# Concrete-Encased Ducts Report | Project 8556.000

In-Slab Duct Research and Monitoring

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# Executive Summary

Current industry practices for the installation of in-slab ducts including building codes, standards, and manufacturer documentation are insufficient to fully mitigate the moisture related issues observed in the Lower Mainland of British Columbia. An analysis of interior moisture sources including clothes dryers confirmed the importance of maintaining adequate airflow rates and velocities to balance wetting and drying periods within the ducts.

In addition to an analysis of in-slab duct design, the primary purpose of this research report was a monitoring study of installed systems. RDH investigated three separate sites experiencing a range in the severity of moisture related issues. Significantly, the study found that even an undamaged system with airflow rates approaching the dryer manufacturer's recommendations experienced periods of condensation within the in-slab duct during normal operation. The study also found that the severity of the moisture related issues increased with decreasing exhaust airflow. Remediation aimed at increasing airflow rates including duct cleaning was shown to temporarily reduce moisture build-up.

When in-slab ducts are used, architects and mechanical designers should consider layouts which reduce the effective duct length and should include the ducts in the mechanical commissioning process to ensure the installed airflow rates meet or exceed the design.

This report concludes with recommendations for remediation of in-slab ducts experiencing moisture issues including regular inspections and duct cleaning. However, given the relative difficulty of repairing in-slab duct systems and the inability to fully control the moisture risks, many designers or occupants may instead choose ductless equipment as a more permanent solution.

# 0 Introduction

## 0.1 Overview

It is common design and construction practice in Metro Vancouver to incorporate ventilation ducts into the reinforced concrete slabs of multi-unit residential buildings. While there are benefits to installing in-slab ducts, a variety of performance issues, especially moisture-related issues, have been identified by the industry.

Moisture buildup within in-slab ducts is a widespread issue that affects a large number of existing buildings and has potential to continue to adversely affect new construction. To provide a better understanding of the nature and cause of these issues RDH conducted a monitoring study of three suites with in-slab ducts. This research project also aimed to identify potential remediation and design solutions to prevent future issues.

The first section of this report provides a general background of the topic and investigates the potential causes of moisture buildup within in-slab ducts using first principles. Section 2 presents the monitoring results and an analysis of three suites. The severity of the moisture issues observed in these suites varied from no observable moisture buildup to a steady drip of water exiting the exhaust vent. Together, these investigations provide insight into the conditions within the in-slab ducts and the failure mechanisms. The third section of this report provides best-practice recommendations to mitigate and remediate moisture-related issues with in-slab ducts.

## 0.2 Objective

The primary objective of this research project is to improve the quality of British Columbia's built environment by advancing the industry's understanding of in-slab ductwork through the combined application of building science principles and real-world monitoring. This research study aims to answer the following questions:

→ Is moisture buildup a concern within properly installed in-slab ducts?

→ How and why is water forming in the in-slab ducts?

→ What are the remedial steps for in-slab ducts with high moisture accumulation?

→ What are appropriate design recommendations for new construction?

# 1 Background

Industry professionals and consumers have observed various levels of moisture buildup within in-slab ducts; from a fine mist of water droplets to several inches of standing water. Despite a large body of evidence of moisture buildup in the field, little to no research has been conducted on in-slab ducts. A literature review conducted by RDH revealed no pre-existing research related to moisture build-up within air ducts. The few papers which were found with a link to ductwork and moisture generally covered microbial growth on the duct materials and condensed moisture on the outer surfaces of the duct.

Prior to this monitoring study, BC Housing published a bulletin on avoiding Exhaust Duct Problems (Building Maintenance Bulletin #14). This 8-page bulletin provides an excellent summary of common duct issues, their potential causes, and recommended maintenance items. However, while the bulletin identifies in-slab ducts as having the highest prevalence of issues, it does not provide a reason for why this is the case.

The bulletin can be downloaded from BC Housing's research library using the following link: https://www.bchousing.org/research-centre/library.

Section 1 of this report begins with an overview of in-slab ducts along with the current practices for in-slab duct design and installation. The remainder of Section 1 examines the potential for moisture accumulation within the ducts.

## 1.1 In-Slab Ducts

For the purpose of this report, the term "in-slab ducts" refers to forced air ductwork installed within a concrete slab. In-slab ducts may also be used for passive air inlets to provide make-up air or natural ventilation. The system traditionally consists of narrow rectangular segments of galvanized sheet steel ductwork, couplers, and fittings which are cast-in-place between the steel reinforcing of the concrete slab. Figure 1.1 shows examples of in-slab ducts being installed.

Ref: http://www.eccoduct.com/installation.html

***Figure 1.1*** *Installation of in-slab ducts.*

## 1.2 Design & Installation

The purpose of in-slab ductwork is to provide an airflow path between the inside and outside of a building. Similar to conventional dropped ceiling or bulkhead installations of ductwork, in-slab ducts need to be designed and installed to allow for an adequate airflow rate considering the following variables:

→ Fan capacity

→ Duct size

→ Equivalent duct length

→ Undamaged and sealed

The following sub-sections provide an overview of these factors based on available resources from multiple manufacturers and code jurisdictions. The purpose is to provide context for an analysis later in the report. Always review and comply with the specific requirements of the applicable building codes for each construction project.

### 1.2.1 Fan Capacity

A typical new dwelling will include several different fans to meet continuous and intermittent ventilation requirements. In BC, the ventilation requirements are stated in Sections 6.3 and 9.32 of the BCBC or VBBL for Part 3 and Part 9 buildings respectively. For mid- to high-rise multi-unit residential buildings, which are the focus of this report, Section 6.3 applies. This section in turn references ASHRAE Standard 62 for the minimum design ventilation rates.

Focusing on exhaust rates, ASHRAE Standard 62.2-2019 requires the following minimum intermittent (demand controlled[1]) exhaust flows:

→ Kitchen: 50 L/s to 150 L/s (100 cfm to 300 cfm)

→ Bathroom: 25 L/s (50 cfm)

The minimum flow rates are intended to be based on the measured installed performance, although ASHRAE 62.2-2019 includes a prescriptive duct sizing method for short duct systems (< 8 m) with no more than 3 elbows.

In addition to exhaust requirements for kitchens and bathrooms, exhaust ventilation is required for specific appliances such as clothes dryers[2] and fuel burning appliances. Neither the BCBC, VBBL, or the referenced ASHRAE Standard 62 provide specific clothes dryer exhaust flow rates, relying instead on the manufacturer's requirements for the proper operation of the equipment.

While there is a range in the minimum exhaust flow requirements, exhaust airflow rates greater than 50 – 70 L/s (100 – 150 CFM) are typical[3]. Based on ASHRAE Standard 62.2-2019 prescriptive duct sizing, the minimum rigid duct diameter for this airflow is 125 mm to 150 mm (5" to 6"), which translates to airflow velocities greater than 3 to 6 m/s (550 to 1200 ft/min). In the case of clothes dryer exhaust, maintaining high airflow velocities can help to limit the amount of lint buildup within the ductwork and reduce the residency time of the moisture laden air which can mitigate the risk of condensation.

[1] *ASHRAE 62.2 also requires continuous local ventilation of these spaces*
[2] *Except condensing dryers which are plumbed to drain*
[3] *A review of manufacturer literature found flow rates in excess of 115 L/s (230 CFM)*

In some cases, internal fans will be sufficient to meet the manufacturer's minimum exhaust requirements. However, in practice, especially in the case of in-slab ducts, the length and complexity of duct runs can result in lower-than-expected flow rates. In these cases, it is common for the mechanical designer or manufacturer to specify booster fans to supplement the exhaust flow rate.

### 1.2.2 Duct Size

ASHRAE Standard 62.2 provides prescriptive duct sizing requirements based on the minimum airflow rate in L/s (cfm). Based on Table 5-3 of the standard, the minimum diameter of a rigid round duct designed for airflow rates between 25 L/s (50 cfm) and 120 L/s (250 cfm) ranges from 100 mm (4") to 205 mm (8"). In the specific case of a 50 L/s (100 cfm) exhaust flow rate, the minimum round duct diameter is 125 mm (5").

Due to height restrictions imposed by slab thicknesses, in-slab ducts are not generally capable of meeting the prescriptive duct sizing requirements for airflow rates more than 70 L/s (150 cfm) which require duct diameters greater than 150 mm (6"). Height restrictions within a slab also dictate the shape of in-slab ducts which are typically rectangular or oval.

For noncircular ducts, the ASHRAE prescriptive duct sizing method requires the use of the hydraulic diameter which is calculated as four times the cross-sectional area divided by the perimeter, Equation 1.

$$d_h = \frac{4 * A}{P} \tag{1}$$

***Example 1 – Hydraulic Diameter of a Rectangular In-slab Duct***

*Problem:*
What is the hydraulic diameter of a 300 mm x 44 mm rectangular in-slab duct?

*Solution:*
Using Equation 1,

$$d_h = \frac{4 * (300 * 44)}{(2 * 300) + (2 * 44)}$$

*Answer:*
The hydraulic diameter of the rectangular duct in this example is 76.7 mm (3"). Since the minimum ASHRAE prescriptive duct diameter is 100 mm (4"), this duct would not meet the prescriptive sizing requirements.

*Note:*

The hydraulic diameter is used for analysing the flow of fluids through non-circular channels and is different than the equivalent round diameter. The equivalent round diameter of a rectangular duct with a width (a) and height (b) that would result in the same pressure drop due to friction is calculated using the following equation.

$$d_e = \frac{1.3 * (a * b)^{0.625}}{(a + b)\text{^}0.25}$$

Using the same example, the equivalent round diameter is 114 mm (4.5")

When ducts fail to meet the prescriptive ASHRAE sizing requirements, designers may rely on manufacturer documentation for the sizing and selection of equipment.

### 1.2.3 Duct Length and Layout

The maximum duct length is dependent on the equipment and duct manufacturers' specifications for each system including the required fan capacity and duct size. In addition to manufacturer requirements, local codes and standards may prescribe a maximum duct length or minimum duct size.

The ASHRAE Standard 62.2-2019 prescriptive duct sizing method limits the duct length to 8 m (25 ft). This length assumes up to three elbow fittings and a minimum diameter for exterior fittings.

In contrast, Table 9.32.3.8.(3) of the BCBC/VBBL limits the equivalent duct length to 13 m (42 ft) to well over 28 m (92 ft) depending on the duct diameter and flow rate. While these lengths appear to be much greater than the value presented in ASHRAE Standard 62.2, the BCBC/VBBL states the requirement as an "equivalent" duct length, which combines the actual duct length and the equivalent duct length, $L_{eq}$, of fittings, connectors, bends, and grilles. When an exterior grille, three elbows, and inlet boot are included, the maximum duct length for a 125 mm (5") diameter duct with a fan capacity of 50 L/s (100 cfm) is 9 m (30 ft).

The difference between the way the maximum duct length is specified in ASHRAE 62.2 and the BCBC/VBBL highlights how the additional pressure drop due to fittings, bends, etc., is accounted for. The process involves adding an equivalent length of duct for each fitting. This process is best illustrated through an example.

***Example 2 – Equivalent Duct Length Calculation***

*Problem:*
What is the equivalent duct length of an in-slab duct system consisting of an inlet boot, 4.6 m (15 ft) of duct, a 45˚ elbow, and a wall discharge with grille?

*Solution:*
First, determine the equivalent duct length for each fitting. Manufacturer specifications typically provide this information and Table 1.1 reproduces values from one manufacturer of in-slab ducts (ECCO Manufacturing, 2013).

TABLE 1.1 EQUIVALENT DUCT LENGTH FOR VARIOUS IN-SLAB DUCT FITTINGS

| Fitting | Equivalent Duct Length – m (ft) |
| --- | --- |
| Inlet Boot | 7.9 (26) |
| Wall Discharge Damper and Grille | 1.8 (6) |
| 30˚ | 2.1 (7) |
| 45˚ | 2.1 (7) |
| 90˚ | 3.7 (12) |
| Soffit Discharge with Grille | 4.0 (13) |

Once the equivalent duct lengths have been determined, sum all of the lengths:

$$L_{eq} = 7.9 + 4.6 + 2.1 + 1.8 = 16.4\,m\ (54\,ft)$$

*Answer:*
The total equivalent duct length for the system in this example is 16.4 m (54 ft).

### 1.2.4 Undamaged & Sealed

Although not strictly a design criterion, it is important to consider the risk of damage to these systems during construction. For example, concrete can block poorly sealed/fitted ducts or workers can crush ducts prior to concrete placement, Figure 1.2.

***Figure 1.2:*** *In-slab duct damaged during construction (left & upper right), and damaged during concrete pour (bottom right)*

If the ducts are not protected during construction, airflow can be reduced or in some cases fully prevented. Poorly sealed or damaged ducts also increase the risk of moisture migrating from the duct to the ceiling in the event of moisture buildup.

While construction damage is a potential concern for all systems, since in-slab ducts are encased in concrete, inspection and repair of the damage is significantly more difficult after installation.

Bringing these elements together, a ‘properly’ designed residential in-slab duct system will typically feature:

→ Fan capacities from 25 L/s (50 cfm) to over 70 L/s (150 cfm)

→ Hydraulic diameters from 100 mm (4”) to 150 mm (5”) or sized per the duct manufacturer’s literature[4]

→ Duct lengths less than 8 m (25 ft) with few bends

→ Sealed ducts with no visible damage

Despite this guidance from manufacturers and the prescriptive requirements laid out in the building code and associated standards, there remain many examples of in-slab duct installation with observable moisture issues.

