Spatio-temporal Indoor Human Exposures in Homes Affected by Chemical-contaminated Soil and Groundwater

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TABLE OF CONTENTS

Page

TABLE OF C	CONTENTS	i
CONTRIBUT	TION TO KNOWLEDGE	v
ABSTRACT		v
DECLARAT	ION	xiii
ACKNOWL	EDGMENTS	xiv
LIST OF TA	BLES	XV
LIST OF FIG	JURES	xvi
LIST OF AB	BREVIATION, ACRONYMS AND SYMBOLS	xix
LIST OF API	PENDICES	xxvi
THESIS OVE	ERVIEW	xvii
1 GENI	ERAL INTRODUCTION	1
1.1 V	APOUR INTRUSION	1
1.1.1	Background to the issue of vapour intrusion	1
1.1.2	Vapour intrusion modelling	5
1.2 H	IUMAN HEALTH RISK ASSESSMENT	9
1.2.1	Introduction	9
1.2.2	Identifying concerns (problem formulation and scoping)	18
1.2.3	Hazard assessment	19
1.2.4	Exposure assessment	21
1.2.5	Environmental and chemical-specific parameters, and exposure factors	23
1.2.6	Risk characterisation	25
1.2.7	Biological monitoring	26
1.2.8	Environmental epidemiology	28
10 0		20

 1.3
 PUBLIC HEALTH SIGNIFICANCE OF VAPOUR INTRUSION
 28

 1.3.1
 Nature and extent of the problem
 28

 1.3.2
 Toxicology of vapour intrusion contaminants
 30

 1.3.3
 Epidemiological evidence of health concerns
 36

 1.4
 CONCLUDING COMMENTS
 38

2	CRI	TICAL LITERATURE REVIEW	39
	2.1	Reader NAVIGATION	39
	2.2	OBJECTIVES OF THE LITERATURE REVIEW	39
	2.3	LITERATURE SEARCH STRATEGY	41
	2.3.1	Summary of key relevant papers	42
	2.3.2	Critical review of key relevant papers	56
	2.4	CURRENT AUSTRALIAN REGULATORY GUIDANCE ON VAPOUR INTRUSION	
	ASSESS	MENT	76
	2.4.1	National Environment Protection (Assessment of Site Contamination)	
	Mea	sure (1999) (NEPM)	76
	2.4.2	State Environment Protection Authorities (EPAs)	78
	2.5	INTERNATIONAL GUIDANCE ON VAPOUR INTRUSION	83
	2.5.1	Canada	83
	2.5.2	European Environment Agency	84
	2.5.3	New Zealand	84
	2.5.4	The Netherlands	85
	2.5.5	United Kingdom	86
	2.5.6	United States of America	88
	2.6	CONCLUDING COMMENTS ON THE REGULATORY ENVIRONMENT	92
	2.7	UNCERTAINTIES AND GAPS IN KNOWLEDGE IN RELATION TO VAPOUR INTRU	SION
	ASSESS	MENT	<u>93</u>
	2.8	PROPOSED DIRECTION FOR THE CURRENT RESEARCH	<u>95</u>
	2.9	AIMS AND RESEARCH QUESTIONS	97
	2.9.1	Phase 1 – critical literature review	97
	2.9.2	Phase 2 – Case Study 1	98
	2.9.3	Phase 3 – Case Study 2	98
	2.10	WHAT IS NOT ADDRESSED IN THIS RESEARCH	99
3	CAS	E STUDY 1 - EVALUATION OF A SUSPENDED-FLOOR HOUSE	101
	3.1	PURPOSE OF CASE STUDY	101
		INTRODUCTORY BACKGROUND	
		EXPERIMENTAL METHODS	

3.3.2	General experimental approach	105
3.3.3	Description of chemical application procedure	105
3.3.4	Soil sampling and testing methods	106
3.3.5	Dwelling features, ventilation and meteorological assessments	110
3.4 V	APOUR INTRUSION MODELLING	111
3.5 R	ESULTS	114
3.5.1	Indoor air concentrations of xylene	114
3.5.2	Air exchange rates and meteorological variables	117
3.5.3	Evaluation of measured against predicted air xylene concentrations and	1
ventila	ation observations	122
3.6 C	ONCLUDING COMMENTS	128

