Sustainable Energy Research, Development & Demonstration Programme

The Relationship between Radon and Ventilation in Retrofit Buildings: Experimental Validation of Model Predictions

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Authors:

James A. McGrath and Miriam A. Byrne

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DISCLAIMER

Details of Project Partners

James A. McGrath
Centre for Climate of Air Pollution Studies,
School of Physics
National University of Ireland Galway
Galway
Ireland
Tel.: +353 91 493437
E-mail: james.a.mcgrath@nuigalway.ie

Miriam A. Byrne
Centre for Climate of Air Pollution Studies,
School of Physics
National University of Ireland Galway
Galway
Ireland
Tel.: +353 91 493394
E-mail: miriam.byrne@nuigalway.ie

Summary

A modelling framework can be used to predict indoor radon concentrations in dwellings that have undergone an energy retrofit, and have experienced a consequent air tightness change. The framework is flexible, and allows for simulations to be carried out under various pre-retrofit radon concentration levels, multi-zone building geometries, ventilation configurations and retrofit types. However, detailed real-time radon concentration and ventilation data is necessary for model validation, and such data is non-existent in the Irish context. The generation of these data, which allows for full model validation and testing, is the focus of the current study. The objectives of the current study are to (i) fully characterise the ventilation status of selected Irish dwellings, through measurement, and determine the real-time radon concentrations therein (ii) parameterise the model for these selected dwellings, and make comparative predictions of radon concentrations. The current study focused on measuring hourly radon concentrations, using real-time radon monitors, in dwellings that are representative of the buildings stock undergoing energy retrofit. Each dwelling was monitored to establish time-varying fluctuations in indoor radon concentrations and obtain data on the minimum and maximum range. In addition, air exchange was measured using the tracer gas decay method with CO_2 as the tracer. Air exchange comprised of multiple selected hourly measurements per dwelling over the measurement period to ensure that the effect of meteorological variations was captured. The data generated will be used in model simulations to predict indoor radon concentrations based on local meteorological conditions, building characteristics and in-situ characterisation of radon entry rates.

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1. Introduction

1.1. Overview

The negative impact on human health due to exposure to ionising radiation is well documented (WHO, 2009). In Ireland, radon gas is considered the greatest source of radiation exposure to the general population accounting for just over 55% of the average radiation dose (O'Connor et al., 2014). Radon gas (222Rn) is a naturally occurring odourless, colourless and tasteless gas; it arises as a product of Uranium (238U) decay, which is a radioactive material found in varying quantities in soil and rocks. Radon decays by emitting an α particle into a series of short-lived radioactive progeny, two of which are polonium (218Po and 214Po). If inhaled, the vast majority of radon is exhaled almost immediately. However, the short-lived decay products of radon can deposit on the bronchial epithelium and be exposed to alpha radiation (IARC, 2001).

Radon is the second highest leading cause of lung cancer, after smoking, in many countries. In an OECD survey of 30 countries, Ireland was found to have the eighth-highest average indoor radon concentration, accounting for up to 250 cases of lung cancer each year (WHO, 2009, Colgan et al., 2008). Since, the population of western countries spends on average 92% of their time indoors per day, with approximately 60% of their time in the residential environment (Broderick et al., 2015, Klepeis et al., 2001), the residential environment therefore deserves particular attention. Darby et al. (2005) examined radon levels from 13 European case-control studies and the associated risk of lung cancer; the study found that for every 100 Bq m^{-3} increase in measured radon, there was an 8.4% (95% CI [3.0%, 15.8%]) increase in the risk of lung cancer.

The European Energy Efficiency Directive (2012) sets the policy roadmap for the period until 2020, and each Member State is required to reduce their energy consumption by 20% to meet the EU's greenhouse gas emission reduction commitments. In 2014, Irish buildings accounted for 35% of the total national energy consumption and approximately 59% of electricity consumption (SEAI, 2016). Retrofitting of the building fabric has been identified as one of the most cost-effective energy-efficiency improvements to achieve energy savings in the economy (Johnston et al., 2005).

In the Irish context, the scope for energy efficiency gains to be made through retrofitting of the existing building stock has been continuously identified within the National Energy Efficiency Action Plans (DCENR, 2014b, DCENR, 2009, DCENR, 2011a). To this end, the Irish National Energy Retrofit Programme aims to upgrade 1.2 million residential, public and commercial buildings by 2020 (DCENR, 2011b, DCENR, 2014a). However, recent research has shown that energy retrofitting of dwellings may lead to greater airtightness, and there is a possibility that radon concentrations may accordingly increase (Pressyanov et al., 2015, Fojtikova and Rovenska, 2014, Jiránek and Kačmaříková, 2014, Fojtíková and Navrátilová Rovenská, 2015).

Studies have reported that indoor radon concentrations are strongly associated with the geogenic radon potential, building material, construction type, foundation and the year of construction (Demoury et al., 2013, Drolet and Martel, 2016, Borgoni et al., 2014, Collignan et al., 2016). However, even dwellings located in the same area, with assumed relatively homogeneous radon potential, have reported localise heterogeneities exert a strong influence on indoor radon concentrations (Drolet and Martel, 2016).

Small pressure differences between the indoor and outdoor environments gives rise to the convective transport of radon gas into dwellings; various factors including the stack effect, wind interaction with the building fabric, heating and mechanical ventilation all contribute to the pressure differences (Nazaroff, 1992).

Previous studies have modelled indoor radon concentrations in the residential microenvironment (Revzan and Fisk, 1992, Sherman, 1992, Man and Yeung, 1999, Fang and Persily, 1995, Keskikuru et al., 2001, Milner et al., 2014, Riley et al., 1999, Diallo et al., 2013). However the majority of these studies focussed either simulating the sub-slab gravel layer had on radon entry rates into buildings. Milner et al. (2014) investigated the impacts of indoor radon concentrations as a consequence of increasing the airtightness of the English housing stock; however, this study only assumed a steady state radon entry rate and did not account for dynamic radon entry rates into dwellings.

Collignan et al. (2012) reported dynamic radon entry rates that results in a high temporal variability of radon concentrations in residential buildings; factors that influence radon entry rate include wind speed, moisture content, pressure differences and radon concentration in the soil (Keskikuru et al., 2001, Riley et al., 1999, Andersen, 2001).

