0 | 18.6 | 781.2 | 35.7 | 18 | 14.2 ^e | 596.4 | 18.5 | 38 |
| Closet door (inside) | 12.6 | 18.6 ^c | 234.4 | 10.7 | 5 | 7.8 ^e | 98.3 | 3.1 | 6 |
| Closet door (outside) | 12.6 | 18.6 ^c | 234.4 | 10.7 | 5 | 2.3 ^e | 29.0 | 0.9 | 2 |
| Laminated floor | 68.8 | 36.5 | 2511.2 | 114.8 | 59 | 10.4 ^e | 715.5 | 22.2 | 46 |
| Cabinet | 11.5 | 16.8 | 193.2 | 8.8 | 5 | 1.4 ^e | 16.1 | 0.5 | 1 |
| Countertop | 3.3 | 2.5 ^d | 8.3 | 0.4 | 0 | 1.2 | 4.0 | 0.1 | 0 |
| Outdoor air (C _{out}) | | | | 3.0 | 2 | | | 1.1 | 2 |
| Sink | A _w (m ²) | k _w (m h ⁻¹) | k _w *A _w (m ³ h ⁻¹) | k _w *A _w /Q (unitless) | | k _w (m h ⁻¹) | k _w *A _w (m ³ h ⁻¹) | k _w *A _w /Q (unitless) | |
| Removal by walls | 323.2 | 0.20 | 64.6 | 3.0 | | 0.20 | 64.6 | 2.0 | |
| Concentration | | C _{ss} (μg m ⁻³) | | | Diff (%) | C _{ss} (μg m ⁻³) | | | Diff (%) |
| Predicted conc. | | | | 49.4 | 22 | | | 16.1 | 25 |
| Measured conc. | | | | 40.3 | | | | 12.9 | |

Note: ^a The air change rate per house (ACH) was calculated based on the house volume of 418.5 m³; ^b The EF for baseboard and door trim was not measured and, therefore, the window trim data was used; ^c The closet door was not measured for EF and, therefore, the interior door data was used. ^d The mean value of two countertops in the kitchen and bathroom was used; and ^e The mean value of two materials (1st and 2nd floor) was used.

