



# **VOLATILE ORGANIC COMPOUNDS IN NEW HOMES**

**Pilot Study Report on Building Product  
Emissions and Indoor Air Quality**



Health  
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**NRCC-CNRC**

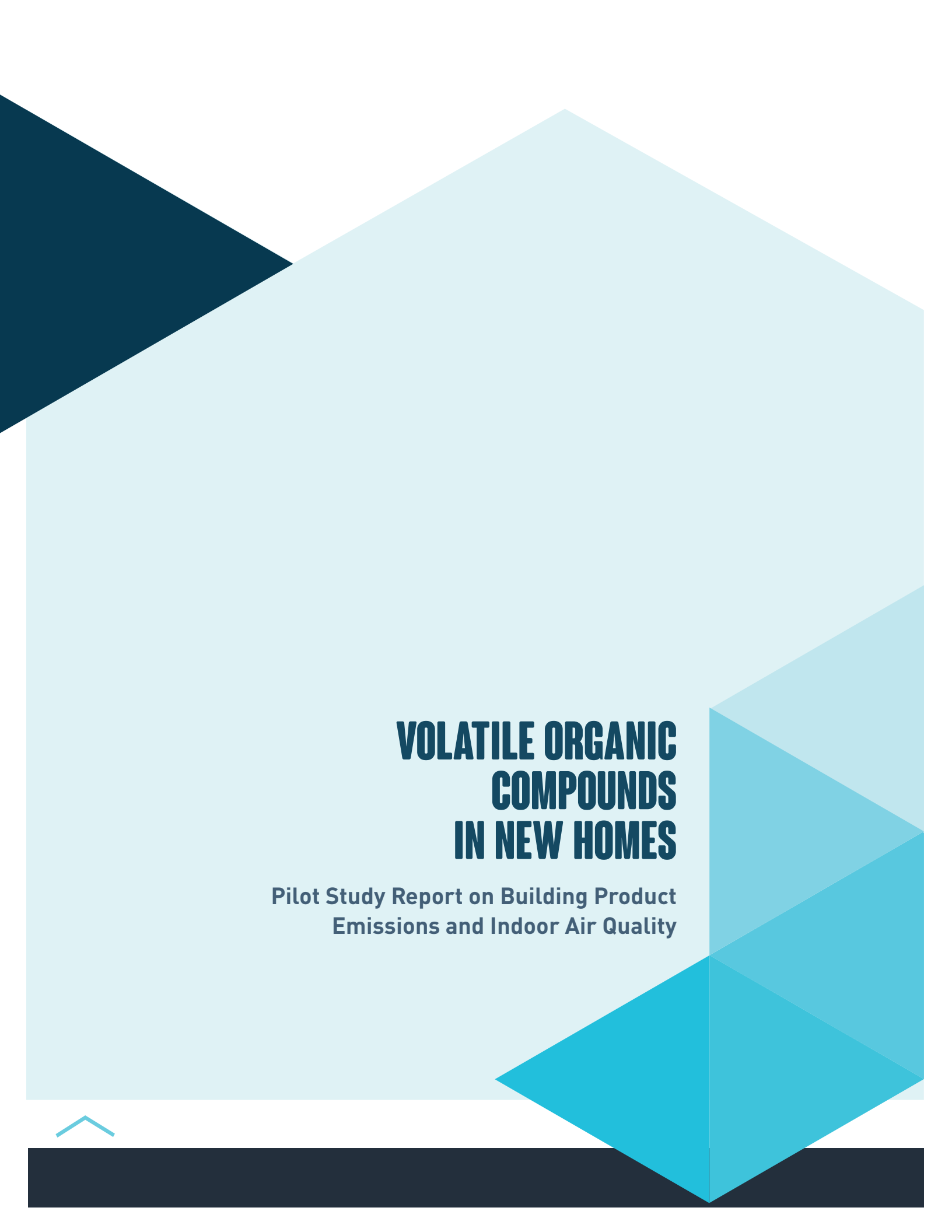


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# LIST OF ABBREVIATIONS AND ACRONYMS

<b>BNL</b>	Brookhaven National Laboratory
<b>CIS</b>	cooled injection system
<b>CSA</b>	Canadian Standards Association
<b>DNPH</b>	dinitrophenylhydrazine
<b>GC/MS</b>	gas chromatography-mass spectrometry
<b>HFB</b>	hexafluorobenzene
<b>HPLC</b>	high-performance liquid chromatography
<b>HVAC</b>	heating, ventilating and air conditioning
<b>IAQ</b>	indoor air quality
<b>MDF</b>	medium-density fibreboard
<b>MDL</b>	method detection limit
<b>NRC</b>	National Research Council
<b>OFT</b>	octafluorotoluene
<b>OSB</b>	oriented strand board
<b>PDCB</b>	perfluorodimethylcyclobutane
<b>PFT</b>	perfluorocarbon tracer
<b>RH</b>	relative humidity
<b>RSD</b>	relative standard deviation
<b>SF6</b>	sulfur hexafluoride
<b>SPF</b>	spruce-pine-fir
<b>TD</b>	thermal desorption
<b>TVOC</b>	total volatile organic compounds
<b>VOC</b>	volatile organic compound



# 1. INTRODUCTION

Building materials have consistently been found to emit volatile organic compounds (VOCs), including formaldehyde, into indoor air (Weschler 2009; ECA 2013). Exposure to VOCs has been associated with adverse health outcomes, dependent on the species of VOC, its concentration, and the duration of exposure (Kampa and Castanas 2008). The National Research Council of Canada (NRC) has previously measured emissions of these chemicals from various products and modelled expected indoor air concentrations. Based on this testing as well as exposure and toxicological data from scientific literature, the Canadian Standards Association (CSA) developed health-based voluntary standard CAN/CSA-0160-16 for formaldehyde emissions from composite wood products (CAN/CSA, 2016), which was harmonized with the existing California Air Resources Board's Airborne Toxic Control Measure (ATCM) 93120 relating to responsibilities of manufacturers and third party certifiers.

While there was considerable interest in expanding the voluntary standard to include other VOCs of concern emitted from building materials, the available data was deemed insufficient at that time to proceed. One of the main uncertainties being that it was unclear how well the indoor air quality emission simulation tool developed by NRC (IA-Quest) could predict VOC concentrations under real world scenarios. For example, it remained unclear whether factors such as the application of coatings or the use of barriers would limit emissions into the living space. Also, it was not well understood how patterns of use, age of the materials, and the home environmental conditions (e.g., temperature, humidity, ventilation rate, and presence of reactive compounds) would affect the relationship between the predicted concentration based on the emissions rate and the measured indoor air concentration. This pilot study was conducted in order to address these data gaps, and inform future standards regarding composite wood products as well as other building materials and consumer products.

This report presents the results for emissions testing of material specimens collected during construction of two homes (H1 and H2) in the Ottawa region. The objective of this study was to provide data on VOC emissions, primarily from composite wood materials used in home construction and finishing, which can be used to (a) improve/validate the modelling approach used in CAN/CSA-0160 for setting limits on permissible chamber concentrations of tested materials, and (b) support possible expansion of the scope of the standard to health-relevant VOCs.

This report comprises a summary of the emissions testing results as well as an attempt to utilize the emissions test results to model indoor VOC levels immediately following construction, as compared to actual measurements of VOCs in the two homes. While the original study design called for longer sampling in a larger cohort of homes, builder interest and participation in this study was low resulting in the recruitment of only 2 homes. Furthermore, tight builder timelines meant that only 24-h sampling could be accommodated. As a result of these study limitations, the results of this study should be interpreted with caution and further data are required to fully validate the modelling approach used in CAN/CSA-0160. Future work is planned to commence FY2019–2020 to better understand formaldehyde, VOCs, and semi-volatile organic compounds in newly constructed homes.

Note that tables and figures with alphanumeric prefixes (e.g. Table A. 1; Figure B. 2) are found in the corresponding appendices (e.g., Table A. 1 in appendix A, Figure B. 2 in appendix B) in the companion report titled “Volatile Organic Compounds in New Homes: Supplemental Material”, while tables and figures without prefixes are included within the main section of the report.



## 2. EMISSIONS TESTING

### 2.1 METHODS

Documentation of home construction schedules and collection of material specimens for emissions testing was conducted by Health Canada in accordance with the study design. The study plan called for testing of up to 15 specimens from two homes. This report provides results for 17 materials. For each material, chamber testing was conducted for a total of 14 days in order to meet testing requirements of both the CSA-O160 standard (2016; an 8 day time point for conformance evaluation based on 7 days of specimen conditioning followed by a 1 day chamber test) and the widely adopted standard method v1.1 from the California Department of Public Health in North America (CDPH “Method 1”—standard time period of 14 days, i.e., 10 days of conditioning followed by 4 days of testing).

#### 2.1.1 List of target volatile organic compounds

The full list of target VOCs is presented in Table A. 1.

#### 2.1.2 Test specimen collection, handling, preparation, and testing

According to the study objectives, the building material specimens were collected directly from the construction sites of the homes under investigation or, where necessary due to the unavailability of clean specimens, matched materials were obtained from retail distributors. In the case of the cabinet materials, cabinet specimens matching the styles used in the kitchen and bathrooms of H1 and H2 were purchased separately from the cabinet supplier of the test homes.

Materials selected for testing included structural products (I-joist, oriented strand board [OSB] subfloor, plywood underlay), flooring materials (two hardwood flooring products, carpet, ceramic tile assembly), an interior door, interior trim (three medium-density fibreboard [MDF] baseboard specimens), latex caulk, interior paint (on drywall substrate), and cabinet systems (two kitchen and two bathroom units, including countertops).

Protocols established for specimen collection are provided in Table B. 1.

Descriptions of the individual test specimens that were subjected to emissions testing follow. In all cases, testing was conducted to best reflect actual installation configurations of the materials in the homes. This meant that in some cases, holders were used to limit exposed surfaces in the chamber such that the emissions monitored came from surfaces typically exposed to indoor air.

Testing was conducted in 50 L electro-polished chambers, except for the four cabinet and interior door specimens where a 31 m<sup>3</sup> version of NRC's full-scale chamber system was used. The test conditions were set at 50% relative humidity (RH), 23 °C, and an air change rate of 1 h<sup>-1</sup>, with the exception of the interior door for which it was set at 0.49 h<sup>-1</sup> as the door size was relatively small with a loading ratio of 0.07 m<sup>2</sup> m<sup>-3</sup>. Clean air for the 50 L chambers was supplied with an Aadco Model 737 pure air generator. Relative humidity was controlled at 50% by mixing dry and humidified airstreams and continuously monitoring the RH of the exhaust air. The 50 L chambers were housed in a Forma™ environmental chamber that can maintain a constant temperature of 23 ± 0.5 °C.

The 31 m<sup>3</sup> chamber had a dedicated heating, ventilating, and air conditioning (HVAC) system, including charcoal and HEPA filters to control chamber flow rate, RH, and temperature. All components of the HVAC system downstream of the filters were in stainless steel.

Individual tests typically lasted 14 days, with air sampling at 0 d (background), 1 d, 4 d, 6 d, 8 d, 11 d, 12 d, and 14 d. Due to technical difficulties (e.g., power failure), tests for hardwood floors (HWF1 and HWF2) lasted 12 days in two 50 L chambers and for an interior door specimen (IDr) 13 days in one 31 m<sup>3</sup> chamber. Duplicate samples were taken at 8 d and 14 d. Background samples helped verify chamber cleanliness. More detailed information about sampling can be found in the next section.

Table 1 summarizes specimen characteristics and test conditions. Details of specimen preparation are found in sections 2.1.2.1 to 2.1.2.17.



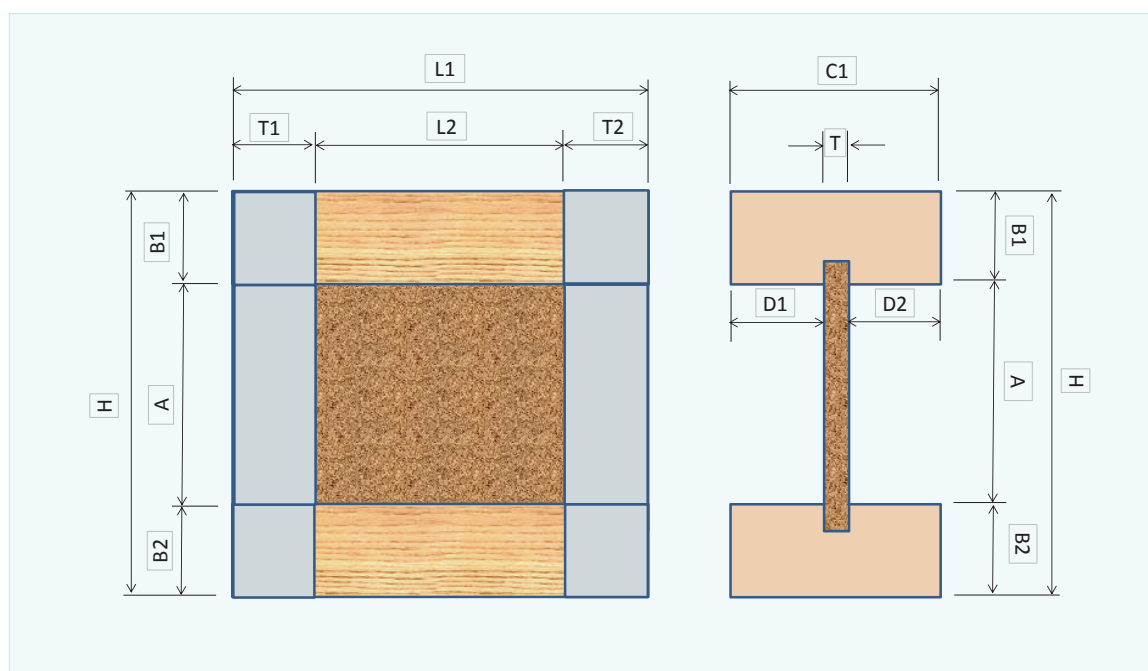
TABLE 1: Summary of test materials and conditions

Test ID	Type	Subtype	Surface control method	Chamber vol. (m³)	Air change rate (h <sup>-1</sup> )	Temperature (°C)	RH (%)	Loading factor (m² m <sup>-3</sup> )	Weight (initial, g)	Weight (final, g)
IJ	Structural framing	Wood I-joist	Aluminum tape	0.05	1.00	23	50	2.18	423.94	424.45
OSB-SF	Subflooring/ structural	Subflooring, panel-type OSB	Aluminum tape	0.05	1.00	23	50	1.02	137.90	138.00
Ply-UL	Underlay between ceramic and OSB	Plywood underlay	Aluminum tape	0.05	1.00	23	50	1.01	90.61	90.72
HWF1	Finished flooring	Flooring, red oak veneer, pine core, pre-stained	Small sample holder	0.05	1.00	23	50	0.40	117.73	118.15
HWF2	Finished flooring	Flooring, white oak veneer, pre-stained	Small sample holder	0.05	1.00	23	50	0.20	174.29	174.39
Carp	Flooring	Carpet, polyester	Small holder	0.05	1.00	23	50	0.40	35.88	35.87
Ceram	Flooring	Ceramic tile-adhesive-plywood-OSB	Aluminum tape; top & bottom exposed	0.05	1.00	23	50	1.92	764.98	
IDr	Door, interior, closet	Molded-hardboard-faced wood doors; painted at construction site	None	31	0.49	23	50	0.07		
MDF-bb1	Finishing, baseboard trim	MDF Baseboard, 5.5", primed	Aluminum tape; stainless steel plate	0.05	1.00	23	50	1.00	227.43	228.15
MDF-bb2	Finishing, baseboard trim	MDF Baseboard, 1.5", primed	Aluminum tape; stainless steel plate	0.05	1.00	23	50	0.50	34.81	35.42
MDF-bb3	Finishing, baseboard trim	MDF Baseboard primed and painted, 1.5", primed	Aluminum tape; stainless steel plate	0.05	1.00	23	50	0.50		
Caulk	Finishing, trim	Caulk, latex	Stainless steel caulk holder #9	0.05	1.01	23	50	0.03	16.70	14.10
Paint1	Interior finish	Primer (latex) and paint (acrylic latex) applied on drywall (1/2" Easi-Lite)	Small holder	0.05	1.00	23	50	0.40	164.57	
Cab1	Cabinetry for H1	Bathroom base cabinet, stone countertop	None	31	1.00	23	50	0.08		
Cab2	Cabinetry for H1	Kitchen wall & base cabinetry, style 1	None	31	1.00	23	50	0.16		
Cab3	Cabinetry for H2	Kitchen wall & base cabinetry, style 2	None	31	1.00	23	50	0.16		
Cab4	Cabinetry for H2	Bathroom base cabinet, laminate countertop	None	31	1.00	23	50	0.09		

### 2.1.2.1 Structural: I-joist, OSB web (test: IJ)

Samples of structural I-joist (241 mm height OSB web, flatwise spruce-pine-fir [SPF] flange) were collected from H1 on June 30, 2016 and stored in the lab in Tedlar bags at 23 °C. For testing, two specimens were cut from two samples provided. The edges of the specimens were sealed with aluminum tape. Figure 1 provides a schematic of the prepared specimens, with dimensions provided in Table B. 2. The resulting exposed surface areas (total, SPF, OSB) are indicated in Table B. 2. The two specimens were placed on a stainless steel mesh support in the centre of the 50 L chamber such that all non-taped surfaces were exposed to the chamber air. The resulting loading factors for total surface, OSB web, and SPF flange were 1.094, 0.505, and 0.589 m<sup>2</sup> m<sup>-3</sup>, respectively. Loading factors based on I-joist length rather than area may be preferred for estimating indoor air quality (IAQ) impact (but this would be specific to the 241 mm I-joist only).

**FIGURE 1: Schematic of I-joist specimens**



### 2.1.2.2 Flooring: sub, panel-type, OSB (test: OSB-SF)

Samples of OSB subflooring (15.1 mm thick) were collected from H1 on June 30, 2016 and stored in the lab in Tedlar bags at 23 °C. For testing, three specimens were cut from the samples provided. The edges of the specimens were sealed with aluminum tape. Final test specimen dimensions and total exposed surface areas after the edges had been taped are provided in Table B. 3. Specimen weights are summarized in Table B. 4. The three specimens were placed on a stainless steel mesh support in the centre of the 50 L chambers such that all non-taped surfaces were exposed to the chamber air. The resulting loading factor for the total exposed OSB surface was 1.02 m<sup>2</sup> m<sup>-3</sup>.



### 2.1.2.3 Flooring: underlay, plywood (test: Ply-UL)

Plywood underlay (~15.4 mm thick) was used in the test homes at locations where ceramic flooring was installed. Samples of this underlay were collected from H1 on September 20, 2016. For testing, three specimens were cut from the samples provided. The edges of the specimens were sealed with aluminum tape. Final test specimen dimensions and total exposed surface areas after the edges had been taped are provided in Table B. 5. Specimen weights are provided in Table B. 6. The three specimens were placed on a stainless steel mesh support in the centre of the 50 L chamber. The resulting loading factor for the total exposed plywood surface was  $1.01 \text{ m}^2 \text{ m}^{-3}$ .

### 2.1.2.4 Flooring: red oak veneer, pine core (test: HWF1)

Hardwood flooring used in H2 was collected on October 17, 2016. The flooring material was an oak surface with a pine core. The test specimens cut from the samples provided were mounted in a stainless steel holder to reflect emissions from the upper surface only. The two specimen pieces were mounted such that a joint in the flooring ran down the centre of the sample holder. Once the top plate of the sample holder was installed, the exposed surface area of the test specimen to the chamber air was  $0.020 \text{ m}^2$ , giving a chamber loading ratio of  $0.40 \text{ m}^2 \text{ m}^{-3}$ . The dimensions and weights of the test specimens are provided in Table B. 7.

### 2.1.2.5 Flooring: white oak veneer, oak core (test: HWF2)

Laminate flooring used in H1 was collected on October 26, 2016. The flooring material was an oak surface with an oak core. The test specimens cut from the samples provided were mounted in a stainless steel holder to reflect emissions from the upper surface only. The two specimen pieces were mounted such that a joint in the flooring ran down the centre of the sample holder. Once the top plate of the sample holder was installed, the exposed surface area of the test specimen to the chamber air was  $0.020 \text{ m}^2$ , giving a chamber loading ratio of  $0.40 \text{ m}^2 \text{ m}^{-3}$ . The dimensions and weights of the test specimens are provided in Table B. 8.

### 2.1.2.6 Flooring: carpet, polyester (test: Carp)

Carpeting used in H1 was collected on November 2, 2016. The carpet was a polyester material with a plastic backing. It had been treated with two commercial protectant products. Two test specimens cut from the samples provided were mounted in a stainless steel holder to reflect emissions from the upper surface only (specimens provided were too small to cut a single specimen to fit the holder). Once the top plate of the sample holder was installed, the exposed surface area of the test specimen to the chamber air was  $0.020 \text{ m}^2$ , giving a chamber loading ratio of  $0.40 \text{ m}^2 \text{ m}^{-3}$ . The dimensions and weights of the test specimens are provided in Table B. 9.

### 2.1.2.7 Flooring assembly: ceramic tile-adhesive-plywood-OSB (test: Ceram)

Ceramic tile was installed in the entry, mudroom, laundry room, kitchen, and bathrooms. It was applied using a thinset adhesive over plywood underlay mounted over OSB subfloor. The plywood and OSB materials were tested separately (as described above). To reflect actual installed use of the ceramic tile, it was decided to test an assembly of ceramic tile-adhesive-plywood-OSB as shown in Figure 2. Once assembled, the edges of the assembly were sealed with aluminum tape and the assembly mounted on a stainless steel mesh support in the test

chamber. Thus the exposed surfaces were the ceramic flooring as well as the OSB subfloor exposed to the storey below. The weights and areas of the specimen are provided in Table B. 10 and Table B. 11.

**FIGURE 2:** Schematic of ceramic tile assembly



#### **2.1.2.8 Door: interior, closet (test: IDr)**

The door was painted at the construction site and the paint was still fresh when it was received. The door specimen was received on October 5, 2016 and tested on October 25, 2016 in the 31 m<sup>3</sup> chamber with all surfaces exposed to air. Since the door size was considered “small” relative to the chamber size, the air change rate was set at 0.49 h<sup>-1</sup> (versus 1 h<sup>-1</sup> used in other tests). The dimensions and areas of the door specimen are provided in Table B. 12.

#### **2.1.2.9 Trim: baseboard, MDF, 5.5”, primed (test: MDF-bbt1)**

The baseboard trim specimen (5.5”) made of factory primed MDF was collected on September 28, 2016 and stored in the lab in a Tedlar bag until testing on October 6, 2016. Two units of the baseboard were tested in a 50 L chamber. Two ends of the specimens were sealed with aluminum tape. A stainless steel plate was used to hold the specimens. Dimensions, areas, and weights of the specimens are provided in Table B. 13 and Table B. 14.

#### **2.1.2.10 Trim: baseboard, MDF, 1.5”, primed (test: MDF-bbt2)**

The baseboard trim specimens (1.5”) made of factory-primed MDF were collected at the construction site. A portion of the trim surface was unfinished. Four units of baseboard trims were tested with the same method as MDF-bbt1. Dimensions, areas, and weights of the specimens are provided in Table B. 15 and Table B. 16.

#### **2.1.2.11 Trim: baseboard, MDF, 1.5”, painted (test: MDF-bbt3)**

The trim specimens from the “MDF-bbt2” test were painted with the same primer and paint used to make the paint specimen “Paint1” (see Section 2.1.2.13). Four trim specimens were conditioned for ~8 days, primed on March 22, 2017, painted on March 23, 2017, and tested in a

50 L chamber on March 23, 2017. The test method and specimen dimensions were the same as “MDF-bbt2.” The specimen weights after painting are presented in Table B. 17.

#### **2.1.2.12 Finishing: caulk, latex (test: Caulk)**

Siliconized acrylic latex caulk used to install baseboard trim was purchased from a local retail store by Health Canada. The product was applied into a special holder made of stainless steel. The holder had a narrow channel (~¼” depth x ¼”width x 10” length) that could hold liquid products such as caulking. Caulking specimen dimensions and weights are provided in Table B. 18.