In response to the National Radon Control Strategy (NRCS, 2014), the modelling framework IAPPEM (McGrath et al., 2014a, McGrath et al., 2014b, McGrath et al., 2017, McGrath, 2011) was redeveloped during the EPA project UNVEIL: UNderstanding VEntilation and radon in energy efficient buildings in IreLand (2015-HW-DS-4)(McGrath and Byrne, 2018). The model predicts radon concentrations in dwellings that have undergone an energy retrofit, and have experienced a consequent air tightness change. The framework is flexible, and allows for simulations to be carried out under various pre-retrofit radon concentration levels, multi-zone building geometries, ventilation configurations (i.e. vent size/type) and retrofit types (e.g. cavity filling and external insulation). However, detailed real-time radon concentration and ventilation data is necessary for model validation, and such data is non-existent in the Irish context. The generation of these data, which would allow full model validation and testing, is the focus of the current study.

2. Methodology

2.1. Overview

In the sections that follow, the site selection criteria used and the experimental methodologies employed are described in full.

2.2. Site Selection

Irish dwellings were recruited through existing local authority contacts, that are representative of those referred to in NSAI S.R. 54:2014 Code of Practice: Methodology for the energy efficient retrofit of existing dwellings (i.e. bungalow, semi-detached, terraced dwellings) (NSAI, 2014). Dwellings were selected where radon levels are both above and below the 200 Bq m^{-3} Irish reference level, as pre-determined from passive radon monitoring carried out by the EPA.

For Galway-based dwellings, outdoor temperature and pressure data for the measurement dates were obtained from the Informatics Research Unit for Sustainable Engineering (IRUSE) at the National University of Ireland Galway, which maintains a full record of weather conditions in Galway, Ireland (53.280148, -9.059237). For dwellings based outside Galway, meteorological data was derived from Met Eireann repositories.

Table 2-1. A summary of household characteristics.

	House Type	Era
House A	Semi-detached, 2 storey	1970
House B	Semi-detached, 2 storey	2000
House C	Semi-detached, 2 storey	1930
House D	Semi-detached, 3 storey	2000
House E	Detached, 2 storey	1910
House F	Detached, 2 storey	1930
House G	Detached, 2 storey	2010
House A	Semi-detached, 2 storey	1970

2.3. Airflow and Air Tightness measurements

Air exchange rate measurements were carried out for each dwelling using the CO_2 tracer gas decay technique. Air exchange comprised of up to eight selected hourly measurements per dwelling over each measurement week to ensure that the effect of meteorological variation was captured. The CO_2 tracer gas decay measurements involved releasing CO_2, from a sealed cylinder, into the room, until concentrations exceeded 2500 ppm. A GrayWolf probe (GrayWolf Sensing Solutions; Shelton, CT, USA) was used for gas detection at one-minute intervals.

Air tightness testing was conducted in accordance NSAI Certification I.S. EN ISO 9972:2015 - Thermal Performance of Buildings – Determination of Air Permeability of Domestic Buildings – (Single or Single & Multi) Fan Pressurisation Method. A single measurement per dwelling was carried out, as weather variations over the course of the experimental period will induce pressure differentials of far less than 50 Pa, which is the design pressure for air-tightness testing.

2.4. Field Measurements and Data Collection

In order to obtain representative values for radon entry rates into Irish dwellings, the methodology developed by (Collignan and Powaga, 2014) to characterise radon potential in existing dwellings was employed. The methodology involved a blower door test to maintain the dwelling at successively different depressurization levels that heighten the convective radon flux into the dwelling. In steady state conditions, the radon flow leaving the building through the blower door corresponds to the radon entry rate.

Hourly radon concentrations were measured with a continuous radon monitor, a Rstone Continuous radon gas sensor (Radiansa Consulting S.L., Girona, Spain), for a period of the order of one week in each dwelling, to establish time-varying fluctuations in indoor radon concentrations and obtain data on the minimum and maximum range.

2.5. Results

2.6. Airtightness measurements

Table 3.1 shows a representative selection of the air tightness measurements made in the tested dwellings. It can be observed that the largest air tightness values (i.e. leakier dwellings) correspond to those dwellings that are comparatively new within the sample.

Table 2-2. A summary of airtightness measurements for selected homes.

House	**Airtightness (m^3/h/m^2 @50pa)**
House A	5.042
House B	7.033
House C	4.830
House D	9.423

2.7. Tracer Gas Measurements

Figures 3-1, 3-2 and 3-3 show representative (a) C02 tracer gas decay curves and (b) logarithmic transformations of the data, from which air exchange rates are derived. As indicated previously, up to eight tracer gas measurements were made in each dwelling, and Tables 3.2 , 3.3 and 3.4 shows, by way of example, the entire datasets for Houses A, B and E. The three tables also show correlation coefficients arising from linear fits to the logarithmic plots.

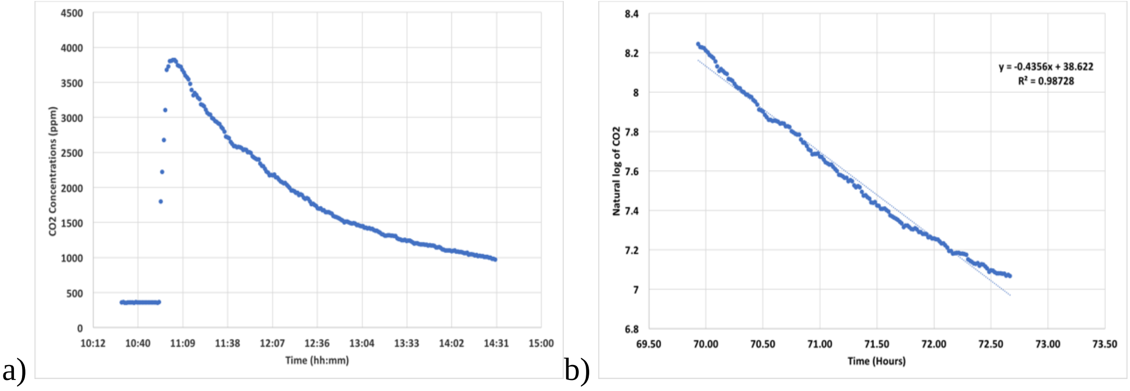

Figure 2-1. A selected time-series measurement; a) the CO₂ concentration and b) a selected period for determining the air exchange rate.