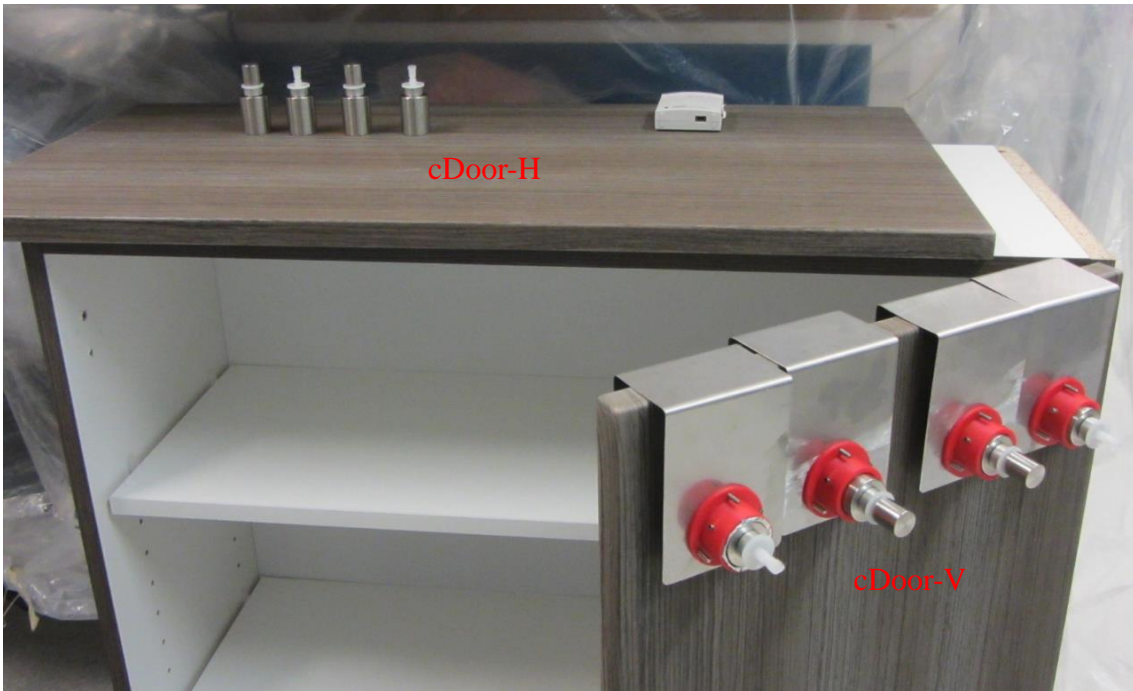


Fig. A. 1. PFS-D1 placed on cabinet doors horizontally (cDoor-H) and vertically (cDoor-V).