[4] *When the ASHRAE prescriptive sizing is not met, this may result in changes to the fan equipment to meet the minimum flow rates*

## 1.3 Moisture Sources

The purpose of exhaust ventilation is to remove indoor air contaminants. In the case of kitchen, bathroom, and dryer exhaust one of the main contaminants being controlled is moisture. For this reason, an understanding of the interior moisture sources provides a useful context for the observed issues. Table 1.2 summarizes the moisture generating rate of typical indoor sources of moisture.

**TABLE 1.2** INTERIOR MOISTURE SOURCES (TENWOLDE & PILON, 2007)

| Source | Moisture (kg/hr) | Notes |
|---|---|---|
| Occupants | 0.03 – 0.47 | Dependent on activity level. Moisture generation rate approx. 0.05 kg/hr per occupant when at rest |
| Laundry | 0.05 – 2.5 | Dependent on size of load and moisture remaining after washing. |
| Bathroom | 0.70 – 2.6 | Moisture released during a bath (0.7 kg/hr) or shower (2.6 kg/hr). Assumes a 15 min. activity over the hour. |
| Kitchen | 0.20 – 1.0 | Moisture released by food, combustion, and dishwashing activities; Estimated 0.3 kg/hr for a load in a dishwasher, 0.2 to 1.0 kg/hr cooking |
| Pet | 0.01 | Small pet (<10 kg) |
| Plants | 0.01 – 0.02 | Per plant |

Figure 1.3 illustrates the relative moisture generation rate (kg/hr) .


***Figure 1.3:*** *Relative moisture generation rate by source (kg/hr), when operating or present.*

Over the course of a day, the various sources of interior moisture add up to approximately 7 to 12 L/day (1 L of water = 1 kg) of moisture added to a typical residential space. This amount depends on the number of occupants and activity, and is generally consistent with guidance from ASHRAE Standard 160-2021, *Criteria for Moisture-Control Design Analysis in Buildings.* Table 4-3 from that that standard is reproduced below to express the moisture generation rate as a function of the number of occupants.

| **Table 1.3** RESIDENTIAL MOISTURE GENERATION RATES PER ASHRAE STD .160-2021 | | |
|---|---|---|
| **No. Bedrooms** | **No. Occupants** | **Moisture Generation Rate (L/day)** |
| 1 | 2 | 7 |
| 2 | 3 | 9 |
| 3 | 4 | 10 |
| 4 | 5 | 11 |
| Additional | + 1 | +1 |

To ensure a healthy and comfortable indoor environment, the moisture generated in the space must be removed by ventilation. For non-localized or small sources of moisture such as occupants and plants, continuous ventilation is needed. However, where the moisture generation rate is both high and localized (e.g., a shower, cooking over a stovetop, or operating a dryer), exhaust fans and ductwork provide a more effective means of controlling excess moisture.

Mechanical control strategies can only be effective when they are used. Since many exhaust fans are manually controlled, it is common for occupants to leave fans off due to noise, habits, or other factors outside of a designer's control. Automated fan controls which turn on at high humidity levels or are interlocked with operation of the moisture generating equipment can greatly improve the realized efficacy of the exhaust systems.

### 1.3.1 Condensation

In an ideal scenario, the excess moisture generated by indoor activities is perfectly exhausted to the exterior environment without having a chance to deposit on interior surfaces. However, when moisture laden air is transported, especially towards a cooler exterior environment, there is a chance of condensation forming.

The following section estimates the dew point temperature of interior, exterior, and exhaust air along with the surface temperature of the in-slab duct to assess the potential for condensation. This analysis assumes Vancouver, BC climate conditions.

#### *Air Properties*

Table 1.4 summarizes the interior and exterior air properties at the summer and winter design conditions for Vancouver, BC.

| **TABLE 1.4** AMBIENT INTERIOR AND EXTERIOR AIR PROPERTIES | | | |
|---|---|---|---|
| | **Parameter** | **Interior**[1] **(ASHRAE 160-2009)** | **Exterior**[2] **(ASHRAE 169-2013)** |
| Winter | Temperature | 21.1 ˚C | -7 ˚C |
| | Relative Humidity | 40% | 53% |
| | **Dew Point Temperature** | **6.7 ˚C** | **-13.9 ˚C** |
| Summer | Temperature | 25.8˚C | 23 ˚C |
| | Relative Humidity | 70% | 62% |
| | **Dew Point Temperature** | **19.8 ˚C** | **15.1 ˚C** |

1. *Interior conditions based on ANSI/ASHRAE Standard 160-2009*
2. *Exterior conditions based on ANSI/ASHRAE Standard 169-2013*

Based on the winter design conditions, simply exhausting interior air to the exterior cold environment (without additional moisture from laundry, showers, or cooking) can result in condensation at the exterior end of the duct when the exterior temperature is less than 7 ˚C. In Vancouver, this would equate to roughly 3 months in a standard weather year.

The potential for condensation is much higher in the case of moisture laden exhaust air from dryers, kitchens, and bathrooms. While the exhaust air properties vary widely, two measurement studies are referenced to provide context for this report.

### *Dryer Exhaust Air Characteristics*

The first study, from the Consumer Product Safety Commission, presents temperature and relative humidity data for a dryer tested in a laboratory setting (Butturini, Lee, & Dunmore, 2004). The second study provides field measured data for a bathroom. The data from the first of these studies is summarized in Table 1.5 and Figure 1.4.

**TABLE 1.5** DRYER EXHAUST DESIGN CONDITIONS

| Parameter | Average | Max | Reference |
|---|---|---|---|
| Temperature | 50 ˚C | 80 ˚C | (Butturini, Lee, & Dunmore, 2004) |
| Relative Humidity | 45% | >90% | (Butturini, Lee, & Dunmore, 2004) |
| **Dew Point Temperature** | **30 ˚C to >45 ˚C** | | |

The dewpoint temperature of dryer exhaust is significantly higher than the interior ambient air temperature and therefore very likely to condense within the ductwork year-round.

One of the reasons observable moisture issues are not more prevalent is that the temperature and humidity of dryer exhaust varies over the course of the drying cycle. The highest levels of humidity (70% to >90%) are typically experienced in the first 5 to 15 min of a 45 - 60 min drying cycle. During this period the temperature of the exhaust air is kept relatively low due to evaporation of moisture from the clothing. This period of high moisture and low temperature can lead to wetting. As the clothes continue to dry, less water evaporate and the exhaust air temperature rises. This period of low humidity and high temperature can lead to drying. This cycle is shown in Figure 1.4.

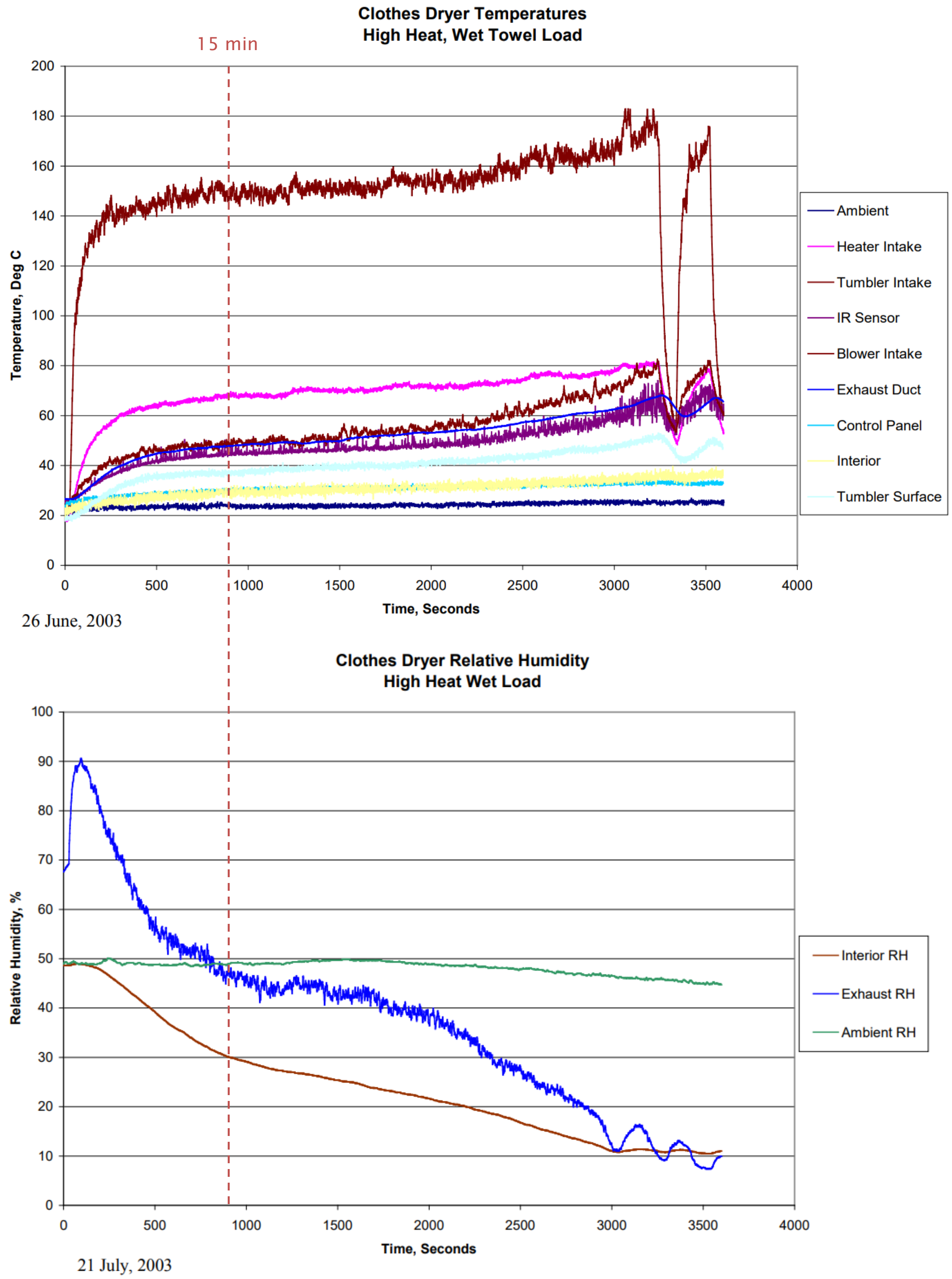



***Figure 1.4:*** *Temperature and Relative Humidity measurements from a dryer (Butturini, Lee, & Dunmore, 2004)*

This cycle of a relatively short period of wetting followed by a long period of drying was measured at the suite with no significant moisture issues; refer to Figure 2.5 later in this report.

### *Bathroom Exhaust Air Characteristics*

In the case of bathroom exhaust, the high moisture load is typically limited to the duration of the activity and a short period of time after the event.

**TABLE 1.6** BATHROOM EXHAUST DESIGN CONDITIONS

| Parameter | Average | Max | Reference |
| --- | --- | --- | --- |
| Temperature | 23˚C | 30˚C | (Slávik & Čekon, 2014) |
| Relative Humidity | 85% | 96% | (Slávik & Čekon, 2014) |
| **Dew Point Temperature** | **20 ˚C to 29 ˚C** | | |

The measurements by (Slávik & Čekon, 2014) and similar unpublished studies in the Lower Mainland suggest that the dewpoint temperature of bathroom exhaust air is at risk of condensation throughout the year.

Unlike dryer exhaust, bathroom fans do not have the advantage of a heating element to create drying conditions during operation. Despite this, anecdotally there have been fewer observed issues with in-slab ducts connected to bathrooms. This is likely due to the shorter duration of showering events compared to a complete dryer cycle, and the fact that not all the bathroom moisture is captured by the ducts. Since bathroom exhaust is not connected to an airtight enclosure, some of the moisture is deposited on surfaces within the bathroom or moves to other rooms. During some parts of the year, running bathroom exhaust fans for a period after showering may assist in drying accumulated moisture within the duct and in removing excess interior moisture. However, as noted in Table 1.4, this may also lead to additional condensation near the end of the duct during colder parts of the year.

The next section examines the temperature profile along the duct to estimate the extent of the risk area.

## *Duct Temperatures*

To illustrate the potential extent of condensation issues, two in-slab duct configurations were simulated to show the temperature profile along the duct. The two scenarios were:

1. Interior insulated concrete wall with 4" closed cell spray foam (Figure 1.4)
2. Exterior insulated concrete wall with 4" mineral wool insulation (Figure 1.5)

The exhaust fans were assumed to be off in both scenarios. The interior and exterior boundary conditions temperatures were 21˚C and -7˚C respectively.