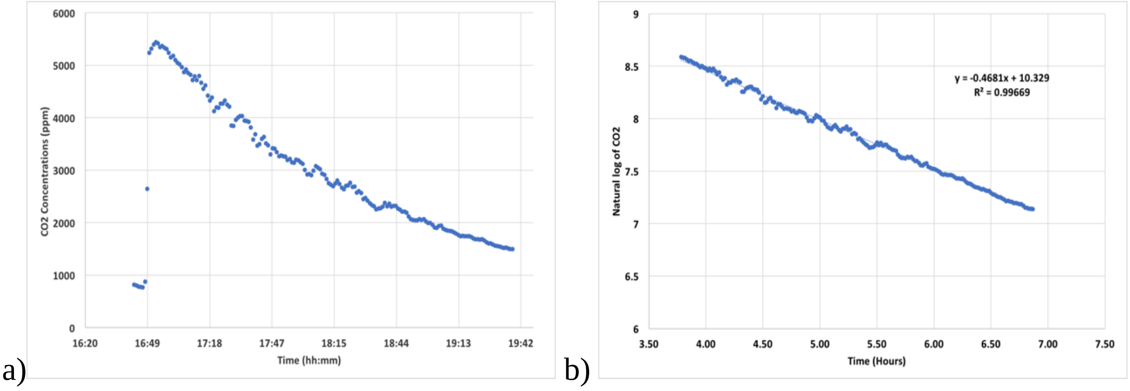

Figure 2-2. A selected time-series measurement; a) the CO_2 concentration and b) a selected period for determining the air exchange rate.

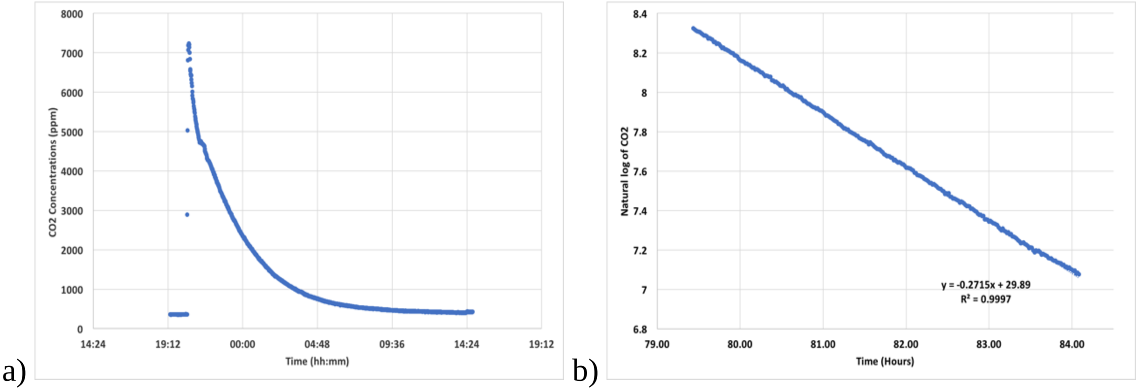

Figure 2-3. A selected time-series measurement; a) the CO_2 concentration and b) a selected period for determining the air exchange rate.

Table 2-3. A summary of eight measurements carried out in the living room for House A, containing purpose provided ventilation, of a semi-detached dwelling.

	Air Changes per Hour	**R^2**
Test 1	0.80	0.99
Test 2	0.71	0.99
Test 3	0.48	0.99
Test 4	0.47	0.99
Test 5	0.30	0.95
Test 6	0.30	0.99
Test 7	0.44	0.98
Test 8	0.27	0.99

Table 2-4. A summary of eight measurements carried out in the living room for House B, containing a chimney and purpose provided ventilation, of a semi-detached dwelling.

	Air Changes per Hour	R^2
Test 1	1.99	0.99
Test 2	0.95	0.99
Test 3	1.00	0.99
Test 4	1.23	0.99
Test 5	1.81	0.97
Test 6	2.29	0.98
Test 7	2.76	0.99
Test 8	2.91	0.97

Table 2-5. A summary of eight measurements carried out in the living room for House E, which contained a chimney, of a detached dwelling.

	Air Changes per Hour	R^2
Test 1	1.51	0.99
Test 2	0.60	0.98
Test 3	0.97	0.98
Test 4	1.31	0.97
Test 5	1.17	0.92
Test 6	1.11	0.92
Test 7	0.65	0.98
Test 8	0.74	0.99

For the complete dataset of up to eight measurements per house, a minimum value of 0.3 air changes per hour was recorded; the maximum value was 1.87 air changes per hour (ach). The significant variability in the air exchange for any particular house can be seen from the data shown in Tables 3-2, 3-3 and 3-4: House A has an average air exchange rate of 0.47 air changes per hour, but the standard deviation is 0.19 air changes per hour. For House E, the average is 1.0 ach and the standard deviation is 0.32 ach, and for House B, the average is 1.87 ach and the standard deviation is 0.76 ach.

2.8. Radon Concentration Measurements during Building Pressurisation

Figures 3-4, 3-5 and 3-6 show time-varying radon concentrations measured in three of the selected dwellings, in each case during periods when the dwellings were iteratively pressurised from 25 Pa to 15 Pa and then to 5 Pa. Evidence for the different radon entry rates in each of the three dwellings is provided by comparing the maximum radon concentration reached at the same time lapse (which would correspond to an equal pressure in each case) in each of the three plots. Considerable variation is observed, with maximum values of 35, 180 and 115 Bq m^{-3} apparent in the three sample datasets shown.