4 CASE STUDY 2A AND 2B – EVALUATION OF A SLAB-ON-GROUND

HOUSE13		
4.1 (Case Study 2a	133
4.1.1	Purpose of the case study	
4.1.2	Introductory background	134
4.1.3	Description of property and location	
4.1.4	Experimental summary	
4.1.5	Data preparation, calculations and statistical methods	
4.1.6	Results	
4.1.7	Concluding comments	
4.2 0	Case Study 2b	201
4.2.1	Purpose of case study	
4.2.2	Introductory background	
4.2.3	Experimental methods	
4.2.4	Results and observations	
4.2.5	Concluding comments	

5 GI	ENERAL DISCUSSION	215
5.1	READER NAVIGATION	
5.2	NOVELTY OF THE RESEARCH	
5.3	MAJOR FINDINGS OF THE STUDIES	216

5.3.1	Time-dependent changes in indoor air concentrations	216
5.3.2	Environmental factors affecting indoor air TCE concentrations	221
5.3.3	Exposure assessment and biological monitoring	226
5.4	SUMMARY IMPLICATIONS	228
5.5	GENERALISABILITY OF RESULTS	229
5.6	STRENGTHS AND LIMITATIONS OF THE OVERALL RESEARCH	230
5.6.1	Strengths	230
5.6.2	Limitations	231

6CONCLUSIONS AND RECOMMENDATIONS2336.1CONCLUSIONS2336.2RECOMMENDATIONS2366.3FUTURE RESEARCHERS2366.4REGULATORY AGENCIES, SITE CONTAMINATION CONSULTANTS, AUDITORS AND

7	REFERENCES	5 <u></u> 24	0
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COMMUNITIES 237

APPENDIX 1 PUBLISHED PAPERS	270
APPENDIX 2 PAPER BY TURCZYNOWICZ AND ROBINSON (2001)	<u>271</u>
APPENDIX 3 CASE STUDY 1 STATA® LOG FILE	<u></u> 272
APPENDIX 4 HOBO U30 STATION TECHNICAL DETAILS	273
APPENDIX 5 RADIELLO® ANALYTICAL METHOD	<u></u> 274
APPENDIX 6 CASE STUDY 2A EXAMPLE DATA FILE	275
APPENDIX 7 SGS LEEDER CONSULTING LABORATORY REPORTS	
APPENDIX 8 CASE STUDY 2A STATA® LOG FILES AND PLOTS	277
APPENDIX 9 CASE STUDY 2B ETHICS APPROVAL AND FORMS	278
APPENDIX 10 ENVIROLAB SERVICES BLOOD TCE ANALYTICAL	
METHOD	279
APPENDIX 11 BIOLOGICAL MONITORING REPORTS	280
APPENDIX 12 EXAMPLE OF BLOOD TCE CHROMATOGRAM	281
APPENDIX 13 E-COPY OF THESIS AND DATA ON DISC	282

CONTRIBUTION TO KNOWLEDGE

This research provides new insights concerning indoor air contaminant exposure assessment associated with vapour intrusion (VI).

A summary position from the literature, identifies knowledge gaps. Case studies explore these gaps and provide quantitative data related to volatile organic compound (VOC) concentrations in terms of within-building spatial and temporal variance and the factors that influence that variance. The findings can be used to establish a new evidence-based indoor air sampling strategy that represents 'worst case' conditions, consistent with the public health precautionary principle. Furthermore, this enables an improved understanding of the human health effects of volatile substances from ground contamination and identifies the need to develop a dynamic, time-dependent model of vapour intrusion in buildings. In addition, the research explores a biological monitoring approach, with end-exhaled breath sampling and testing under environmental conditions. This approach shows promise as a non-invasive means of assessing exposure and uptake.

ABSTRACT

INTRODUCTION

Public health problem statement

Vapour intrusion is a process that involves the migration of volatile chemicals from contaminated soil and/or groundwater into dwellings or other confined structures where inhalational exposure may occur. The process is exemplified by naturally occurring soil radon, which is considered a major risk factor for lung cancer in a number of countries. However, the extensive use of industrial chemicals and fuels over many years has left a legacy of soil and groundwater contamination potentially posing an even wider variety of disease endpoints. Volatile substances such as benzene and trichloroethylene (TCE) have also been shown to intrude into buildings from single or multiple sources off site. Limited environmental epidemiological studies have reported increased risks of cancer and non-cancer effects. Owing to the number of people potentially exposed including vulnerable subpopulations, regulatory agencies have developed frameworks for risk assessment based on environmental sampling and predictive models.

These approaches, however, are based on idealized contaminant source and migration

characteristics, and have been found to have limited predictive value for health risk assessment. Further research is required to provide more confidence in risk assessment outcomes.