#### **2.1.2.13 Finishing: paint-drywall assembly (test: Paint1)**

The primer (latex) and paint (acrylic latex) specimens were purchased by Health Canada and delivered to the NRC on November 28, 2016. The primer and paint were applied onto a drywall (½” Easi-Lite) specimen that was put into a stainless steel specimen holder. The drywall substrate was conditioned in a clean 50 L test chamber for 5 days at an air change rate of 1 h<sup>-1</sup> and at 23 °C. The primer was applied on the substrate and conditioned for 1 day. The paint was applied on the primed substrate the same day the chamber test was initiated (Table B. 19). The specimen area exposed to air was 0.02 m<sup>2</sup>, giving a chamber loading ratio of 0.40 m<sup>2</sup> m<sup>-3</sup>. The weights of the test specimens are provided in Table B. 19.

#### **2.1.2.14 Cabinet: bathroom cabinet with stone countertop (test: Cab1)**

A bathroom base cabinet with a stone countertop was obtained directly from the manufacturer on December 22, 2016. The specimen was stored in a room without major VOC sources until tested. An air change rate of 1 h<sup>-1</sup> was used for the test. Dimensions and areas exposed to air are provided in Table B. 20.

#### **2.1.2.15 Cabinets: kitchen wall and base, style 1 (test: Cab2)**

Kitchen wall and base cabinets identical to those installed in H1 were obtained directly from the manufacturer on December 22, 2016. Storage and test conditions for Cab2 were the same as those for Cab1. Dimensions of the specimen tested in the 31 m<sup>3</sup> chamber and areas exposed to air are provided in Table B. 21.

#### **2.1.2.16 Cabinets: kitchen wall and base, style 2 (test: Cab3)**

Kitchen wall and base cabinets identical to those installed in H2 were obtained directly from the manufacturer on December 16, 2016. Dimensions of the specimen tested in the 31 m<sup>3</sup> chamber and areas exposed to air are provided in Table B. 22.

#### **2.1.2.17 Cabinet: bathroom cabinet with laminate countertop (test: Cab4)**

A base cabinet identical to the one installed in H2 bathroom was obtained directly from the manufacturer. The cabinet was constructed from particleboard panels with a particleboard-core laminate countertop. The dimensions of the specimen and the areas exposed to air are provided in Table B. 23.

## 2.1.3 Sampling and chemical analysis

### 2.1.3.1 Sampling and gas chromatography-mass spectrometry analysis for VOCs

Air samples from the chambers were collected on two-layer sorbent tubes filled with Tenax TA and Carboxen 100 (GERSTEL Inc.) from sample ports mounted on the chamber exhaust manifolds. Sampling was conducted using mass flow-controlled sampling pumps at 200 mL min<sup>-1</sup> for 10 min (calibrated vs. traceable bubble flowmeter) to give sampling volumes of ~2 L.

Volatile organic compounds analysis of the collected air samples was performed using a GERSTEL Thermal Desorption System TDS 3 connected to an Agilent 6890 Series Gas Chromatograph coupled to a 5973N Mass Selective Detector, equipped with a DB-624 capillary column (30 m × 0.25 mm ID × 1.4 µm thickness). The desorbed analytes were injected using a GERSTEL programmable temperature vaporizer called a Cooled Injection System (CIS), which concentrated the sample prior to injection onto the Agilent 6890 column. Helium carrier gas flow in the analytical column was 1.2 mL min<sup>-1</sup>. All samples were analyzed using a split flow at 20 mL min<sup>-1</sup> after a splitless desorption. The mass spectrometry was operated in full ion scan mode ( $m/z$  35 to 300).

Temperature profiles for the thermal desorption (TD) and gas chromatography-mass spectrometry (GC/MS) analyses are as follows:

- ▶ Thermal desorption conditions:
  - ▶ initial temperature: 30 °C
  - ▶ ramp at 60 °C min<sup>-1</sup> to final temperature of 300 °C
  - ▶ 5 min hold at 300 °C
- ▶ CIS conditions:
  - ▶ initial temperature: -90 °C
  - ▶ ramp at 12 °C s<sup>-1</sup> to final temperature of 300 °C
  - ▶ 3 min hold at 300 °C
- ▶ GC conditions:
  - ▶ 6 min hold at initial temperature of 25 °C
  - ▶ ramp at 6 °C min<sup>-1</sup> to final temperature of 230 °C

For the current target VOC list, calibration of 117 individual VOCs was performed using three sets of liquid mixtures. One commercial calibration mixture (Japanese Indoor Air Standard Mix; 100 µg mL<sup>-1</sup> each in methanol: water = 19:1) and two custom-made standard mixtures (Custom A and Custom B, 500 µg mL<sup>-1</sup> for each chemical in methanol) were purchased from Supelco. The liquid calibration mixtures were injected onto the glass frit of the two-layer sorbent tube while laboratory air was pumped into the tube at 50 to 100 mL min<sup>-1</sup> for 2 min. A five-point calibration was achieved via introduction of 1 µL of calibration mixture to five concentration levels onto the tubes. Calibration curves for each VOC were established by plotting the peak area of their specific quantification ion versus the injected mass. R<sup>2</sup> values of linear calibration curves were between 0.90 and 0.99, with



lower values for acids, esters, and glycol ethers. The method detection limit (MDL) for the 117 VOCs ranged from 0.33 to 19.14 ng. The MDL was determined in accordance with the Code of Federal Regulations established by the US EPA (2011) (40 CFR 136 Appendix B) by analyzing seven replicate samples spiked with the calibration mixture at the lowest calibration level. The information on the target VOCs and their MDLs can be found in Table A. 1.

The air samples from the emissions chamber were scanned for the presence of these 117 compounds, and when found, their individual calibration curves were used to report concentrations. The most abundant VOCs (above 1% of total volatile organic compounds [TVOC]), other than target VOCs, were identified by comparing their mass spectrum with the NIST Mass Spectral Library, and quantified as toluene equivalents. The chemicals were termed as either “abundant” or “non-target” VOCs. If the chemical identification could not be done with confidence, it was termed as “abundant (unidentified)” VOC.

Total volatile organic compounds were obtained by summing all peaks eluted between 3 and 35 min (Total Ion) as a toluene equivalent. Therefore, this estimate is semi-quantitative at best. Depending on the relative abundance of the specific VOCs present, the reported TVOC, expressed as a mass concentration, can be off by a factor of 10 or more.

### **2.1.3.2 Sampling and high-performance liquid chromatography analysis for low molecular weight aldehydes**

Air samples for low molecular weight carbonyl compounds were collected on Waters Sep-Pak XPoSure Aldehyde samplers, which contained acidified 2,4-dinitrophenylhydrazine (DNPH)-coated silica. Mass flow-controlled pumps were used to sample exhaust air at 400 mL min<sup>-1</sup>, leading to sampling volumes of ~40 L.

Analysis of carbonyl compounds was performed in accordance with ASTM D5197 and EPA TO11. Exposed cartridges were extracted with acetonitrile to a final volume of 10 mL. An eluate of 20 µL was then analyzed by reverse phase HPLC with UV detection at 360 nm. The HPLC system included Agilent Technologies 1260 Quaternary Solvent Delivery System/1260 Variable Wavelength Detector VL/1260 Infinity Standard Autosampler with two SUPELCO SIL LC-18 columns (25 cm x 4.6 mm, 5 µm) in series maintained at 30 °C. A gradient of acetonitrile in water from 60% to 100% was used for separation of the carbonyl compounds. System calibration was performed using a six-point calibration from a commercial DNPH derivative mixture (TO11/IP-6A Aldehyde/Ketone-DNPH Mix certified reference material from Supelco). Linear calibration curves were produced with R<sup>2</sup> between 0.9997 and 0.9999. The MDLs were determined to be 6.9, 8.9, and 5.7 ng for formaldehyde, acetaldehyde, and propanal, respectively.

Although the DNPH cartridge and HPLC analysis method can provide information on higher molecular weight carbonyls such as butanal, hexanal, benzaldehyde, and acetone, GC/MS was used as the method of choice for these compounds. This is because the DNPH-HPLC method has been reported to underestimate the concentrations of high molecular weight aldehydes in comparison to the sorbent tube (Tenax TA) and GC/MS analysis method (Salthammer and Mentese 2008). Therefore, the results from the DNPH-HPLC method were reported only for three low molecular weight aldehydes, i.e., formaldehyde, acetaldehyde, and propanal.

### 2.1.3.3 Quality assurance and control

The quality control procedure involved the analysis of blank and background samples. Blank samples were analyzed for each run of GC/MS and HPLC/UV. The DNPH cartridges showed the blank level of 45 ng for formaldehyde, 93 ng for acetaldehyde, and 10 ng for propanal on average. In general, the DNPH blank levels were higher than the MDL. Therefore, blank corrections were done for DNPH samples. The sorbent samples also showed blank levels that were comparable to the MDLs for some chemicals (Table B. 24). As such, blank corrections were also employed for the two-layer sorbent tubes.

Background samples were collected in empty chambers prior to each test. In general, the background levels were higher than the MDL. Consequently, background levels were subtracted from the chamber concentrations and the chamber concentrations reported in Appendix D are background corrected.

Duplicate samples collected at 8 d and 14 d showed good agreement, with a median difference of 15% for all tests. One exception was duplicate samples taken at 8 days in the Cab3 test that showed a difference of a factor of 10.

### 2.1.4 Modelling of emission factor

The emission factor was calculated based on the background-corrected concentration, as shown in equation (1):

$$E = Q C / A \quad (1)$$

where  $E$  is the emission factor ( $\mu\text{g m}^{-2} \text{h}^{-1}$ ) at time  $t$ ,  
 $Q$  is the chamber flow rate ( $\text{m}^3 \text{h}^{-1}$ ),  
 $C$  is the chamber air concentration ( $\mu\text{g m}^{-3}$ ) corrected for the background level,  
 $A$  is the specimen surface area exposed to air ( $\text{m}^2$ ).

The time-varying emission factor was assumed to follow a power-law model, which is known to perform better for predicting long-term emissions than an exponential decay model (Liu et al. 2015; Ye, Won and Zhang 2016).

$$E = b t^m \quad (2)$$

where  $b$  and  $m$  are empirical constants,  
 $t$  is the time (h).

The constants  $m$  and  $b$  were obtained through curve fitting of the time and emission factor data for each combination of compound and material. Least square method was used for curve fitting. Concentrations below MDL were also included in the curve fitting to maximize the number of data points. Since equation (2) does not allow for a zero or negative value for  $E$ ,  $E = 0$  was replaced with a small value (0.0001) for the curve fitting.



## 2.2 RESULTS

The chamber concentrations and emission factors found for each test are in Appendix D. The emission factors were calculated based on the chamber concentration using equation (1). The coefficients of an emission model—equation (2)—are also included in the appendix.

### 2.2.1 Concentrations and emission factors organized for individual materials

In this section, 10 to 20 major VOCs emitted from each material are presented in tables and figures. Table B. 25 to Table B. 41 present the emission factors predicted using emission models for 1 day, 8 days, and 14 days. To differentiate them from the emission factors based on measured chamber concentrations, the term “nominal emission factors” was used for the modelled emission factors. Since the exact time of sampling varied slightly between tests, the measured emission factors are not used for comparison. Figure B. 1 to Figure B. 17 compare the chamber concentrations (background level corrected) for the 10 most abundant VOCs. In short, the tables contain the emission factors calculated based on the emission models, and the figures compare the background corrected chamber concentrations.

#### 2.2.1.1 Structural: I-joist, OSB web (test: IJ)

Table B. 25 provides emission factors for 20 major compounds emitted from the I-joist specimen with OSB web and SPF flange. Acids (acetic acid), aldehydes (hexanal and acetaldehyde), terpenes (alpha-pinene), and alcohols (ethanol) were the main compounds emitted. Figure B. 1 presents the chamber concentrations for 10 major compounds from IJ. The decay curves follow power-law equations relatively well. Most VOCs had concentrations which decreased over time (> 90% of VOCs emitted).

#### 2.2.1.2 Flooring: sub, panel-type, OSB (test: OSB-SF)

Table B. 26 provides emission factors for 20 major compounds emitted from the OSB subfloor specimen. As with the I-joist specimen, acids (acetic acid), aldehydes (hexanal, pentanal), and alcohols (1-pentanol) were the main compounds emitted. Acetone was also measured in abundance. Terpenes were not found to be major contributors to VOC emissions from the OSB subfloor specimen. Figure B. 2 presents the chamber concentrations for 10 major compounds from OSB-SF. The decay of VOCs was slower than the decay of those emitted from IJ.

#### 2.2.1.3 Flooring: underlay, plywood (test: Ply-UL)

Table B. 27 provides emission factors for 20 major compounds emitted from the plywood underlay specimen. Ketones (acetone), aldehydes (hexanal and acetaldehyde), and terpenes (alpha-pinene) were the main compounds emitted. Figure B. 3 presents the chamber concentrations for 10 major compounds from Ply-UL. The decay rates of VOCs from Ply-UL were slower than the decay of those from IJ, with a decay constant  $b$  close to zero. Emission rates for 41% of VOCs from Ply-UL were almost constant or increasing with time over the 14-day test period.



#### **2.2.1.4 Flooring: red oak veneer, pine core (test: HWF1)**

Table B. 28 presents emission factors for 20 major compounds emitted from the engineered hardwood floor with red oak veneer and pine core (HWF1) installed in H2. Terpenes from HWF1 had the largest emission rates. Figure B. 4 presents the chamber concentrations for 10 major compounds from HWF1. Most VOCs (> 70%) had emission rates which decreased over time.

#### **2.2.1.5 Flooring: white oak veneer, oak core (test: HWF2)**

Table B. 29 provides emission factors for 20 major compounds emitted from the hardwood floor with white oak veneer and oak core (HWF2) installed in H1. Ketones (benzophenone) and acids (acetic acid) were the main compounds emitted. Overall, the emission rates of VOCs from HWF2 were lower than those from HWF1. Unlike HWF1, terpenes were not the main VOCs emitted from HWF2. The differences in VOC species and emission rates of these VOCs are likely to be attributed to the difference in core wood species (pine core in HWF1 vs. oak core in HWF2). Figure B. 5 presents the chamber concentrations for 10 major compounds from HWF2. The majority of VOCs emitted from HWF2 (> 70%) also had concentrations which decreased over time, although acetic acid and propanal showed an increasing concentration trend (Figure B. 5).

#### **2.2.1.6 Flooring: carpet, polyester (test: Carp)**

Table B. 30 provides emission factors for 20 major compounds emitted from the polyester carpet (Carp) installed in H1. Unidentified C14 alkenes and 4-phenyl cyclohexene were the main compounds emitted. The emission rates of VOCs were relatively low. Figure B. 6 presents the chamber concentrations for 10 major compounds from Carp. Most VOCs (91%) had concentrations which decreased over time.

#### **2.2.1.7 Flooring assembly: ceramic tile-adhesive-plywood-OSB (test: Ceram)**

Table B. 31 presents emission factors for 20 major compounds emitted from the ceramic tile assembly of tile, adhesive, plywood, and OSB subfloor (Ceram). Unidentified C11 and C12 branched hydrocarbons were the main compounds emitted. Among target VOCs, acetic acid and hexanal had relatively high emission factors. Figure B. 7 presents the chamber concentrations for 10 major compounds from Ceram. Many VOCs (46%) had concentrations which increased over time, likely due to the slow drying process of adhesive sandwiched between tile and subfloor.

#### **2.2.1.8 Trim: baseboard, MDF, 5.5", primed (test: MDF-bbt1)**

Table B. 32 provides emission factors for 20 major compounds emitted from the MDF baseboard trim (MDF-bbt1). Acids (acetic acid), aldehydes (formaldehyde and hexanal), and ketones (acetone) were the main compounds emitted. Figure B. 8 presents the chamber concentrations for 10 major compounds from MDF-bbt1. Most VOCs (85%) had concentrations which decreased over time.





### 2.2.1.9 Trim: baseboard, MDF, 1.5", primed (test: MDF-bbt2)

Table B. 33 presents emission factors for 20 major compounds emitted from the MDF baseboard trim (MDF-bbt2). The main compounds emitted were similar to those from MDF-bbt1, including acids (acetic acid and hexanoic acid), aldehydes (hexanal and formaldehyde), and ketones (acetone). Figure B. 9 presents the chamber concentrations for 10 major compounds from MDF-bbt2. As with MDF-bbt1, most VOCs (87%) had concentrations which decreased over time.

### 2.2.1.10 Trim: baseboard, MDF, 1.5", painted (test: MDF-bbt3)

Since a portion of the MDF baseboard trim (MDF-bbt2) had an unfinished surface, it was painted with Paint1 and re-tested (MDF-bbt3). Table B. 34 shows that the major VOCs from the painted MDF baseboard trim were associated with paint, i.e., Texanol (2,2,4-trimethyl-1,3-pentanediol isobutyrate) and propylene glycol. The presence of acetic acid was also observed with MDF-bbt3, as with MDF-bbt1 and MDF-bbt2. Figure B. 10 presents the chamber concentrations for 10 major compounds from MDF-bbt3. Most VOCs (81%) had concentrations which decreased over time, following power-law equations relatively well.

### 2.2.1.11 Finishing: caulk, latex (test: Caulk)

Table B. 35 provides emission factors for 20 major compounds emitted from the latex caulk used to install baseboard trims (Caulk). Alcohols, glycols, glycol ethers, and esters were the main compounds emitted. Figure B. 11 presents the chamber concentrations for 10 major compounds from Caulk. Most VOCs (91%) showed decaying trends that can fit well with power-law equations.

### 2.2.1.12 Finishing: paint-drywall assembly (test: Paint1)

Table B. 36 provides emission factors for 20 major compounds emitted from the painted drywall (Paint1). As with Caulk, glycols, glycol ethers, and esters were the main compounds emitted. Aldehydes, including formaldehyde, acetaldehyde, and benzaldehyde, were also emitted. Figure B. 12 presents the chamber concentrations for 10 major compounds from Paint1. As with VOCs from Caulk, most VOCs (86%) had decaying concentration trends that could be well modelled by power-law equations.

### 2.2.1.13 Door: interior, closet (test: IDr)

Table B. 37 provides emission factors for 20 major compounds emitted from the interior door (IDr) collected at H1. Aldehydes (formaldehyde) and terpenes (alpha-pinene) were the main compounds emitted. The emission rates were relatively low. While it is not shown in this table, the TVOC level was zero because the chamber concentrations were lower than the background concentrations for multiple VOCs. Figure B. 13 presents the chamber concentrations for 10 major compounds from IDr. The concentrations of some chemicals (e.g., 2,2,4-trimethyl-1,3-pentanediol diisobutyrate) had increasing trends as they were not detected at the beginning (e.g., at 24 h and 96 h). For simulation purposes, the emission factors were assumed to be constant for these chemicals.

#### **2.2.1.14 Cabinet: bathroom cabinet with stone countertop (test: Cab1)**

Table B. 38 provides emission factors for 20 major compounds emitted from the bathroom cabinet and stone countertop (Cab1) from H1. Aldehydes (formaldehyde) and ketones (acetone) were the main compounds emitted. As with the interior door specimen, the emission rates were relatively low. The TVOC level was also zero at 1 d, 4 d, 6 d, and 14 d (Table D. 14) because the chamber concentrations were lower than the background concentrations. Figure B. 14 presents the chamber concentrations for 10 major compounds from Cab1. Most VOCs (83%) had concentrations which increased over time.

#### **2.2.1.15 Cabinets: kitchen wall and base, style 1 (test: Cab2)**

Table B. 39 provides emission factors for 20 major compounds emitted from the kitchen cabinet wall and base unit (Cab2) from H1. Aldehydes (formaldehyde) and alcohols (1-butanol) were the main compounds emitted. The emission rates of most VOCs were higher than those in Cab1 (Table D. 15). Unlike Cab1, TVOC levels were above zero. Figure B. 15 presents chamber concentrations for 10 major compounds from Cab2. Many VOCs (47%) had concentrations which increased over time.

#### **2.2.1.16 Cabinets: kitchen wall and base, style 2 (test: Cab3)**

Table B. 40 provides emission factors for 20 major compounds emitted from the kitchen cabinet wall and base unit (Cab3) from H2. Acids (acetic acid), ketones (acetone), and aldehydes (hexanal) were the main compounds emitted. Among the four cabinets tested in this study, Cab3 had the highest emission factors (Table D. 16). Figure B. 16 presents the chamber concentrations for 10 major compounds from Cab3. Many VOCs (42%) also had concentrations which increased over time. The sudden increase of concentration at 8 d was caused by a duplicate sample with abnormally high concentrations, leading to low  $R^2$  values for curve fitting.

#### **2.2.1.17 Cabinet: bathroom cabinet with laminate countertop (test: Cab4)**

Table B. 41 provides emission factors for 20 major compounds emitted from the bathroom base cabinet and laminate countertop (Cab4) from H2. Acids (acetic acid), ketones (acetone), and aldehydes (formaldehyde) were the main compounds emitted. Overall, the emission rates were low, as shown with TVOC levels that were zero (Table D. 17). Figure B. 17 presents the chamber concentrations for 10 major compounds from Cab4. Many VOCs (59%) had concentrations which increased over time.

### **2.2.2 Emission factors for selected volatile organic compounds**

This section summarizes the emission factors for selected VOCs. Table B. 42 summarizes the detection frequency for 120 target VOCs and several non-target VOCs that were emitted in abundance based on their emission factors at day 8. The most frequently detected VOCs were aldehydes, including acetaldehyde, formaldehyde, propanal, benzaldehyde, furfural, hexanal, and pentanal. Ketones (acetone, methylethyl ketone), acids (acetic acid), and alcohols (2-propanol, 1-butanol, and phenol) were also detected frequently. In the category of aromatic hydrocarbons, toluene, styrene, and 1,3(4)-dimethylbenzene were detected more frequently

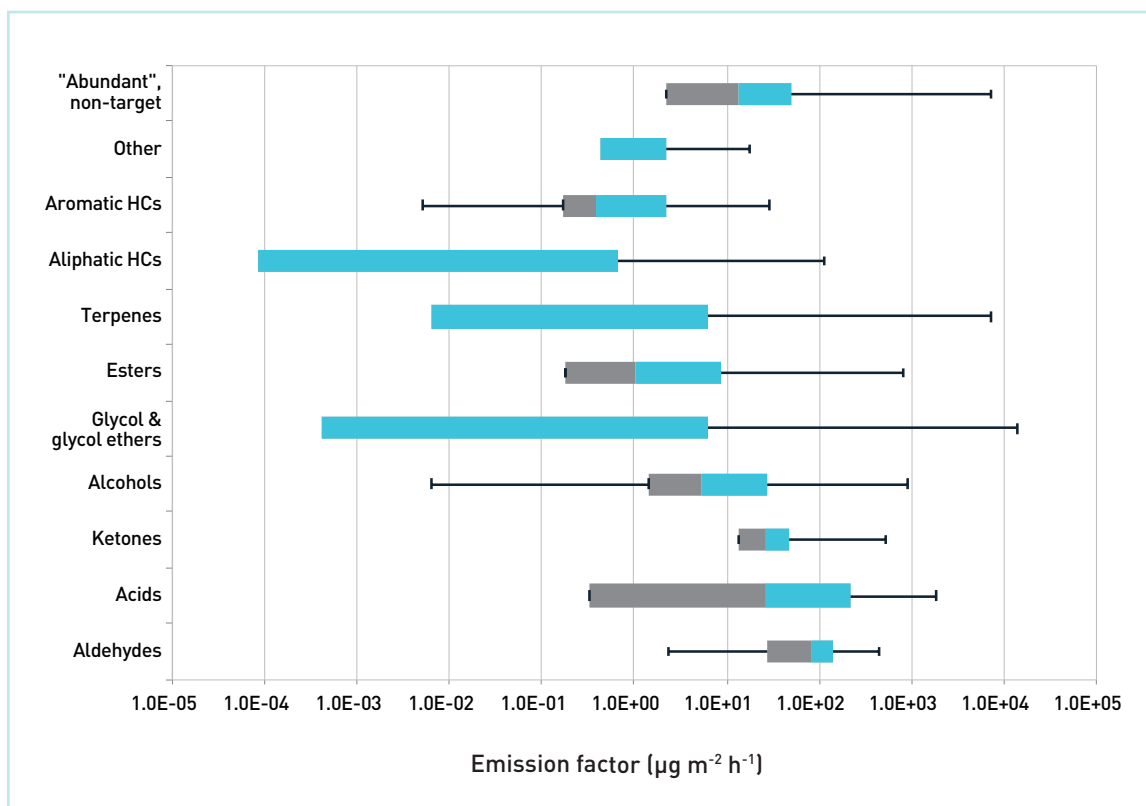


than other aromatic hydrocarbons. While these chemicals were found in various materials, some were found more frequently in a certain group of materials (e.g., glycols, glycol ethers, and esters in paint and caulk specimens).