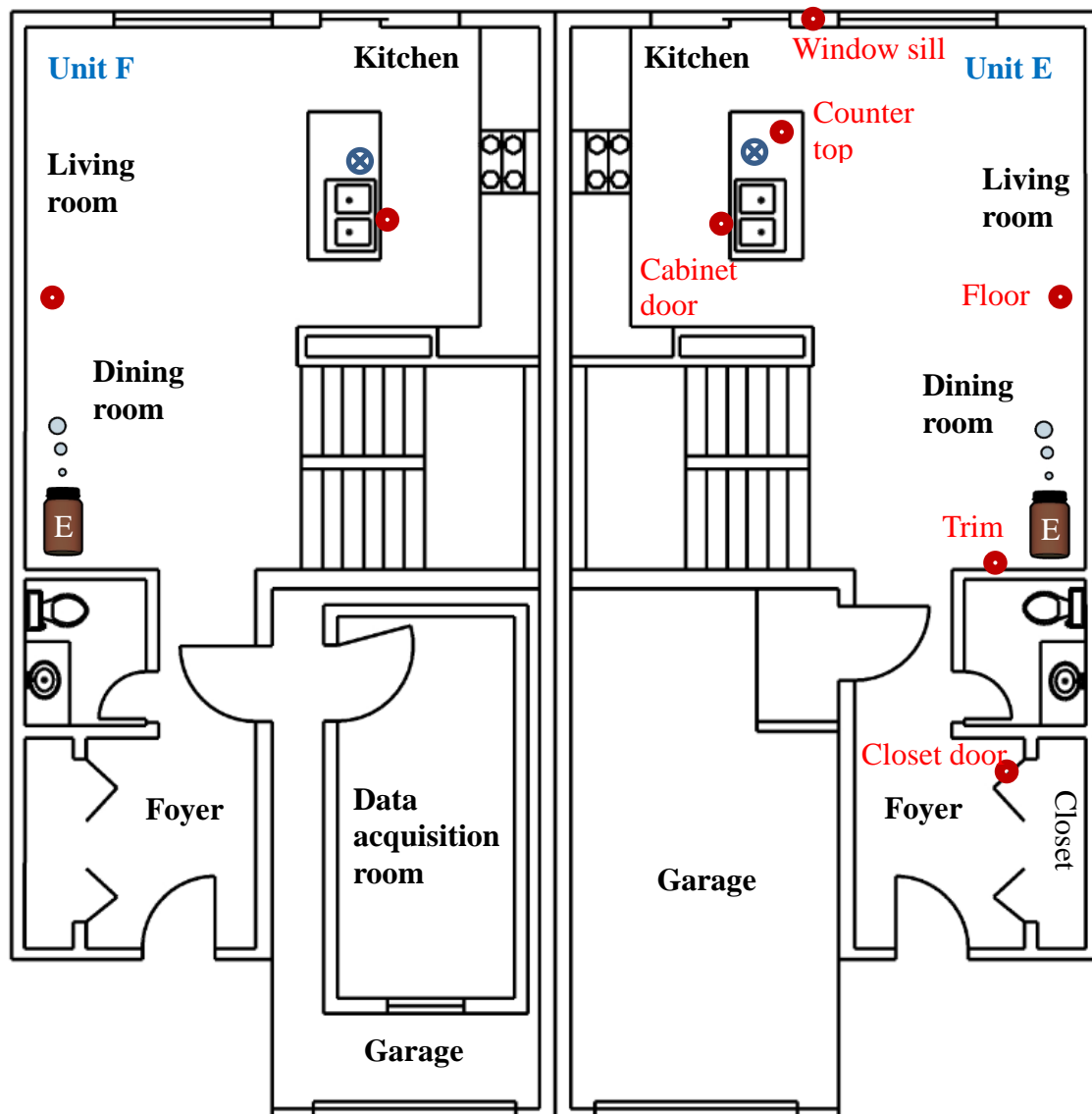





Fig. A. 2. Floor plan of the duplex research house (1st floor).

Note:  perfluoro-carbon tracer (PFT) gas emitter;  PFS (passive flux sampler) and  PAS (passive air samplers) for formaldehyde (DNPH cartridge) and PFT (Carbopack B tube).

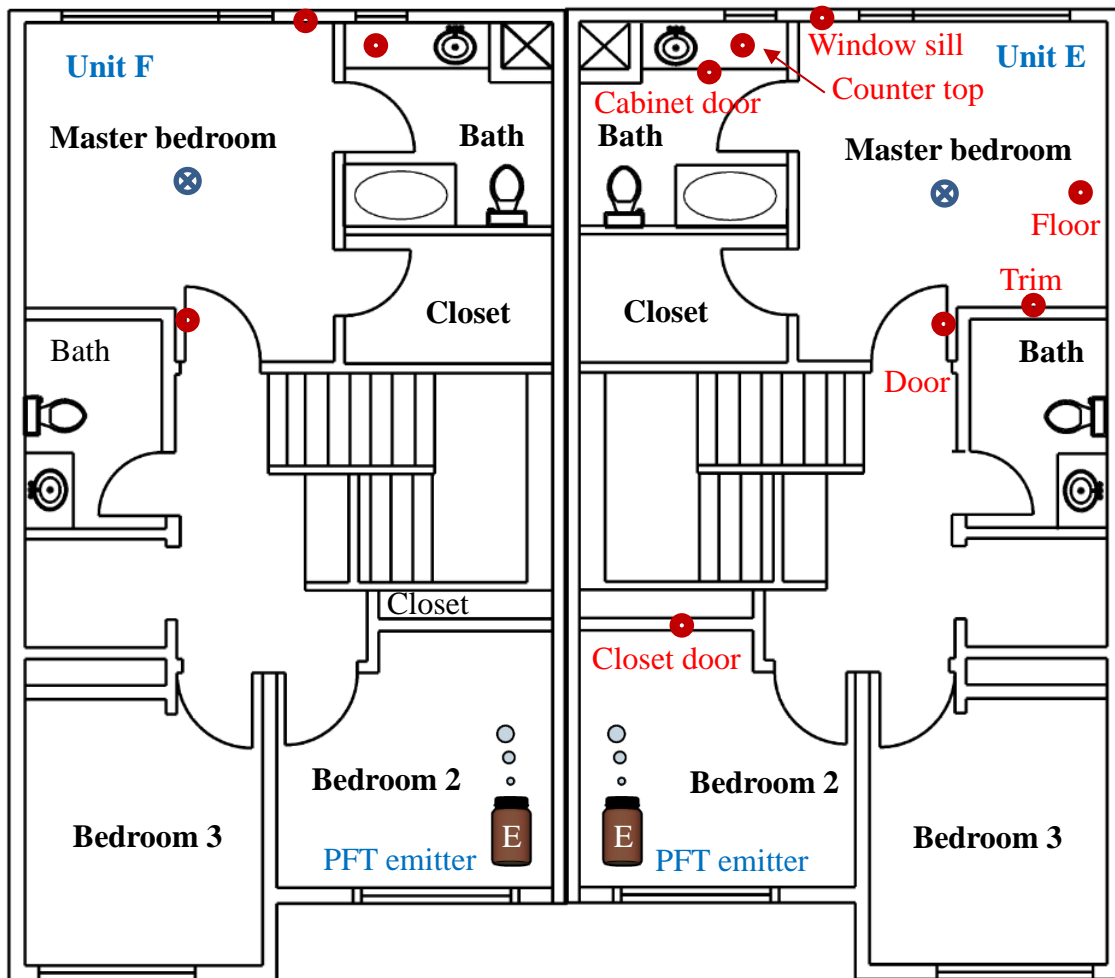





Fig. A. 3. Floor plan of the duplex research house (2nd floor).