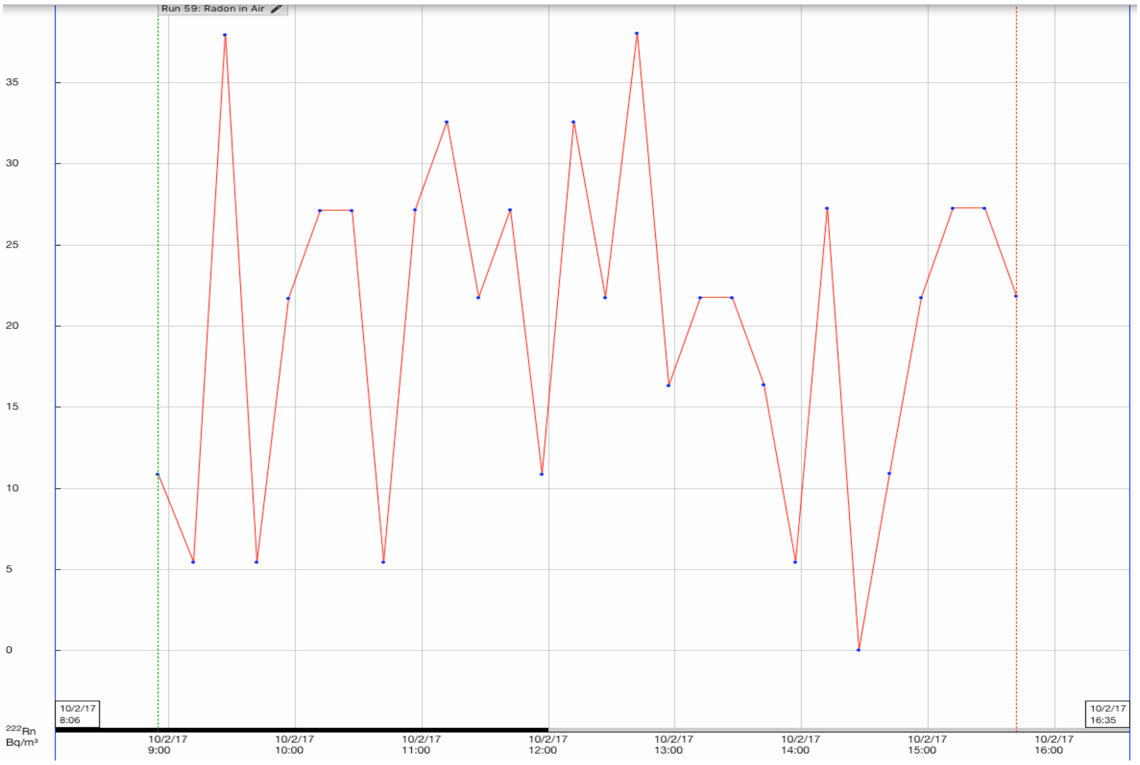

Figure 2-4. Radon-entry rates measurements in the House B dwelling.

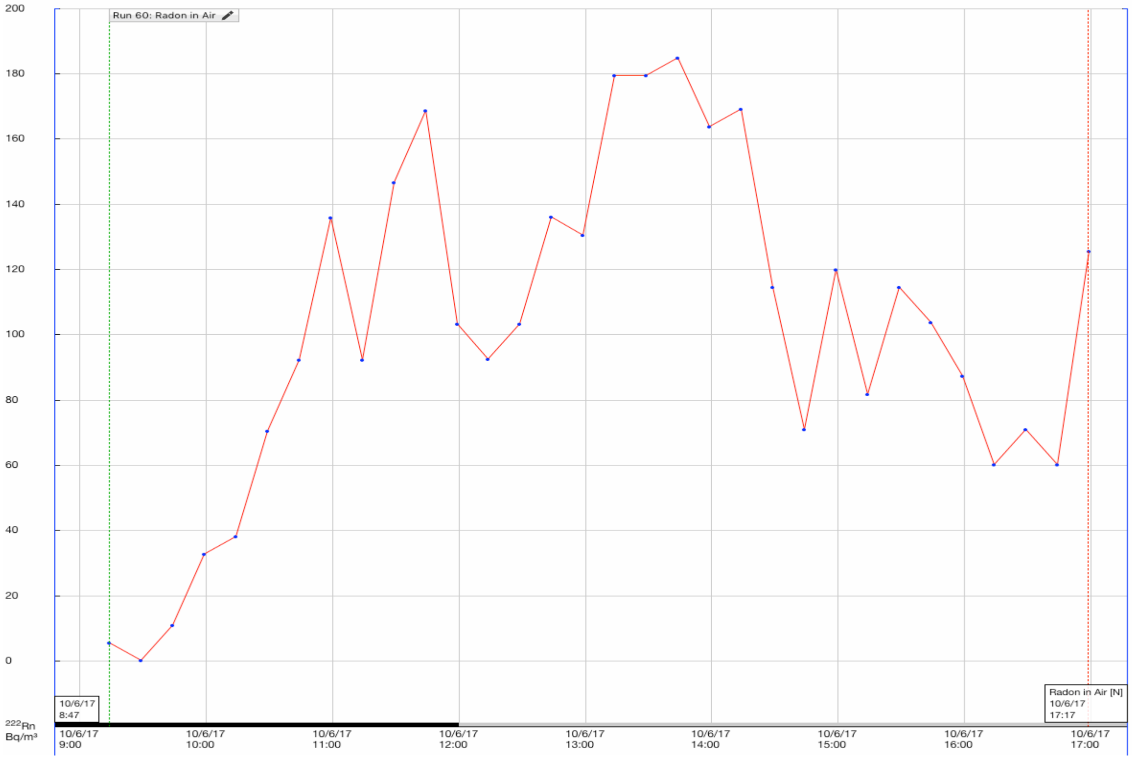

Figure 2-5. Radon-entry rates measurements in the House C dwelling.