Figure 3 presents the ranges of emission factors at day 8 for different chemical groups. Halocarbons and cyclo-alkanes were removed due to low detection frequencies. The highest mean emission factors were associated with aldehydes—the group of chemicals with high detection frequencies as well as high emission factors. Acids and ketones had the second highest mean emission factors. The chemical group with the widest range of emission factors was glycols and glycol ethers. Aromatic and aliphatic hydrocarbons had the lowest mean emission factors.

More detailed information about specific emission factors is given below for selected VOCs with high detection frequencies.

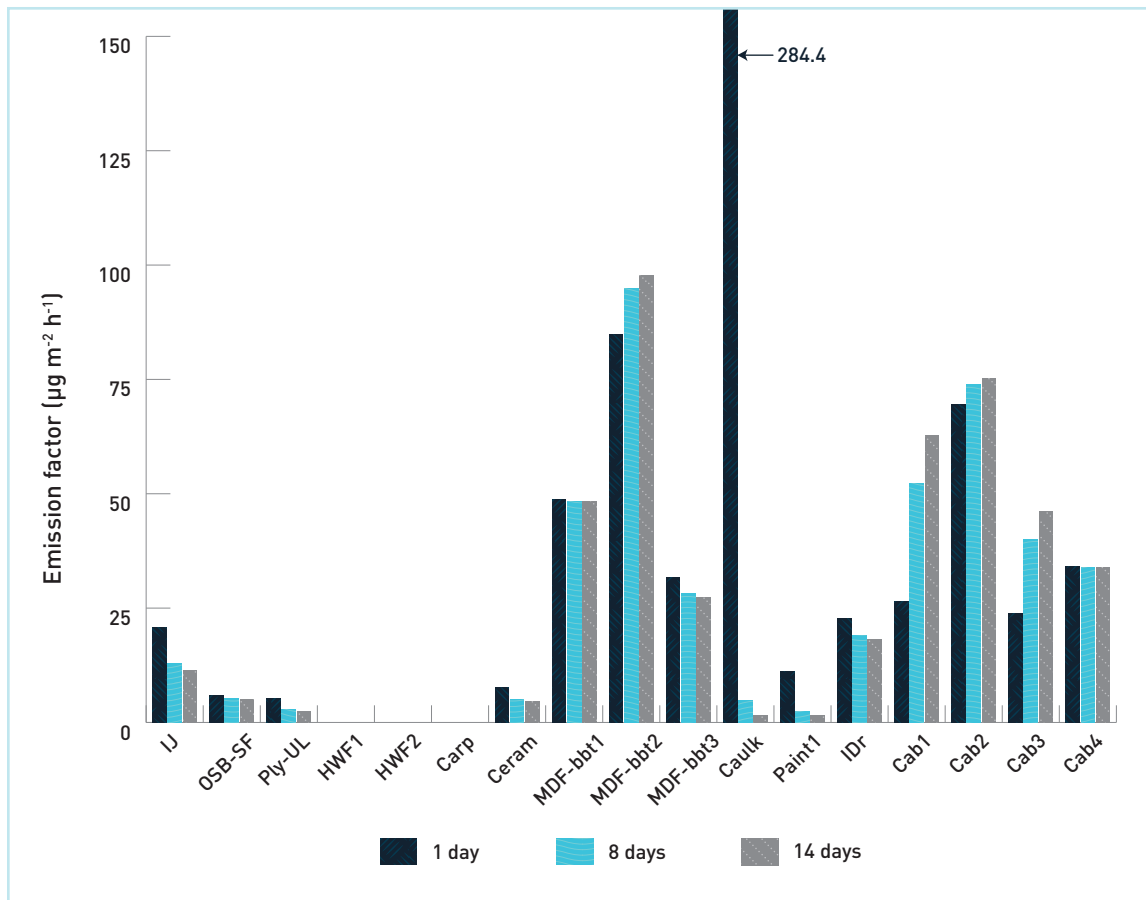
**FIGURE 3:** Range of emission factors for different categories of compounds



### 2.2.2.1 Formaldehyde

Figure 4 compares the formaldehyde emission factors at 1 day, 8 days, and 14 days for 17 specimens tested. The formaldehyde emission factor was the highest at 1 day for the caulk specimen (Caulk), but it decayed quickly. At 8 days and 14 days, the MDF baseboard trim specimen (MDF-bbt2) had the highest emission factors. The emission factors for formaldehyde did not change significantly from 1 day to 14 days for most of specimens except for Caulk. For some materials such as MDF-bbt2, Cab1, Cab2, and Cab3, the formaldehyde emission factors increased over time.

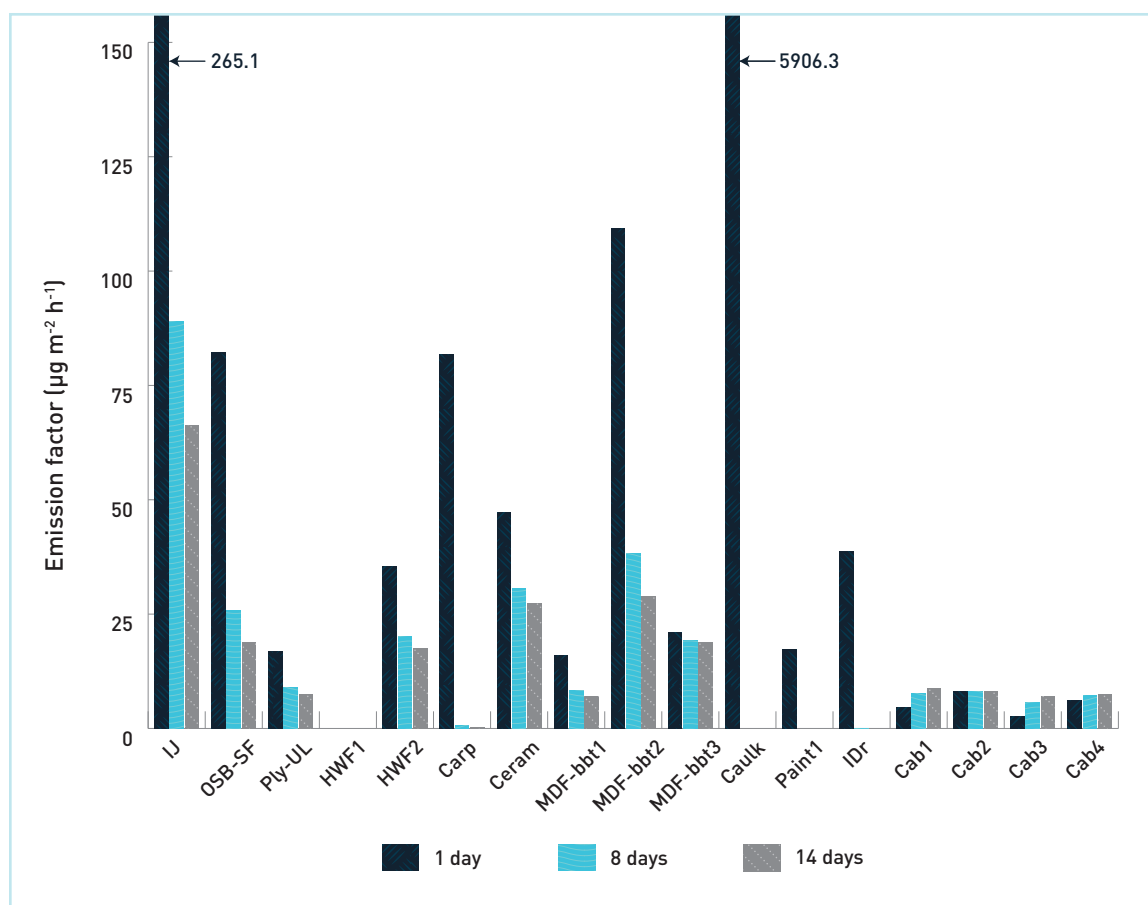
**FIGURE 4:** Emission factors for formaldehyde



### 2.2.2.2 Acetaldehyde

Figure 5 compares the acetaldehyde emission factors at 1 day, 8 days, and 14 days for 17 specimens tested. As with formaldehyde, the acetaldehyde emission factor was the highest at 1 day for the caulk specimen (Caulk). At 8 days and 14 days, the I-joist specimen (IJ) had the highest emission factors, followed by the MDF baseboard trim specimen (MDF-bbt2). The decrease of emission factors from 1 day to 8 days was significant for most materials, except for Cab1, Cab3, and Cab4 for which the acetaldehyde concentrations increased from 1 day to 14 days.

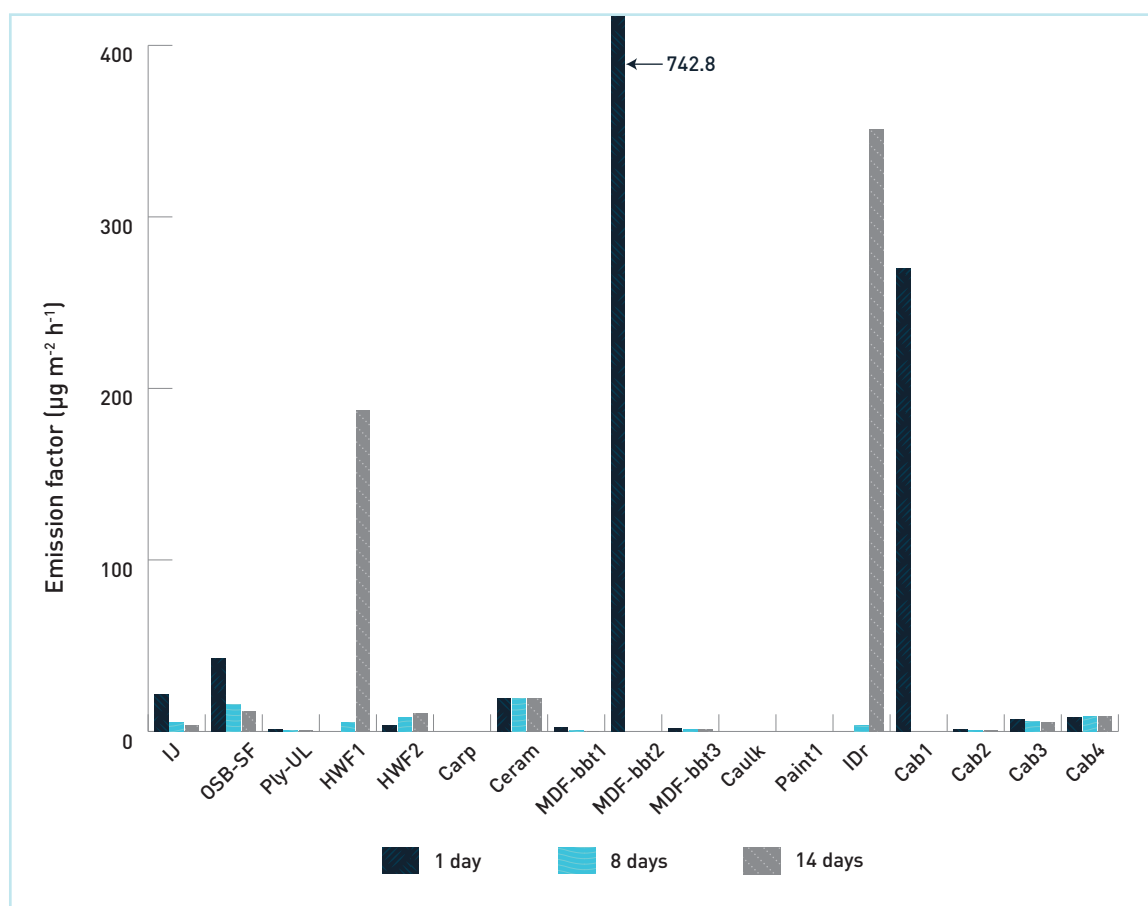
**FIGURE 5:** Emission factors for acetaldehyde



### 2.2.2.3 Propanal

Figure 6 compares the propanal emission factors at 1 day, 8 days, and 14 days for 17 specimens tested. The propanal emission factor was the highest at 1 day for the MDF baseboard trim specimen (MDF-bbt2). For MDF-bbt2 and Cab1, the propanal emission factors decreased significantly from 1 day to 8 days. On the other hand, the emission factors increased considerably from 1 day to 8 days for HWF1 and IDr. The changes of emission factors over time were more pronounced for propanal than formaldehyde.

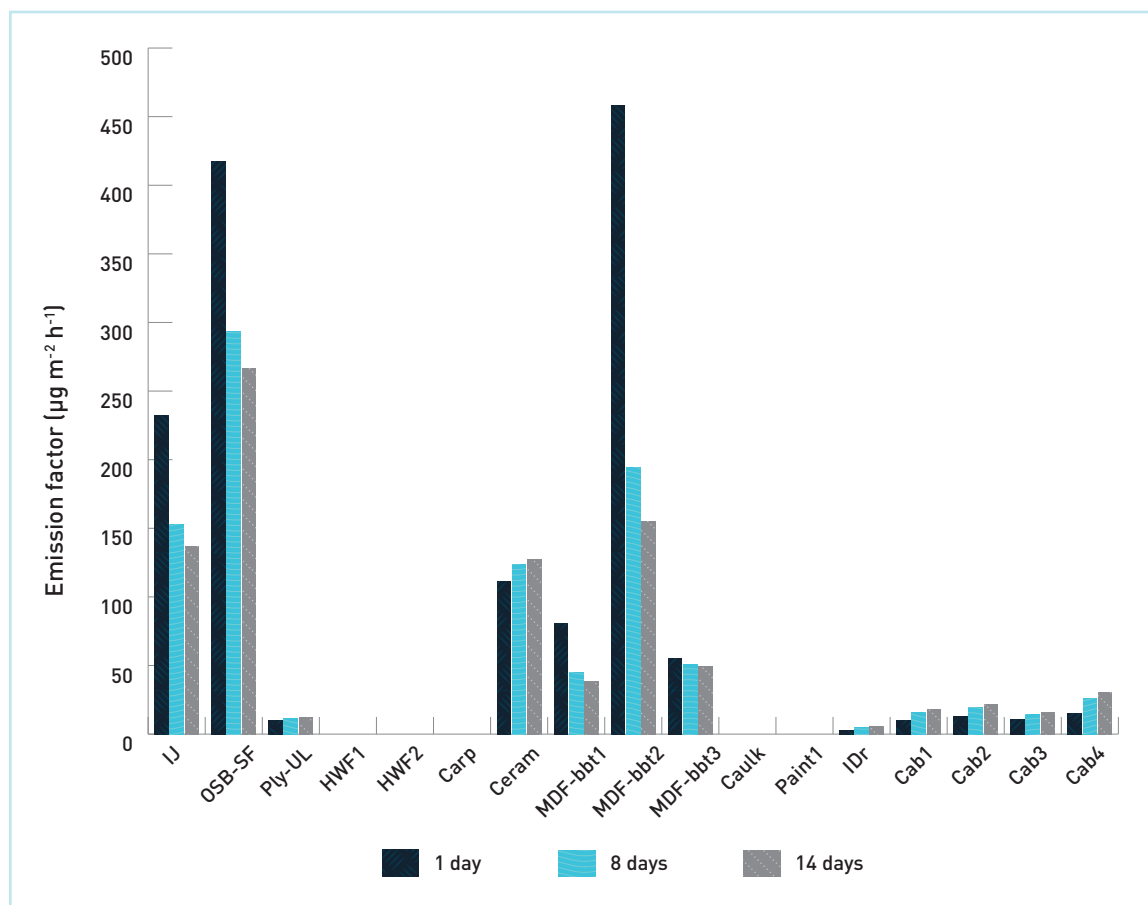
**FIGURE 6:** Emission factors for propanal



### 2.2.2.4 Hexanal

Figure 7 compares the emission factors for hexanal at 1 day, 8 days, and 14 days for 17 specimens tested. The hexanal emission factors were the highest at 1 day for the OSB subfloor (OSB-SF) and the MDF baseboard trim (MDF-bbt2) specimens. Since the decay of hexanal was faster with MDF-bbt2 than OSB-SF, OSB-SF became the highest emitter at 8 days and 14 days.

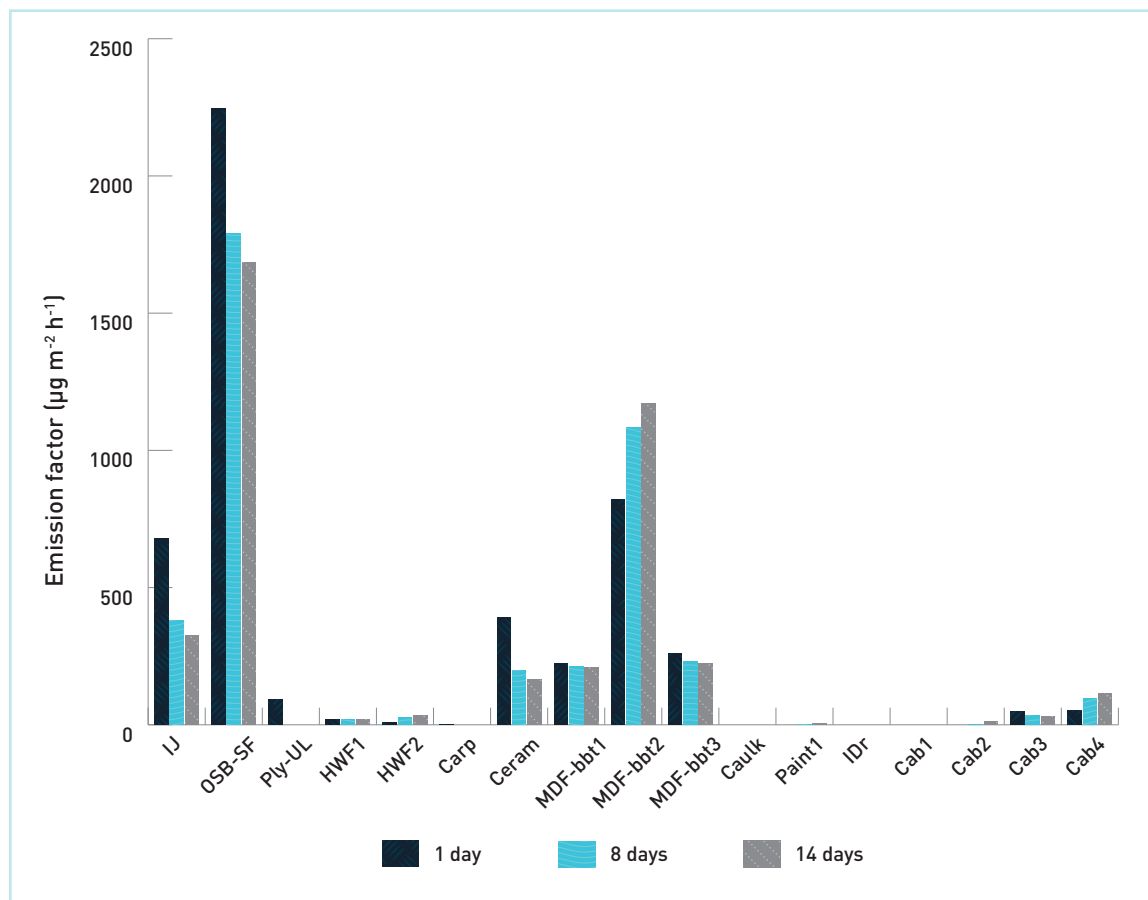
**FIGURE 7:** Emission factors for hexanal



### 2.2.2.5 Acetic acid

Figure 8 compares the emission factors for acetic acid at 1 day, 8 days, and 14 days for 17 specimens tested. The acetic acid emission factors were the highest at 1 day, 8 days, and 14 days for the OSB subfloor specimen (OSB-SF), followed by the MDF baseboard trim specimen (MDF-bbt2). The emission factors for acetic acid increased over time for HWF2, MDF-bbt2, and Cab4.

**FIGURE 8:** Emission factors for acetic acid

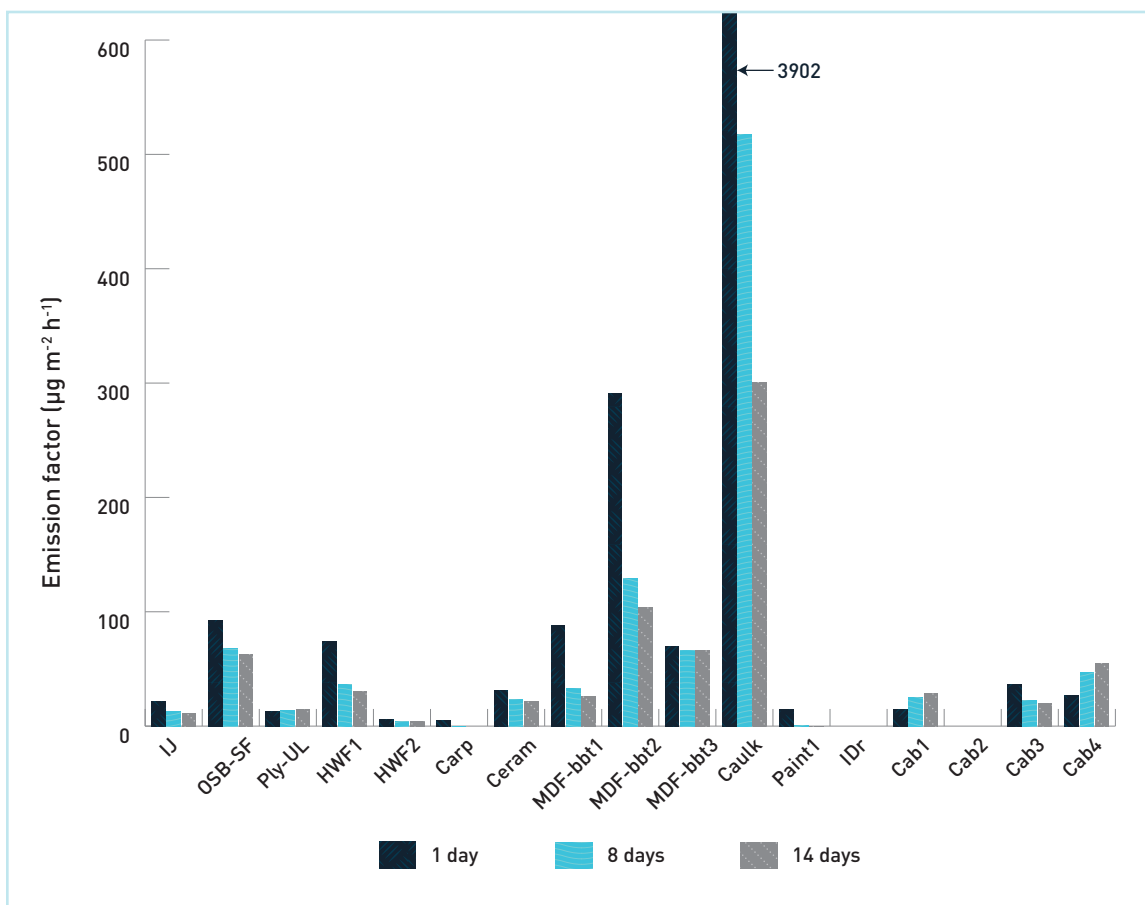




### 2.2.2.6 Acetone

Figure 9 compares the emission factors for acetone at 1 day, 8 days, and 14 days for 17 specimens tested. The acetone emission factors were the highest for the caulk specimen (Caulk), followed by the MDF baseboard trim specimen (MDF-bbt2). There was a significant decrease in emission factors from 1 day to 8 days for Caulk, which can be considered as a typical emission characteristic of liquid construction products.