Initial literature review

In Australia, the federal enHealth's human health risk assessment framework and a National Environment Protection Measure provide the basis for site contamination assessment. These documents, although recognizing the complexity of vapour intrusion, provide limited guidance on exposure assessment and have a focus on petroleum hydrocarbons.

The human health risk assessment of vapour intrusion can be structured into three key areas:

• Sub-surface fate and transport models and vapour measurement that establishes the vapour concentration at the building boundary.

• Ventilation models and measurement which consider indoor air concentrations in space and over time within the building; and

Human inhalation dosimetry which considers absorbed doses over time. • The peer-reviewed scientific literature on vapour intrusion over the past thirty years combined with the international regulatory documentation is extensive. However, the majority of this literature is oriented towards the initial phase of sub-surface transport to the building boundary. There has been limited focus on ventilation dynamics and less so on inhalation dosimetry. In the past five years, however, increasing attention has focused on spatial and temporal indoor air contaminant changes with one public health publication on residential indoor air spatio-temporal variability and another on linking indoor air contaminant concentrations to biological markers. In terms of considering inhalation dosimetry, however, there is as yet, no discourse on how these indoor environments may result in differing inhalation doses. This may be particularly important where high level peak doses due to environmental effects on the distribution of an indoor volatile, result in adverse pathologies. Indeed, there is some evidence, for example, in the case of TCE, for peak tissue concentrations precipitating acute neurotoxic effects.

Gap in knowledge

The gaps in knowledge in vapour intrusion exposure assessment include the following:

• Models of dynamic and time-dependent (non-steady state) vapour migration processes and their validation.

• An understanding of spatio-temporal variability in indoor concentrations and the correlates of the variability that might lead to an evidenced-based indoor air sampling protocol.

• The time dependence of absorbed dose, especially tissue concentrations, that results from time-dependent inhaled air concentrations.

PURPOSE STATEMENT

Through a critical review of the literature and a series of empirical case studies, this research seeks to:

• Elucidate the nature of spatial-temporal changes in indoor contaminant concentrations within houses affected by vapour intrusion and the factors that may influence those changes.

• Provide an evidence base for a time-dependent vapour intrusion model with empirical evaluation, applicable to Australian conditions.

• Explore the utility of biological monitoring for risk assessment in a common vapour intrusion scenario.

GENERAL RESEARCH QUESTIONS

• What is the short- and long-term spatio-temporal variability of indoor air contaminants arising from vapour intrusion?

• Which factors are significantly associated with indoor air concentration variability?

• What is the relationship between biological monitoring data and indoor TCE concentrations?

METHODS

A critical literature review and experimental case study approach were used. The experimental case studies were opportunistic and reflected real-life conditions. Case Study 1 was a termiticide treatment (including xylene) in a suspended floor home and Case Study 2 was a slab-on-ground house in a TCE-affected area.

Critical literature review

Computerised searches of the published literature were conducted using the Web of Science, Scopus and PubMed. The logic grid included "*vapour intrusion*"; "*ventilation*"; "*inhalation dosimetry*" and "*exposure*". The yields were complemented with author searching and forwards and backwards searching. The literature on vapour intrusion was critically reviewed in terms of its utility for human health risk assessment.

Case Study 1 – Suspended timber floor home construction - Indoor air concentrations The upper portion of the soil in the subfloor of a 1950's home was treated with technical grade xylene containing m-, p- and o-xylenes as part of a termiticide treatment. Analyses were conducted of soil xylene and moisture concentrations; subfloor and indoor air xylene concentrations; and air exchange rates in the subfloor space and occupied space. Concurrent meteorological data were collected from a weather station. A published Australian non-steady state model, developed in previous national guidance, was used to estimate (and compare with) indoor air concentrations based on the empirical measurements.

Case Study 2a – Concrete slab on ground home construction - Indoor air concentrations

A four-bedroom public housing property in a residential area impacted by chlorinated hydrocarbon contaminated groundwater was used over a period of 14 months to assess indoor air TCE levels. Passive TCE sampling occurred at five indoor and two outdoor locations over various time intervals. Air exchange rates were calculated at front and rear indoor sampling locations. Detailed local meteorological data were gathered from a weather station. Indoor temperature and indoor relative humidity were measured at 30 minute intervals over a 3-month period at each of five indoor air sampling locations. Soil vapour, sub-slab vapour and flux chamber measurements were carried out during

one week concurrent with 6 hour passive sampling.