Note:  perfluoro-carbon tracer (PFT) gas emitter;  PFS (passive flux sampler) and  PAS (passive air samplers) for formaldehyde (DNPH cartridge) and PFT (Carbopack B tube).

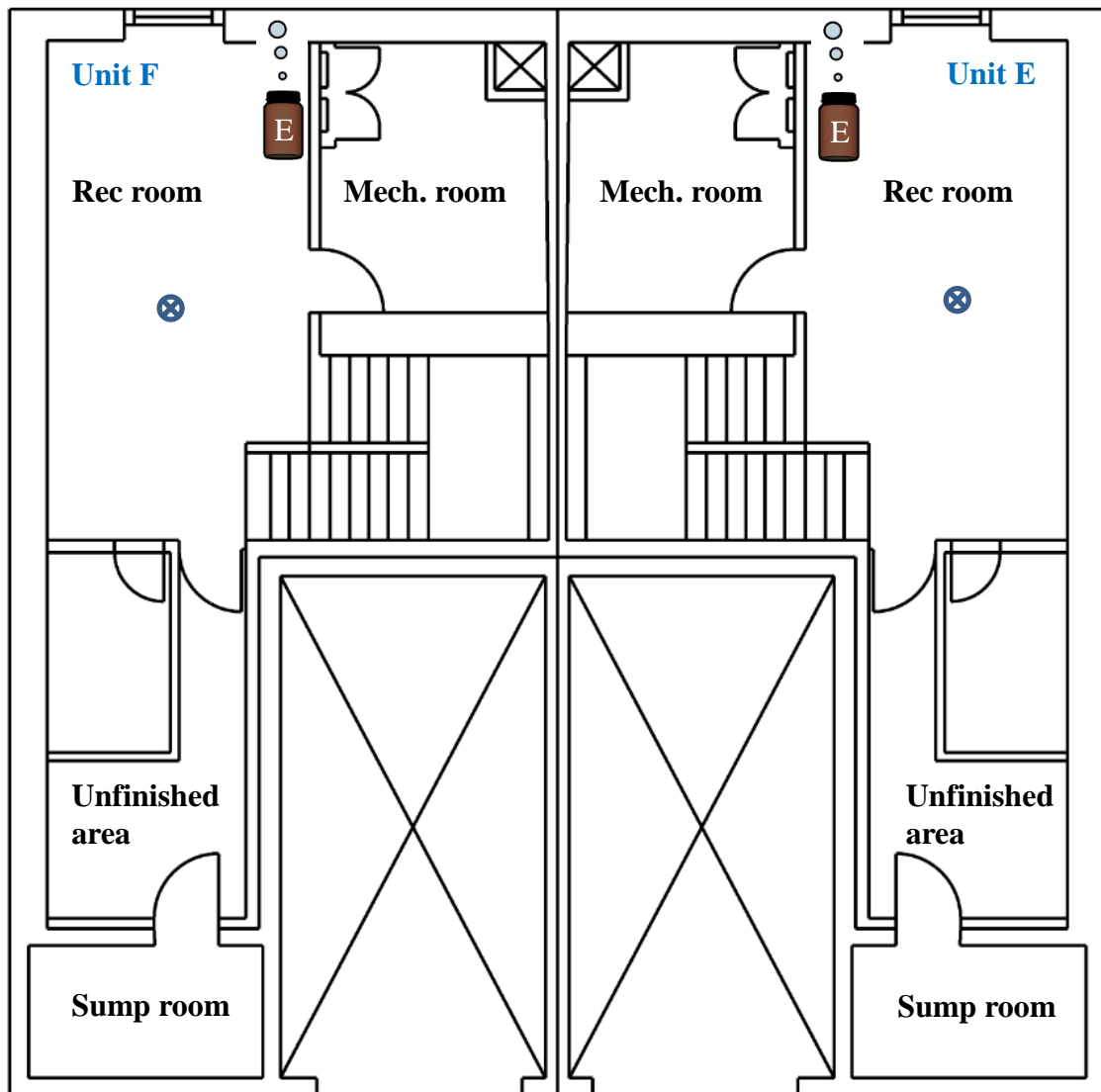





Fig. A. 4. Floor plan of the duplex research house (basement).