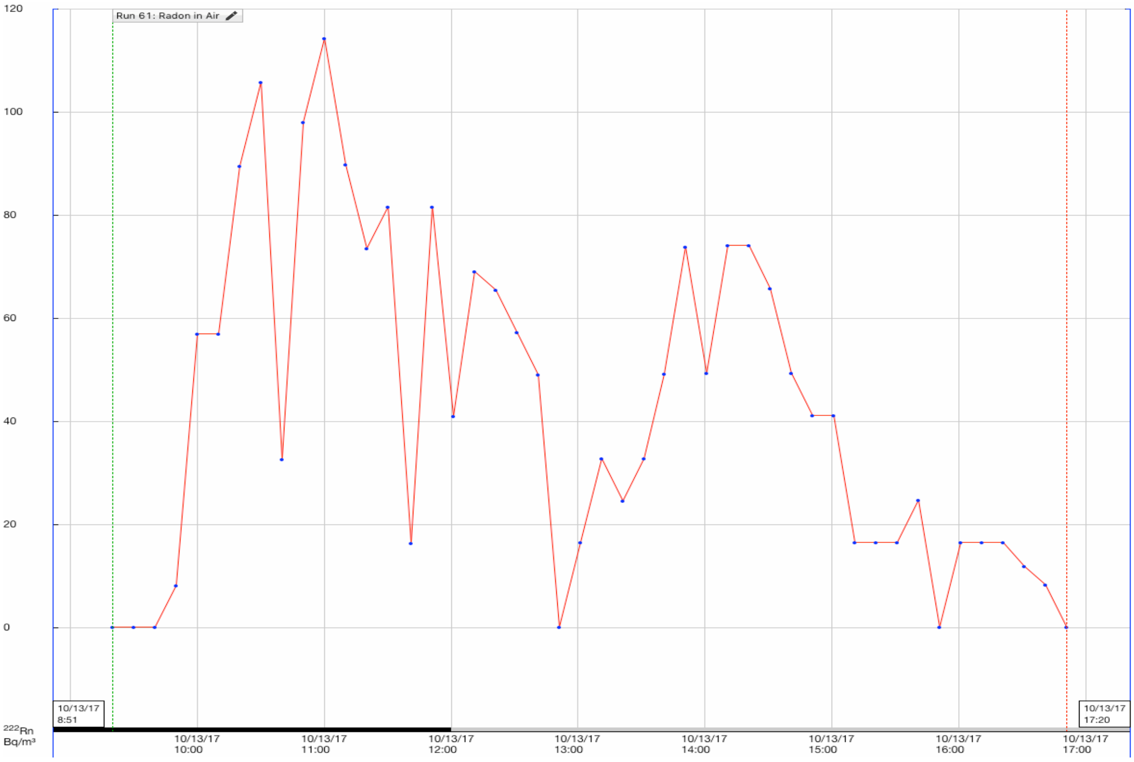

Figure 2-6. Radon-entry rates measurements in the House A dwelling.

2.9. Radon Measurements

Figures 3-7 to 3-13 show the time-varying radon concentrations recorded in each of Houses A-G. In each figure, extensive fluctuation in radon concentration can be observed in the data. A summary of data from all seven houses is shown in Table 3-5, which shows minimum, maximum and average radon concentrations. It can be observed that in every case, the maximum concentration in each house exceeds the average value for that house, with the exceedances ranging from 203% to 402%.

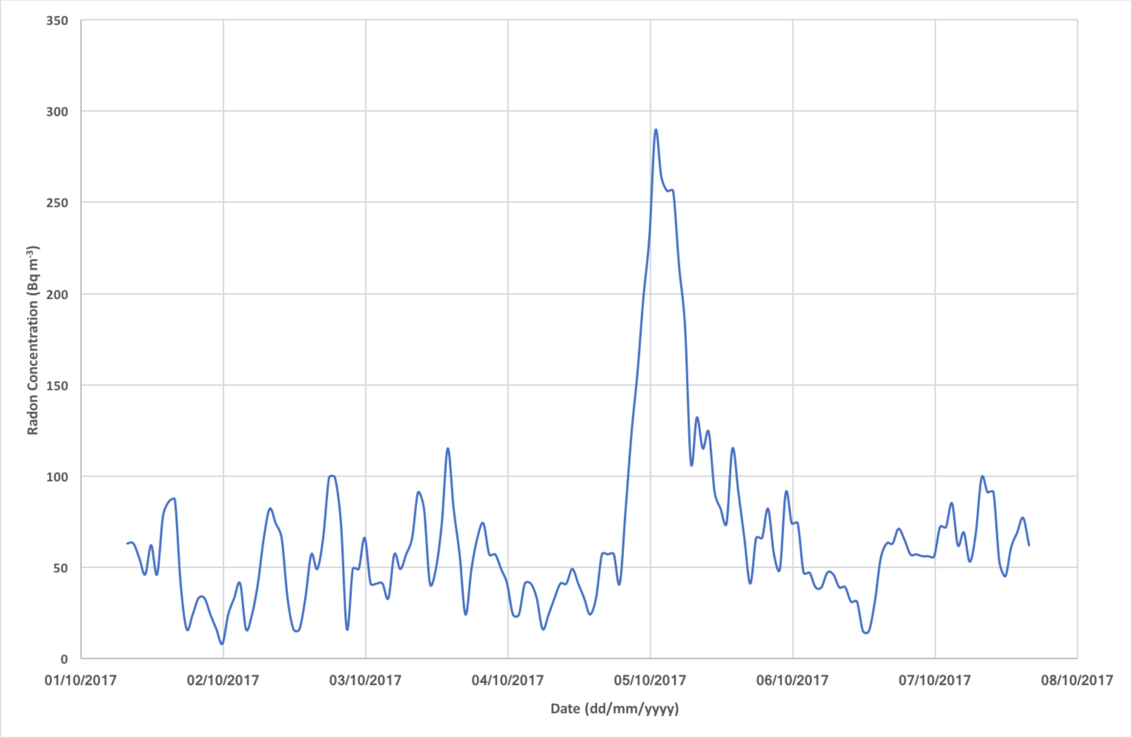

Figure 2-7. Time-series data in the House A dwelling.