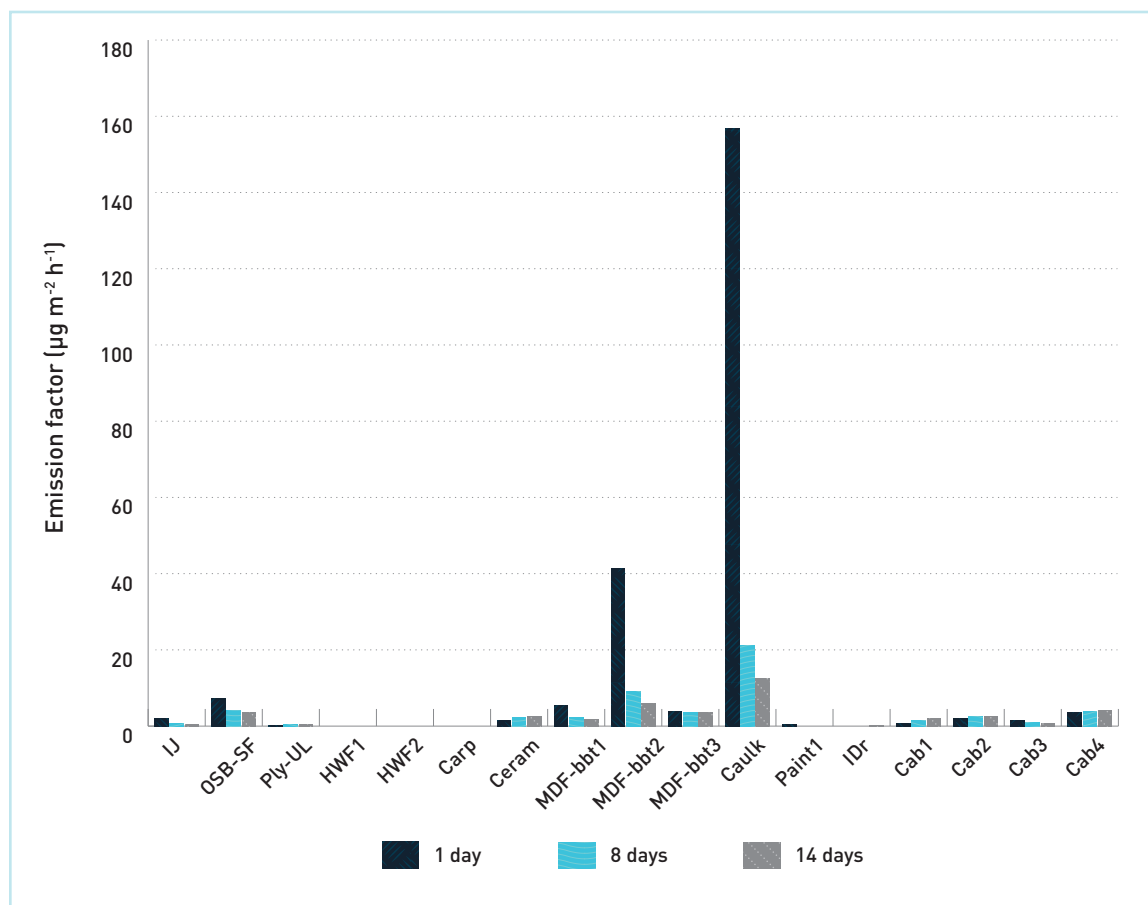
**FIGURE 9:** Emission factors for acetone



### 2.2.2.7 2-Propanol

Figure 10 compares the emission factors for 2-propanol at 1 day, 8 days, and 14 days for 17 specimens tested. As with acetone, the 2-propanol emission factors were the highest for the caulk specimen (Caulk), followed by the MDF baseboard trim specimen (MDF-bbt2). The sharp decrease in emission factors from 1 day to 8 days for Caulk was observed for 2-propanol, as with acetone.

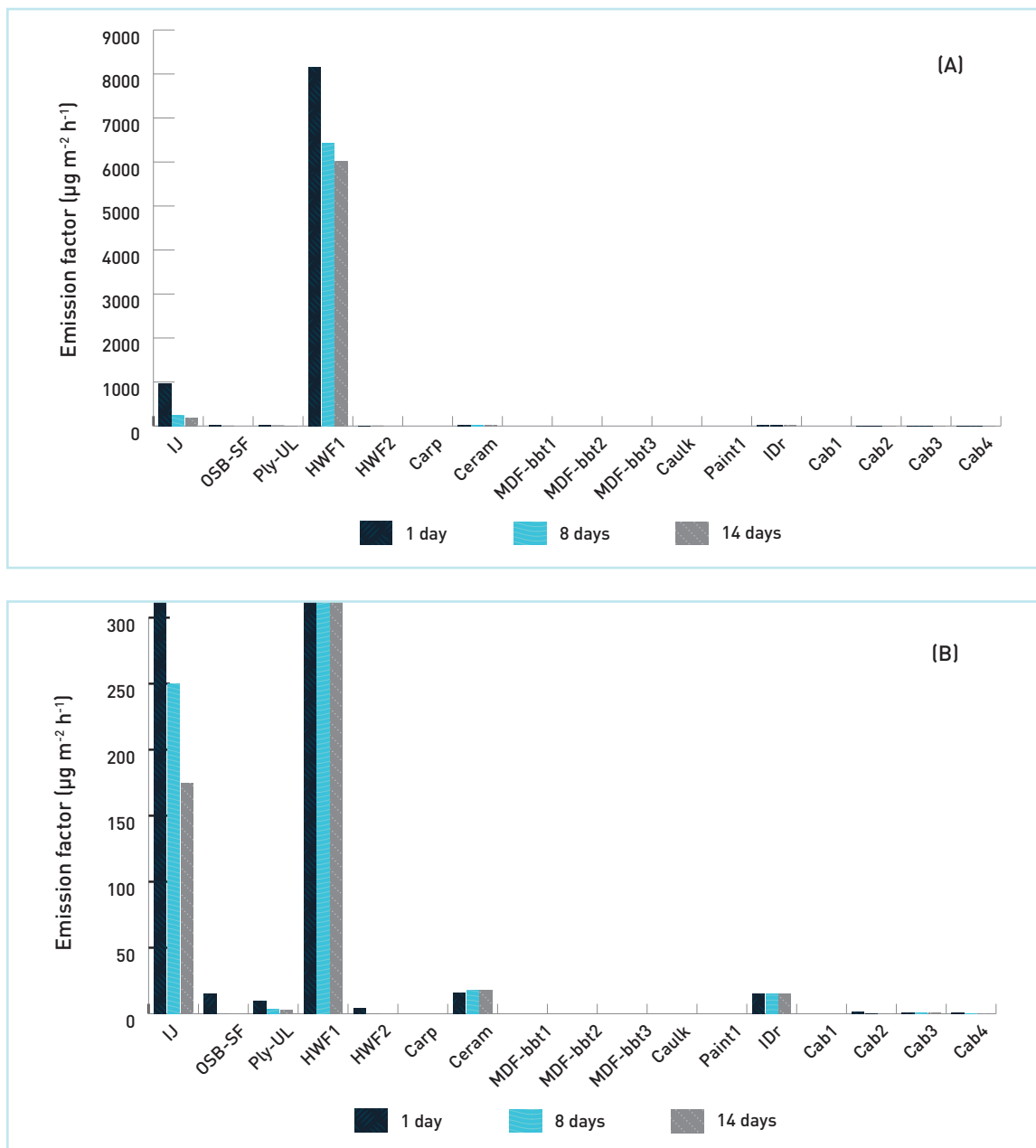
**FIGURE 10** Emission factors for 2-propanol



### 2.2.2.8 Alpha-pinene

Figure 11 compares the emission factors for alpha-pinene at 1 day, 8 days, and 14 days for 17 specimens tested. The emission factors for the hardwood floor specimen (HWF1) were the most prominent. The same observation was made for other terpenes, including beta-pinene, limonene, 3-carene, and camphene. As mentioned previously, the high emission rates of terpenes are likely due to the pine core of HWF1. The figure was re-drawn to better represent emission factors for other specimens by using a smaller range of emission factors (Figure 11 [b]). The emission factors for the I-joist specimen (IJ) were the next highest (> 10 times smaller than those of HWF1).

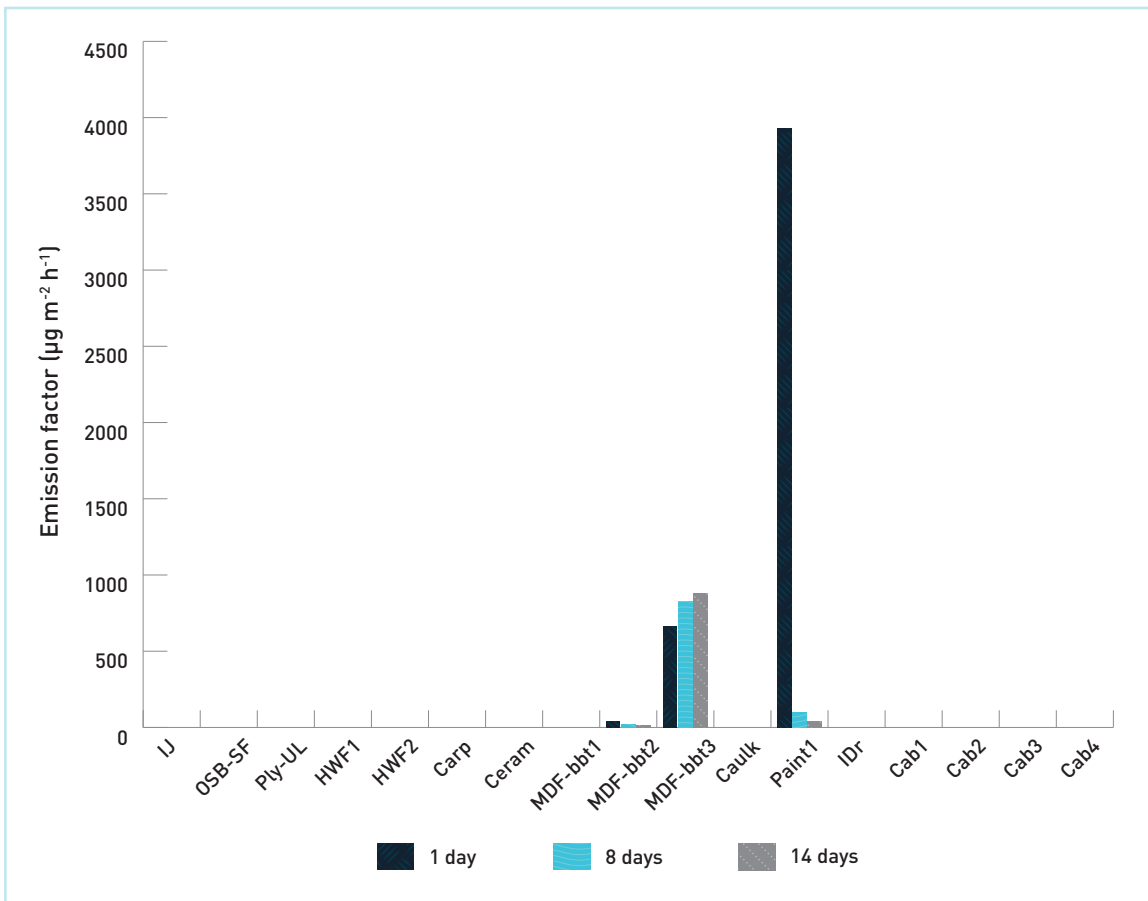
**FIGURE 11** Emission factors for alpha-pinene



### 2.2.2.9 Texanol

Figure 12 compares the emission factors for Texanol at 1 day, 8 days, and 14 days for 17 specimens tested. The emission factor for the latex primer/paint applied on a drywall specimen (Paint1) was particularly high at 1 day. Due to the fast decay of Texanol with Paint1, the material became only the second highest emitter at 8 days. On the other hand, the MDF baseboard trim applied with the same primer/paint (MDF-bbt3) became the highest emitter at 8 days. The difference of emission factors at 1 day between Paint1 and MDF-bbt3 is likely affected by the difference in the amount of primer/paint applied (i.e., 7.13 g for Paint1 vs. 4.39 g for MDF-bbt3 ). The emission factors increased over time for MDF-bbt3.

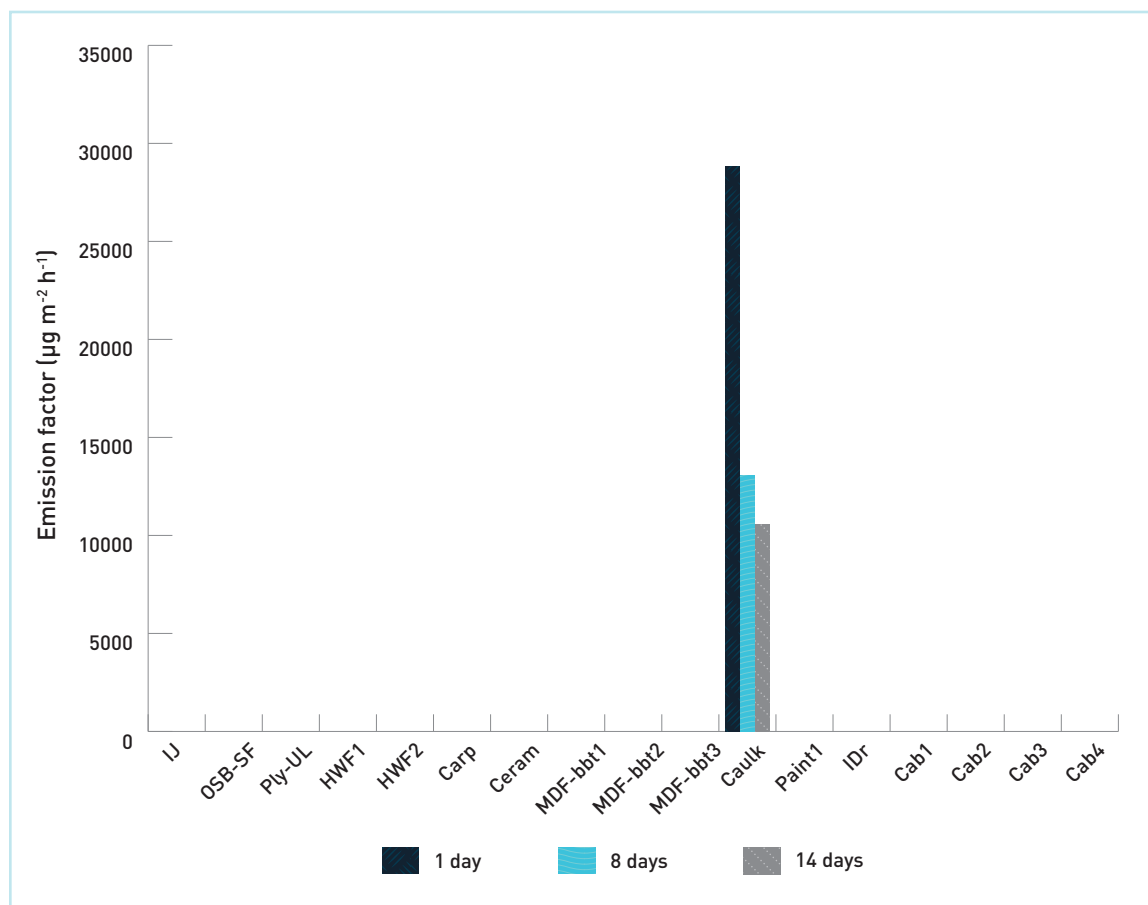
**FIGURE 12:** Emission factors for Texanol



### 2.2.2.10 1,2-Ethanediol

Figure 13 compares the emission factors for 1,2-ethanediol at 1 day, 8 days, and 14 days for 17 specimens tested. 1,2-Ethanediol (ethylene glycol) was mainly emitted from the caulk specimen (Caulk). According to the Household Products Database (U.S. Department of Health and Human Services 2016), 1,2-ethanediol is a known component of Caulk. The emission factor for 1,2-ethanediol decreased sharply from 1 day to 8 days, and more slowly from 8 days to 14 days.

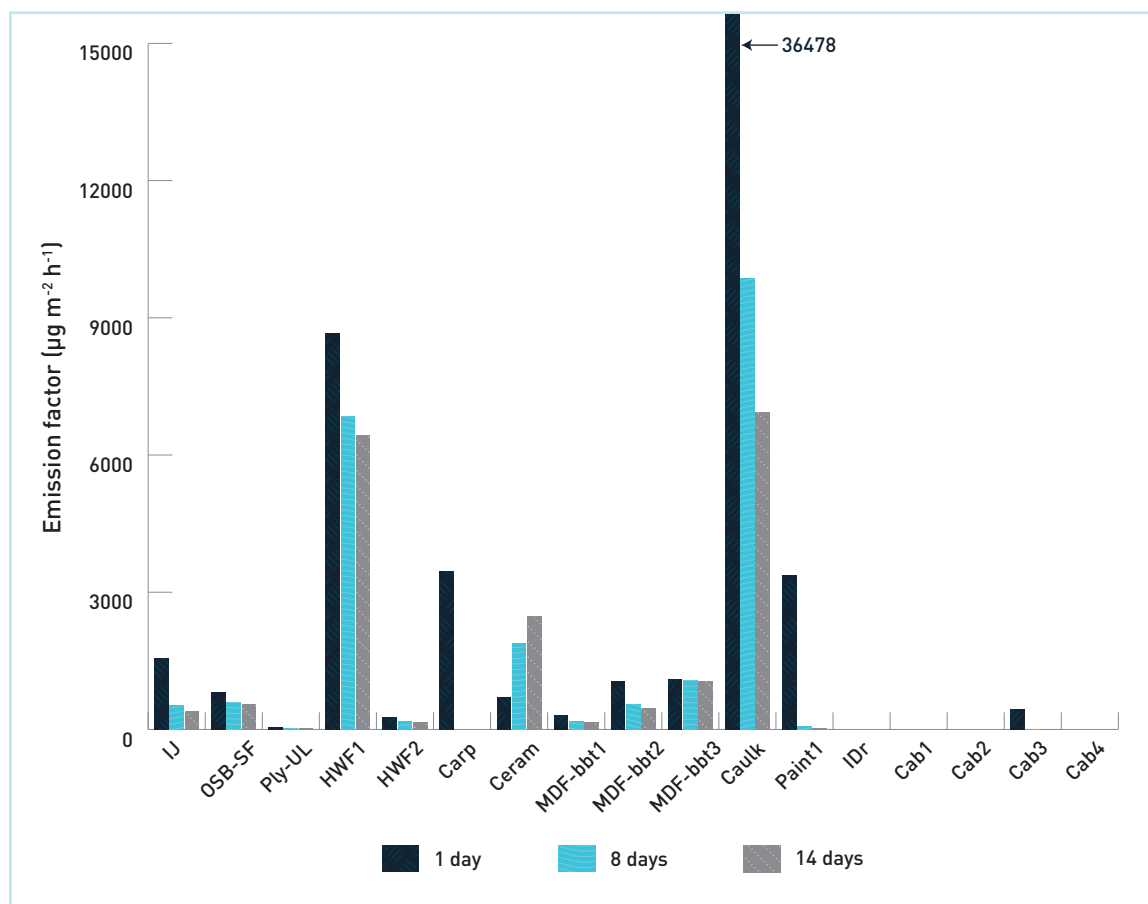
**FIGURE 13:** Emission factors for 1,2-ethanediol



### 2.2.2.11 Total volatile organic compounds

Figure 14 compares the emission factors for TVOC at 1 day, 8 days, and 14 days for 17 specimens tested. The caulk specimen (Caulk) had the highest emission factor, which is not surprising since liquid building materials tend to have higher emission factors than dry ones. Interestingly, the hardwood floor with pine core (HWF1) had the second highest emission factor, with terpenes as the dominating VOCs. With the exception of the ceramic tile assembly, the emission factors for TVOC decreased over time for all materials.

**FIGURE 14:** Emission factors for TVOC



### 2.2.2.12 Non-target volatile organic compounds

Some chemicals that were not included in this list were still found at high concentrations (> 1% of TVOC). Table 2 is a list of these “abundant” non-target VOCs. Their emission factors at 8 days can be found in Table B. 42. The “abundant” VOCs found most frequently were siloxanes, including “cyclotrisiloxane, hexamethyl-” and “cyclotetrasiloxane, octamethyl-.” Various esters, including “propanoic acid, ethyl ester,” and “propanoic acid, 2-methyl-, 2-ethyl-3-hydroxyhexyl ester,” were also found frequently in specimens of paint and caulk. Some esters could not be identified with confidence. “Acetamide, N,N-dimethyl-” that is known to have reproductive toxicity (European Chemicals Agency 2014) was found in the carpet specimen (Carp). C11, C12, and C14 hydrocarbons were emitted in high concentrations from the ceramic tile assembly (Ceram) or Carp.

**TABLE 2: List of non-target volatile organic compounds**

Test ID	Type	Surface control method	Weight (final, g)
Siloxanes	Cyclotrisiloxane, hexamethyl-	541-05-9	OSB-SF, Ply-UL, HWF2, Carp, MDF-bbt1, MDF-bbt3, IDr, Cab1-4
	Cyclotetrasiloxane, octamethyl-	556-67-2	Ply-UL, Carp, MDF-bbt1, IDr, Cab1-4
Esters	Acetic acid, methyl ester	79-20-9	OSB-SF, Ply-UL, Ceram
	Propanoic acid, ethyl ester	105-37-3	Caulk
	Propanoic acid, 2-methyl-, 2-ethyl-3-hydroxyhexyl ester	74367-31-0	Caulk
	Ethanol, 2-(2-butoxyethoxy)-, acetate	124-17-4	MDF-bbt1
	Unidentified esters		MDF-bbt1, MDF-bbt2, Caulk, Paint1, IDr
Glycols	1,3-Pentanediol, 2,2,4-trimethyl-	144-19-4	Paint1
Alcohols	1-Pentanol	71-41-0	OSB-SF, Ply-UL, MDF-bbt1 to 3
Amides	Acetamide, N,N-dimethyl-	127-19-5	Carp
Unidentified	C11 branched chain hydrocarbons		Ceram
	C12 branched chain hydrocarbons		Ceram
	C14 alkenes		Carp





## 3. INDOOR AIR MODELLING

### 3.1 METHODS

#### 3.1.1 Air quality monitoring in two homes

Two newly-built homes were visited before occupancy on Nov 19, 2016 for indoor air quality and ventilation measurements.

##### 3.1.1.1 Sampling of formaldehyde and other volatile organic compounds

The active sampling was conducted on the first floor of each house with a sorbent tube filled with Tenax TA (1/4" OD x 3.5" length from PerkinElmer) and a Sep-Pak DNPH cartridge (Waters) for VOCs and formaldehyde, respectively. The sampling volume was ~4.4 L (~3 mL min<sup>-1</sup> for ~24 h) for Tenax TA and ~70 L (~50 mL min<sup>-1</sup> for ~24 h) for DNPH. The sampling pumps were built in-house at the NRC using commercially available pumps and mass flow controllers (MKS). These pumps had a sampling range of 1 to 20 mL min<sup>-1</sup> (Sampler 1 for Tenax TA), and 50 to 1000 mL min<sup>-1</sup> (Sampler 2 for DNPH). The sampling rate was checked before and after the field deployment with a HORIBA STEC film flow meter VP-2 with a range of 2 to 100 mL min<sup>-1</sup> and VP-3 with a range of 20 to 1000 mL min<sup>-1</sup>.

Additionally, Tenax TA tubes and DNPH cartridges were deployed for ~24 h on the second floor and in the basement of both houses for passive sampling. One side of the Tenax TA tubes and both sides of the DNPH cartridges were opened. All passive tubes were deployed in duplicates. The passive sampling was mainly for checking its performance against active sampling and to assess any concentration variations between floors.