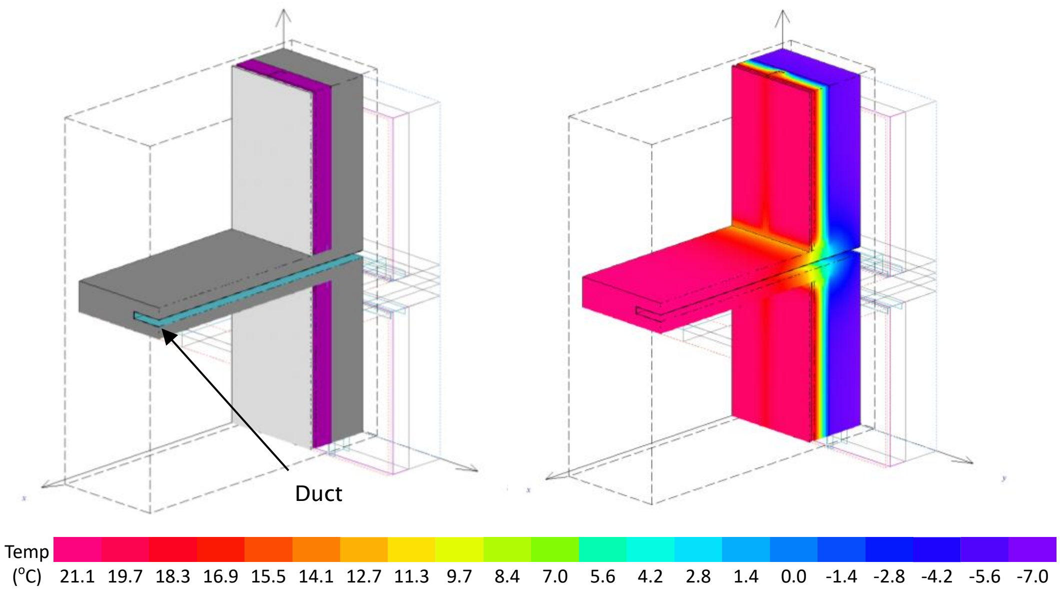



***Figure 1.5**: Cut-away view of an in-slab duct passing through an interior insulated concrete wall.*

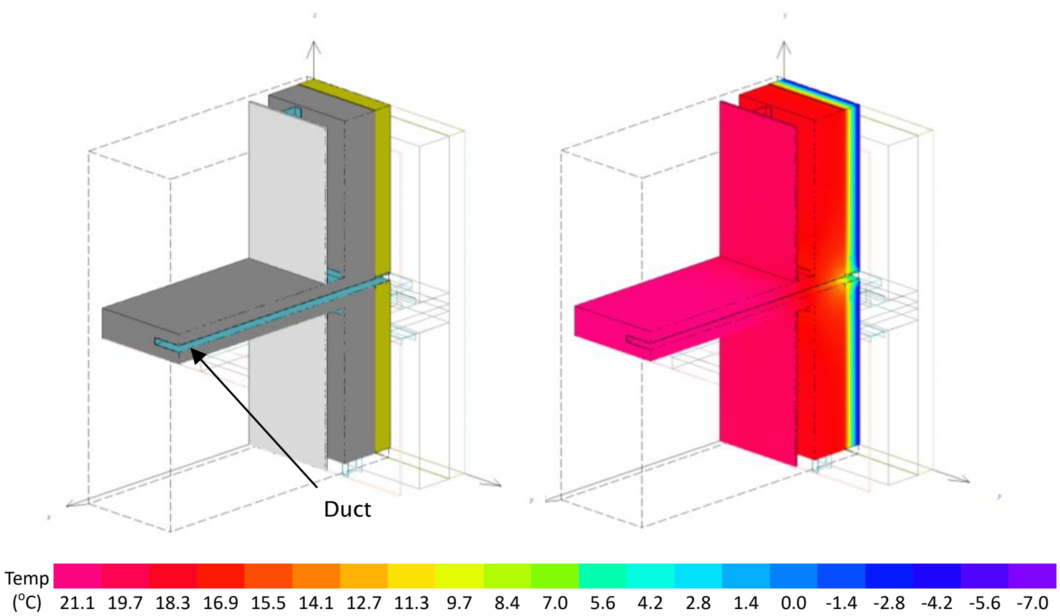



***Figure 1.6:** Cut-away of an in-slab duct passing through an exterior insulated wall.*

As noted in the previous section, during operation humid exhaust air is likely to condense throughout the duct during most of the year. However, the thermal simulations illustrate a relatively small area of elevated condensation risk at the exterior end of the duct. The above examples also suggest that exterior insulation can further mitigate the condensation risk by warming the end of the duct.

The temperature profile of in-slab ducts has also been observed in the field using infrared thermography. The photo in Figure 1.6 clearly shows the outline of multiple in-slab ducts which appear brighter (hotter) based on the colour infrared image. Figure 1.7 also highlights that if ducts extend out into otherwise cold exterior elements such as balconies, the length of duct exposed to condensation risk is increased.

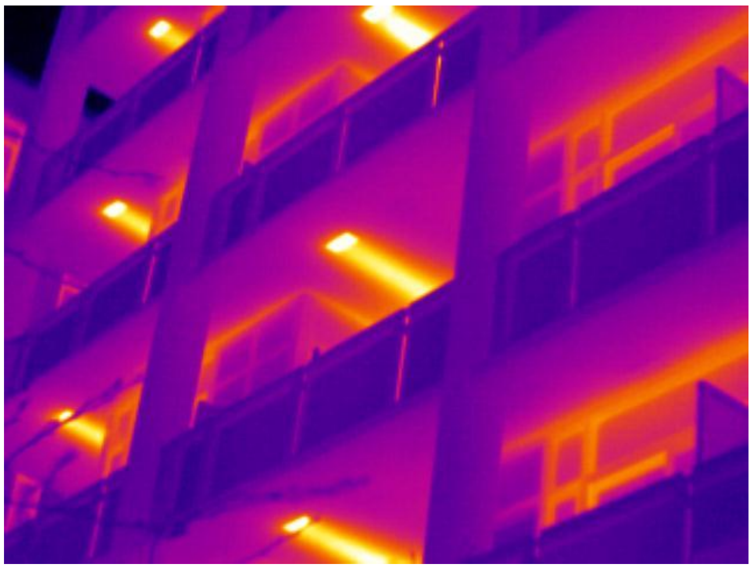


***Figure 1.7:*** *Exterior thermographic image showing the outline of several in-slab ducts exiting the underside of concrete balconies.*

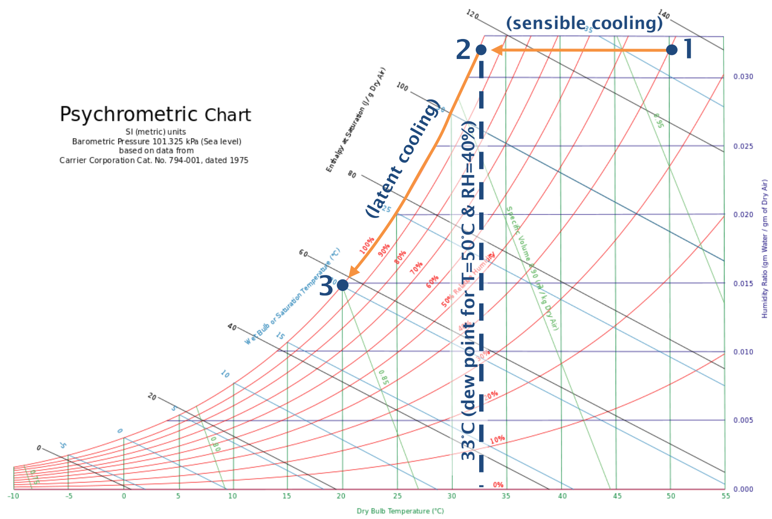
## *Psychrometrics and Condensation*

A comparison of dewpoint and in-slab duct temperatures suggests that condensation will regularly form within the ducts. This process can be illustrated using a psychrometric chart as shown in the example below.

***Example 3 – Psychrometric Chart and Condensation (Simplified)***

*Problem:*

How much water will condense (per minute) if air enters the duct at 50˚C and 40% RH (density of 1.04 kg/m³) and is cooled to 20˚C at the discharge outlet. The airflow rate is 50 L/s (100 cfm). Assume that the inlet and outlet air properties remain constant.




*Solution:*

Starting at 50˚C and 40% RH (Point 1) the air cools up to its dewpoint temperature of 33˚C (Point 2). After this point, additional cooling occurs through condensation, also known as latent cooling, and follows the 100% relative humidity line until it reaches 20 ˚C (Point 3). The change in moisture from Point 1 to Point 3 is:

$$0.032\,\frac{kg_{Water}}{kg_{Air}} - 0.015\,\frac{kg_{Water}}{kg_{Air}} = 0.017\,\frac{kg_{Water}}{kg_{Air}}$$

The amount of air being exhausted per minute is:

$$0.05\frac{m^3}{s} \cdot 1.04\frac{kg_{air}}{m^3} \cdot 60\frac{s}{min} = 3.1\frac{kg_{air}}{min}$$

Finally, the amount of water deposited in the duct would be:

$$3.1\,kg_{air} \cdot 0.017\,\frac{kg_{Water}}{kg_{Air}} = 0.053\frac{kg}{min}$$

*Answer:*

Assuming constant exhaust conditions, 53 g per min of water would be deposited in the duct, or 0.8 kg per 15 min, or 3.2 kg per hour.

This simplified example with fixed exhaust conditions shows how humid exhaust air can lead to meaningful moisture buildup within a duct.

In practice, exhaust conditions vary during operation and are a function of exterior weather conditions, airflow rates, and other factors. Decreasing the residency time of the humid air in the duct by minimizing the length of ductwork, increasing the air flow velocity, and minimizing the length of duct exposed to unconditioned or exterior portions of the slab (i.e., balconies, eyebrows, etc.) can help to reduce the condensation potential.

Relative to the number of investigated ducts, heavy water buildup is rare, but poor airflow rates coupled with repeated operation cycles can lead to significant amounts of water as shown in Figure 1.9.


***Figure 1.8:*** *Screen capture taken from a borescope video of an in-slab duct with severe moisture buildup. Note the standing water (> 1" depth) on the bottom right corner of the image (bottom of the duct).*

### *Other Moisture Sources*

In addition to condensation as a result of humid bathroom, kitchen, and dryer exhaust, moisture may also accumulate within a duct dur to air exfiltration and water ingress.

## Air Exfiltration

The previous sections primarily focused on how intentionally exhausted air from dryers can cause moisture-related issues within a duct. However, interior air can also leak through an in-slab duct unintentionally due to wind, stack, and mechanically induced pressure differences. To minimize air leakage, airflow dampers are typically provided. Since airflow dampers may not be permitted in all ducts, and vary in effectiveness, investigations of in-slab ducts should also consider air leakage as a potential source of moisture-related issues.

***Figure 1.9:*** *Bathroom exhaust fan unit. Air from the interior space can enter the exhaust duct due to the combination of wind, stack effect, and mechanical pressures, where it can then cool and condense.*

### Water Ingress

Moisture accumulation in a duct can also occur as a result of water ingress from the exterior. For example, rainwater may enter ducts through a combination of wind pressure, gravity, and surface tension. It is common practice to prevent water ingress at vent openings using protective hoods, grilles, overhangs, or other architectural details (e.g., balconies). Significant issues can arise when these details are insufficient or are removed (Figure 1.10).

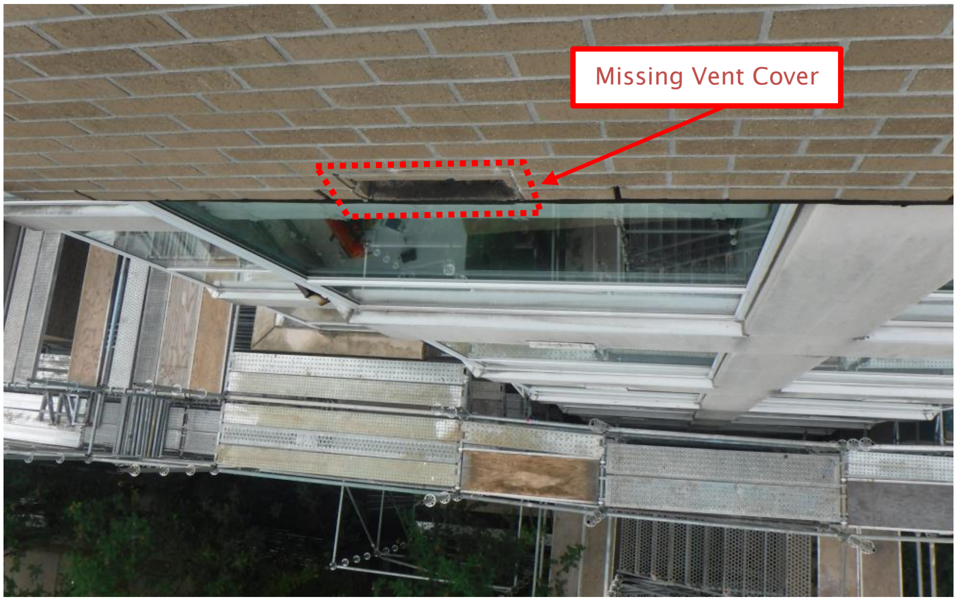



***Figure 1.10:*** *Photograph taken of a wall from above showing an exhaust vent opening. Note the vent cover has been removed and the duct is therefore exposed to rainwater.*

## *Other Contributing Factors*

In addition to moisture sources, there are several contributing factors which can aggravate the moisture problems.

→ Material Buildup: dirt, lint, and dust may collect at grills, dampers, and along the duct. This buildup decreases the total air flow through the duct, which in turn decreases the ability of the duct to dry during normal operation.

→ Stack Effect: the pressure difference induced by stack effect does not act uniformly across all openings in the building envelope. Instead, stack pressure varies with height, temperature, airtightness and distribution of air leakage openings. Practically, this means that the risk of condensation may vary between floors with suites on higher floors experiencing more natural exfiltration than those on lower floors during the heating season.