Case Study 2b - Slab on ground home construction - Human exposure experiments: A biological monitoring pilot study was conducted with 5 volunteer adults who occupied the TCE-contaminated house for 12 hours. End-exhaled breath samples and blood samples were collected. Participants were also asked to provide urine samples at baseline, at the end of the exposure period and on three subsequent occasions. Passive indoor air sampling and surface flux testing was undertaken. Sub-slab TCE samples were also collected inside and outside the house.

RESULTS

Critical literature review

Papers on vapour intrusion mainly focused on issues associated with the sub surface. These included areas such as development of one- and three-dimensional steady-state models; estimation of attenuation factors; lateral exclusion distances; factors affecting subsurface migration such as moisture levels and oxygen concentrations and reconsideration of the United States (US) Environment Protection Agency vapour intrusion database. There have, however, been some new areas of focus in the last five years, which have included the use of new real-time measurement techniques; an increased focus of the role of pressure differences on indoor air contaminant concentrations; seasonal and diurnal differences and spatio-temporal variability in homes across an affected community. One recent study examined indoor air TCE concentrations and blood TCE levels. The recent literature has increasingly examined the above-ground and indoor environment but has not further considered withinbuilding spatial differences nor a more detailed examination of short-term indoor air average concentration changes and associated influencing variables. In addition, the literature is silent on the issue of inhalation dosimetry in vapour intrusion and the potential for non-invasive methods of biological monitoring.

Case Study 1–Suspended floor home construction - Indoor air concentrations

Xylene air concentrations decayed to non-detectable levels within two weeks. Subfloor xylene air concentrations were greater than living space xylene air concentrations, and the decay of the concentrations following a generally consistent pattern. Air exchange rates between the sub-floor and living space differed by up to an order of magnitude and demonstrated the influence of subfloor ventilation on vapour intrusion. Statistically significant associations were found for air exchange in the sub-floor space and locally measured minimum and average wind speed.

Site-specific variables in a non-steady state model showed general consistency with measured data, but the modelling estimated a greater shorter-term initial peak with more rapid decay of xylene concentrations than those measured.

Case Study 2a - Slab on ground home construction - Indoor air concentrations Air sampling data revealed spatial and seasonal indoor TCE variations. Winter month results were up to an order of magnitude greater than summer months. Monitoring over 6-hour (h) periods demonstrated the occurrence of diurnal peaks that were not evident with a 24-h sampling regime. Moreover, the use of a continuous data logging instrument showed occasional spikes over rapid time intervals which were an order of magnitude or greater compared to the common baseline value. Air exchange measurements revealed consistent early morning declines in ventilation. Correspondingly, the highest surface TCE flux was noted during the day with the lowest occurring during the evening. Soil vapour measurements at progressive depths at the rear of the property showed high source concentrations of TCE with lower concentrations progressively up to the subslab.

Using the 6-h average TCE concentration as the outcome variable, it was found that ventilation, internal temperature, barometric pressure and wind direction were significant predictor variables in a multivariate model. Ventilation had the greatest impact in the best fit model with one air change per hour predicting a 4.4 μ g m⁻³ decline in the indoor TCE concentration. Assessment of model predictions showed close agreement with the dataset.

Case Study 2b - Slab on ground home construction - Human exposure experiments The pilot biological monitoring exercise yielded mixed results with most biomonitoring data below the limit of reporting (LOR) which was which was $<5\mu$ g m⁻³ for breath and $<0.01 \mu$ g L⁻¹ for blood. End-exhaled breath TCE concentrations were generally below 5μ g m⁻³ with two results above the LOR. Composite end-exhaled breath samples for baseline and at 02:30 and 08:30 were 2.0, 1.5 and 1.2µg m⁻³ respectively. Blood concentrations were all below the level of reporting of 0.01 µg L⁻¹. While blood TCE concentrations could not be quantified in accordance with standard protocols, discrete peaks were observed on the chromatograms.

CONCLUSIONS AND RECOMMENDATIONS

The recent literature has increasingly examined the above-ground and indoor environment but has not further considered within-building spatial differences nor shortterm indoor air average concentration changes and their influencing variables. In addition, the literature is silent on the issue of inhalation dosimetry in vapour intrusion and the potential for non-invasive methods of biological monitoring.