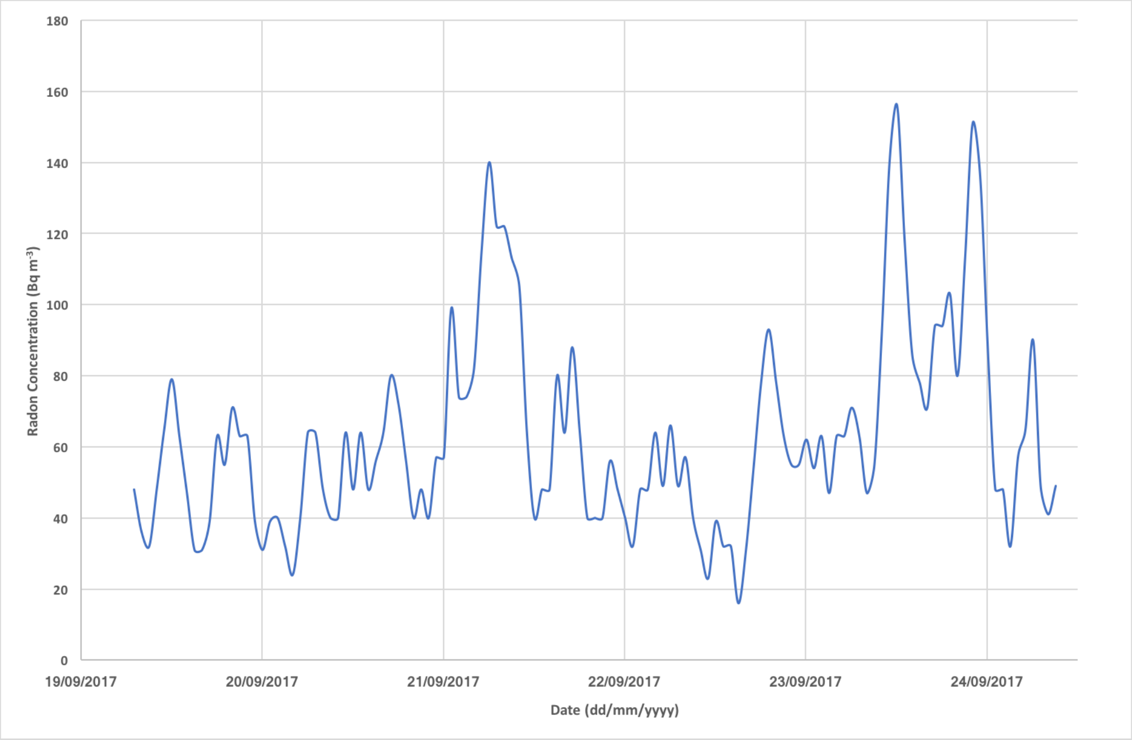

Figure 2-8. Time-series data in the House B dwelling.

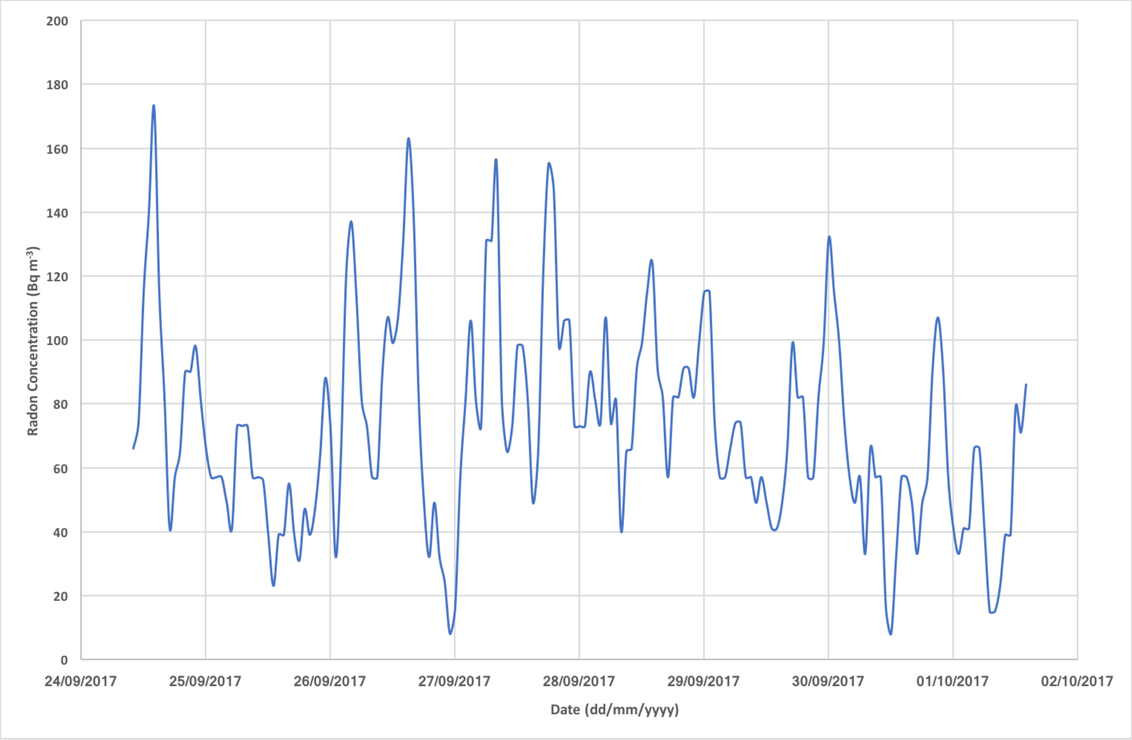

Figure 2-9. Time-series data in the House C dwelling.

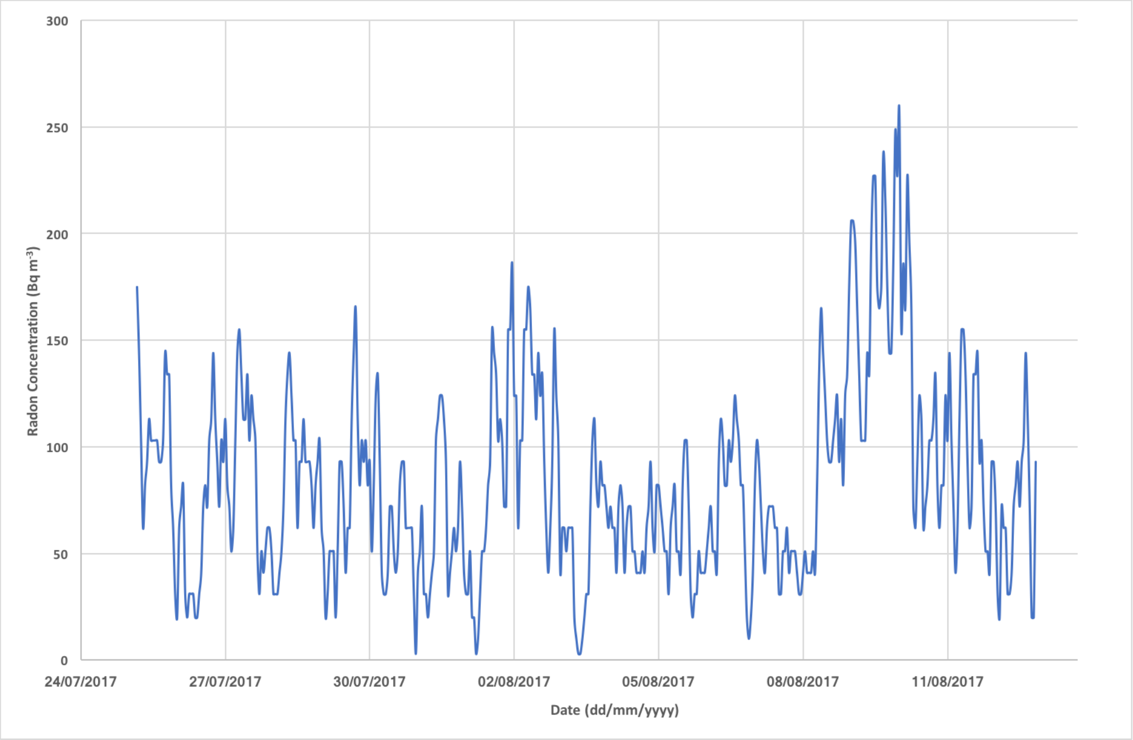

Figure 2-10. Time-series data in the House D dwelling.