→ Wind Pressure: location specific factors such as the height and orientation of the suite or building shape will impact the wind forces exerted on the suite. Combined with stack and mechanical pressures, the balance of forces may lead to increased air leakage through openings in the suite such as ducts. Wind driven rain may also act to directly transport water into the duct from the exterior. In general, east facing orientations are the most susceptible to wind driven rain in Vancouver, Figure 1.11.

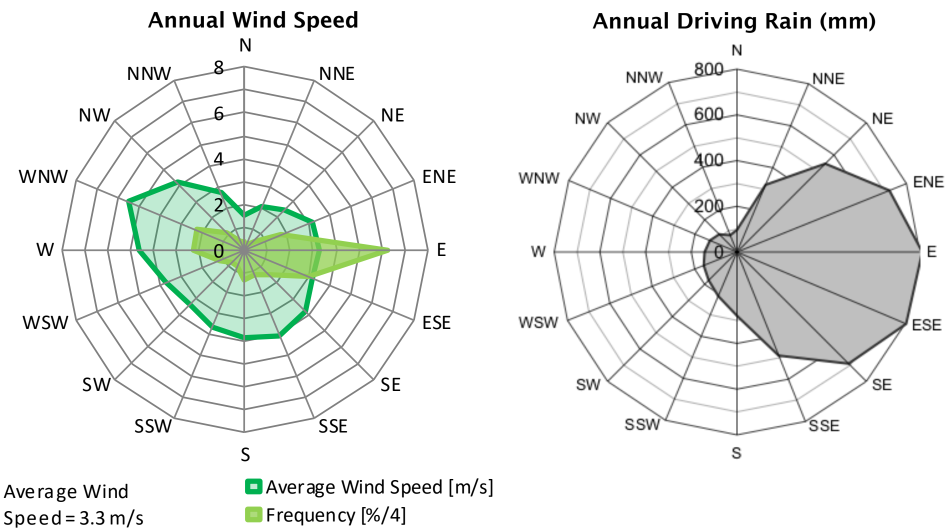



**Figure 1.11:** Wind rose for Vancouver International airport based on CWEC data

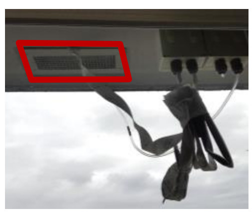
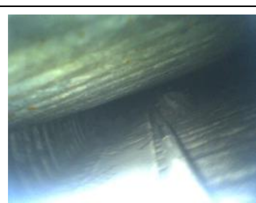
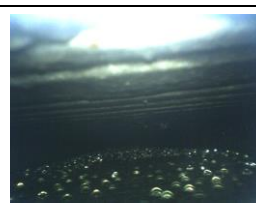
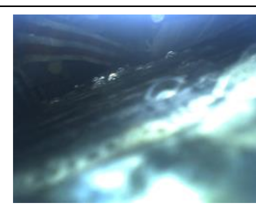
→ Cracks/Holes in Concrete: Accumulated water within a duct in not generally considered an issue until it leaks into the building and begins to damage interior finishes. For this to occur, there needs to be a path for water to flow through to the interior. This path typically consists of an unsealed or corroded gap in the ductwork and a crack in the concrete ceiling.

Reliably preventing cracks in concrete is difficult, but sealing between duct segments can assist in preventing leaks. This can supplement, but not replace the minimum requirement of adequate installed airflows.

# 2 Experimental Investigation

This section describes the method and results of three in-slab duct monitoring investigations. The three sites are labeled Site A, B, and C. The severity of moisture issues at each site varied from no observable moisture buildup to a steady drip of water exiting from the exhaust vent. Together, these three investigations provide insight into the conditions within the dryer exhaust ducts and the potential mechanisms of moisture buildup. Monitoring took place over multiple periods from March 2016 to March 2017. A more detailed presentation of the investigation results is provided in Appendix A enclosed with this report.

TABLE 2.1 SITE CHARACTERISTICS

| ID | Site A | Site B | Site C |
|---|---|---|---|
| **Constructed** | 2006 | 1995 | 2004 |
| **Height in Building** | 3rd Floor *(of 4)* | 2nd Floor *(of 12)* | 37th Floor *(of 37)* |
| **Suite Floor Area ($ft^2$)** | 1,000 | 1,550 | 2,520 |
| **No. of Bedrooms** | 2 | 3 | 2 + den |
| **Duct Location** | Under a Soffit  | Flush with the exterior balcony face  | Underside of the exterior balcony of suite above  |
| **Booster Fan (yes/no)** | yes | yes | yes |
| **Monitoring Period** | March to April 2016 | February to April 2016 | February to March 2017 |
| **Moisture Buildup** | None | Low; droplets observable within the duct, no damage to internal finishes | Severe; Continuous drip at exhaust vent during dryer operation |
| **Photo** |  |  |  |

## 2.1 Methodology

A customized equipment package was developed with SMT Research Ltd. that included the devices listed in Table 2.2. Duct air and surface temperature along with relative humidity were measured at 5' intervals. **Figure 2.1** presents a schematic of the experimental setup. The exact location within the duct was dependent on the investigation team's ability to insert the equipment into the duct.

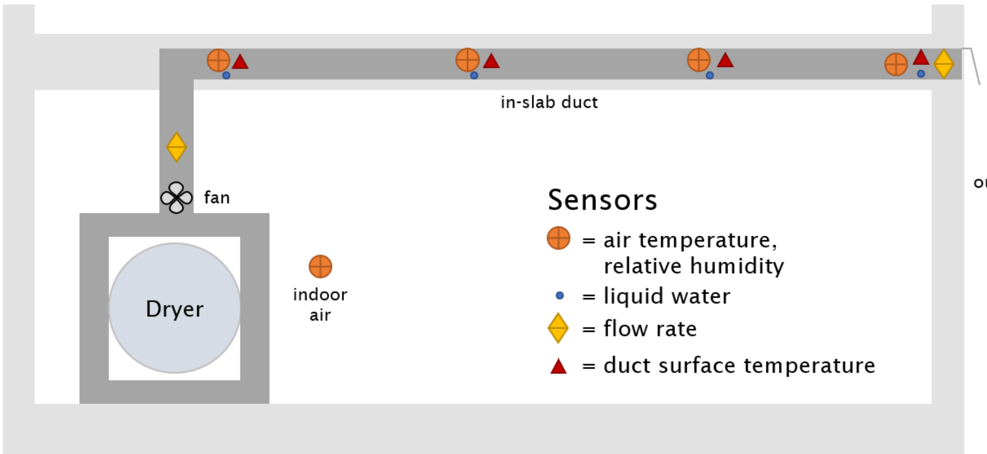



***Figure 2.1:** Schematic diagram of the experimental setup*

| TABLE 2.2 MONITORING EQUIPMENT CHARACTERISTICS | |
|---|---|
| **Parameter** | **Device** |
| Interior Air Temperature (˚C)<br>Exterior Air Temperature (˚C)<br>Duct Air & Surface Temperature (˚C) | MF52 Thermistor  |
| Interior Air RH (%)<br>Exterior Air RH (%)<br>Duct Air RH (%) | HTM2500  |
| Moisture Detection Sensor (on/off) | MDS  |
| Differential Air Pressure (Pa) | SDP1000-L025  |
| Data Logger | SMT-A2  |

## 2.2 Monitoring Results and Analysis

Monitoring occurred at sites with and without observable moisture buildup issues, which allowed for a comparison of in-slab duct conditions. Dew point temperatures were used to predict periods of condensation, which occur when the measured temperature of the duct drops below the dew point temperature of the air measured at that location.

### *Site A*

There was no observed moisture buildup at Site A, and in contrast to the other sites there were relatively few periods of predicted condensation. **Figure 2.2** is a graph showing temperature at 1' (0.3m) and 6' (1.8) from the duct outlet. Periods of condensation are shown based on the dew point temperature. When condensation was predicted, the duration was short and coincided with the first 15 minutes of dryer use. Also, condensation was only predicted at the end of the duct (1' or 0.3m from the exterior) and was not measured further within the duct.

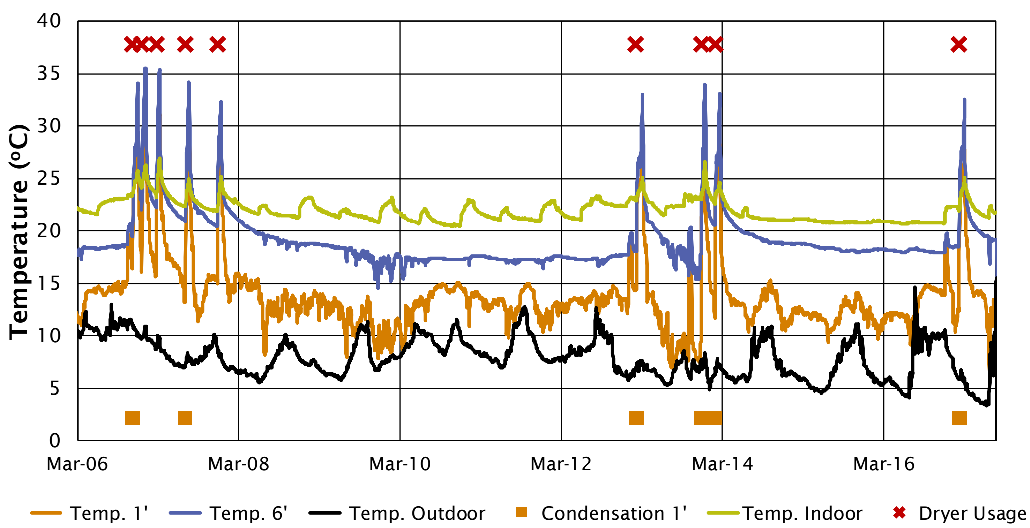



***Figure 2.2:*** *Site A – Graph showing temperature at 1' (0.3 m) and 6' (1.8 m) from the duct outlet. Periods of condensation are shown based on the dew point temperature.*

### *Site B*

Visual inspection of the duct at Site B revealed minor moisture buildup. Per **Figure 2.3**, condensation was predicted at both 5' (1.5 m) and 10' (3.0 m) from the exterior vent. Additionally, moisture buildup at the end of the duct (within the exposed concrete balcony) was observed during a period of inactivity, implying another source of moisture (e.g., air exfiltration) or evaporation of residual moisture and re-condensation further toward the exterior. The data suggests that cool duct temperatures due to the exposed slab edge may have contributed to the observed moisture.

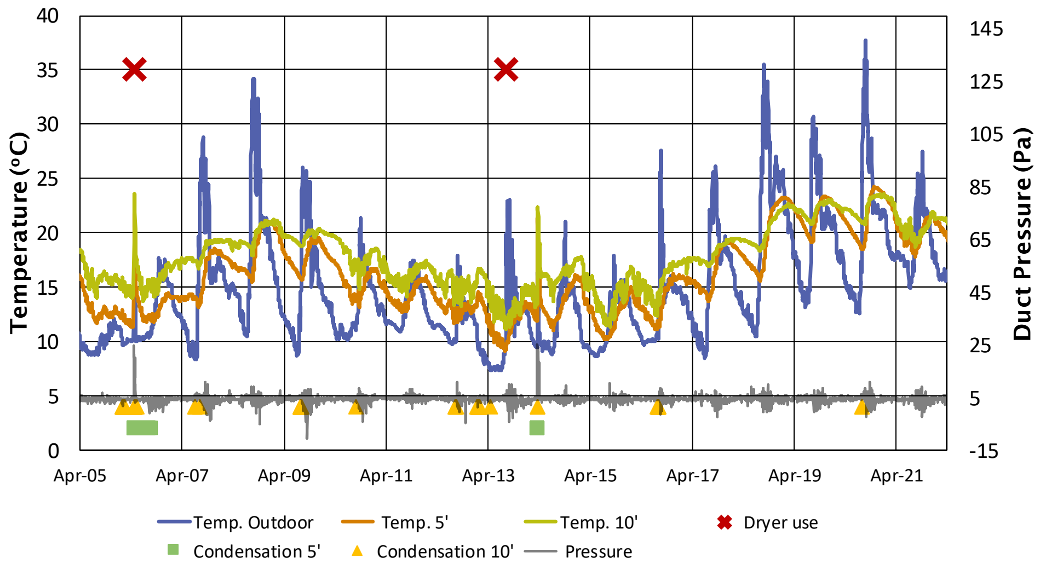



***Figure 2.3:*** *Site B – Graph showing air temperature and periods of predicted condensation within the duct as well as the outdoor temperature and duct pressure.*

## *Site C*

The observed moisture buildup at Site C was the most severe, with a steady stream of water exiting the vent cover onto the balcony when the dryer was in use. Per the results from **Figure 2.4**, condensation was predicted almost continuously throughout the entire monitored length of the duct. The indoor dew point temperature was consistently lower than the measured temperature of the duct, which suggests that the moisture buildup is related to activities such as laundry.