Case Study 1 confirmed the influence of dwelling features and that of ventilation and meteorological variables such as wind speed for a suspended-floor dwelling. Case Study 2 captured greater resolution across all measurements and although the extent of the variables measured varied, sufficient data were captured to provide a more detailed examination of time-dependent change. Statistically significant spatial differences were observed suggesting the need to account for prevailing wind direction in worst case indoor sampling strategies. Mixed-effects regression models were consistent with the observed seasonal and diurnal differences. The two case studies provide evidence for a worst-case sampling strategy, that is, sampling in winter and during the evening and accounting for spatial variance.

Overall, the results demonstrate the complexity of indoor ventilation dynamics and that spatial and temporal influences are important to understand for exposure assessment purposes. Short term, peak TCE exposure periods were observed and may be of toxicological significance based on information suggesting TCE exhibits a non-monotonic dose-response relationship for foetal malformations.

On the basis of the research the following recommendations are made:

- More detailed and extensive (>1 year) longitudinal studies capturing timedependent changes in indoor air concentrations and all influencing variables including air pressure changes, should be undertaken.
- A human volunteer biological monitoring study using end-exhaled breath and blood TCE analyses should be undertaken, using sensitive analytical techniques such as Selected Ion Flow Tube Mass Spectrometry.
- A retrospective epidemiological study in TCE-affected areas should be conducted in Adelaide.

DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Signed: _____

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LIST OF TABLES

TABLE 1-1: TOTAL PETROLEUM HYDROCARBON FRACTIONS AND DATA	31
TABLE 2-1: LOGIC GRID ADOPTED FOR LITERATURE SEARCH STRATEGY	42
TABLE 2-2: SUMMARY OF KEY RELEVANT PAPERS – OBJECTIVE	144
TABLE 2-3: SUMMARY OF KEY RELEVANT PAPERS – OBJECTIVE	249
TABLE 3-1: GENERAL PROTOCOL	
TABLE 3-2: SOIL PROPERTIES FOR MODELLING PURPOSES	109
TABLE 3-3: PHYSICO-CHEMICAL AND BUILDING CHARACTERISTICS USED IN	
MODELLING	112
TABLE 4-1: SUMMARY TCE DATA FOR FLUX CHAMBER MEASUREMENTS	
TABLE 4-2: Summary soil vapour (SV)/sub-slab (SS) results (μ G M ⁻³)	186
TABLE 4-3: RESULTS FOR MULTIVARIATE LINEAR MIXED-EFFECTS MODEL	196
TABLE 4-4: URINE SAMPLING PROCEDURE	
TABLE 4-5: ALL RESULTS FOR PILOT BIOLOGICAL MONITORING EXPERIMENT	

LIST OF FIGURES

FIGURE 1-1: ENVIRONMENTAL HEALTH PARADIGM AND RISK ASSESSMENT	11
FIGURE 1-2: FRAMEWORK FOR HEALTH RISK ASSESSMENT DECISION-MAKING	12
FIGURE 1-3: ENHEALTH RISK ASSESSMENT FRAMEWORK	14
FIGURE 1-4: REVISED OUTLINE OF THE INTERLINKED PROCESSES OF EHRA	15
FIGURE 1-5: HUMAN HEALTH AND VAPOUR RISK ASSESSMENT FRAMEWORK	17
FIGURE 1-6: EXPOSURE AND THE ENVIRONMENTAL HEALTH FRAMEWORK	22
FIGURE 1-7: REDUCTIVE DE-CHLORINATION OF TETRACHOROETHYLENE	33
FIGURE 2-1: CONCEPTUAL STRUCTURE OF AIRWAY COMPARTMENT MODEL	70
FIGURE 3-1: CASE STUDY 1 FLOOR PLAN	. 104
FIGURE 3-2: CASE STUDY 1 - FRONT OF HOUSE	. 104
FIGURE 3-3: AUSTRALIAN NON-STEADY-STATE VAPOUR MODEL SCENARIO	. 113
FIGURE 3-4: SUBFLOOR XYLENE CONCENTRATIONS	. 115
FIGURE 3-5: INDOOR AIR XYLENE CONCENTRATIONS	. 115
FIGURE 3-6: SUBFLOOR SPACE PID, DAY 1 TO DAY 12	.116
FIGURE 3-7: INDOOR AIR PID, DAY 1 TO DAY 12	.116
FIGURE 3-8: SUBFLOOR AIR CHANGES WITH TIME	. 117
FIGURE 3-9: BOM WIND SPEED VS SUBFLOOR ACH	. 119
FIGURE 3-10: BOM WIND DIRECTION VS SUBFLOOR ACH	. 119
FIGURE 3-11: SUBFLOOR ACH VS TEMPERATURE	. 120
FIGURE 3-12: SUBFLOOR ACH VS AVE RH %	. 120
FIGURE 3-13: SUBFLOOR ACH VS WIND DIRECTION	. 121
FIGURE 3-14: SUBFLOOR ACH VS WIND SPEEDS	. 121
FIGURE 3-15: VAPOUR MODELLING OUTPUTS	. 125
FIGURE 3-16: MEASURED INDOOR AIR XYLENE CONCENTRATIONS	. 126
FIGURE 3-17: MODEL OUTPUTS VERSUS PID MEASUREMENTS IN INDOOR AIR	. 126
FIGURE 3-18: PID MEASUREMENTS IN INDOOR AIR	. 127
FIGURE 3-19: PID MEASUREMENTS SHOWING DIURNAL INFLUENCES	. 127
FIGURE 4-1: VAPOUR MIGRATION TRANSPORT PATHWAYS	. 136
FIGURE 4-2: FRONT OF HOUSE USED IN CASE STUDY 2	. 137
FIGURE 4-3: RESEARCH HOUSE FLOOR PLAN WITH SAMPLING LOCATIONS (TO SCALE).	. 138
FIGURE 4-4: HOBO U30 WEATHER STATION	. 139