Active samplers were installed on a tripod or a kitchen countertop, and passive samplers were installed atop a raiser (~8 cm height, plastic or aluminum) on the floor or on a kitchen countertop.

##### 3.1.1.2 Chemical analysis

###### 3.1.1.2.1 GC/MS analysis of volatile organic compounds

Air samples collected on sorbent tubes (at 0 and ~37 min) were thermally desorbed and analyzed with a GC/MS system (TD GC/MS), including a Markes UNITY 2 Thermal Desorber connected to an ULTRA multi-tube autosampler, and an Agilent 6890 Series Gas Chromatograph coupled to a 5973N Mass Selective Detector, equipped with a DB-624 capillary column (30 m × 0.25 mm ID × 1.4 µm thickness). Thermal desorption of the sampling tubes was carried out at 280 °C, with a helium (99.999% purity) flow rate of 50 mL min<sup>-1</sup> for 10 min. The graphitised carbon cold trap (U-T11GPC-2S) was maintained at -30 °C. After desorption, the cold trap was rapidly heated from -30 °C to 280 °C and maintained at this temperature for 6 min with split flow at 20 mL min<sup>-1</sup>. The GC oven temperature was held at 30 °C for 6 min, increased to 230 °C at a rate of 6 °C min<sup>-1</sup>, and held at 230 °C for 5 min. Helium carrier gas flow in the analytical column was 1.2 mL min<sup>-1</sup>. The MS was operated in full ion scan mode (m/z 35 to 300).

The GC/MS was calibrated for 117 individual VOCs using three sets of liquid mixtures. The target compounds are listed in Table A. 1. One commercial calibration mixture (Japanese Indoor Air Standard Mix, 47537-U, 100 µg mL<sup>-1</sup> each in methanol:water = 19:1) and two custom-made standard mixtures (Custom A and Custom B, 500 µg mL<sup>-1</sup> for each chemical in methanol) were purchased from Supelco. The liquid calibration mixtures were injected onto Tenax TA tubes while air was flowed through the tube at 50 to 100 mL min<sup>-1</sup> for 2 min. Five-point calibrations were achieved via introduction of 1 mL aliquots of the calibration mixtures at five concentration levels. R<sup>2</sup> values of linear calibration curves were between 0.96 and 0.99, with lower values for acids, esters, and glycol ethers.

#### **3.1.1.2.2 HPLC analysis of low molecular weight carbonyls**

Waters Sep-Pak XPoSure Aldehyde samplers, which contained acidified 2,4-DNPH-coated silica, were used for sampling low molecular weight carbonyl compounds. Analysis of carbonyl compounds was performed in accordance with ASTM D5197 and EPA TO-11. Exposed cartridges were extracted with HPLC grade acetonitrile to a volume of 10 mL. An eluate of 20 µL was then analyzed by reverse phase HPLC with UV detection at 360 nm. The HPLC system included Agilent Technologies 1260 Quaternary Solvent Delivery System/1260 Variable Wavelength Detector VL/1260 Infinity Standard Autosampler with two SUPELCOSIL LC-18 columns (25 cm x 4.6 mm, 5 µm) in series maintained at 30 °C. A gradient of acetonitrile in water from 60% to 100% was used for separation of the carbonyl compounds. System calibration was performed using a six-point calibration from a commercial DNPH derivative mixture (TO11/IP-6A Aldehyde/Ketone-DNPH Mix certified reference material from Supelco). Linear calibration curves were produced with R<sup>2</sup> between 0.9997 and 0.9999.

### **3.1.2 Ventilation measurements**

#### **3.1.2.1 Perfluorocarbon tracer emitters by the NRC**

The ventilation rate was measured using a perfluorocarbon tracer (PFT) gas method developed by the NRC. Emitters were made of glass vials (2, 7, and 15 mL from Supelco) with silicone rubber septa (Canada Rubber Group). To determine the potential interzonal flows, three PFTs were octafluorotoluene (OFT), and perfluorodimethylcyclobutane (PDCB). Table C. 1 shows the perfluorinated compound used for each floor, emitter size and number, and measured emission rate. The vials were deployed to 3 to 4 different locations on each floor. The emission rate of each vial was calculated based on a weight measurement conducted with a METTLER TOLEDO XS 205 DuralRange analytical balance (max 81 g, 0.01 mg precision) at the NRC before and after the field deployment. The low values of the relative standard deviation (RSD) in the last column of Table C. 1 show small variability across the different emitters for each PFT.

#### **3.1.2.2 Perfluorocarbon tracer sampling and analysis by the NRC**

Since Tenax TA was found to be inadequate in capturing volatile PFTs such as PDCB, active and passive sampling of PFT gases was conducted instead with sorbent tubes filled with Carboxen B (PerkinElmer). The active sampling rates were similar to those employed for the Tenax TA tubes used for the other VOCs investigated. The passive uptake rates for PFTs were measured at the NRC in a 31 m<sup>3</sup> full-scale chamber. The passive sorbent tubes were deployed in duplicates.



The PFTs collected on Carbopack B tubes were analyzed with a TD GC/MS method similar to that for VOCs. The only major difference was the maximum temperature used for the thermal desorption and the cold trap, i.e., 300 °C rather than 280 °C. Other analysis parameters were the same as those described in section 3.1.1.2.1.

### 3.1.2.3 Ventilation measurements with other methods

The ventilation rates were measured with two other methods, including the sulfur hexafluoride (SF<sub>6</sub>) method and the PFT method developed by Brookhaven National Laboratory (BNL). The goal was to determine the variability of ventilation measurements by different methods.

In the SF<sub>6</sub> method, SF<sub>6</sub> was injected in a pulse mode using a lecture bottle with pure SF<sub>6</sub>. The target maximum concentration was 2 ppm. Sulfur hexafluoride concentrations were monitored with a direct reading instrument (INNOVA 1312 photoacoustic detector). In the PFT method, three PFT emitters and capillary absorption tube samplers were deployed by Health Canada staff. Detailed information on this method is not included in this report. Table C. 2 summarizes the injection mode for tracer gases and sampling method for three different ventilation measurement methods.

### 3.1.3 Modelling of emission rates

It has been reported that the emission rate of VOCs can vary over time, and typically follows a power-law decay model (Ye, Won, and Zhang 2016). Therefore, as seen in section 2.1.4, the emission factor can be expressed as in equation 2 above.

A power-law model can lead to an unrealistically high concentration in the early stage of emissions, which can typically stem from the limitation associated with empirical modelling of fast-decaying sources with limited data points. Therefore, during the early stage of emission, i.e., when the simulation time is smaller than the time at which the first data point was taken, the emission factor is assumed to be constant as shown in equation (3) below. Introducing a constant emission factor for the early emission period will not affect the indoor air concentration predictions for the longer emission periods as mentioned in a previous report from Won et al. (2013).

$$E = b t_1^m \quad (3)$$

where  $t_1$  is the time when the first data point was taken (e.g., 24 h).

Since it has been observed that emissions tend to decrease over time, the value of  $b$  is typically negative. However, a positive value of  $b$  can be obtained in some cases. This means that the emission rate increased during the test duration. While it can be true that the emission rate increases over a short period of time, it is expected to eventually decrease over a longer period of time due to source depletion. Therefore, if the emission factor increased over time, it was assumed to be constant as shown in equation (4):

$$E = b \quad (4)$$

### 3.1.4 Modelling of indoor air concentrations

The indoor air concentration of any given species is typically affected by two major processes, i.e., sources and sinks. The source term can be grouped into outdoor and indoor sources, where the outdoor source is the movement of outdoor pollutants to indoors through ventilation, and indoor sources include emissions from building materials, consumer products, and occupant activities. The sink term corresponds to removal processes of pollutants through ventilation, air cleaning, and other natural mechanisms such as adsorption on indoor solid surfaces, absorption into aqueous phase (e.g., moisture), and indoor chemistry (e.g., reaction with ozone) (Plaisance et al. 2013).

In this study, it was assumed that the main VOC source is emissions from building materials and the main sink is the ventilation. The entry of pollutants in the form of VOCs was assumed to be negligible since the outdoor levels of VOCs are known to be generally low in winter. The removal of pollutants by intentional air cleaning was not included since there was no air cleaning device used in either homes.

Assuming only ventilation removes VOCs emitted from building materials and outdoor VOC concentrations are low, the VOC concentration in the house can be expressed as shown in equation (5):

$$V \frac{dC}{dt} = -Q C + \sum_{i=1}^n A_i E_i \quad (5)$$

where  $V$  is the house volume ( $\text{m}^3$ ),  
 $Q$  is the air flow rate between the house and outdoors ( $\text{m}^3 \text{h}^{-1}$ ),  
 $C$  is the concentration of a pollutant in the house ( $\mu\text{g m}^{-3}$ ),  
 $A_i$  is the area of the  $i$ th source in the house ( $\text{m}^2$ ),  
 $E_i$  is the emission factor of the  $i$ th source in the house ( $\mu\text{g m}^{-2} \text{h}^{-1}$ ),  
 $n$  is the number of sources in the house.

Equation (5) can be solved using the explicit Euler method.

$$C^t = C^{t-1} + \left( -N C^{t-1} + \sum_{i=1}^n E_i L_i \right) \Delta t \quad (6)$$

where  $C^t$  is the indoor air concentration at time  $t$  ( $\mu\text{g m}^{-3}$ ),  
 $C^{t-1}$  is the indoor air concentration at time  $t-1$  ( $\mu\text{g m}^{-3}$ ),  
 $N$  is the air change rate ( $Q/V$ ,  $\text{h}^{-1}$ ),  
 $L^i$  is the material loading ratio ( $A_i/V$ ,  $\text{m}^2 \text{m}^{-3}$ ),  
 $\Delta t$  is the time step (e.g., 10 min).



The concentration at steady state can be simplified as follows:

$$C_{ss} = \frac{\sum_{i=1}^n L_i E_i}{N} \quad (7)$$

where  $C_{ss}$  is the indoor air concentration at steady state ( $\mu\text{g m}^{-3}$ ).

The concentration contributed by each material can be approximated as follows:

$$C_{ss,i} = \frac{L_i E_i}{N_i} \quad (8)$$

where  $C_{ss,i}$  is the concentration contributed by the  $i$ th source ( $\mu\text{g m}^{-3}$ ).

The percent contribution of each source can be approximated by:

$$\frac{C_{ss,i}}{C_{ss}} = \frac{A_i E_i}{\sum_{i=1}^n A_i E_i} \quad (9)$$

#### 3.1.4.1 Material area and installation schedule

Table C. 3 presents the interior surfaces identified for modelling, their estimated area, their material test ID, and their installation schedule in H1. Table C. 4 presents the same information for H2. Identical materials were used in both houses with three exceptions, i.e., different materials and pre-fabricated units were used for hardwood floors, kitchen cabinets, and bathroom cabinets in the two houses. Detailed information on the area estimation can be found in Appendix E. Using the floor plans as shown in Appendix E, the volumes of H1 and H2 were estimated to be 1353 m<sup>3</sup> and 1326 m<sup>3</sup>, respectively, including basements. The material installation schedule and elapsed times between installation and sampling were estimated based on the project plan provided by the builder in Appendix F. Time zero for installation was defined as the completion of backfill. The elapsed time between material installation and IAQ sampling ranged from 384 h (~16 d) to 4416 h (~180 d).

#### 3.1.4.2 Ventilation schedule

Ventilation rates during construction are needed to simulate indoor air concentrations. Since only one ventilation measurement was taken on sampling day, arbitrary ventilation rates were assigned to other days by dividing the construction period into three phases. The air change rate was assumed to be 5 h<sup>-1</sup> between backfilling and installation of windows (phase 1), and 1 h<sup>-1</sup> between window installation and painting (phase 2). Measured air change rates (0.059 h<sup>-1</sup> in H1 and 0.15 h<sup>-1</sup> in H2) were used between painting and air sampling (phase 3). Setting

arbitrary air change rates in phases 1 and 2 had no significant impact on the IAQ prediction level on sampling day, which was mostly affected by the ventilation rate in phase 3. For example, using  $10 \text{ h}^{-1}$  instead of  $5 \text{ h}^{-1}$  led to an almost identical predicted air concentration on sampling day. These simulated ventilation schedules are presented in Table C. 5 and Table C. 6.

## 3.2 RESULTS

### 3.2.1 Indoor air quality in H1 and H2

#### 3.2.1.1 Indoor air quality by passive sampling

Table C. 7 presents concentrations of VOCs and aldehydes (formaldehyde, acetaldehyde, and propanal) sampled passively on Tenax TA tubes and DNPH cartridges, respectively, in H1. Table C. 8 presents the same information for H2. Overall, the agreement between duplicate samples was good, with a relative difference of 9% (H1) and 15% (H2) on average. Formaldehyde showed the biggest disparity, with a relative difference of 101% in H1 and 229% in H2 at maximum. This is likely due to the low mass collected on passive DNPH cartridges used to sample low molecular-weight aldehydes (formaldehyde, acetaldehyde and propanal). The formaldehyde mass was lower than the lowest calibration range of 145 ng in two (H1) and four (H2) passive samples.

The concentration on each floor also showed good agreement, in particular between the first and second floors where it was 7% (H1) and 11% (H2) on average. The biggest difference between floors was also observed with formaldehyde. Overall, both houses appeared to be well-mixed, which implied that they could be considered as one zone for modelling purposes.

#### 3.2.1.2 Indoor air quality by active sampling

Table C. 9 compares concentrations determined by active and passive sampling for compounds analyzed in both houses. On average, the difference between active and passive samples was 109% in H1 and 59% in H2. In terms of the ratio between active and passive concentrations, the median value was 1.3 for both houses. With regards to individual chemical species, the variations were more pronounced. The agreement was reasonably good in both houses where concentrations by passive sampling were higher than those by active sampling, i.e., within a factor of 2 for aliphatic hydrocarbons, aromatic hydrocarbons, esters, and terpenes, with the exception of toluene in H1, alpha-pinene in H2, and TXIB in both houses. A potential reason could be that the actively collected samples with tubes were overloaded due to high concentrations of these chemicals. A close examination of GC/MS chromatograms confirmed that peaks of toluene in H1 and alpha-pinene in both houses led to overloading. On the other hand, the discrepancy in TXIB appears to be due to the inherent analytical difficulties that are associated with glycols and that could be exacerbated by the low concentration.

The difference between active and passive samples was greater with oxygenated compounds such as alcohols and ketones. For example, the acetone concentration in the passive sample was 14.5 times greater than that in the active sample in H1. This discrepancy may be associated with the breakthrough volume of a sorbent tube. Tenax TA has a small breakthrough volume for



low molecular weight alcohols and ketones. For example, breakthrough sampling volumes for acetone and 2-propanol are estimated to be 1.08 L and 0.9 L, respectively, assuming 180 mg of sorbent in a tube (SIS Inc. 2004). Since the sampling volume was ~4.4 L, some of these chemicals with small breakthrough volumes might not be fully captured in the active samples, leading to underestimation.

There was good agreement between passive and active samples for aldehydes, including formaldehyde, acetaldehyde, and hexanal. Propanal and butanal were shown to be lower in active samples, but the difference was moderate (e.g., 2.3 times in H1). This may be due to the uncertainties associated with passive uptake rates, inasmuch as the passive uptake rates used in this work were established in 4- to 7-day deployment studies, whereas the samplers were only field-deployed for a single day.

In spite of several limitations, concentrations obtained from active sampling were compared with predicted concentrations in the next section. This is mainly because passive samples were analyzed for a limited number of VOCs as there is limited information available on passive uptake rates. Table C. 10 presents concentrations of VOCs and aldehydes (formaldehyde, acetaldehyde, and propanal) sampled actively on Tenax TA tubes and DNPH cartridges, respectively.

## 3.2.2 Ventilation measurements in H1 and H2

### 3.2.2.1 Perfluorocarbon tracer concentrations

Table C. 11 and Table C. 12 present PFT concentrations in Carbopack B tubes sampled passively. The maximum difference in duplicate samples was 12% in H1 and 14% in H2. The maximum floor difference was 9% in H1 and 36% in H2, which implies that the houses were relatively well-mixed. The same observation was made for the VOCs in the previous section. Therefore, the mean concentration averaged over three floors was used to calculate the air change rates.

Table C. 13 compares PFT concentrations measured with active and passive samplers. The difference was less than 10% for HFB and OFT, but larger for PDCB (~40%). This may be due to the fact that PDCB is more volatile than HFB and OFT, leading to a greater uncertainty in the passive uptake rate.

### 3.2.2.2 Ventilation rates

Table C. 14 and Table C. 15 present air change rates measured in H1 and H2, respectively. The air change rate measured by the NRC's PFT method was calculated based on the emission rate of each PFT from Table C. 1, PFT concentrations from Table C. 13, and the total estimated house volume. The air change rate measured by the BNL's PFT method was provided by Health Canada. The air change rate measured by the SF<sub>6</sub> method was estimated from the curve fitting of the SF<sub>6</sub> decay data as shown in Figure C. 1. While H1 had a relatively constant decay, H2 had three different phases of decay trends. The air change rate of H2 was taken to be the average of the three decay curves (0.13, 0.168, and 0.133 h<sup>-1</sup>).

The three methods (PFT and SF6 by the NRC, and PFT by the BNL) provided similar results. The good agreement between SF6 and PFT (passive sampling) was particularly noticeable. This implies that the NRC's in-house method (constant dosing, passive sampling) can provide equivalent results to those of SF6 (pulse dosing, active sampling). The air change rates measured by PFT passive sampling were used in predicting concentrations as described in the next section.

### 3.2.3 Indoor air quality modelling

#### 3.2.3.1 Prediction at steady state

Table C. 16 compares predicted and measured concentrations in H1 and H2. The predicted concentration was calculated using equation (7), with the assumption that the concentration had reached steady state when air sampling occurred. Calculation details can be found in Appendix G. The predicted concentration ( $C_p$ ) is considered satisfactory if it is within a factor of 2 from the measured concentration ( $C_m$ ), taking into account all uncertainties associated with area estimations and emission models from chamber tests.

#### 3.2.3.2 Aldehydes

The prediction for aldehydes, including formaldehyde, acetaldehyde, propanal, hexanal, and pentanal, was satisfactory, with a ratio of  $C_p$  to  $C_m$  between 0.5 and 2. This is likely due to the fact that the materials tested in this study were mainly composite wood products that are sources of aldehydes. One exception is butanal, which was underpredicted.

Figure 15, Table G. 1, and Table G. 2 indicate that the main sources of formaldehyde were kitchen cabinet and countertop and window and door trims in H1, and I-joist and window and door trims in H2. Since H2 had an unfinished basement, its I-joist area was higher than H1's—possibly explaining why I-joist was the biggest contributor in H2, and not in H1.

FIGURE 16, Table G. 3, and Table G. 4 indicate that I-joist and ceramic tile assemblies were major sources of acetaldehyde in both houses. Hardwood floor was the main source in H1 and I-joist (70%) in H2, again probably because it has the greater area of I-joist. Since the ceramic tile was tested as an assembly of ceramic tiles, adhesive, plywood, and OSB subfloor, it is not clear which component is responsible for emitting acetaldehyde. The OSB subfloor is the likely source of aldehyde emissions based on previous material emissions testing (Won et al. 2014). The lack of contribution of the hardwood floor in H2 is possibly due to experimental difficulties in the emissions testing of the HWF1 specimen, namely high background levels of aldehydes observed in the chamber of this particular test.

Figure 17 indicates that the main source of propanal was ceramic tile with OSB subfloor exposed to air in both H1 (78%) and H2 (68%). Previous work has indicated that OSB was a significant source of propanal emissions (Won et al. 2014).

While butanal was underpredicted in both houses (Table C. 16), Figure 18 indicates that the main sources of butanal could also be I-joist and OSB floor. For hexanal, the main source was I-joist in both houses (Figure 19), while for pentanal, it was also I-joist and OSB subfloor (Figure 20). These observations indicate that composite wood products with no barrier (e.g., I-joist and OSB subfloor) can be the main sources of aldehydes.





### 3.2.3.3 Alcohols and ketones

The majority of alcohols and ketones were underpredicted, with a ratio of  $C_p$  to  $C_m$  smaller than 0.5 (Table C. 16). One exception was cyclohexanone, which showed good agreement between the predicted and measured concentrations. The main source of cyclohexanone was hardwood floor (Figure 21).

### 3.2.3.4 Esters and glycols

The majority of esters and glycols were underpredicted (Table C. 16), with the exception of Texanol and “propanol, 2-methyl-2-,” with a ratio of  $C_p$  to  $C_m$  smaller than 2. The main source of Texanol was predicted to be baseboard trim (Figure 22, Table G. 29, and Table G. 30), of which a portion was painted on-site, unlike other trims that were pre-finished, followed by painted wall and ceiling. The main difference between baseboard trim and painted wall and ceiling was the characteristics of Texanol emissions. While Texanol emissions from baseboard trims were relatively low at the early stage of installation compared to that from painted wall and ceiling (i.e.,  $b = 467$  for baseboard trim vs.  $b = 1.08E+6$  for painted wall and ceiling), the decay rate was much faster for painted wall and ceiling (i.e.,  $m = 0.11$  for baseboard trim vs.  $m = -1.77$  for painted wall and ceiling). This explains why the baseboard trim became the major source of Texanol when sampling occurred.

Figure 23 indicates that the main sources of “propanol, 2-methyl-2-” were painted wall and ceiling, caulking, and ceramic tiles, presumably as it is a solvent used in such materials.

### 3.2.3.5 Terpenes

Terpenes were underpredicted in H1 and slightly overpredicted in H2. The maximum value of the ratio of  $C_p$  to  $C_m$  was 4.6 for alpha-pinene, while it was about 2 for other terpenes in H2 (Table C. 16). Figure 24 to Figure 28 indicate that hardwood floor is the main source of alpha-pinene, beta-pinene, 3-carene, camphene, and limonene in H2 but not in H1 where its contribution was negligible. The difference in terpene concentrations between H1 and H2 can be explained by the difference in hardwood floor materials. The hardwood floor was made of a pine core in H2 (HWF1), which resulted in high emissions of terpenes in the chamber test, while it was constructed of an oak core in H1 (HWF2). Overall, the terpene emissions from HWF1 were higher than those from HWF2 by more than a factor of three.