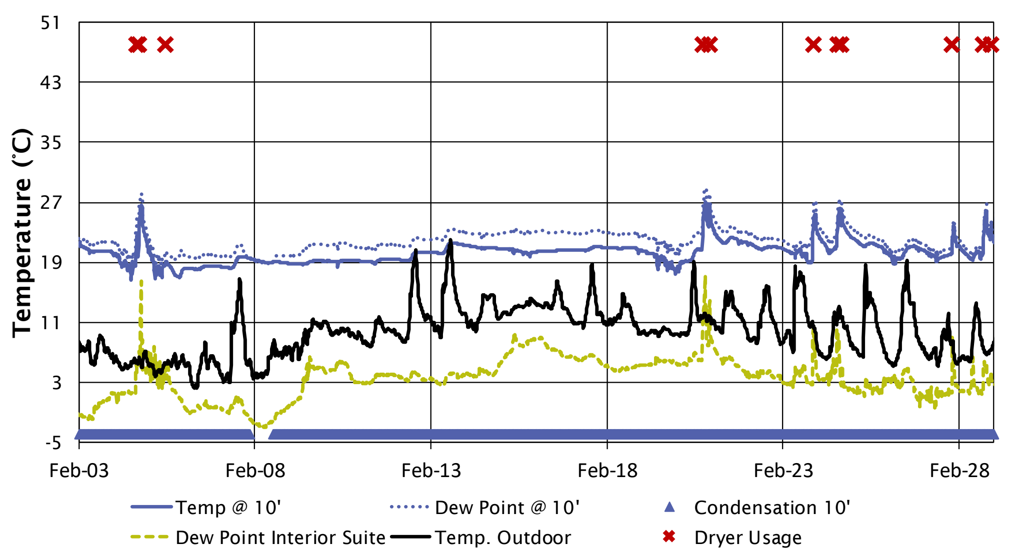



***Figure 2.4:*** *Site C – Graph showing temperature and dew point of the air 10' (3.0 m) from the exterior of the duct as well as the outdoor air temperature and indoor dew point temperature. Dryer usage and periods of predicted condensation are shown.*

## 2.3 Investigation Summary

The following trends were noted based on the results presented from the three monitored cases:

1. Frequent and long periods of condensation deep within the duct coincided with visual observations of moisture buildup and related issues
2. Brief periods of condensation at the beginning of a dryer cycle were not observed to be an issue
3. Interior air exfiltration or drying of residual moisture from within the duct can lead to moisture issues even when the exhaust system is not in use

**Figure 2.5** and **Figure 2.6** focus in on typical dryer cycles with and without moisture related issues. At the monitored location with no observable issues (Site A), dryer use coincided with both an increase in pressure and an increase in temperature at the dryer exhaust and within the duct. In each case, the wetting period was followed by a longer period of drying as the cycle continued. The green shaded area in **Figure 2.5** shows the drying period. This pattern of brief wetting followed by an extended period of drying is what would be anticipated from a dryer with no moisture issues.

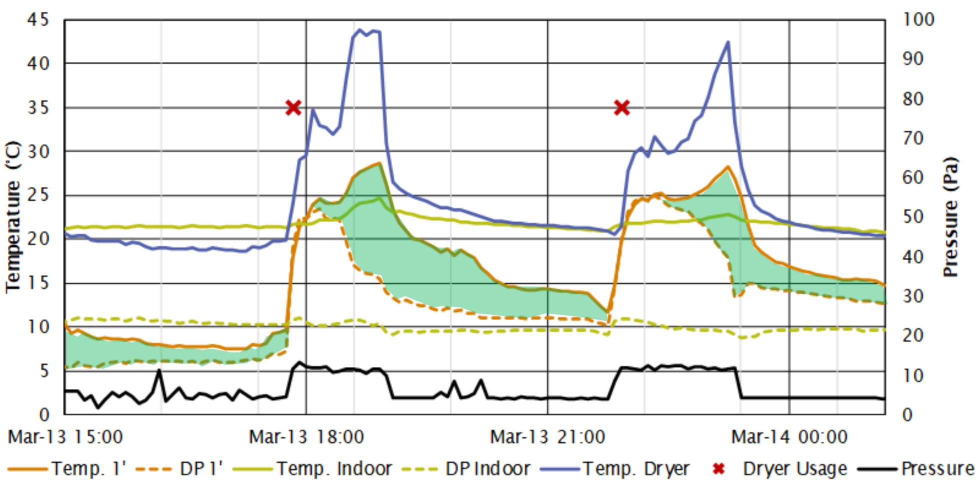



***Figure 2.5:** Site A – Graph air and dew point temperatures over the course of two dryer cycles. Green area designates when duct temperature is above dew point temperature.*

Site C, experienced the most severe moisture issues. Similar to the other sites, the temperature at the dryer exhaust increased during dryer operation. However, the temperature within the duct, and the pressure measured at the end of the duct did not significantly increase. This is suggestive of a flow restriction within the duct.

Also, note that 5' from the end of the duct condensation was measured before the first and after the second dryer cycle (see red shaded area in **Figure 2.6**). This finding is consistent with a flow restriction as the trapped moisture is allowed to continue accumulating even when the exhaust system is off.

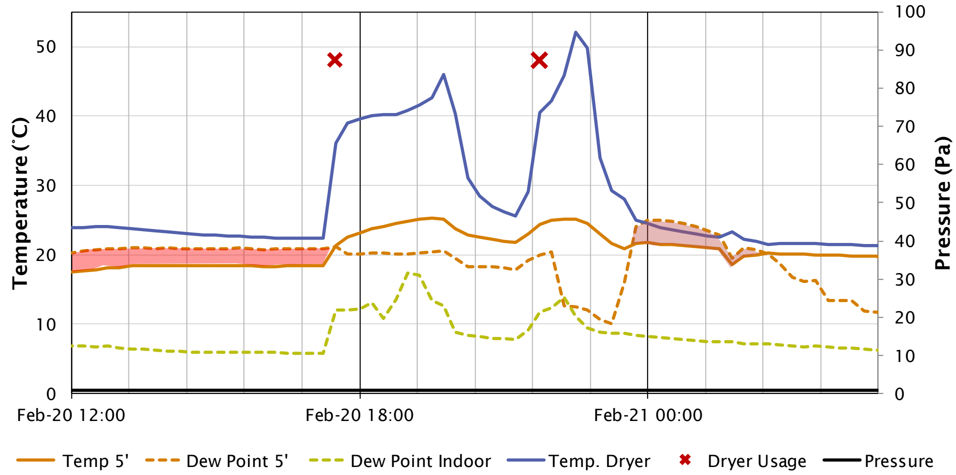



***Figure 2.6:*** *Site C – Graph air and dew point temperatures over the course of two dryer cycles. Red area designates when duct temperature is below dew point temperature.*

Additional figures from the monitoring study are included in the attached Appendix A.

# 3 Remedial Actions

Several investigations conducted by RDH Building Science Inc. have led to successful remediation efforts, including duct cleaning and repairing of collapsed ducts. It is important to note that each scenario is case specific and there has been no one size fits all solution. Nevertheless, this section identifies a range of possible actions to resolve moisture buildup issues within in-slab ducts. A preliminary investigation will help to identify which action or set of actions can be taken to remediate the site-specific issue.

An important decision for the owner will be whether remediation entails solving the root moisture problem (i.e., preventing moisture buildup) or avoiding visible damage. If the latter, mold growth and durability concerns may persist.

Appendix C includes these remedial actions as a checklist. Appendix B includes strategies for new construction.

## 3.1 Deflect

Deflecting water away from the exhaust vents is critical to prevent bulk water from entering the duct from the exterior.

### 3.1.1 Exhaust Vent Cover

Repair or replace the exhaust vent cover with a suitable cover detail including a hood or wind driven rain resistant louver along with sealant and membrane as appropriate. Unprotected vertical grilles that are flush with the vertical enclosure should generally be avoided.


***Figure 3.1:*** *Photo of the exterior of a building with the exhaust vent cover removed (red), exposing the duct to rain.*

## 3.2 Drain

Allow water that has collected in the duct to drain from the duct to the exterior.

### 3.2.1 Sloping

This measure, if not implemented during the initial construction, is costly and difficult to achieve due to rebar. However, in cases where water is building up at the exterior end of the duct, it may be feasible to chip out the concrete and repair to ensure a positive slope towards the exterior. Given limited slab heights, this is only practicable along the last 1'-4' of duct. The cost and invasiveness of this approach means other remedial actions should be attempted first.

### 3.2.2 Waterproofing

Chip out the concrete and waterproofing between duct segments. Alternatively, waterproof the ductwork from the inside. This approach does not remove the root moisture buildup issue, but may prevent water from leaking into the interior where it can cause visible damage. Waterproofing a duct after construction is disruptive, and costly, and other remedial actions should be attempted first.

***Figure 3.2:*** *Photo of a duct which has been remediated by chiping out the concrete and sealing the duct with liquid-applied waterproofing. Extensive work to both the suite above and below was required in order to carry out the repair.*

## 3.3 Dry

Remove moisture buildup before damage can occur by increasing the ventilation runtime and/or flow rate. It is important that the ventilation air is dry (i.e., dew point temperature below the temperature in the duct) or else the problem may worsen.

### 3.3.1 Booster Fans

Install an appropriately sized booster fan to increase the airflow rate during dryer operation.

### 3.3.2 Shut-off Delay

Install a shut-off delay, often included with booster fans, to increase the runtime for a timed or humidity-controlled period after dryer operation. Typical post-cycle runtimes are between 10 to 30 minutes.

## 3.4 Prevent

Prevent factors like air leakage and lint buildup from contributing to the moisture issues.

### 3.4.1 Backflow Dampers

Install a pressure activated (i.e., spring loaded) damper to prevent unintended air leakage when the exhaust is not operating. However, note that by reducing airflow, a damper may also prevent drying. Furthermore, it is important to recognize that fine wire mesh screens and dampers on dryer vents may pose a fire hazard if they clog or fail to open during dryer operation. Dampers should fail in the open position and local mechanical and fire codes should be consulted when dampers are specified.

### 3.4.2 Lint Screens

Install a secondary lint trap, as recommended by the dryer or booster fan manufacturer, to prevent lint buildup in the fan or duct. Note that lint buildup can pose a fire safety concern and regular maintenance of all lint traps is required. A typical sign of poor lint trap maintenance is additional time required to dry clothing.

### 3.4.3 Avoid Unheated Duct Lengths

Cold ducts increase the potential for condensation to occur. There have been cases where rerouted (shorter) ductwork has successfully remediated long duct runs along unheated soffits.

### 3.4.4 Condensing Dryers

Replace the existing dryer with a ductless condensing dryer. A condensing dryer operates using a heat exchanger to condense the moisture in the laundry and does not require exhaust ventilation, completely eliminating the need for in-slab ducts for clothes dryers. This solution is becoming more common, particularly in new construction, where the increased cost of the dryer can be offset against not needing ductwork and associated envelope penetration detailing. As a retrofit option this option has several drawbacks including that fact the heat generated from condensing moisture will warm up the interior space and either a condensate drain will need to be installed or a tank emptied manually.

### 3.4.5 Insulated Ductwork

Insulate around the exterior exposed sections of the ductwork to increase its temperature and to reduce the risk of condensation. This option is not generally feasible for interior insulated wall assemblies. Note that insulation of ductwork on the interior may decrease duct temperature and increase condensation risk.

## 3.5 Maintain and Repair

### 3.5.1 Duct Cleaning

Lint buildup is common with dryer exhaust vents and regular cleaning was recommended by all the reviewed manufacturers. Hire a duct cleaning service to inspect and clean the duct system. Some cleaning services provide airflow testing before and after cleaning which can help identify additional issues with the system (leaks, blocks, etc.). There is a large body of anecdotal evidence that supports regular duct cleaning as a successful remediation approach. Along with fixing obvious leaks from the exterior, this action is often considered to be a first step when moisture issues are observed.

***Figure 3.3:*** *Photo of an exhaust vent cover with extensive lint buildup. Grilles and exhaust ducts should be cleaned regularly.*

### 3.5.2 Chip and Replace

Chip out the concrete and replace damaged (i.e., collapsed) portions the duct. This remediation strategy has been successful when blockages are located at the extreme end of the slab and only minor lengths of duct require repair. Generally, a full replacement of the duct in this manner is economically unfeasible.

***Figure 3.4:*** *Photo of a chip and replace repair. Work consited of mapping out the concrete reinforcing, chiping away the concrete in the suite above and below the duct, sealing the duct with liquid-applied sealant, replacing the concrete, and reparing the interior finishes.*

### 3.5.3 New Ductwork

Rerouting the dryer exhaust duct may be necessary if the existing duct has deteriorated to the point of being unusable (collapsed, heavy corrosion, etc.,). In an existing building, the new ductwork would likely be placed in a new bulkhead, which would partially reduce the ceiling height along its length. If new ductwork is required, a condensing dryer should be considered as an alternative.

# 4 Conclusions

Moisture buildup within in-slab ducts is a widespread issue that affects a large number of existing buildings and has the potential to continue to adversely affect new construction. Dryer, kitchen, and bathroom exhaust ducts within exposed concrete slabs create an ideal scenario for moisture buildup due to condensation of intentional (exhaust) and unintentional (exfiltration) movement of air. Analysis shows that the risk of condensation through both mechanisms persists through-out the year, especially at the ends of the duct. Water ingress from the exterior can also be an issue if exhaust louvers or vents are not properly designed and installed to protect against rainwater.

In-situ monitoring of in-slab ducts showed that when the dryer cycle consists of a brief period of wetting followed by an extended period of drying, moisture issues can be avoided. However, when flow rates are significantly reduced due to poor maintenance, inadequate equipment, poor duct layouts, or blockages, then the result can be sustained wetting periods and subsequent interior water damage.

Best practice is to ensure that exhaust duct runs are designed to be straight and short, with adequate protection at the exterior opening to prevent bulk water ingress. During operation, regular maintenance is required to ensure that ducts remain unobstructed.