FIGURE 4-5: PASSIVE SAMPLING, VENTILATION ASSESSMENT, PID (1_{IN})	144
FIGURE 4-6: RAE SYSTEMS LP1200 AND MEASUREMENT INSTRUCTIONS	147
FIGURE 4-7: FLUX CHAMBER SAMPLING LAYOUT	149
FIGURE 4-8: INDOOR FLUX CHAMBER INDOOR OPERATION AT LOCATION F5	150
Figure 4-9: Flux chamber operation outdoors adjacent $SV3-14m$	150
FIGURE 4-10: INDOOR TEMPERATURE (°C) DISTRIBUTION	159
FIGURE 4-11: INDOOR RELATIVE HUMIDITY DISTRIBUTION	160
FIGURE 4-12: OUTDOOR TEMPERATURE DISTRIBUTION (^o C)	162
FIGURE 4-13: BAROMETRIC PRESSURE DISTRIBUTION (MBAR)	162
FIGURE 4-14: RELATIVE HUMIDITY DISTRIBUTION (%)	162
FIGURE 4-15: WIND SPEED DISTRIBUTION (M S ⁻¹)	163
FIGURE 4-16: GUST SPEED DISTRIBUTION (M S ⁻¹)	163
FIGURE 4-17: WIND DIRECTION DISTRIBUTION	163
FIGURE 4-18: SOLAR RADIATION DISTRIBUTION (W M ⁻²)	164
FIGURE 4-19: WIND ROSE, 24-31 AUGUST 2015	164
FIGURE 4-20: PID FOR 24-31 AUGUST 2015 AT LOCATION R4	165
FIGURE 4-21: PID FOR 01-08 SEPTEMBER 2015 AT LOCATION R1	166
FIGURE 4-22: PID INCREASE 26 AUGUST 2015 AT LOCATION R4	166
FIGURE 4-23: PID INCREASE 27 AUGUST 2015 AT LOCATION R4	167
FIGURE 4-24: PID INCREASE 27-28 AUGUST 2015 AT LOCATION R4	167
FIGURE 4-25: PID INCREASE 29 AUGUST 2015 AT LOCATION R4	168
FIGURE 4-26: PID INCREASE 30 AUGUST 2015 AT LOCATION R4	168
FIGURE 4-27: PID INCREASE 31 AUGUST 2015 AT LOCATION R4	169
FIGURE 4-28: PID INCREASE MORNING OF 1 SEPTEMBER 2015 AT R4	169
FIGURE 4-29: PID INCREASE AFTERNOON OF 1 SEPTEMBER 2015 AT R4	170
FIGURE 4-30: PID INCREASE 5 SEPTEMBER 2015 AT LOCATION R1	170
FIGURE 4-31: 4-H AVERAGE RESULTS ON 15 JULY 2015	171
FIGURE 4-32: 7-D AVERAGE RESULTS FOR WEEK 15-22 JULY 2015	172
FIGURE 4-33: 6-H AVERAGE AT LOCATION 1_IN, 24-31 AUGUST 2015	173
FIGURE 4-34: 6-H AVERAGES AT LOCATION 2_IN, 24-31 AUGUST 2015	173
FIGURE 4-35: 6-H AVERAGES AT LOCATION 3_IN, 24-31 AUGUST 2015	174
FIGURE 4-36: 6-H AVERAGES AT LOCATION 4_IN, 24-31 AUGUST 2015	174
FIGURE 4-37: 6-H AVERAGES AT LOCATION 5_IN, 24-31 AUGUST 2015	175