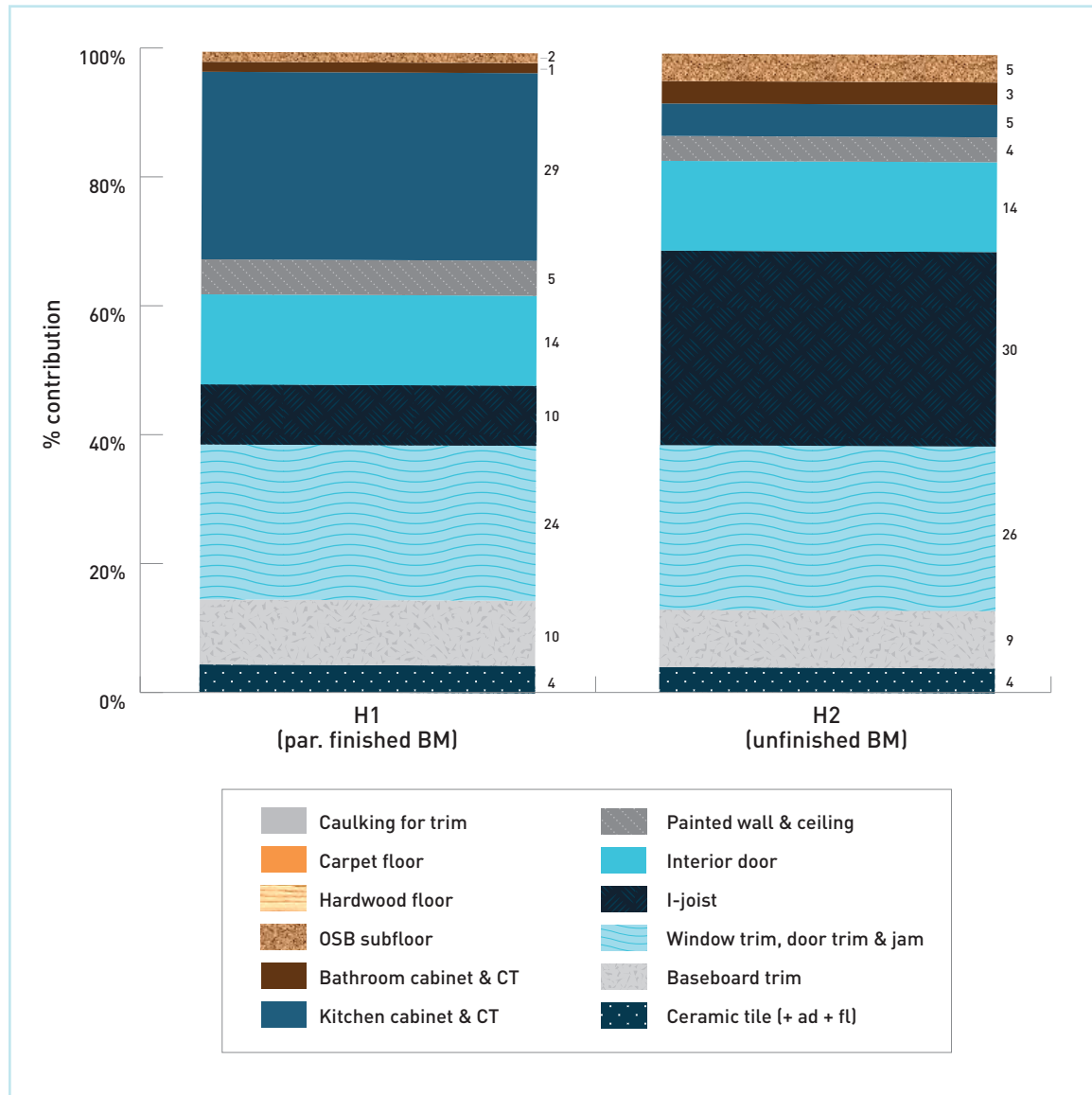
### 3.2.3.6 Hydrocarbons

All aliphatic and aromatic hydrocarbons in Table C. 16 were underpredicted, with a ratio of  $C_p$  to  $C_m$  close to zero. This is not surprising since composite wood products are not a significant source of hydrocarbons. Hydrocarbons are typically emitted from petroleum-based materials and products, and it is likely that activities such as cleaning or touch-ups with oil-based finishes or solvents occurred before sampling. This hypothesis was tested in the next section by assuming that an oil-based finish was applied to a small area (1 m<sup>2</sup>) one day before sampling.

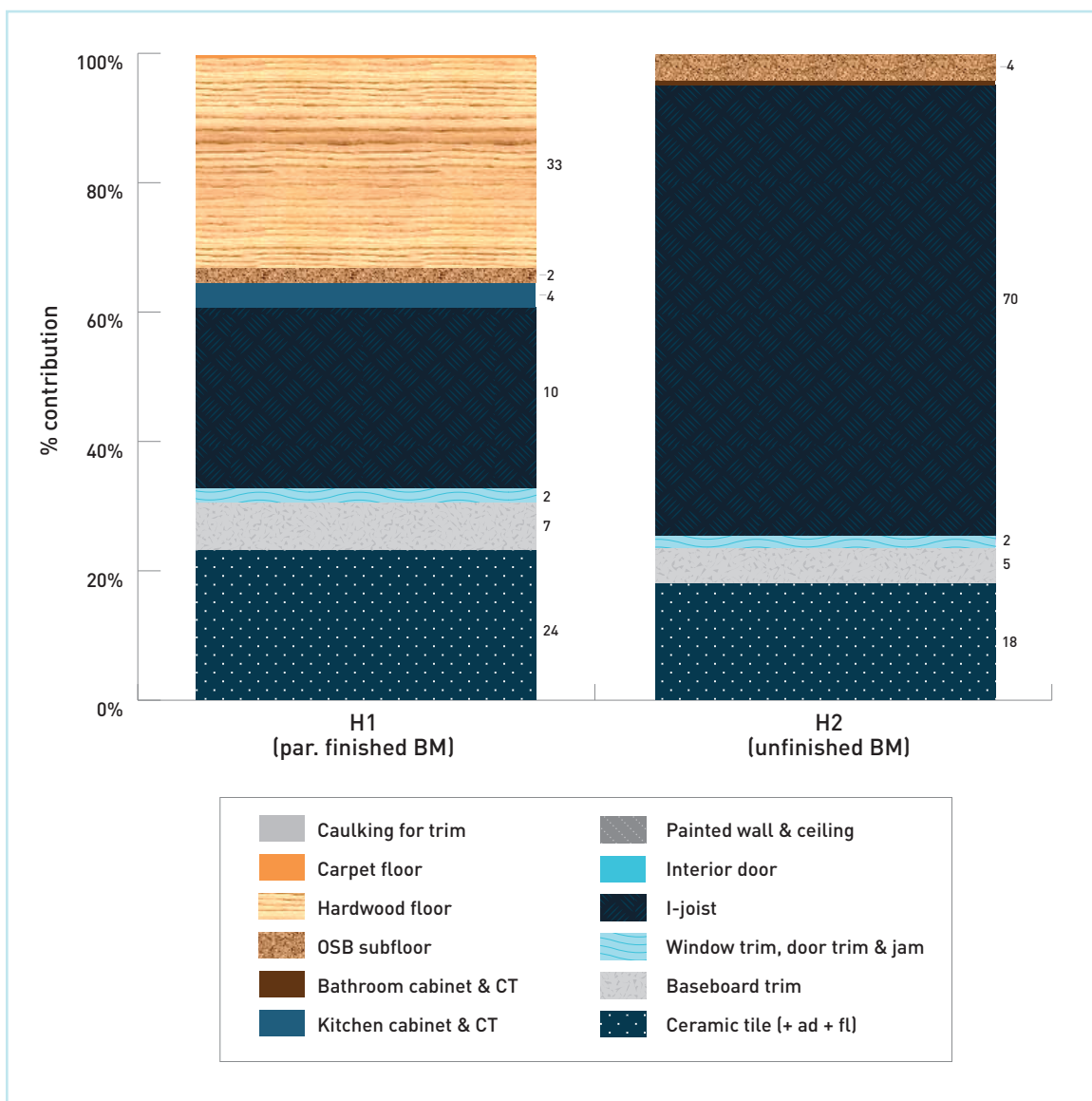
### 3.2.3.7 Other

For three chemicals that were classified as “Other”, there was relatively good agreement between predicted and measured concentrations. For example, acetic acid and butyl ether have a ratio of  $C_p$  to  $C_m$  smaller than 2 in H1. The agreement was also good for “furan, 2-pentyl” in H2. OSB floor was the main source of acetic acid and “furan, 2-pentyl” in both houses (Figure 29 and Figure 30), followed by I-joist. The main source of butyl ether was painted wall and ceiling in both houses (Figure 31).

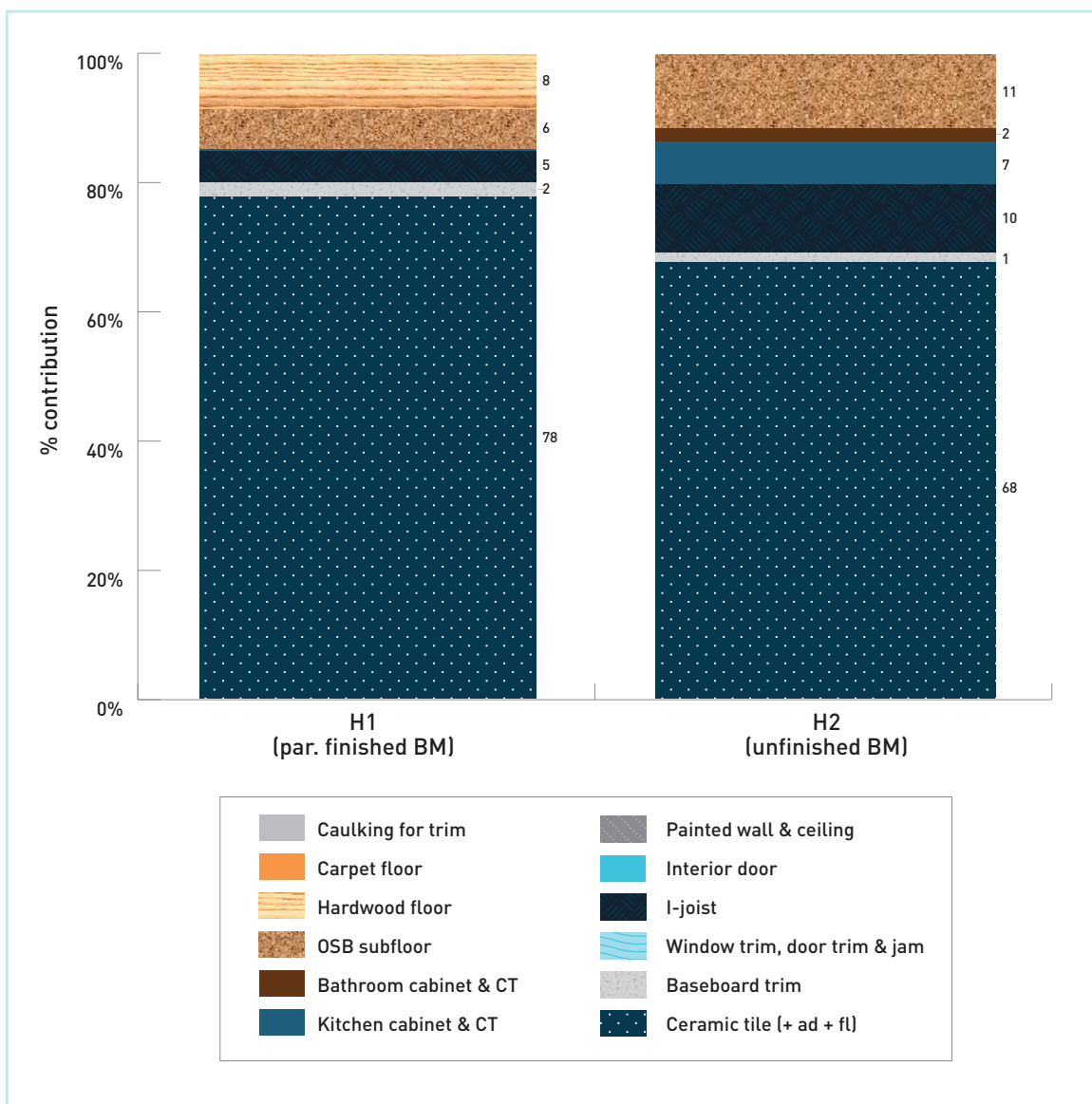
**FIGURE 15: Contribution of each source to formaldehyde**



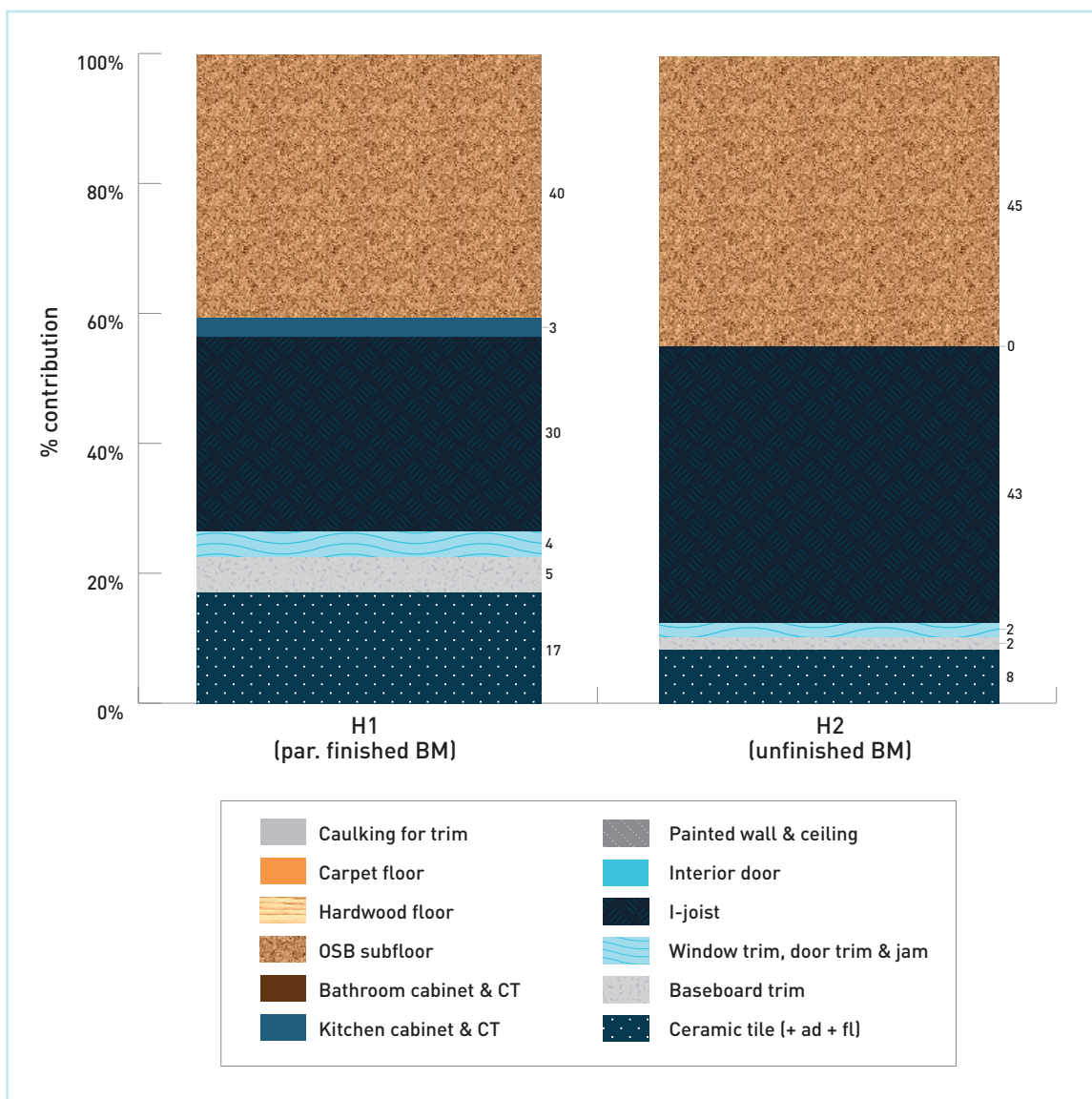
**FIGURE 16: Contribution of each source to acetaldehyde**



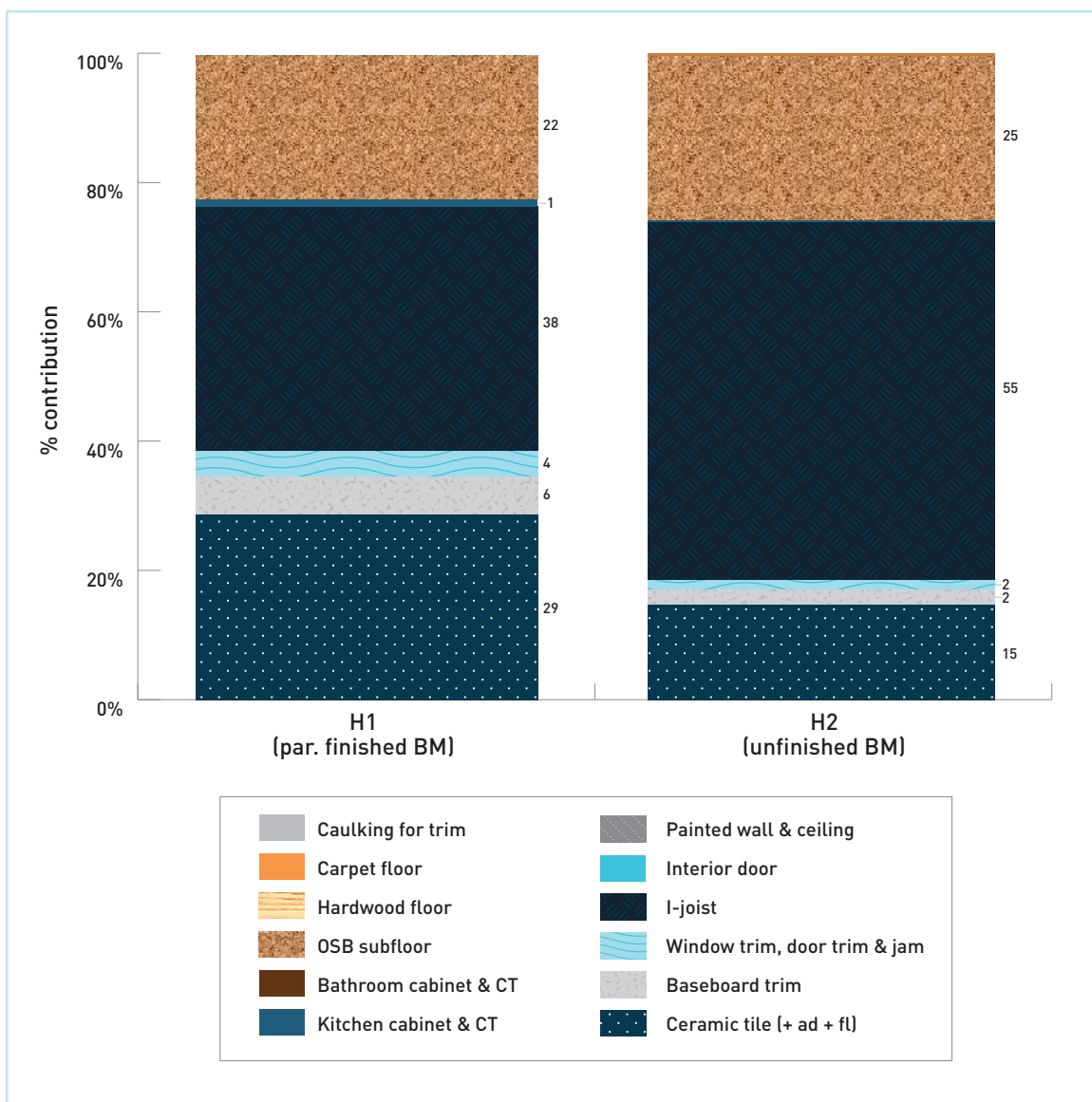
**FIGURE 17: Contribution of each source to propanal**



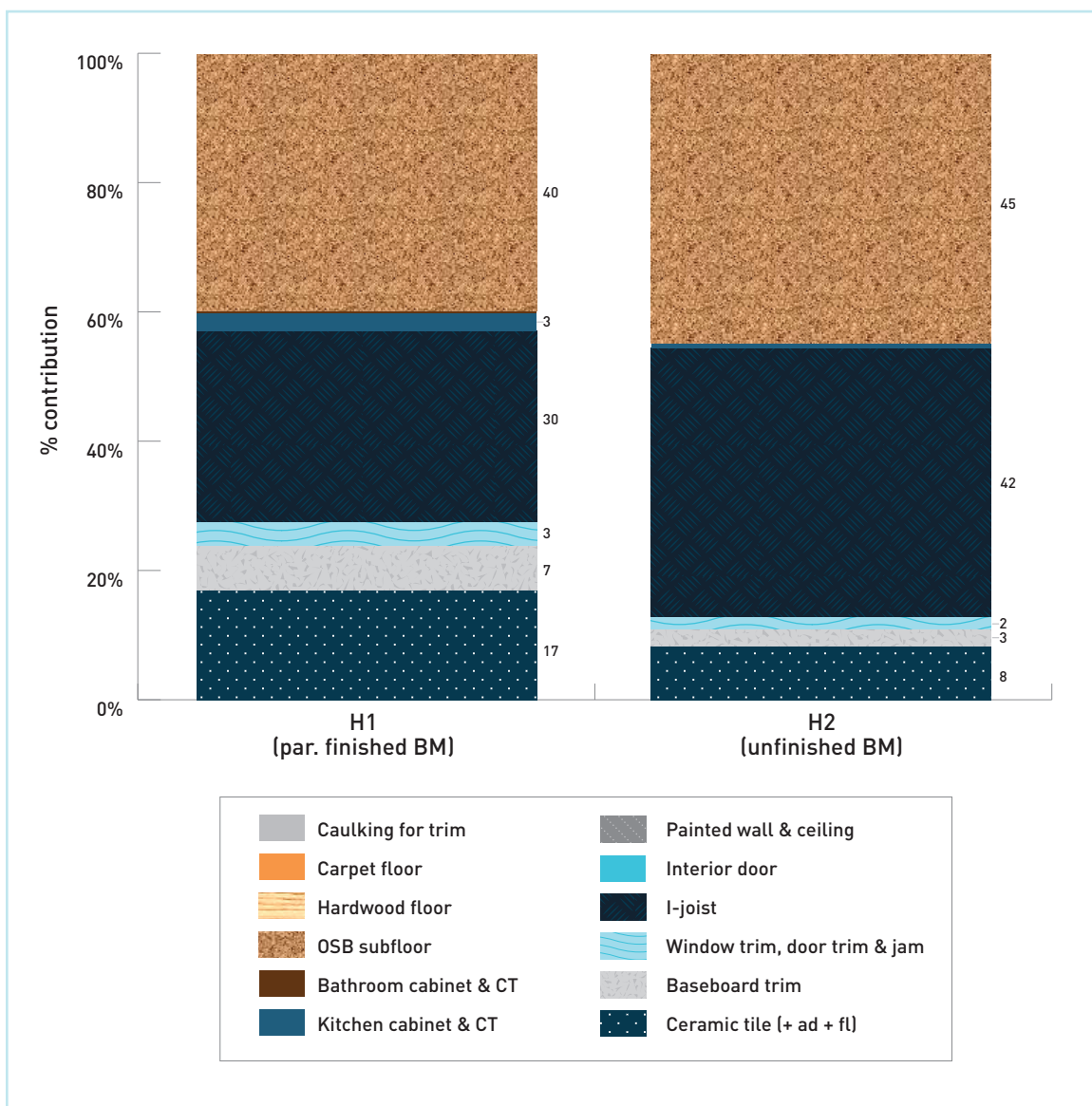
**FIGURE 18: Contribution of each source to butanal**