Note that condensation will likely occur throughout the year even in well designed and installed in-slab ducts. In-slab ducts rely on a wetting/dying balance that prevents water accumulation. If water accumulates and is allowed to reach a crack in the concrete, then leaks will occur triggering a need for remediation. Based on the challenges and potential costs with remediating moisture issues, new construction projects should consider locating dryer ducts within dropped ceilings or bulkheads where they can more easily be repaired or should specify condensing dryers.

We trust that this report and monitoring study has helped to the explain the inherent challenges with in-slab ducts that can lead to moisture related issues, as well as provide a series of potential mitigation strategies.

Yours truly,

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# Appendix A

## Monitoring Study

# A. In-Slab Duct Investigations

This appendix includes additional monitoring results and photos from the three sites.

## A.1 Site A

### Description

Two-bedroom apartment with no observable moisture issues. Building was constructed in 2006. The dryer exhaust vents under a soffit.

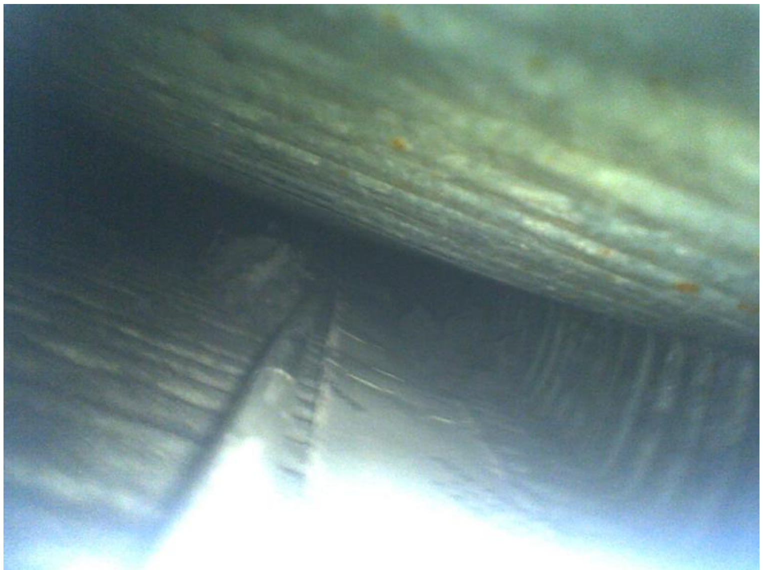

***Figure A.1:*** *Photo of the dryer exhaust duct at site A taken during sensor installation.*

***Figure A.2:*** *Photo of the sensor intallation at Site A. Dryer exhaust vents under a soffit.*

## Results

The average values of the measured parameters for site A are summarized in Table A.1. Graphs of air and dew point temperatures during the monitoring period and during a typical dryer use cycle are shown in **Figure A.3** and **Figure A.4**.

**TABLE A.1 SUMMARY STATISTICS FOR SITE A (MAR-APR 2016)**

| Parameter | Average | Min | Max |
|---|---|---|---|
| Interior Air Temperature (°C) | 20.7 | 18.6 | 25.0 |
| Interior RH (%) | 47 | 40 | 78 |
| Interior Dew Point Temperature (°C) | 8.7 | 4.7 | 20.8 |
| Exterior Air Temperature (°C) | 10.9 | 3.4 | 28.5 |
| Exterior RH (%) | 78 | 31 | >99 |
| Duct Air Temperature 1' from exterior (°C) | 16.4 | 6.0 | 31.2 |
| Duct RH 1' from exterior (%) | 74 | 38 | >99 |
| Duct Air Temperature 6' from exterior (°C) | 20.2 | 35.5 | 14.5 |
| Duct RH 6' from exterior (%) | 58 | 32 | 99 |
| Differential Air Pressure (Pa) | 4.6 | -0.9 | 16.9 |

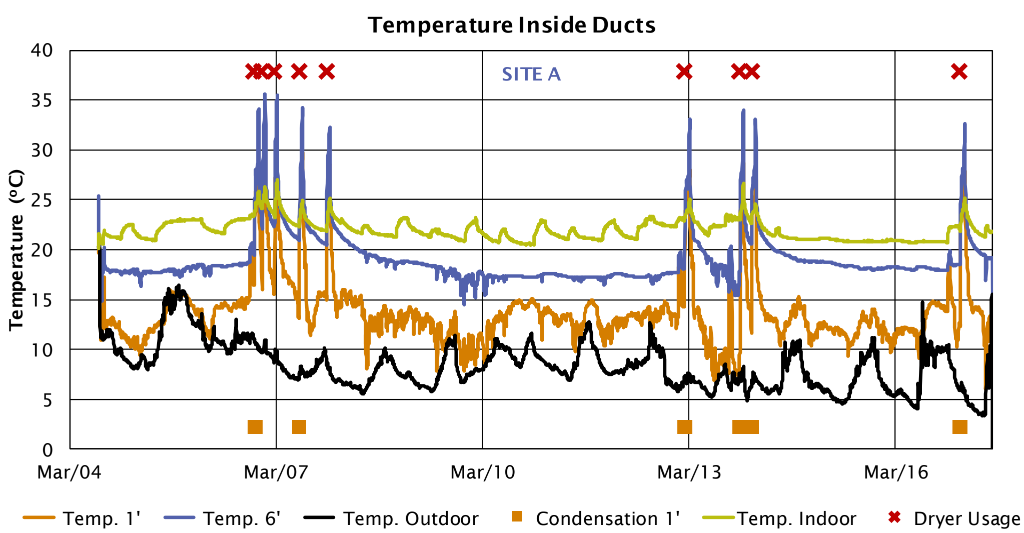


***Figure A.3:*** *Graph showing air temperature and periods of predicted condensation 1' (0.3 m) and 6' (1.8 m) from the exterior of the duct as well as the outdoor air temperature and duct pressure. Dryer usage, and periods of predicted condensation are also shown.*

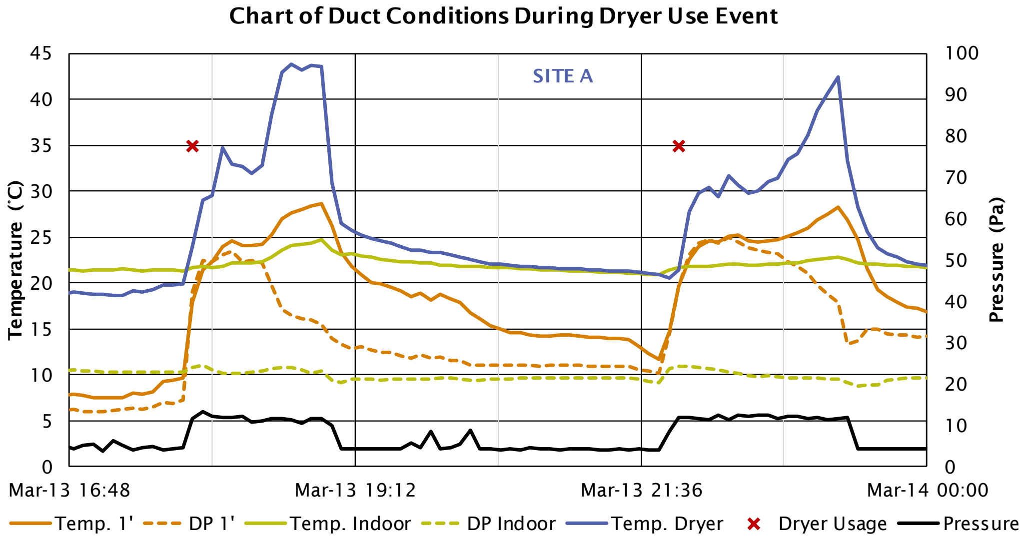


***Figure A.4:*** *Graph showing air and dew point temperatures during a typical dryer use cycle for Site A, which had no observable moisture build-up. The dew point temperature rises during the initial moments of the dryer use cycle and gradually decreases as the cycle continues.*

### Discussion

At Site A, condensation was predicted to occur 1' (305 mm) from the exterior of the duct on 9 separate occasions over a period of 37 days. Each occasion was associated with a dryer use event. Condensation periods typically lasted 5-30 minutes, averaging 15 minutes. No condensation events were predicted 6' (1,829 mm) from the exterior of the duct. This is likely due to the duct being warmer at this location.

While no condensation was predicted to occur without dryer use, it is worth noting that the monitoring period did not coincide with the coldest part of the year, when the likelihood of condensation would be higher. The average exterior temperature during this period was above the interior dew point temperature and therefore condensation without the dryer use would generally be unexpected. While true for the bulk of the monitoring period, there were several periods when the temperature in the duct 1' from the exterior dropped below the interior dew point temperature. Since the moisture detection sensors were unavailable, it was not possible to directly detect condensation or water infiltration at this site.

While the predicted condensation periods averaged 15 minutes, the average dryer operation period was 95 minutes, more than six times as long. RH reached a minimum when the exhaust fan turned off and then steadily approached the interior humidity levels, which suggests that in this case the standard operation of the dryer is sufficient to dry out condensation which occurs at the beginning of the dryer cycle.

During dryer operation the differential air pressure (duct vs. exterior) increased on the order of 10 Pa compared to the differential air pressure when the dryer was off. The sign of the differential air pressure indicates that the direction of air flow in the duct would have been from the interior to the exterior during the entire monitoring period. **Figure A.5** reveals periods of predicted condensation. There are two different condensation conditions shown. The first is predicted condensation based on the measured temperature and RH in the ducts, which is a prediction of condensation related to dryer operation. The second condensation prediction is based on the temperature in the ducts versus the interior dewpoint temperature and is intended to reflect the potential for condensation due to air exfiltration. Based on the measured data, there is more time when condensation could occur due to air exfiltration than would occur due to dryer use, during the monitoring period. These observations suggest that air exfiltration could result in moisture issues separate from dryer use.

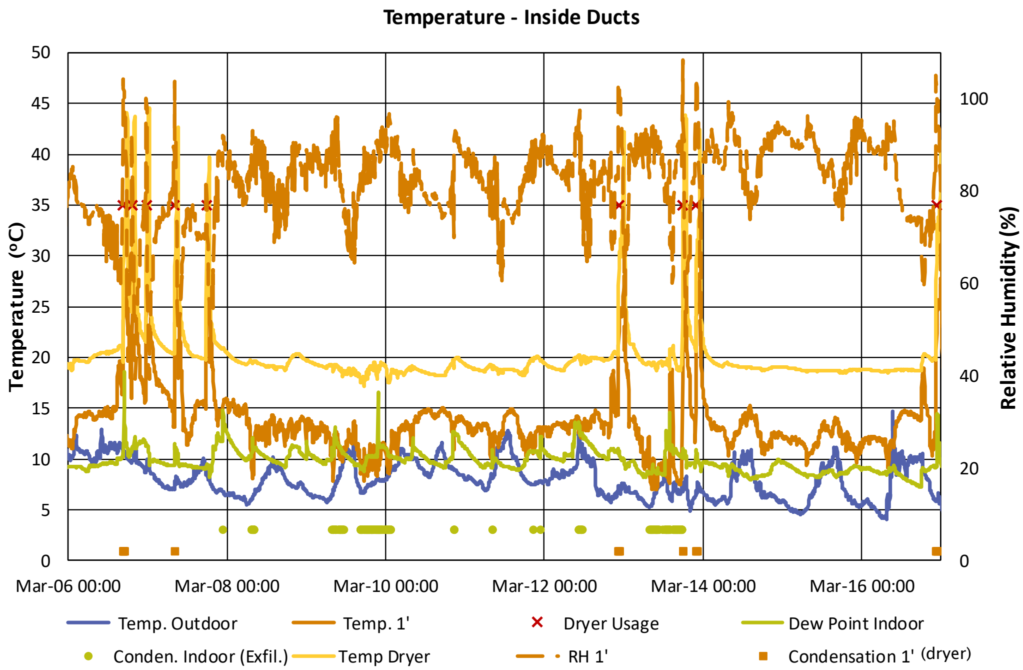


***Figure A.5:*** *Graph showing air and dew point temperatures. Dryer usage and condensation periods are also shown.*

## A.2 Site B

### Description

Three-bedroom apartment with minor moisture build-up within the duct (droplets). Building was constructed in 1995. The dryer exhaust vents at the end of an exposed concrete balcony.

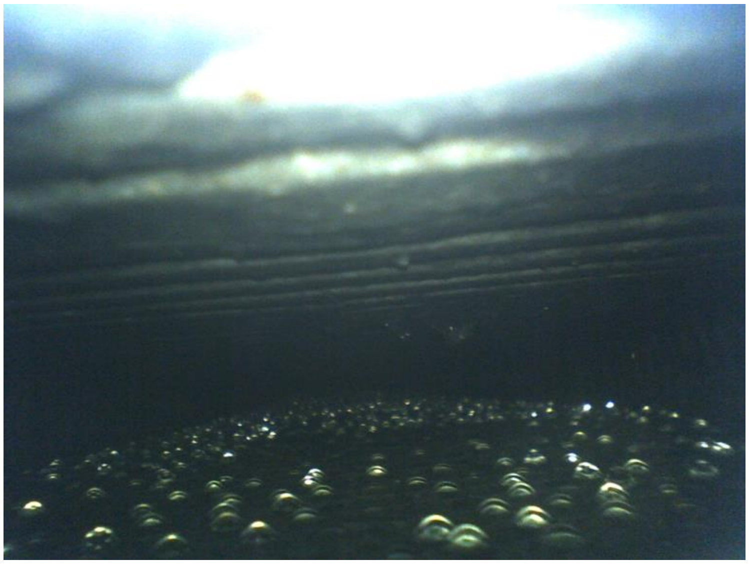

***Figure A.6:*** *Photo of moisture build-up at Site B, observed during sensor intallation.*

***Figure A.7:*** *Photo of the sensor intallation at Site B. Dryer exhaust vents at the end of the exposed concrete balcony of the unit above.*

## Results

The average values of the measured parameters for Site B are summarized in Table A.2. Graphs of air and dew point temperatures during the monitoring period and during a typical dryer use cycle are shown in **Figure A.8** and **Figure A.9** respectively.