FIGURE 4-38: 6-H AVERAGES, ALL LOCATIONS, 24-31 AUGUST 2015	175
FIGURE 4-39: 24-H AVERAGES, BY LOCATION, 24-31 AUGUST 2015	176
FIGURE 4-40: 7-D AVERAGES, BY LOCATION, 24-31 AUGUST 2015	. 177
FIGURE 4-41: 12-H AVERAGES, LOCATION 1_IN, 9-16 AUGUST 2015	178
FIGURE 4-42: 24-H AVERAGES, LOCATION 1_IN, 9-16 AUGUST 2015	178
FIGURE 4-43: 7-D AVERAGES, BY LOCATION, 9-16 AUGUST 2015	. 179
FIGURE 4-44: 24-H AVERAGES, OCTOBER 2014 TO NOVEMBER 2015	180
FIGURE 4-45: 7-D AVERAGES, OCTOBER 2014 TO NOVEMBER 2015	181
FIGURE 4-46: INDOOR FLUX RESULTS 25-31 AUGUST 2015	184
FIGURE 4-47: 6-H AVERAGES AND INDOOR FLUX MEASUREMENTS AT R5/F5	184
FIGURE 4-48: ACH, LOCATION 1_IN, 15-16 JULY 2015	187
FIGURE 4-49: 12-H ACH, LOCATION 1_IN, 9-16 AUGUST 2015	188
FIGURE 4-50: 12-H ACH, LOCATION 4_IN, 9-16 AUGUST 2015	188
FIGURE 4-51: 6-H ACH, LOCATION 1_IN, 42-31 AUGUST 2015	190
FIGURE 4-52: 6-H ACH, LOCATION 4_IN, 24-31 AUGUST 2015	190
FIGURE 4-53: 24-H ACH, 1_IN/4_IN, 9-16 AUGUST 2015	. 191
FIGURE 4-54: 24-H ACH, 1_IN/4_IN, 24-31 AUGUST 2015	. 191
FIGURE 4-55: COMPARISON OF MODEL-PREDICTED AND MEASURED VALUES	197
FIGURE 4-56: PARTICIPANTS AT THE REAR OF THE HOUSE	204
FIGURE 4-57: BREATH SAMPLING SETTING	205
FIGURE 4-58: A HAPPY PARTICIPANT DURING BLOOD SAMPLING!	206
FIGURE 4-59: INDOOR AIR TCE CONCENTRATIONS (BIOLOGICAL MONITORING)	211
FIGURE 4-60: PID (PPB) RESULTS OVER 12 HOURS (BIOLOGICAL MONITORING)	. 211

LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

θ _G	Air-filled porosity or volumetric air content	
α		
~	Alpha = attenuation factor (AF) Approximately	
	Degradation rate constant of contaminant in soil	
μΤ		
μ _a °C	Degradation rate constant of contaminant in air	
-	Degrees Centigrade	
ρ _B	Dry bulk density	
4-h	Four hour	
>	Greater than	
1_IN	Location one inside also referred to as R1	
2_IN	Location two inside also referred to as R2	
3_IN	Location three inside also referred to as R3	
4_IN	Location four inside also referred to as R4	
5_IN	Location five inside also referred to as R5	
6_OUT	Location six outside	
μg L ⁻¹	Micrograms per litre	
μg m ⁻³	Micrograms per cubic metre	
µg m ⁻² min ⁻¹	Micrograms per square metre per minute	
3	n-by-1 observation error vector	
1-D	One-dimensional	
β	p-by-1 fixed-effects vector	
ρ _P	Particle density	
%	Percentage	
% v/v	Percentage by volume	
®	Registered trademark	
7-d	Seven day	
7 OUT	Radiello location 7 outside	
6-h	Six hour	
6 OUT	Radiello location 6 outside	
3-D	Three-dimensional	
φ	Total soil porosity	
3-D	Three-dimensional	
12-h	Twelve hour	
24-h	Twenty-four hour	
$\Omega_{\rm D}$	Volume of interior of the house	
$\Omega_{\rm CS}$	Volume of subfloor space	
θ_L	Water-filled porosity or volumetric water content	
A	Area	
ACH	Area Air changes per hour	
ACH_1_IN	Ventilation variable for air exchange at location R1/1_IN (6-h average)	
ACH_1_IN30min	Ventilation variable for air exchange at location R1/1_IN (30min average)	
ACH_4_IN	Ventilation variable for air exchange at location R1/1_IN (50him average) Ventilation variable for air exchange at location R4/4_IN (6-h average)	
	ventuation variable for an exchange at location R4/4_IN (6-II average)	