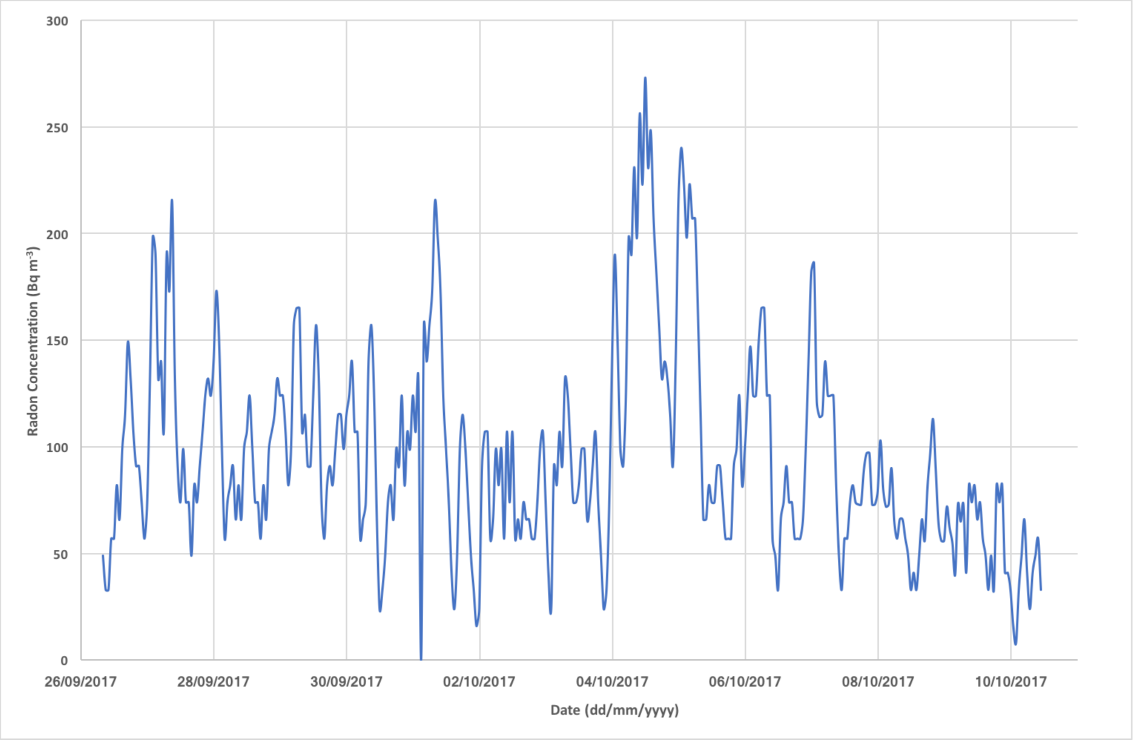

Figure 2-11. Time-series data in the House E dwelling.

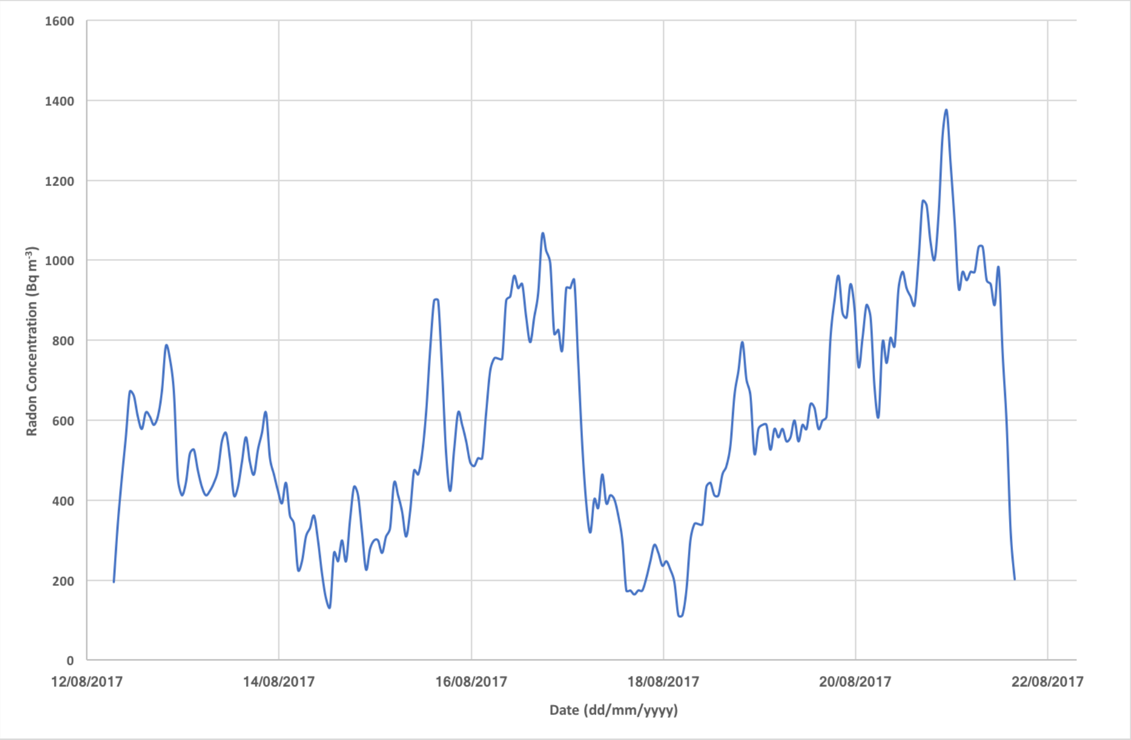

Figure 2-12. Time-series data in the House F dwelling.