Note:  perfluoro-carbon tracer (PFT) gas emitter;  PFS (passive flux sampler) and  PAS (passive air samplers) for formaldehyde (DNPH cartridge) and PFT (Carbopack B tube).

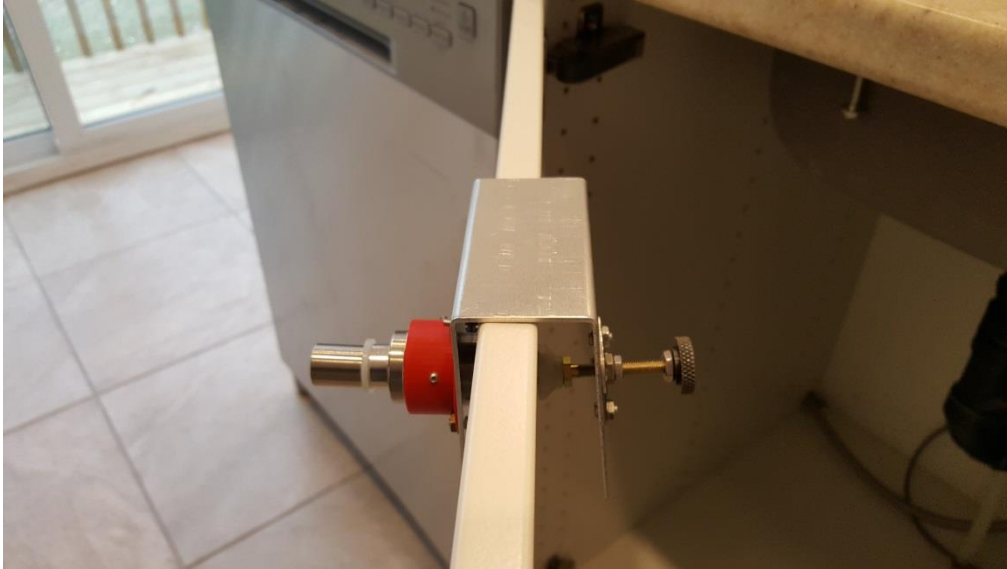


Fig. A. 5. PFS placed on the surface of a cabinet door with a clamping device (kitchen, 1st floor).



Fig. A. 6. PFS placed on the surface of a baseboard trim (living room, 1st floor).



Fig. A. 7. Passive flux sampler (PFS) and passive air sampler (PAS) in the duplex research house (kitchen, 1st floor).



Fig. A. 8. Passive air sampler (PAS) outside of the duplex research house.

Appendix B. Determination of formaldehyde removal rate coefficient of the wall with formaldehyde removing feature

The formaldehyde removal coefficient of the drywall materials in Unit F with a formaldehyde scrubbing feature was determined from the chamber experimental data reported in Zuraimi et al. [22], in which the performance of 8 sorptive-materials were tested in a 400-L chamber with the chamber air dosed with formaldehyde ($100 \mu\text{g m}^{-3}$).

Eq. B. 1 shows the mass balance of formaldehyde in the chamber:

$$V \frac{dC}{dt} = Q \cdot C_{in} - Q \cdot C - k_s \cdot A_s \cdot C - k_w \cdot A_w \cdot C \quad (\text{B. 1})$$

where V is the chamber volume (0.4 m^3); Q is the chamber flow rate ($0.2 \text{ m}^3 \text{ h}^{-1}$); C_{in} is the concentration of the air entering the chamber ($\mu\text{g m}^{-3}$); C is the chamber concentration ($\mu\text{g m}^{-3}$); C_{in} is the concentration of the air entering the chamber ($\mu\text{g m}^{-3}$); k_s is the formaldehyde removal rate coefficient (m h^{-1}) by the chamber interior (stainless steel); A_s is the area of chamber interior (m^2); k_w is the formaldehyde removal rate coefficient (m h^{-1}) by the test material; and A_w is the area of the test material with the formaldehyde scrubbing feature (m^2).