TABLE A.2 SUMMARY STATISTICS FOR SITE B (FEB-APR 2016)

| Parameter | Average | Min | Max |
|---|---|---|---|
| Interior Air Temperature (°C) | 22.1 | 21.4 | 27.0 |
| Interior RH (%) | 39.5 | 25.4 | 77.6 |
| Interior Dew Point Temperature (°C) | 6.4 | 2.7 | 10.5 |
| Exterior Air Temperature (°C) | 11.9 | 2.4 | 31.7[1] |
| Exterior RH (%) | 80.8 | 27.5 | >99 |
| Duct Air Temperature 5' from exterior (°C) | 13.5 | 6.1 | 24.5 |
| Duct RH 5' from exterior (%) | 77.4 | 39.4 | >99 |
| Duct Air Temperature 10' from exterior (°C) | 16.8 | 9.2 | 26.3 |
| Duct RH 10' from exterior (%) | 64.3 | 33.3 | >99 |
| Differential Air Pressure (Pa) | 5.0 | -66.8 | 99.7 |

[1] *Measured temperature affected by solar radiation*

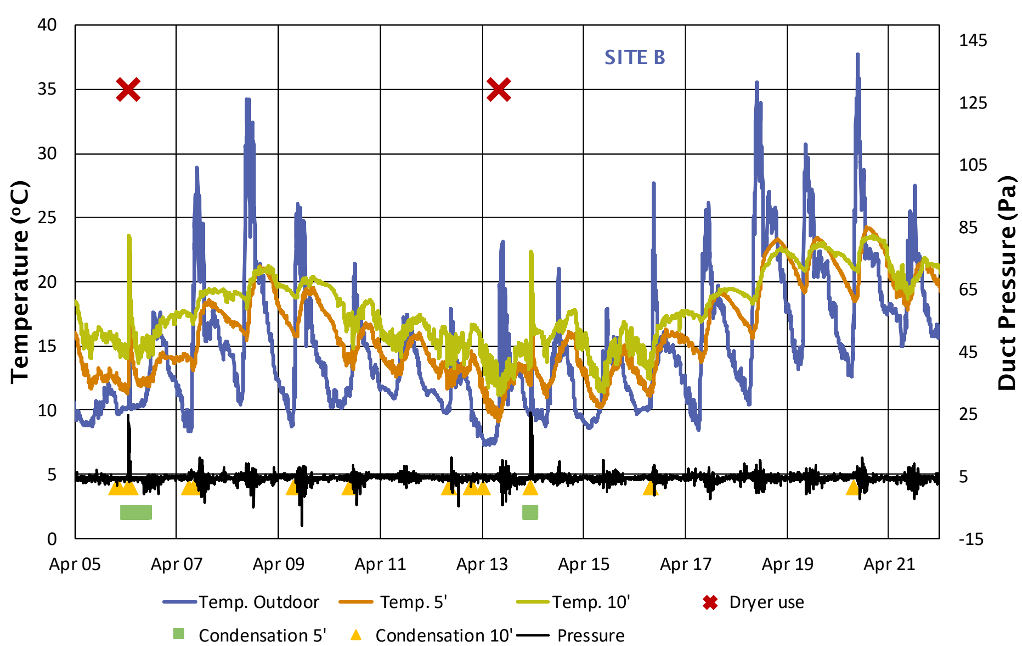


***Figure A.8:*** *Graph showing air temperature and periods of predicted condensation 5' (1.5 m) and 10' (3 m) from the exterior of the duct as well as the outdoor air temperature and duct pressure. Dryer usage, and periods of predicted condensation are also shown.*

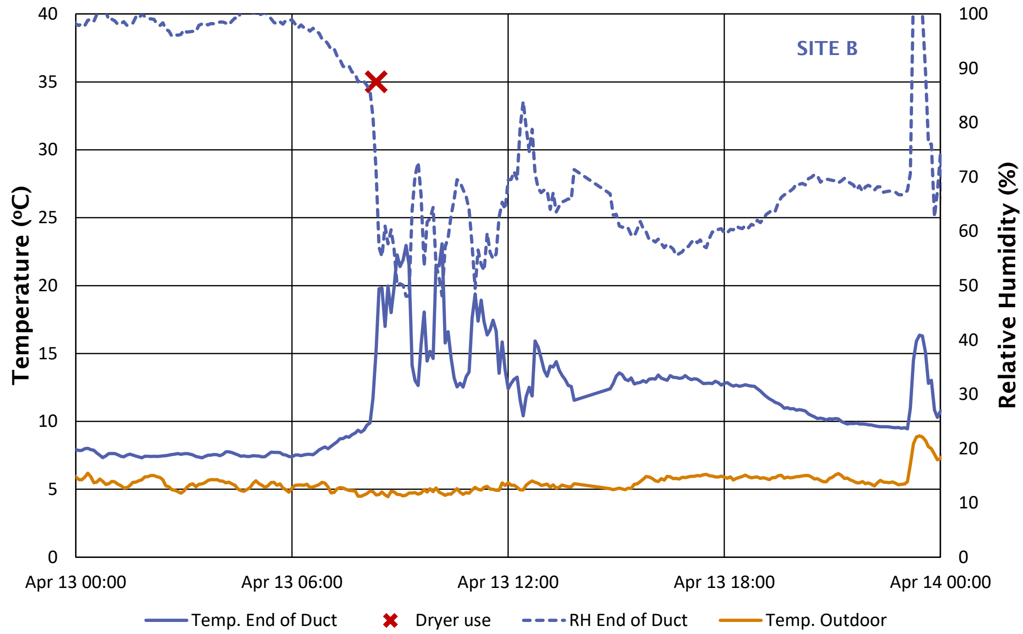


***Figure A.9:** Graph showing air temperature and RH at the end of the dryer exhaust duct during a typical dryer use cycle for Site B, which had minor observable moisture build-up.*

## Discussion

At location B, condensation was predicted to occur 5' (1.5 m) and 10' (3 m) from the exterior of the duct. Condensation at the end of the duct coincided with dryer use events, while condensation further within the duct was more sporadic. Condensation periods typically lasted greater than 60 minutes, but did not last longer than a day.

The average dryer operation period was 35 minutes, based on the in-slab duct pressure readings. Compared to Site A, where the typical dryer cycle length well exceeded the high moisture period in the duct, the length of the drying cycle at Site B was too short and likely contributed to the observed moisture build-up.

The pressure difference between the end of the duct and the exterior varied considerably, from -66 Pa to 100 Pa. The average pressure difference was 5 Pa (exfiltration), similar to Site A. After more than 2 weeks of inactivity, moisture droplets were observed within the duct. These observations support the conclusion that dryer use may not be the only source of moisture in the duct.

# A.3 Site C

## Description

Large two-bedroom penthouse suite with significant moisture build-up issues. The building was constructed in 2004. The dryer exhaust vents under an exposed concrete balcony.

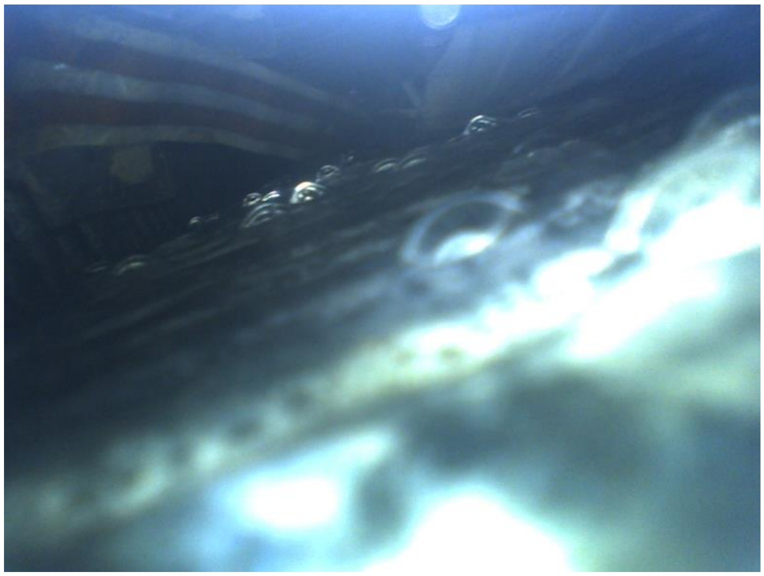

***Figure A.10:*** *Photo of moisture build-up at Site C, observed during sensor takedown.*

***Figure A.11:*** *Photo of the sensor intallation at Site C. Dryer exhaust vents under the exposed concrete balcony of the unit above.*

## Results

The average values of the measured parameters for site C are summarized in Table A.3. Graphs of air and dew point temperatures during the monitoring period and during a typical dryer use cycle are shown in **Figure A.12** and **Figure A.13** respectively.

TABLE A.3 SUMMARY STATISTICS FOR SITE C (FEB-MAR 2017)

| Parameter | Average | Min | Max |
|---|---|---|---|
| Interior Air Temperature (°C) | 22.1 | 19.4 | 38.2[1] |
| Interior RH (%) | 37.6 | 6.9 | > 99 |
| Interior Dew Point Temperature (°C) | 3.4 | -5.3 | 17.3 |
| Exterior Air Temperature (°C) | 10.0 | 2.2 | 22.1 |
| Exterior RH (%) | 79.0 | 27.6 | >99 |
| Duct Air Temperature 5' from exterior (°C) | 17.2 | 6.5 | 27.3 |
| Duct RH 5' from exterior (%) | 99 | 34.8 | >99 |
| Duct Air Temperature 10' from exterior (°C) | 20.3 | 10.7 | 29.8 |
| Duct RH 10' from exterior (%) | >99 | 30.5 | >99 |
| Duct Air Temperature 15' from exterior (°C) | 21.4 | 14.3 | 32.8 |
| Duct RH 15' from exterior (%) | >99 | 28.4 | >99 |
| Differential Air Pressure (Pa) | 0.8 | -5.6 | 3.0 |

*[1] Measured temperature affected by dryer temperature, temperature probe located on top of the unit inside a dryer closet.*

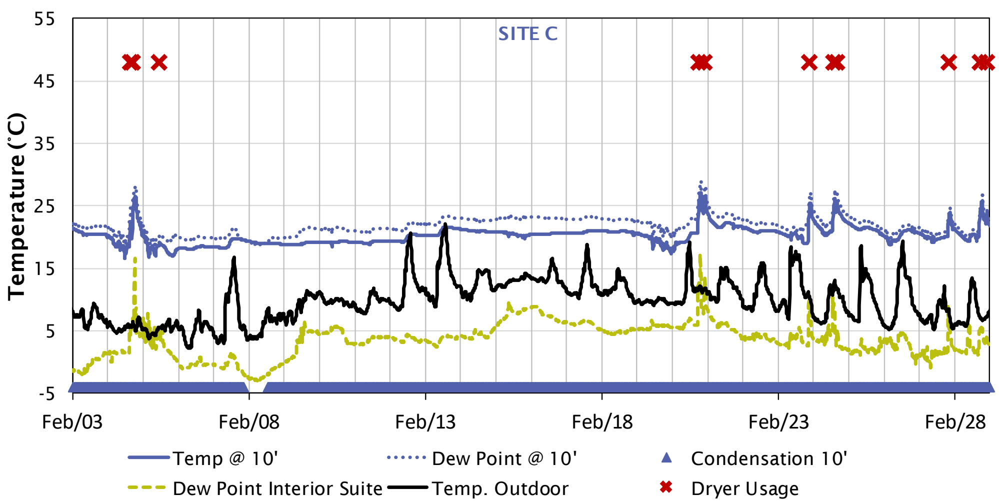


***Figure A.12:** Graph showing temperature and periods of predicted condensation 10' (3 m) from the exterior of the duct. Dryer usage events are also shown.*

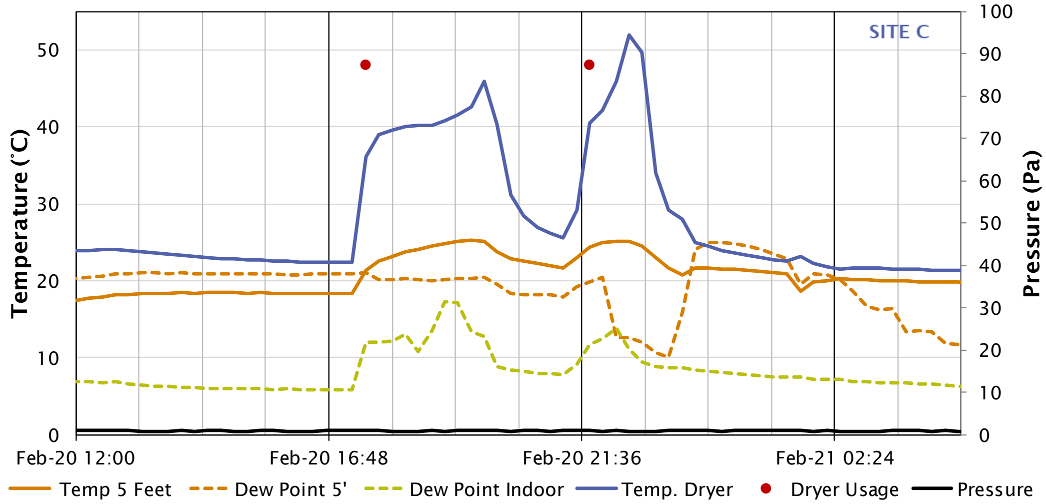


***Figure A.13:*** *Graph showing air temperature and RH at the end of the dryer exhaust duct during a typical dryer use cycle for Site C, which had significant moisture issues.*

## Discussion

At Site C, condensation was predicted to occur at all monitoring positions within the duct: 5' (1.5 m), 10' (3 m), and 15' (4.6 m) from the exterior. Significantly, condensation was predicted throughout the duct for almost the entire monitoring period. Unlike Sites A and B, dryer use was seen to temporarily improve the moisture conditions within the duct, notably when the dryer was operated consecutively with the same load and succeeded in raising the interior temperature of the duct.