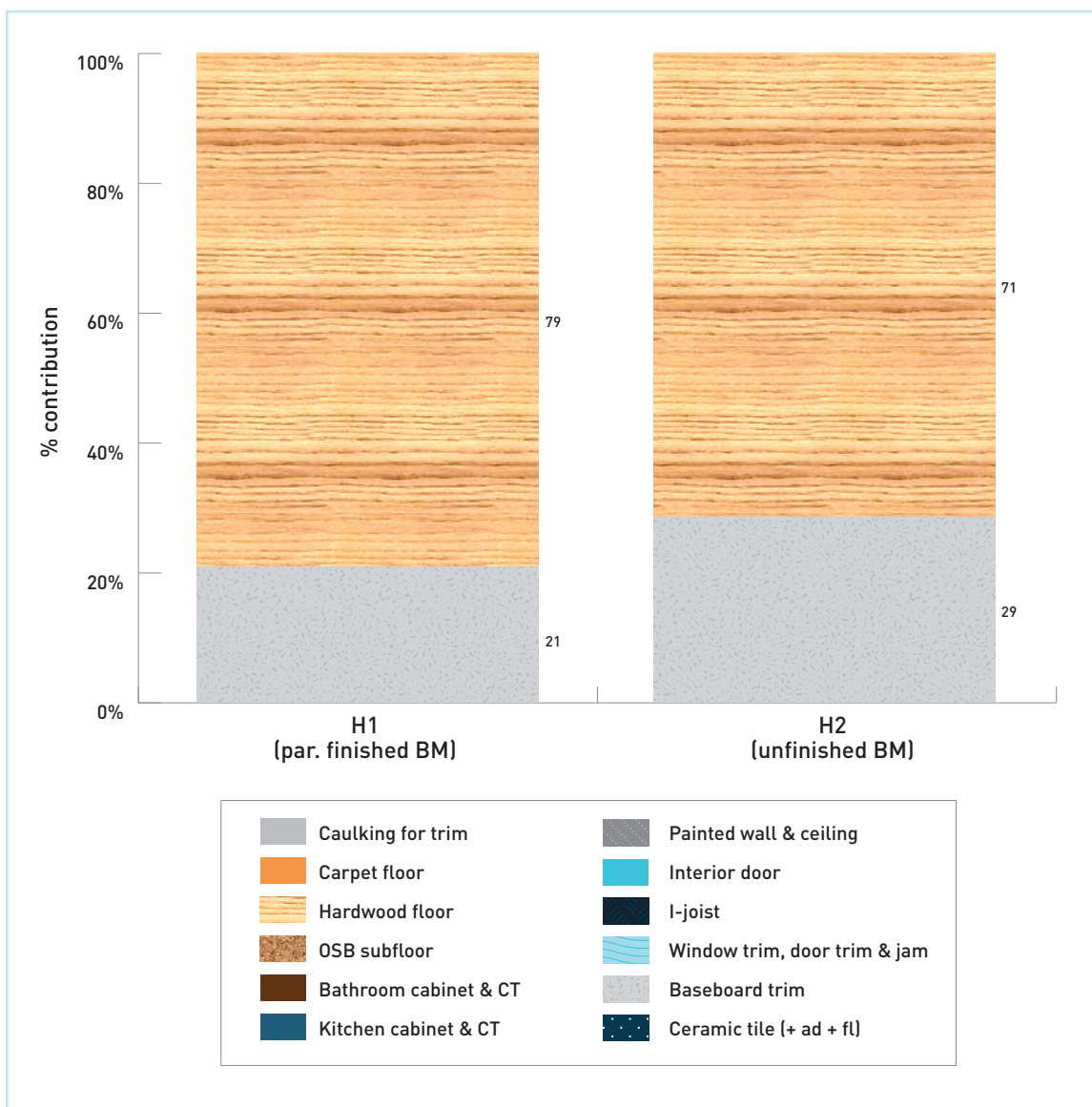
**FIGURE 19: Contribution of each source to hexanal**



**FIGURE 20: Contribution of each source to pentanal**

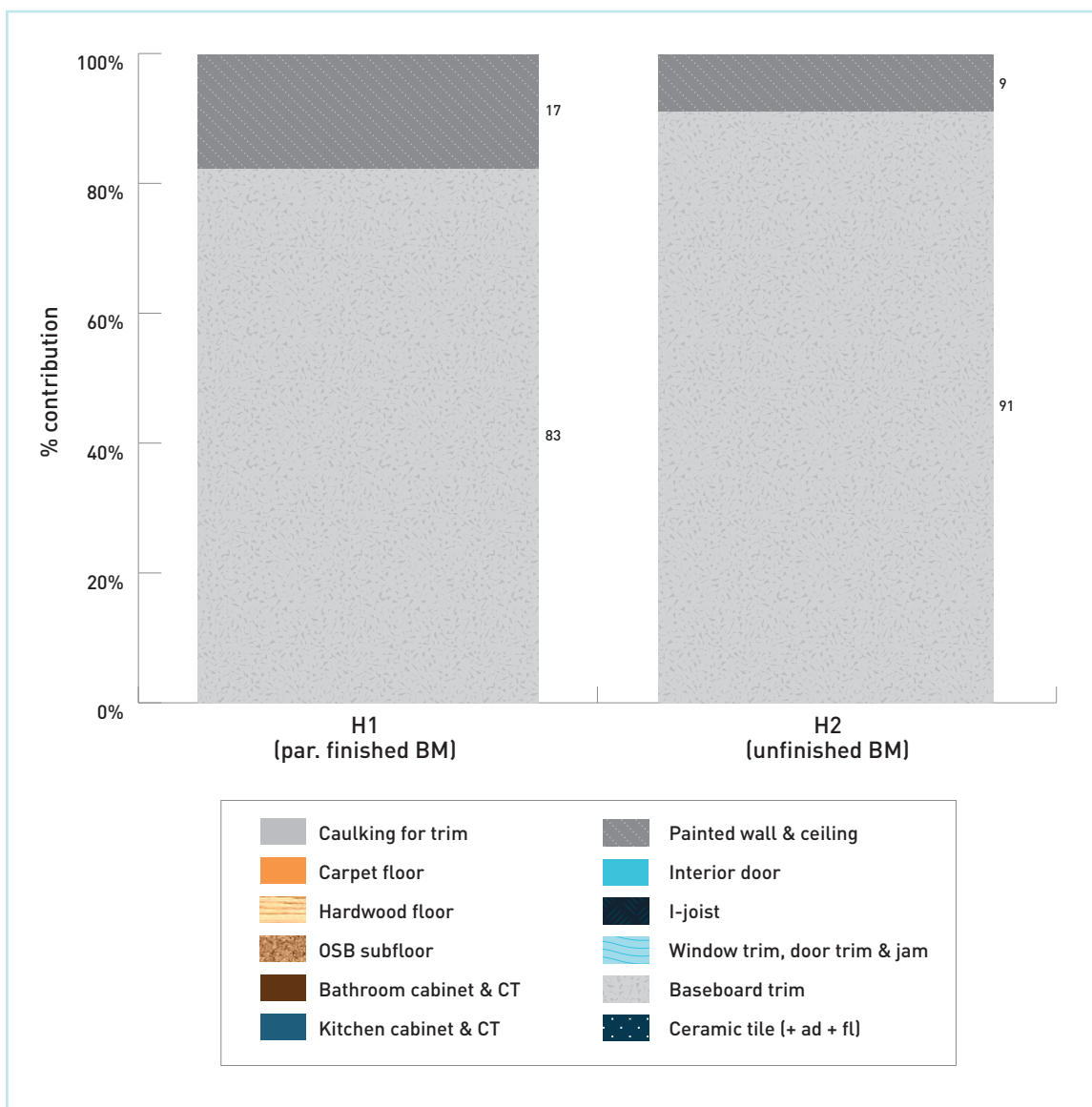


**FIGURE 21:** Contribution of each source to cyclohexanone

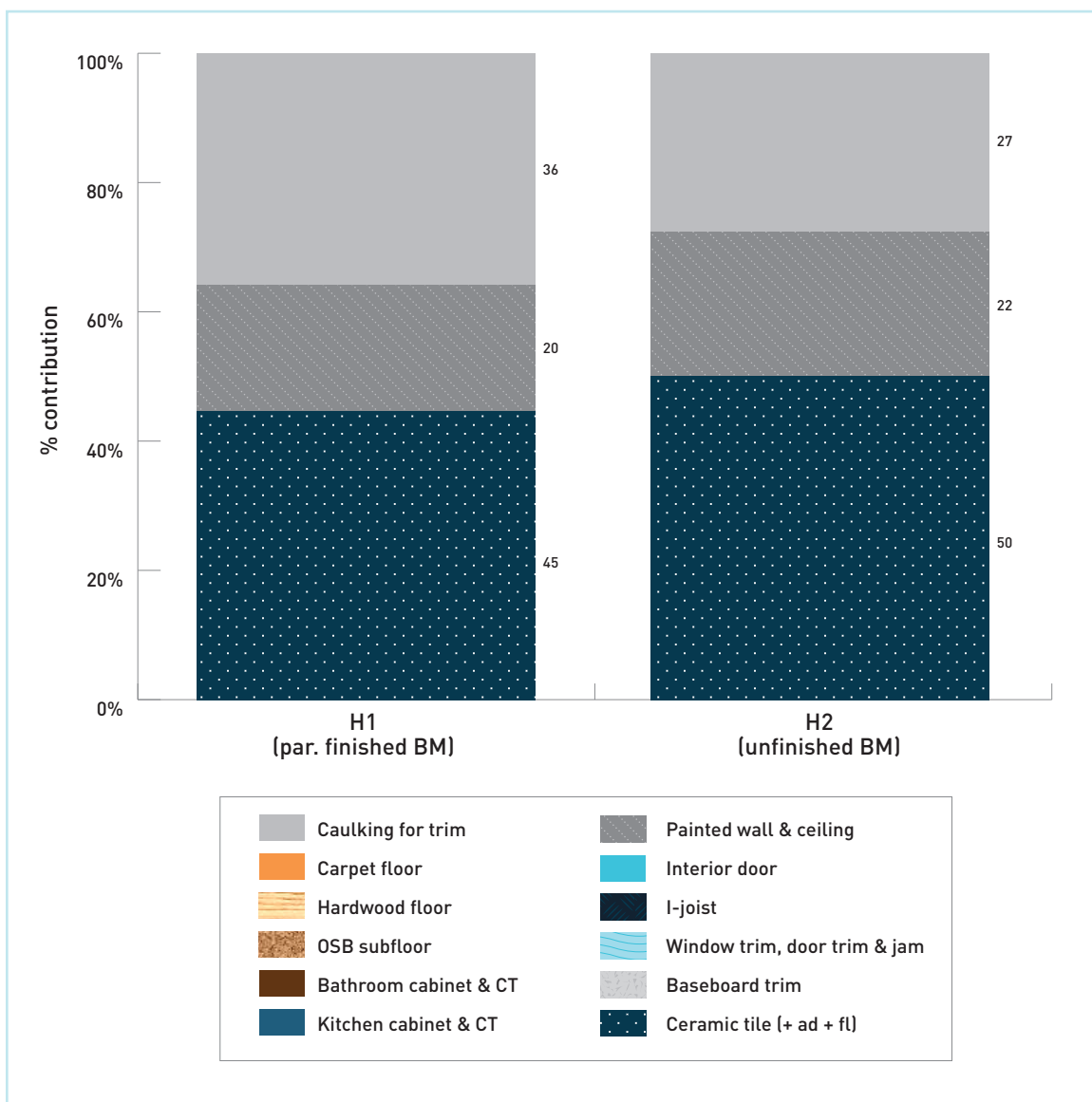




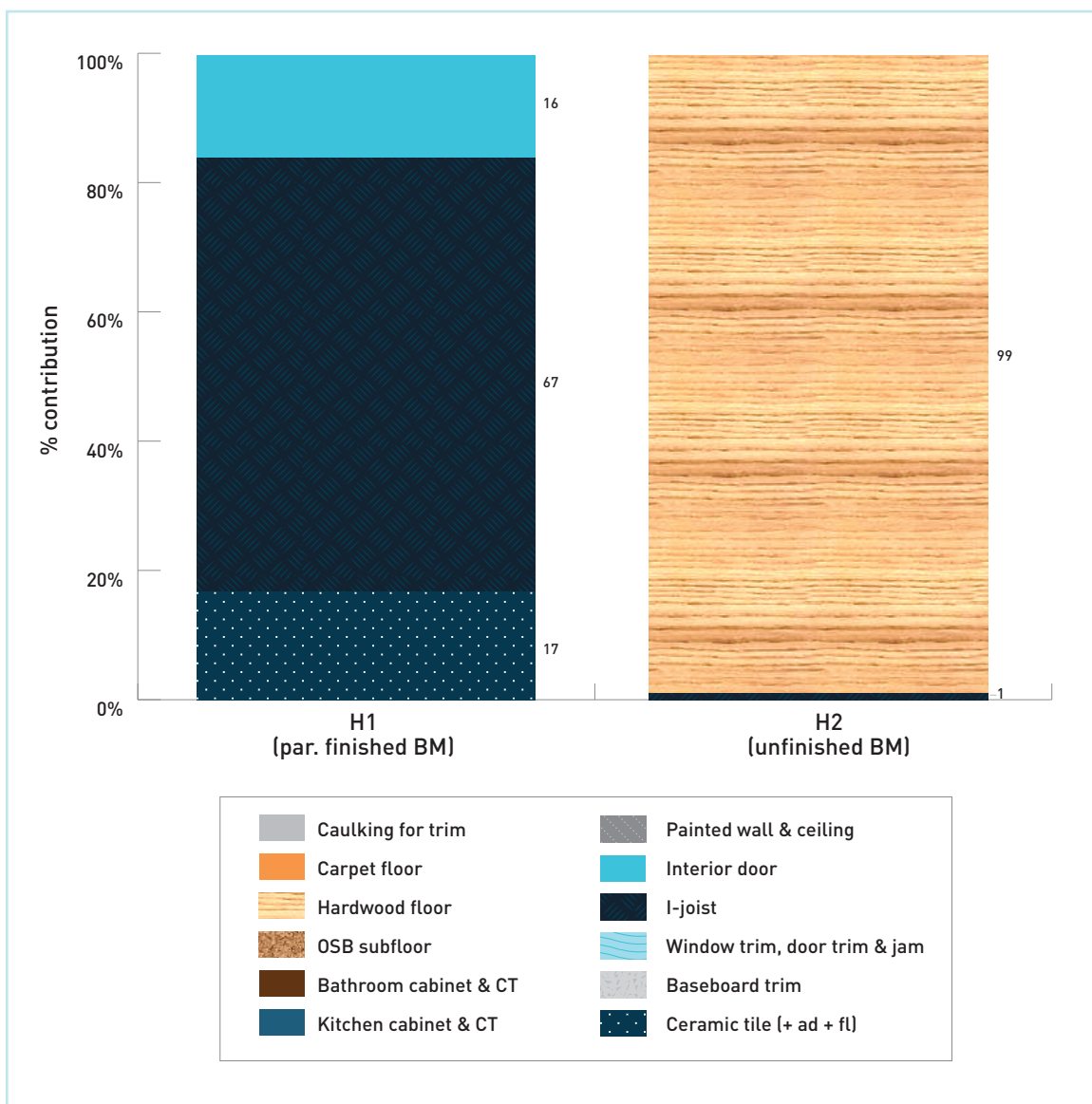
**FIGURE 22: Contribution of each source to Texanol**



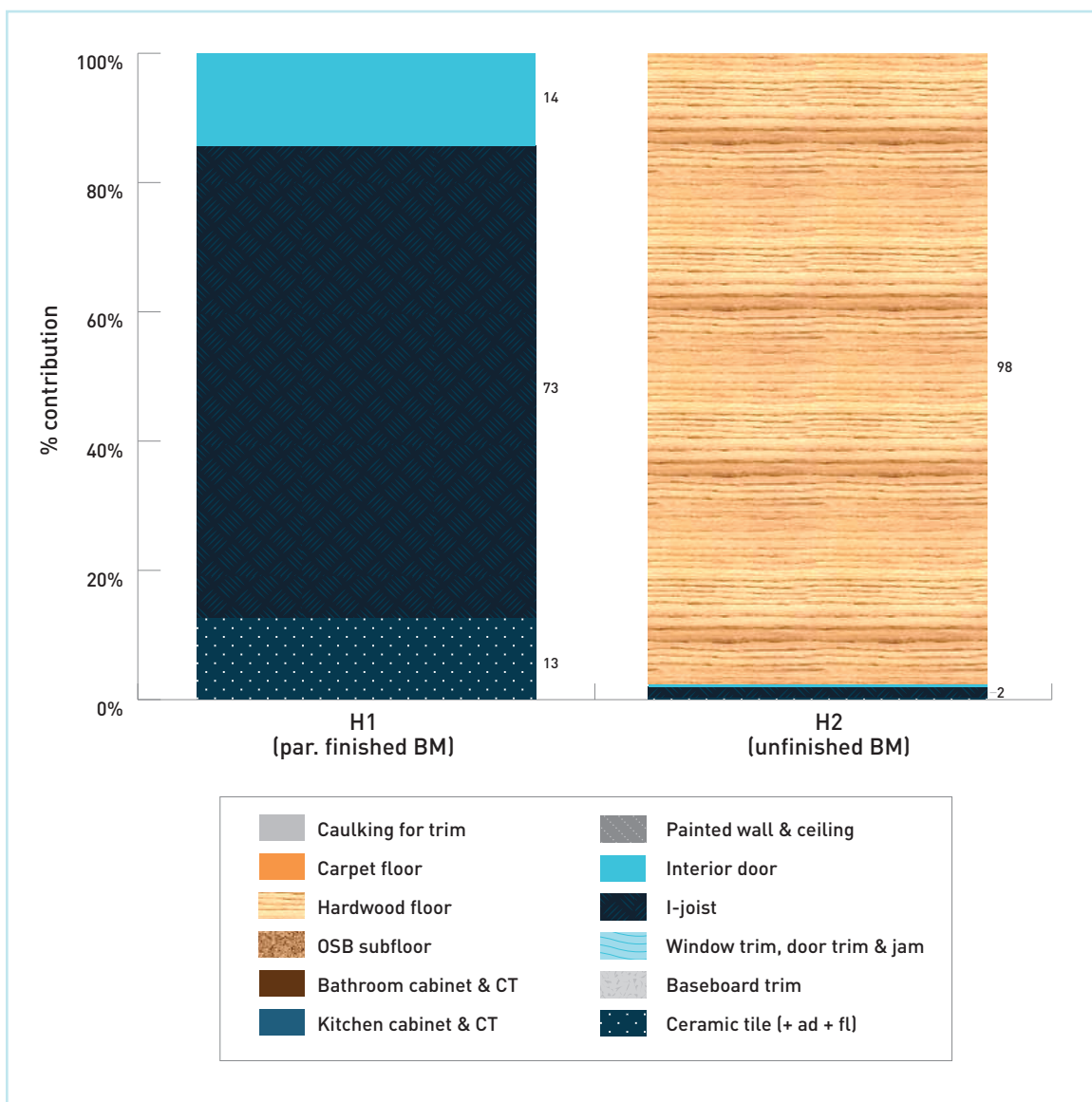
**FIGURE 23:** Contribution of each source to “propanol, 2-methyl-2-”



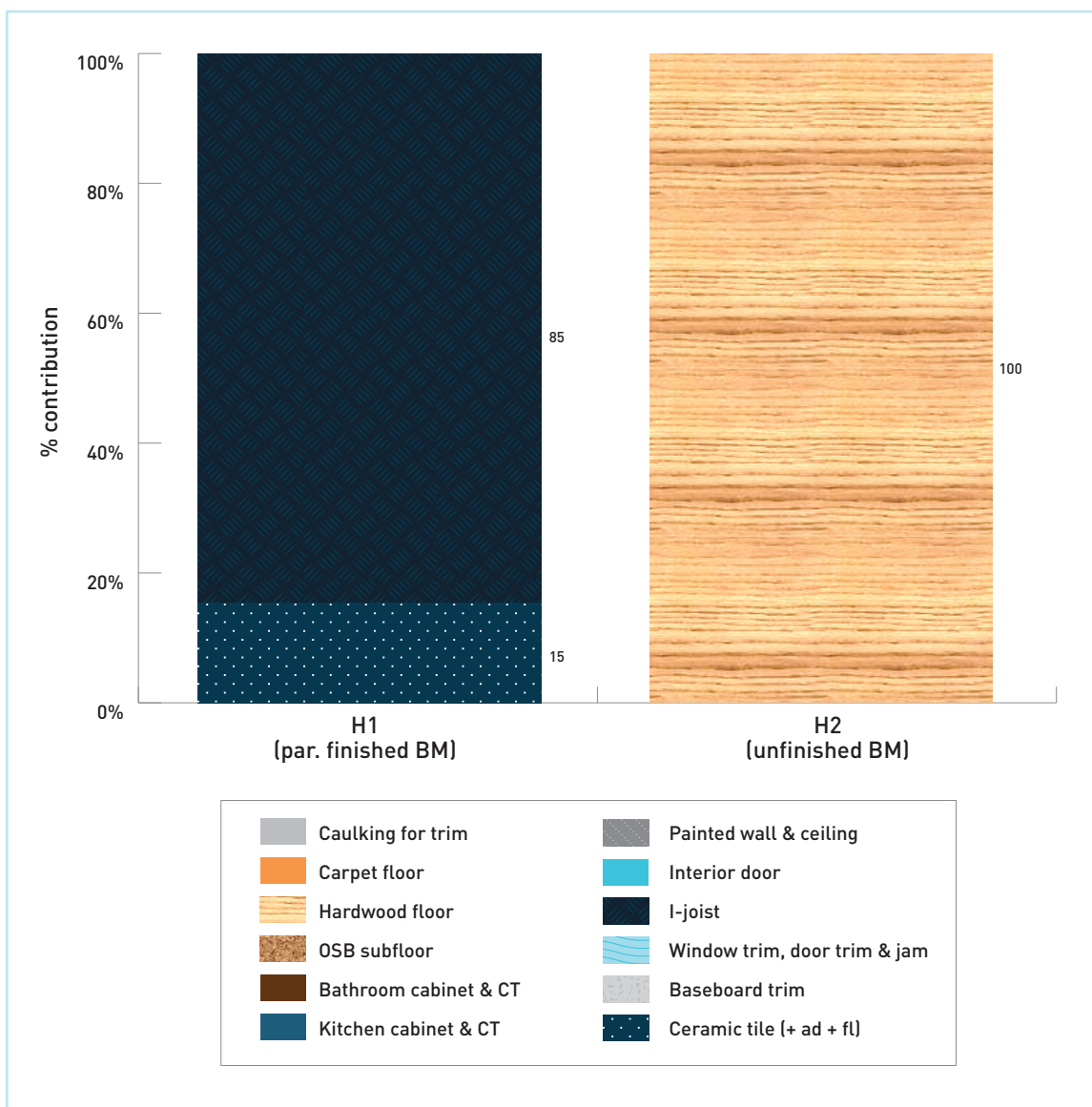
**FIGURE 24:** Contribution of each source to alpha-pinene



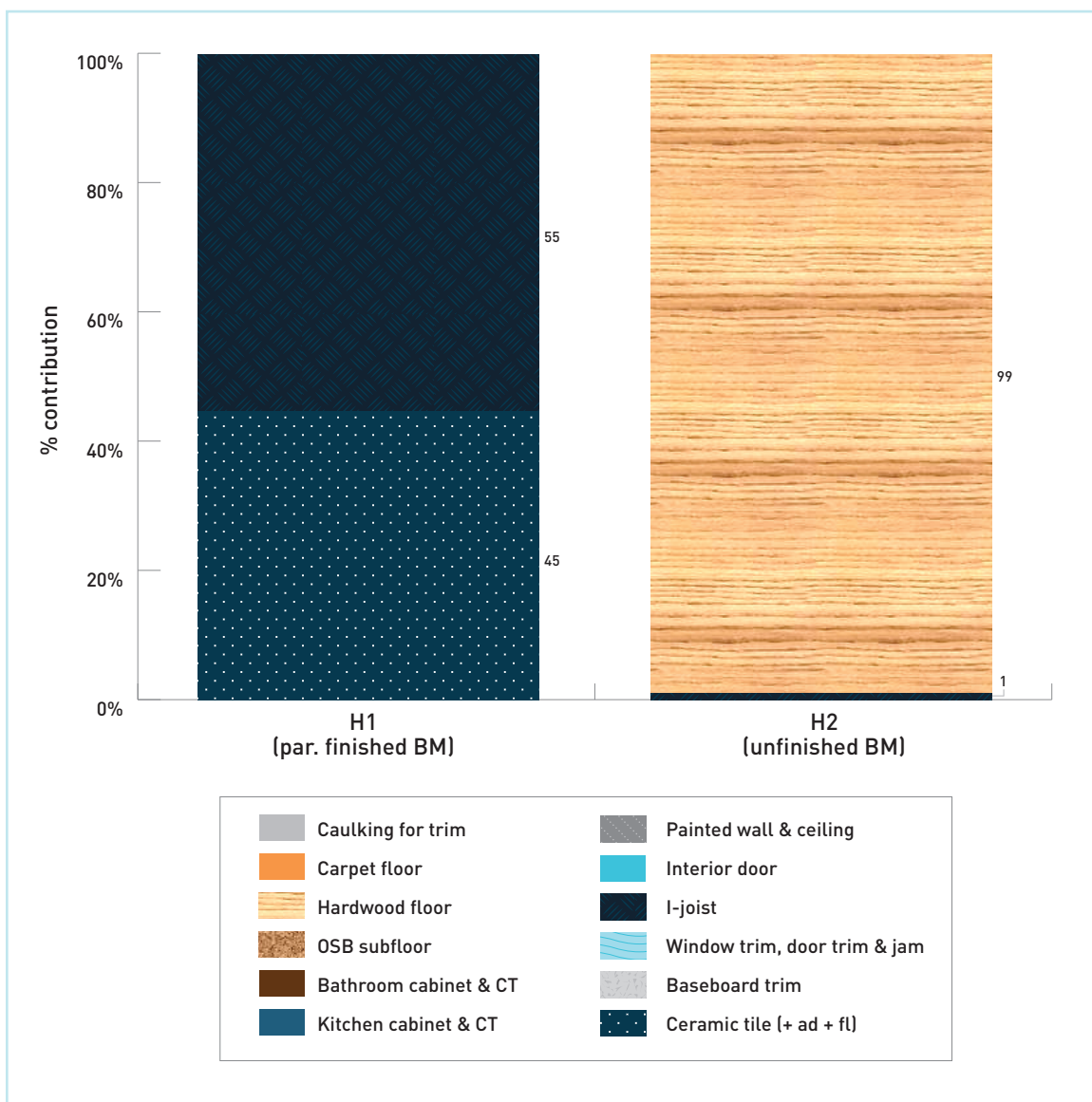
**FIGURE 25: Contribution of each source to beta-pinene**