Solving Eq. B. 1 leads to:

$$\frac{C}{C_{in}} = \frac{Q/V}{\alpha} [1 - e^{-\alpha t}] \quad (\text{B. 2})$$

where $\alpha = Q/V + k_w \cdot A_w/V + k_s \cdot A_s/V$.

The removal rate by the chamber interior (k_s) was first determined by curve-fitting Eq.

B. 2 to the experimental data for a stainless steel plate (SS_F in Zuraimi et al. [1]). The non-linear regression was performed with SigmaPlot (Version 11.0). The area of stainless steel was measured to be 5.206 m^2 , including the chamber interior and the stainless steel plate used as a test specimen. The removal rate of formaldehyde by the painted wall material (k_w) was determined with the experimental data for painted gypsum fiberboard (PS1_GYP_F in Zuraimi et al. [22]) and the specimen area (0.089 m^2). In this case, the chamber stainless steel area was reduced to 5.117 m^2 since the stainless steel plate was replaced with the test specimen. The measured and fitted data with the resulting coefficients are shown in Fig. B. 1.

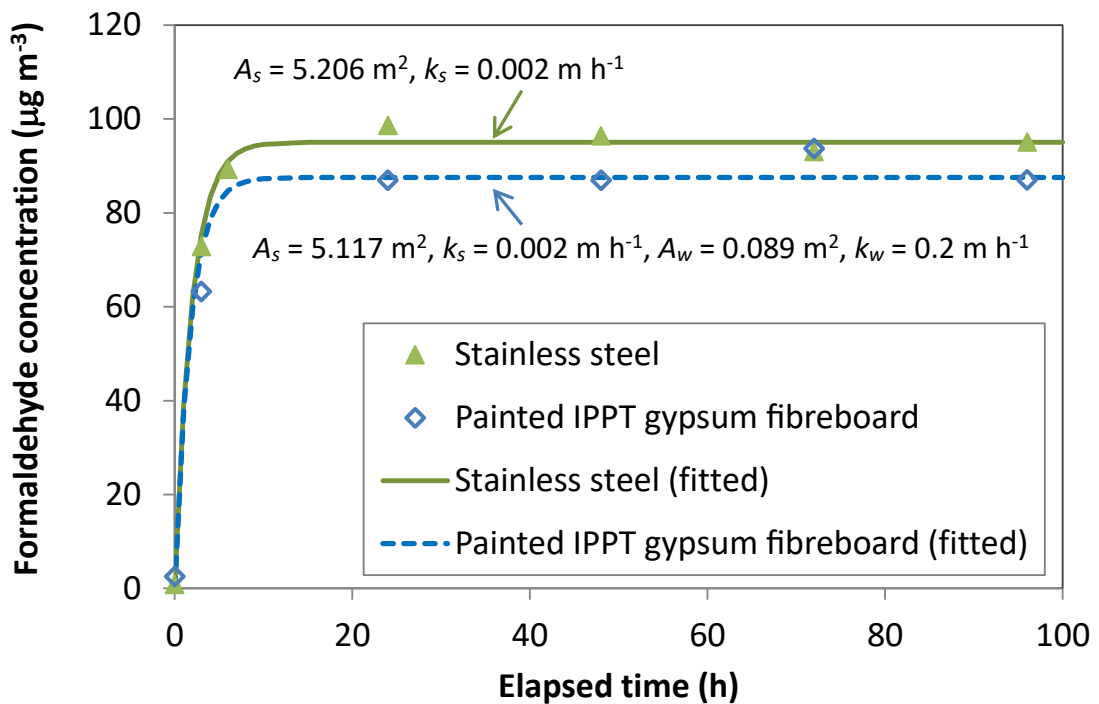


Fig. B. 1. Formaldehyde concentration profiles for stainless steel and painted gypsum fiberboard as indoor passive panel technology (IPPT).