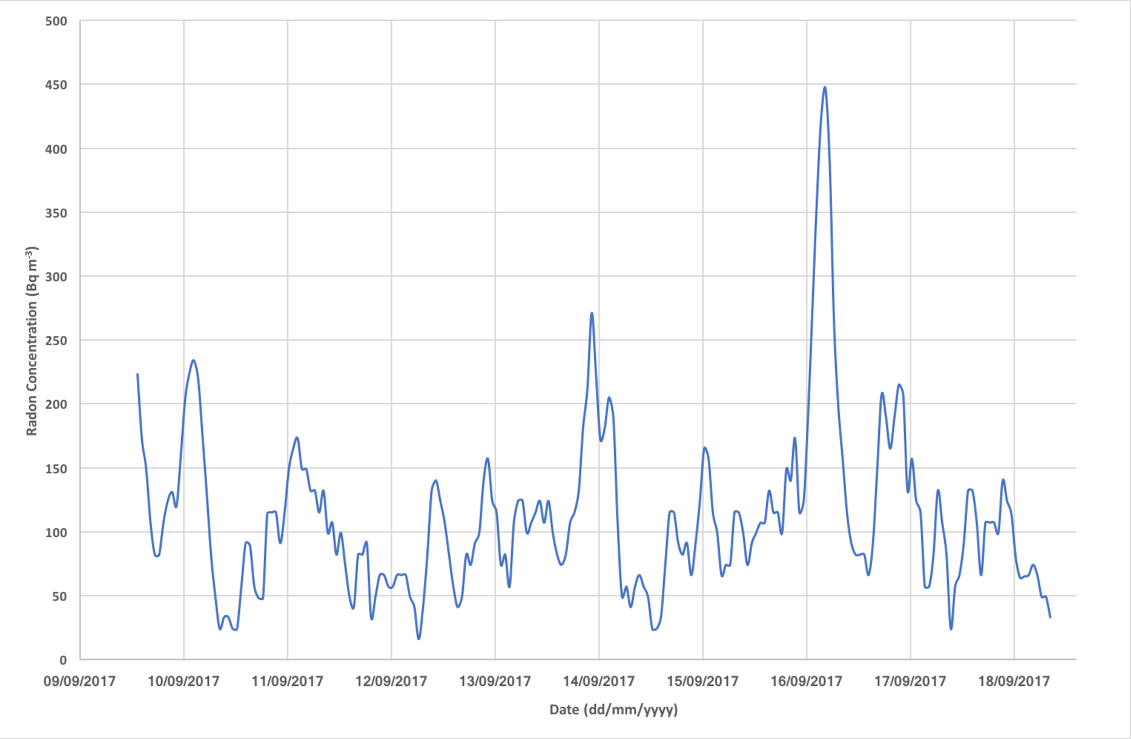

Figure 2-13. Time-series data in the House G dwelling.

Table 2-6. Radon concentration measurement summary.

	Measurement Days	Minimum Radon Level (Bq m^{-3})	Maximum Radon Level (Bq m^{-3})	Average Radon Level (Bq m^{-3})
House A	6.41	8	289	66
House B	5.2	16	156	63
House C	7.3	8	173	72.7
House D	18.9	3	258	84
House E	14.3	0	273	97
House F	9.5	113	1376	589
House G	8.9	16	447	112

3. Discussion and Conclusions

This study represents the first published research in Irish dwellings that combines real-time radon concentration measurements with air exchange rate measurements and building pressurisation test results, with all data collected within the same measurement period. Measurements were made in a range of dwellings that varied by age of building, geographical location, and average indoor radon concentrations that were both below and above the radon reference level of 200 Bq m^{-3}; measurements in individual dwellings were taken over periods ranging from five days to three weeks. Semi-detached and detached two-storey houses were included in the study, and the range of building ages spanned the period from 1908 to 2010. The motivation for the data collection was to capture some of the variability in radon and ventilation data, thus providing parameterisation information for computational modelling initiatives that can simulate radon concentrations in dwellings under various ventilation conditions. The main findings of the study were as follows:

- In each dwelling, hourly radon concentrations were observed to exceed the values over the whole measurement period by a factor that ranged from 203% to 402%, according to which dwelling was studied. This indicates that averaged values do not reliably capture fluctuations in radon concentrations.

- Significant variations were observed in air exchange rates between dwellings, and also across a dataset of multiple air exchange rate values in a single dwelling. A range of factors, such as meteorological changes, are likely to contribute to these variations, which are an indicator of changes in indoor/outdoor pressure differences. These pressure differences are an important driver of radon in-flow to dwellings, and therefore the air exchange rate data goes some way towards explaining the observed radon concentration variations.

- Pressurisation tests, conducted at 50Pa, in each dwelling yielded values in the range 4.83 m3/hr/m^2 – 9.42 m^3/hr/m^2, with the older dwellings found to be consistently more airtight than the newer dwellings. Across the entire dataset, no correlation was found between air tightness values and air exchange rate, highlighting the distinction that should be made between air permeability and air flow in the context of radon entry.

The motivation for the data collection was to capture some of the variability in radon and ventilation data, thus providing parameterisation information for computational modelling initiatives that can simulate radon concentrations in dwellings under various ventilation conditions, and allow more accurate prediction than was previously possible of, for example, the effect on indoor radon concentrations of energy retrofit initiatives in dwellings. Future work should extend this database, by including additional dwelling types (e.g. bungalows and terraced houses), a wider geographical spread (so as to capture the full extremes of wind conditions prevailing in exposed parts of Ireland), and a greater range of radon concentration levels.

Research Outputs

- Poster Presentation at 2017 AIVC (Air Infiltration and Ventilation Centre) Conference, Nottingham, September 2017

- Poster Presentation at Annual Aerosol Science Conference, Birmingham, October 2017

- Oral presentation of selected data at the ROOMS Radon Conference, Galway, October 2017

- Preparation of a Ulysses French-Irish collaboration grant with Bernard Collignan and Emilie Powage, CSTB, aimed at advancing knowledge regarding radon entry rates: October 2017

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Abbreviations

CI	Confidence interval
CSTB	Centre Scientifique et Technique du Bâtiment
DCCAE	Department of Communications, Climate Action and Environment
DCENR	Department of Communications, Energy and Natural Resources
DECLG	Department of Environment, Community and Local Government
DHPLG	Department of Housing, Planning and Local Government
DSTL	Defence Science and Technology Laboratory
EPA	Irish Environmental Protection Agency
HSE	Health Service Executive
NUIG	National University of Ireland Galway
NSAI	National Standards Authority of Ireland
Po	Plutonium
PPV	Purpose Provided Ventilation
Rn	Radon
RPII	Radiological Protection Institute of Ireland (RPII)
SEAI	Sustainable Energy Authority of Ireland
WHO	World Health Organization