The pressure differential measured between the end of the dryer duct and the exterior did not vary significantly during periods of dryer operation, which indicates a low exhaust flow rate. The average pressure difference was <1 Pa (exfiltration), which suggests very little air movement within the duct.

Interior humidity levels were kept low throughout the monitoring period. The most likely source of moisture was hot humid air leaving the dryer as opposed to water ingress from the outside or exfiltration of interior air. The high level of moisture accumulation is likely due to insufficient exhaust airflow rates.

# Appendix B

## Strategies for New Construction

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# B. Design Strategies for New Construction

Avoiding in-slab ducts and using condensing or heat pump dryers is the only solution which can completely avoid the risks associated with their use. However, the following are design strategies for new construction projects.

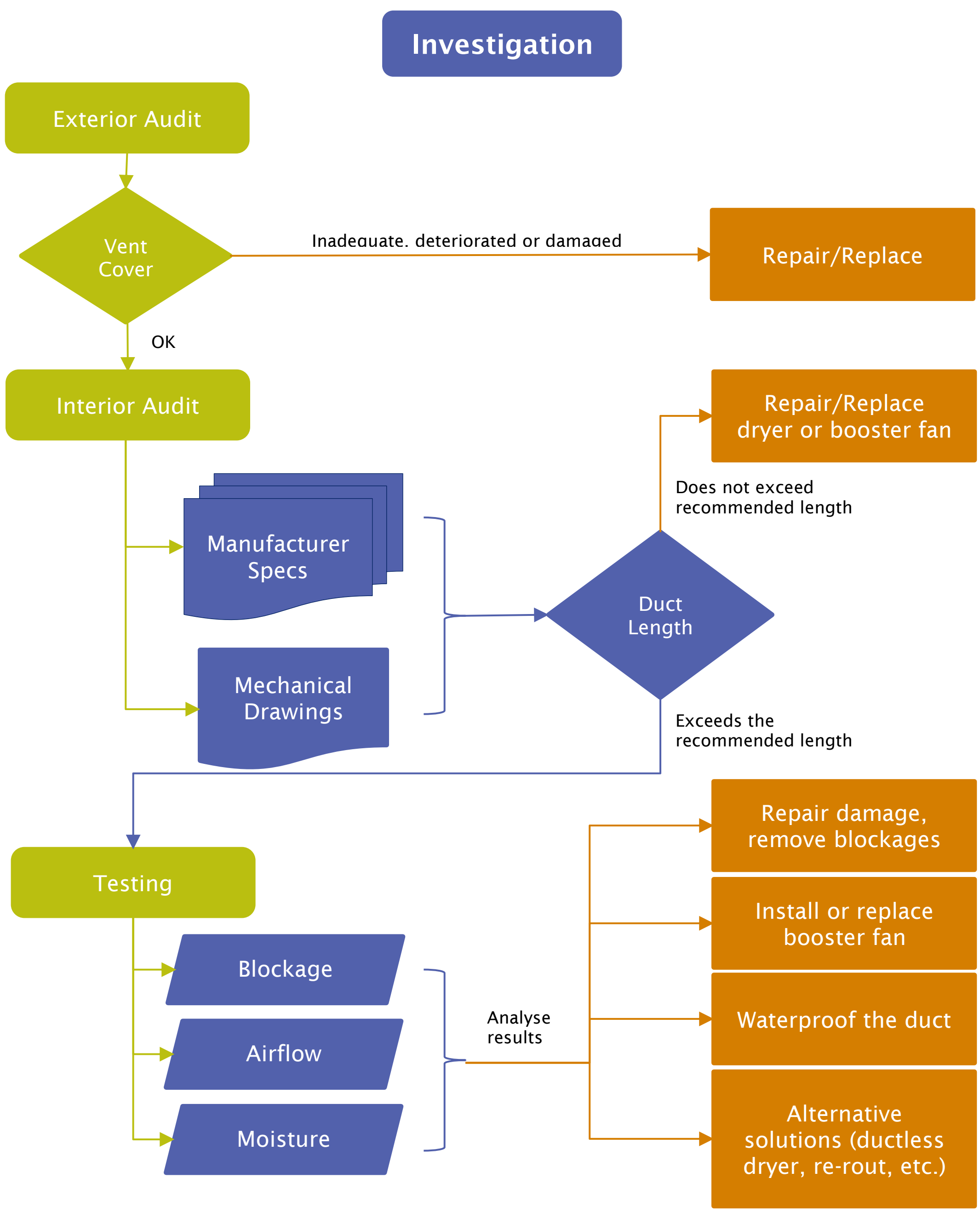
| RECOMMENDATIONS FOR NEW CONSTRUCTION | |
|---|---|
| 1 | Avoid in-slab ducts, and use a **ductless** (condensing or heat pump) dryer |
| 2 | **Slope** to the exterior wherever possible, especially for the last 1'-2'. e.g., use a prefabricated boot on sloped supports at the exhaust outlet |
| 3 | **Minimize** the effective **length** of duct by avoiding unnecessary bends and considering the impact of the floor layout on the exhaust ductwork |
| 4 | **Avoid unheated** lengths of duct (e.g., avoid extended runs along soffits or through deep balconies) |
| 5 | **Waterproof** joints in the duct prior to pouring concrete |
| 6 | **Minimize** the exhaust vent **exposure** (e.g., venting under an overhang instead of exhausting flush with the vertical enclosure) |
| 7 | Install an **adequate** exterior vent **cover** detail based on the anticipated level of rainwater exposure |
| 8 | Follow the **manufacturer's** installation **guidelines** in terms of maximum duct length, minimum airflow rate, booster fan, etc. |
| 9 | **Measure, validate** and **correct** the performance of exhaust fans during building commissioning |
| 10 | Inform owners of the need to perform **regular maintenance**. Maintenance should include ensuring grille covers are unobstructed and duct cleaning |

# Appendix C

## Remediation Checklist

# C. Remediation Checklist

If an in-slab duct moisture issue is suspected, the following procedure can aid the investigator in determining a recommended set of remedial actions.




The steps identified in the flowchart above chart are described in more detail below.

## C.1 Exterior visual audit

Walk around the exterior of the building and identify the exhaust vent locations. Look for blocked vents and assess the adequacy of vent covers based on the level of exposure. If accessible, examine waterproofing (sealants etc.,) of the vent covers. If the adequacy of the vent cover is uncertain, spray wand testing may help diagnose poor performance.

TABLE C.1: EXTERIOR WALK-AROUND AUDIT

| Observation | Remedial Actions |
|---|---|
| Blocked vent cover | Remove and clean the vent cover. Ensure the vent cover meets local code requirements for dryer exhaust vents. |
| Missing or unprotected vent covers | Replace the existing vent cover with a vent cover detail appropriate for the level of anticipated exposure |
| Staining around exhaust vent | Depending on the pattern of the staining, this observation may indicate an elevated level of moisture buildup and a need for a more detailed investigation of the ducts. |
| Damaged or discontinuous seal around vent opening | Repair or replace sealant to restore water tightness around the opening. |

## C.2 Interior visual audit

Record the make and model of all associated equipment (exhaust fans, dryer, booster fan etc.,). Obtain the mechanical as-built drawings and verify that the effective length of the duct length meets the manufacturer's installation instructions. If the mechanical as-built drawings are not available, use the straight-line distance from the dryer to the exhaust vent and assume an inlet boot, a 90˚ bend and an exhaust grille. Note, once an inlet boot, effective length 7.9 m (26') and exhaust grille 2 m to 4 m (7' to 13') are added to the duct length, the maximum duct length may be exceeded. For this reason, the specific manufacturer's equipment specifications should be obtained.

Check the flexible duct connecting the dryer to the inlet boot for kinks or excessive twists and bends as these will introduce an avoidable pressure drop. Check for visual damage of the interior finishes and compare the location of damage to the location of the ductwork.

TABLE C.2: INTERIOR WALK-AROUND AUDIT

| Observation | Recommended Action |
|---|---|
| Duct length exceeds 8 m (25 ft) or the manufacturer's recommended duct length | Measure the airflow and install a booster fan as appropriate. It may also be sensible to reroute accessible lengths of the existing ductwork to shorten the length |
| Twists, kinks or crushed flexible duct connector from dryer to exhaust duct inlet boot | Shorten or replace the flexible duct connector to avoid unnecessary twists and bends |
| Visible moisture damage inline with the duct | Continue with borescope imaging of the duct to verify presence of moisture at the location of the damage. Consider the adequacy of the |

| | |
|---|---|
| | waterproofing details at the exterior duct penetration as well as sealing any gaps in the ductwork. |
| Occupant indicates that loads are taking longer to dry | This is the typical indication that the duct is at least partially blocked. Duct cleaning should be considered. |
| No obvious problems, and duct length does not exceed 35' (or manufacturer's recommended length) | Check dryer and booster fan to ensure they are fully functional. Replace as required. If the exhaust fans are ok, check for blockages. |
| Damage does not line up with ducts | Consider sources other than in-slab ducts for the cause of the moisture damage |

## C.3 Testing for blockage

When the exterior and interior visual audits have failed to diagnose the problem, the next step is to test for duct blockages. The first option is to use a borescope camera. A borescope camera can be useful in detecting areas of lint buildup or water accumulation. However, a borescope may not be able to examine the entire length of the duct. In these cases, a calibrated fan and pressure sensor can be used to detect blockages.

TABLE C.3: TESTING FOR BLOCKAGE

| Observation | Recommended Action |
|---|---|
| Excessive lint buildup | Hire a local duct cleaning service to cleanout the duct. Cleaning services typically offer cleaning from the exterior only or from both directions. Cleaning from both directions will require suite access and higher costs, but will be more effective at cleaning the duct. Regular duct cleaning is a recommended for all dryer ducts. |
| Damaged, crushed or blocked duct | Depending on the location of the damage, it will be necessary to repair, abandon or replace the duct. Switching to condensing (ductless) dryers is another option. |

## C.4 Test for airflow

Exhaust fans should be tested for airflow to ensure they are operating according to their design intent. It is a common observation in suites with moisture issues related to dryer exhausts that the dryer exhaust fans are operating below the design airflow rate. Airflow can be measured using a calibrated flow hood at the exhaust vent or other means. Differential air pressure measurements can be used to detect the direction of airflow. Attention should be paid to the air temperature at the exhaust vent. Low exhaust temperatures (during dryer operation) are indicative of duct runs that are too long, air flow rates that are too small, or significant flow blockages. Auxiliary devices such as booster fans should also be tested to determine whether or not they are functioning properly.

| TABLE C.4: TESTING FOR AIRFLOW | |
|---|---|
| **Observation** | **Recommended Action** |
| Insufficient airflow | Replace faulty or inadequate equipment (dryer, booster fan, damper, etc.,) to ensure the manufacturer's flow rate is met |

## C.5 Test for Moisture

If no blockages are detected and airflow rates are within the design parameters (rule of thumb 100 CFM for dryer exhaust) additional diagnostic tests can be performed. The temperature and relative humidity of the interior, exterior and exhaust air can be measured to evaluate the need/benefit of additional humidity control measures such as running ventilation equipment when the devices are not in operation.

| TABLE C.5: TESTING FOR MOISTURE | |
|---|---|
| **Observation** | **Recommended Action** |
| High interior moisture load | Reduce interior moisture load by turning off humidifiers and operating local exhaust fans during/after moisture generating events (e.g., showering and cooking). Consider automated controls |

In summary, the following set of recommendations can be followed for a typical dryer exhaust duct moisture related issue.

| RECOMMENDATIONS FOR REMEDIAL ACTION | |
|---|---|
| 1 | Replace or repair inadequate or damaged vent cover details at the exterior to prevent bulk water ingress. |
| 2 | Inspect duct for damage or blocks and repair/clean as necessary. |
| 3 | Measure the exhaust flow rate and compare against the manufacturer's specifications. Repair, replace or supplement equipment. Reroute ductwork. |
| 4 | Monitor interior/exterior/exhaust temperature and humidity to determine if a larger system issue exists requiring new ductwork or a ductless dryer. |