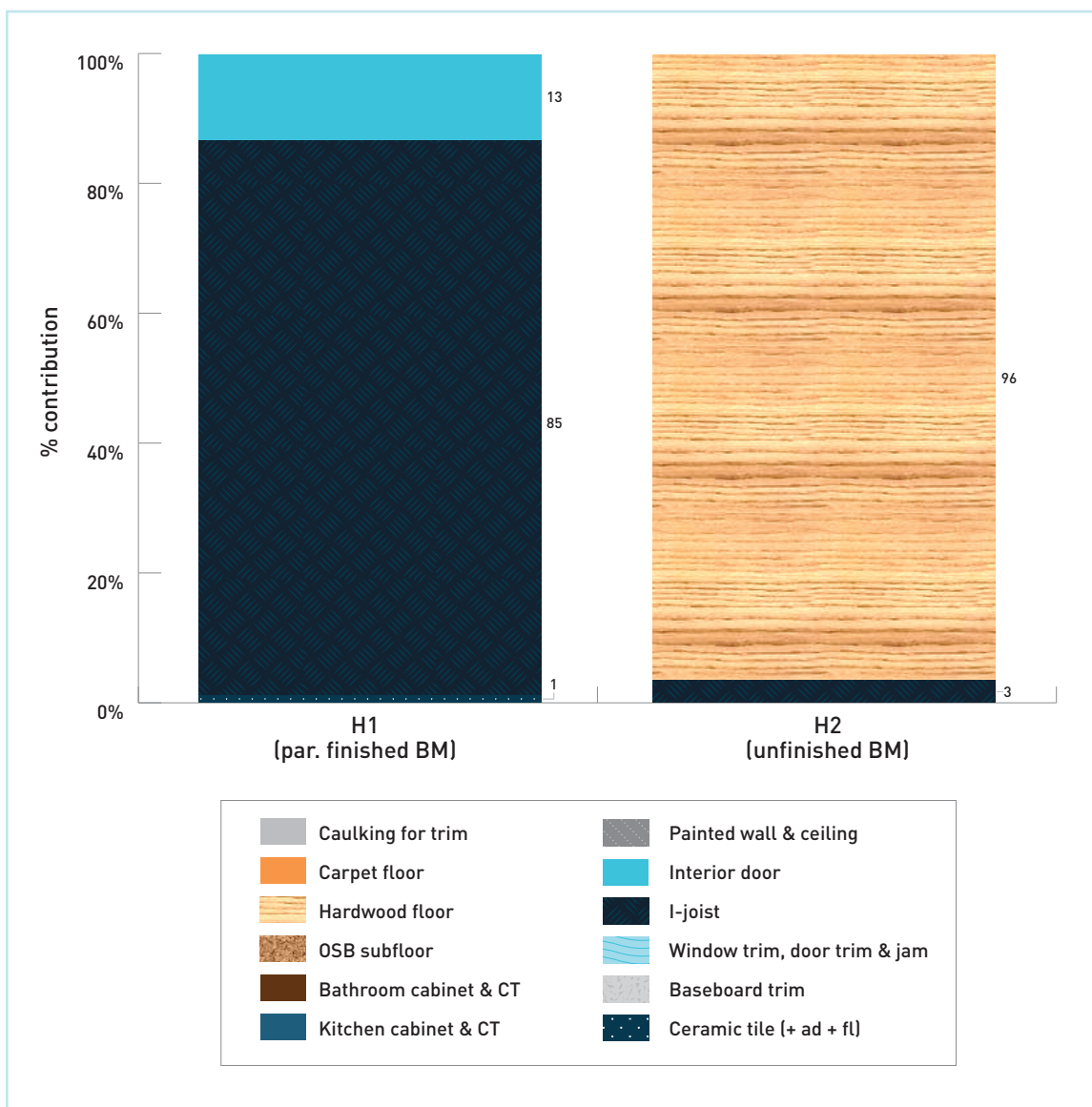
**FIGURE 26: Contribution of each source to 3-carene**



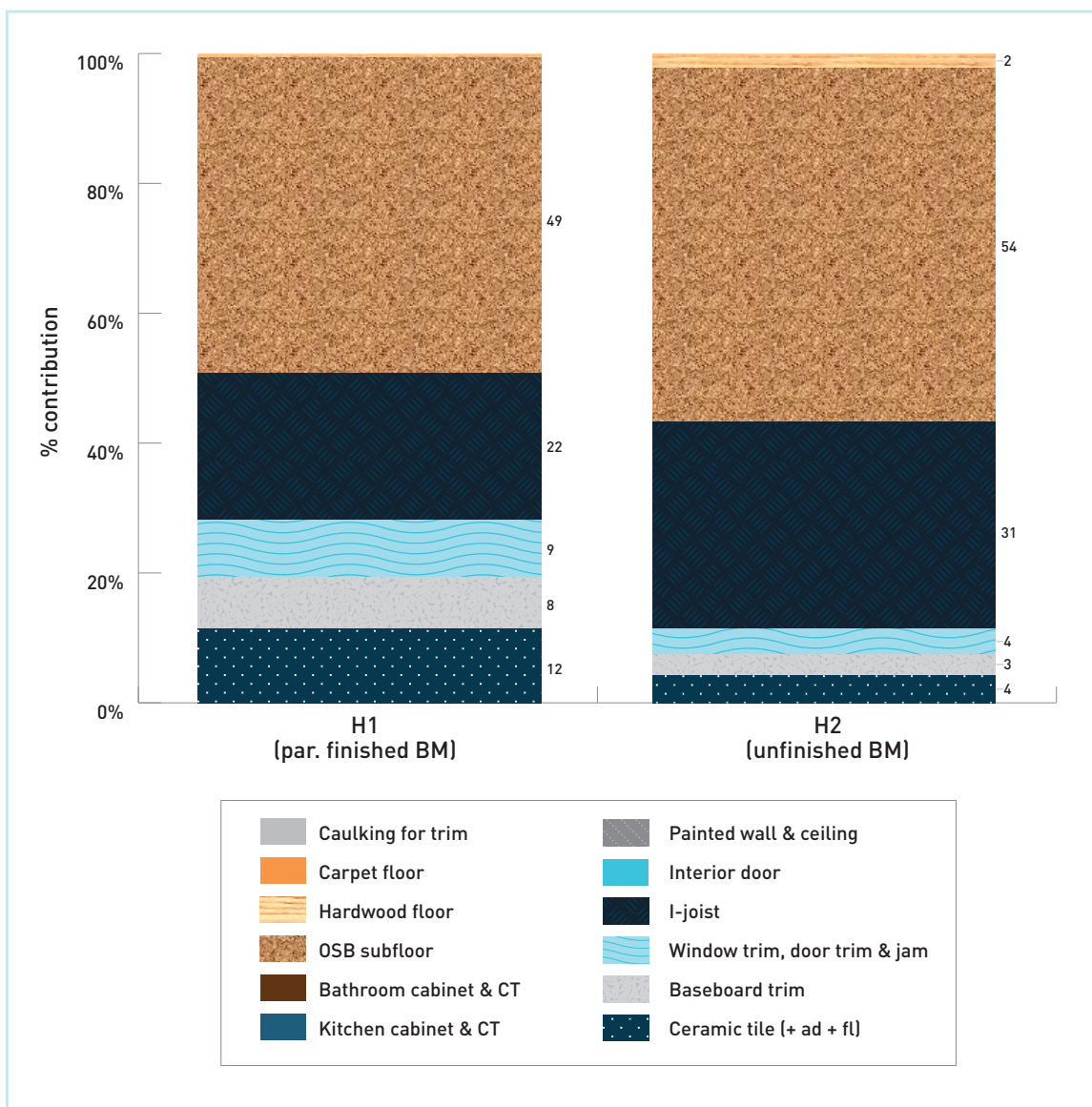
**FIGURE 27: Contribution of each source to camphene**



**FIGURE 28: Contribution of each source to limonene**

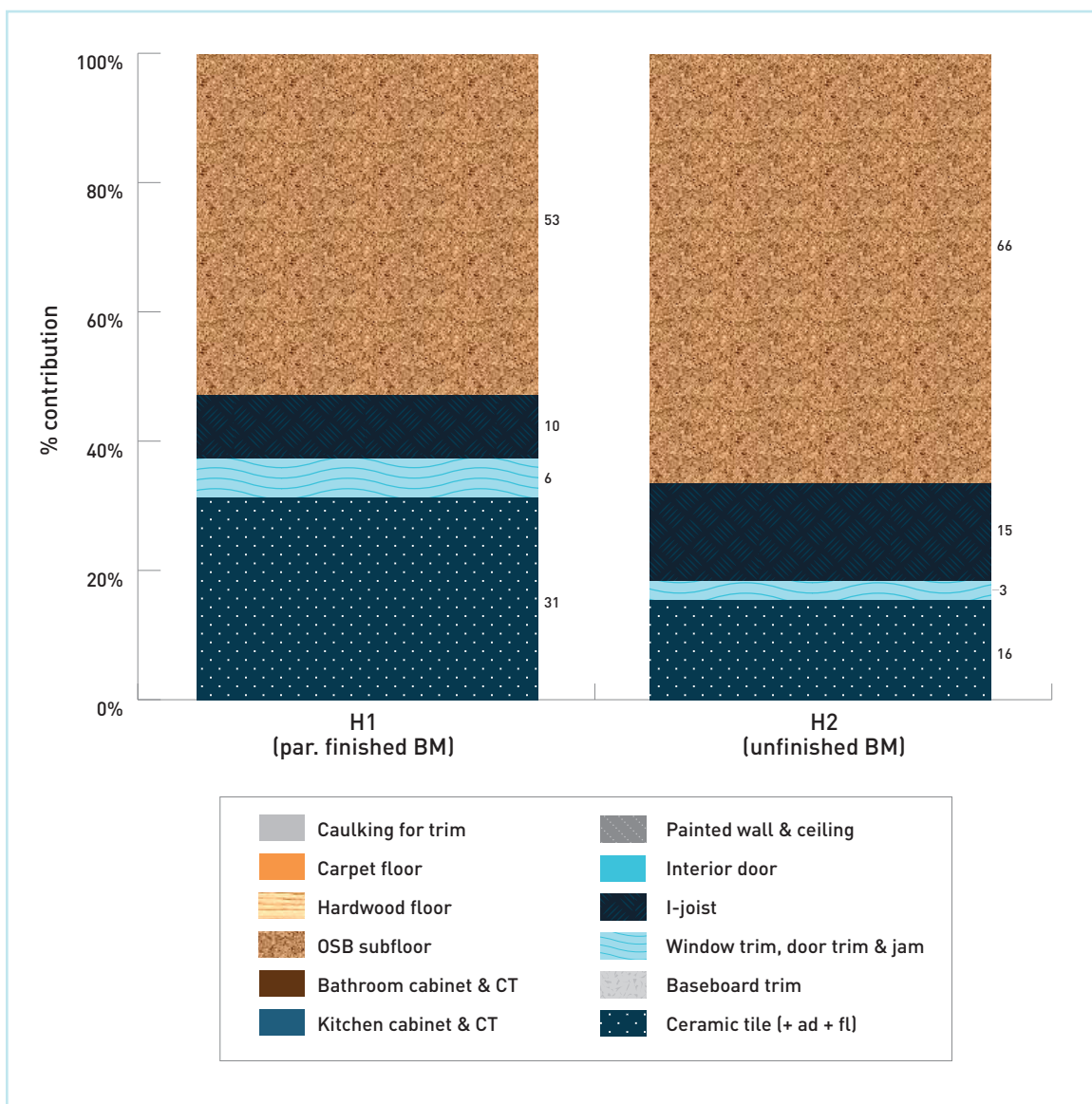


**FIGURE 29: Contribution of each source to acetic acid**

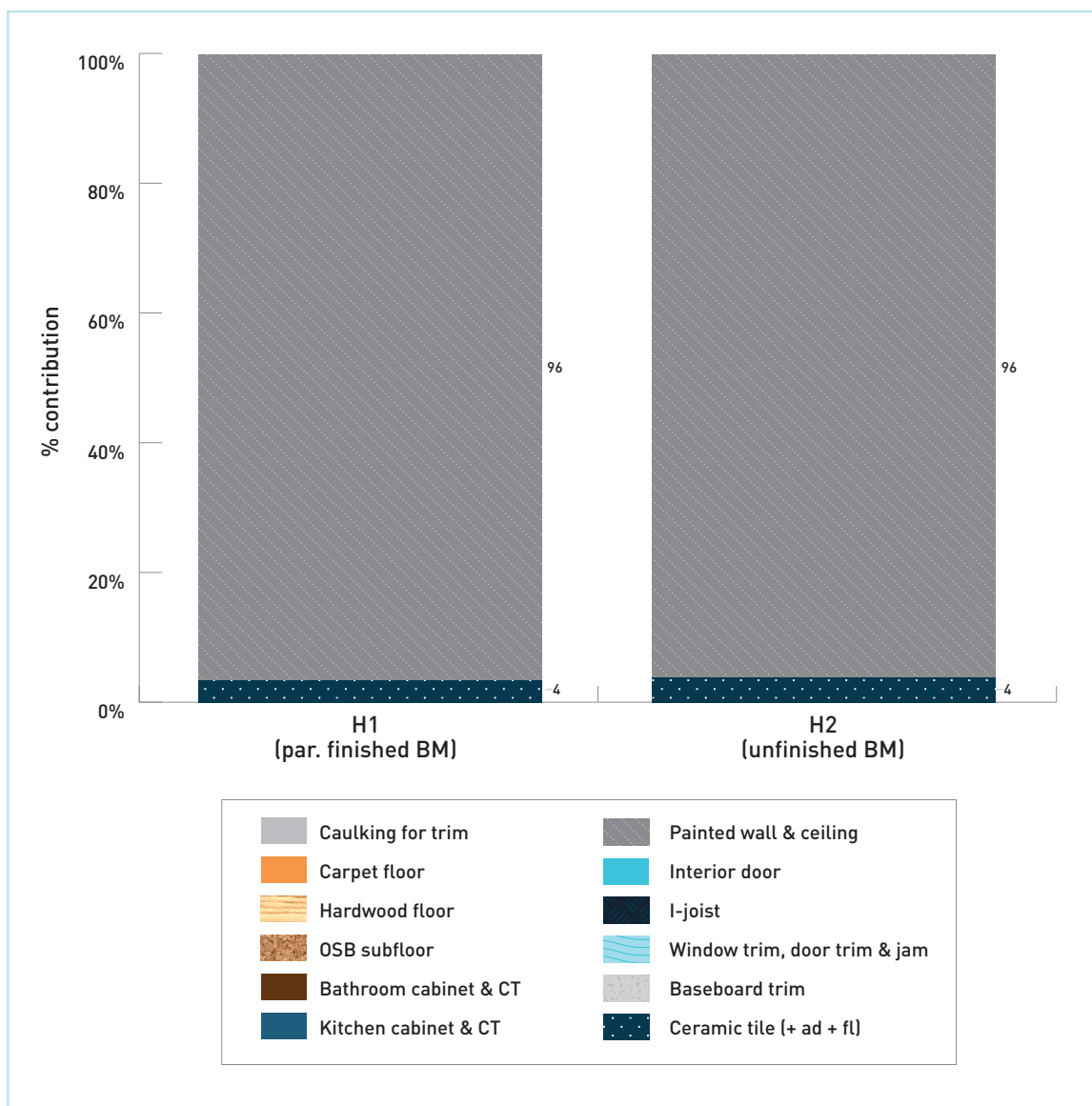




**FIGURE 30: Contribution of each source to furan, 2-pentyl**



**FIGURE 31: Contribution of each source to n-butyl ether**



### 3.2.4 Prediction at steady state with an additional source

To test the hypothesis that there were activities which resulted in high concentrations of hydrocarbons, it was assumed that an oil-based touch-up finish was applied to a 1 m<sup>2</sup> area. Since no oil-based products were tested in this study, the emission information for an oil-based product was obtained from the previous study (Won et al. 2013). The selected material was UR9 with VOC < 350 g L<sup>-1</sup>. More detailed information on the modelling input can be found for aliphatic and aromatic hydrocarbons in sections G.8 and G.9.

The modelling results are summarized in Table C. 17. Compared to Table C. 16, the predicted results were improved for aliphatic and aromatic hydrocarbons. This indicates that the materials to be tested need to be carefully selected with respect to the chemical of interest even if the amount to be tested is small.



## 4. SUMMARY AND CONCLUSIONS

The objective of this study was to provide data on VOC emissions, primarily from composite wood materials used in home construction and finishing, and to validate the indoor air quality model for predicting VOCs emitted from building materials.

A total of 17 tests were conducted with materials that were considered to cover major interior surfaces, including structural and non-structural materials, in two new homes. The materials tested included structural products (I-joist, OSB subfloor, plywood underlayment), flooring materials (two hardwood flooring products, carpet, ceramic tile assembly), an interior door, interior trim (three MDF baseboard specimens), latex caulk, interior paint (on drywall substrate), and cabinet systems (two kitchen and two bathroom units, including countertops).

Five material assemblies (four cabinets and one door) were tested in the 31 m<sup>3</sup> chamber with an air change of 0.49 or 1 h<sup>-1</sup>. The other materials were tested in 50 L chambers with an air change of 1 h<sup>-1</sup>. All tests were conducted at 23 °C and 50% RH. The material loading ratio ranged from 0.03 (caulk) to 2.18 m<sup>2</sup> m<sup>-3</sup> (I-joist). Except for caulk, low loading ratios (0.08 to 0.16 m<sup>2</sup> m<sup>-3</sup>) were associated with materials tested in the 31 m<sup>3</sup> chamber. The total test period was 14 days in order to meet the testing requirements of both the CSA-0160 standard and the widely adopted in North America CDPH “Method 1” (2017).

The emissions data were analyzed for 120 target VOCs (117 VOCs obtained by the GC/MS analysis and 3 low molecular weight aldehydes by the HPLC analysis) and several non-target compounds found in abundance. The target VOC list was developed by the NRC with minor modifications over time to include chemicals that are frequently found indoors and/or emitted from building materials (Won, Luszyk, and Shaw 2005). The emissions data were used to calculate the coefficients of emission factors based on fitted power-law equations.

Based on the emission factors obtained from the chamber tests, the following observations were made:

- ▶ Aldehydes, including formaldehyde and acetaldehyde, were the most frequently detected VOCs in the 17 materials tested and had the highest mean emission factors.
- ▶ Acids and ketones were detected less frequently than aldehydes, but more frequently than the remaining compounds.
- ▶ Glycols, glycol ethers, and esters were found at high concentrations in a certain group of materials (i.e., paint and caulk).
- ▶ Terpenes had one dominating source, i.e., hardwood floor with pine core.
- ▶ Aliphatic and aromatic hydrocarbons were associated with low emission factors and low detection frequencies.
- ▶ Halocarbons and cyclo-alkanes were rarely detected in the 17 materials.

The emissions data were used to validate the indoor air quality model as discussed in Section 3, which is designed to predict indoor air concentrations of various VOCs based on the material emissions data from chamber testing. The indoor air quality model is a mass balance model, using material emissions data from chamber tests, material surface areas, and ventilation rates as input data, in order to predict indoor concentrations over time. Material emissions data

were obtained from 14-day chamber tests of 17 materials that were considered to cover major interior surfaces in the two homes. Since the focus was on aldehydes such as formaldehyde and acetaldehyde, the emphasis of the emissions testing was given to composite wood products that are known sources of these chemicals.

The material emissions were assumed to follow a power-law decay equation. The model coefficients were obtained from the chamber test data. The two homes investigated were considered to have a well-mixed zone, which was supported by the good agreement of tracer gas concentrations on three floors. The modelling incorporated different elapsed times for different materials, which were calculated based on construction schedules provided by the builder. The elapsed time between installation and air sampling ranged from 16 to 180 days. The surface area of each material was estimated based on the dimensions measured in each house (e.g., kitchen and bathroom furnishing area) or from the floor plan (e.g., wall area).

The indoor air concentrations were predicted to be within a factor of 2 from the measured concentrations for aldehydes in high abundance, including formaldehyde, acetaldehyde, propanal, hexanal, and pentanal. Texanol, which is known to be the main component of coatings such as water-based paints (Corsi and Lin 2009), also showed good agreement between the predicted and measured concentrations. On the other hand, aromatic and aliphatic hydrocarbons, which are generally associated with petroleum-based products, were severely underestimated. This can be probably explained by the fact that no petroleum-based products were identified and tested in this study.

Among materials tested in this study, composite wood products (e.g., wood trims, cabinets, doors, hardwood floors, I-joists, and OSB subfloor) were shown to be the main source of aldehydes detected in the two homes. The contribution of unfinished composite wood products (e.g., I-joist and OSB subfloor) was greater than the contribution of those with finishes (e.g., cabinets, hardwood floors, trims), as observed in H2 which has an unfinished basement. This confirms that structural composite wood products can be significant sources of aldehydes.

The main conclusion of this study is that indoor air concentrations can be predicted with reasonable accuracy (i.e., within a factor of 2) when sources, and ventilation and construction schedules, are well characterized. While this study is limited to two homes, its results support the feasibility of using 14-day emissions tests in predicting long-term emissions (e.g., 16 to 180 days). Using a detailed floor plan combined with field measurements seems to be a reasonable approach for obtaining information about interior surface areas. The detailed information on the construction schedule was helpful for identifying the elapsed time after material installation. Additionally, it was demonstrated that the ventilation measurements based on the passive PFT gas method can provide comparable results to those obtained by the active SF<sub>6</sub> method.

One limitation of this study was that the materials tested were largely focused on composite wood products, inasmuch as the main VOCs of interest were aldehydes. More careful inventory of potential sources, including touch-up and cleaning products typically used to prepare for the move-in of occupants, is recommended if a broad range of VOCs are of interest. Additionally, IAQ measurements were only possible for a single day mainly due to the tight schedule between construction and occupancy. More IAQ measurements over a longer period time, including the pre- and post-occupancy period, are recommended to better understand the timevariant VOC concentrations in new homes and to validate the IAQ model over a longer period of time. In addition, builder interest and participation in this study was low resulting in the recruitment of



only 2 homes. As a result of these study limitations, the results should be interpreted with caution and further data are required to fully validate the modelling approach used in CAN/CSA-0160.

For future work, more discussion is needed with respect to the test period. While the emission rate of VOCs tended to decrease over time, the opposite was observed for several composite wood products. For example, more than 50% of VOCs from the cabinets and the interior door tested in the 31 m<sup>3</sup> chamber had emission factors that displayed increasing trends over the testing period of 14 days. This is most likely attributed to the emission characteristics of composite wood products which tend to have relatively constant emission rates over a long period of time. In order to better capture the decaying trends of emission rates, it may be necessary to increase the testing period of 14 days (e.g., to 28 days) in spite of increased costs and time. For example, CEN, the European Committee for Standardization (2013), recommends a 3-day test for short-term emissions and a 28-day test for long-term emissions.

Future work is planned to commence FY2019–2020 to better understand formaldehyde, VOCs, and SVOCs in newly constructed homes during the first year of occupancy.



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