LIST OF ABBREV	IATIONS, ACRONYMS AND SYMBOLS (CONTD.)	
ACH_4_IN30min	Ventilation variable for air exchange at location R4/4_IN (30min average)	
AEA	Australian Environmental Auditors Pty Ltd	
AF	Attenuation factor	
AHTA	Adelaide Health Technology Assessment	
AMTB	Air-Mucous-Tissue-Blood	
ASC-NEPM	Australian Site Contamination National Environment Protection Measure	
ASL	Arterial Spin Labelling	
AS/NZS	Australian Standard/New Zealand Standard	
ASTM	American Society for Testing and Materials	
ATSDR	Agency for Toxic Substances and Disease Registry	
AUC	Area Under Curve	
AVE RH	Average relative humidity	
AVE temp °C	Average temperature degrees celsius	
AVE WD	Average wind direction	
b	q-by-1 random-effects vector	
BOM	Bureau of Meteorology	
bp	Barometric pressure variable	
BRAC	Base Realignment and Closure (Act)	
BSI	British Standards Institute	
BTEX	Benzene, Toluene, Ethyl benzene and Xylene	
CARACAS	Concerted Action on risk Assessment for Contaminated Sites in the	
	European Union	
bp	Barometric pressure variable	
с	Concentration	
CCME	Canadian Council of Ministers of the Environment	
CFD	Computational Fluid Dynamic	
CFD-PBPK	Computational Fluid Dynamic-Physiologically-Based Pharmaco-Kinetic	
CI	Confidence Interval	
CIHD	Cumulative Indoor Human Dose	
CIRIA	Construction Industry Research and Information Association	
CL:AIRE	Contaminated Land: Applications in Real Environments	
CLEA	Contaminated Land Exposure Assessment model	
CLM Act	Contaminated Land Management Act	
cm	Centimetre	
cm ³	Centimetre cubed	
cm ³ cm ⁻³	Centimetre cubed per centimeter cubed	
C _{max}	Maximum concentration	
C ₀	Initial concentration of soil contaminant	
CO ₂	Carbon Dioxide	
СО	Carbon Monoxide	
COPC	Chemicals of Potential Concern	
СРМ	Controlled Pressure Method	
CRC CARE	Cooperative Research Centre for Contamination and Remediation of the	
	Environment	

LIST OF ABB	REVIATIONS, ACRONYMS AND SYMBOLS (CONTD.)	
CSIRO	Commonwealth Scientific and Industrial Research Organisation	
CSM	Conceptual Site Model	
CVI	Chemical Vapour Intrusion	
Cxt	Concentration multiplied by time	
d _{air}	Depth of the soil/atmosphere boundary layer	
D_G^{air}	Volatile diffusivity in air	
D_L^{water}	Volatile diffusivity in water	
Day ⁻¹	Per day	
DCE	Cis-1,2-dichloroethylene/trans-1,2-dichloroethylene	
DEFRA	Department for Environment, Food and Rural Affairs	
deg	Degrees	
DER	Department of Environmental Regulation	
DHHS	Department of Health and Human Services	
DoD	Department of Defence	
DT	Effective diffusion co-efficient	
DTSC	Department of Toxic Substances Control	
DV	Dependent Variable	
E	East	
EC	Equivalent Carbon	
ECOS	Environmental Council of the States	
EDC	Endocrine Disruptor	
EEA	European Environment Agency	
EHRA	Environmental health risk assessment	
EPA	Environment Protection Authority or Agency	
Epi	Epithelium	
ERIS	Environmental Research Institute of the States	
ESCALE	Etude Sur les Cancers et les Leucémies de l'Enfant	
EU	European Union	
F2	A notation for twice the stimulation frequency	
F5	Flux sampling location 5	
f _{oc}	Organic carbon fraction	
Fout	Flux monitoring location outside	
FRC	Functional Residual Capacity	
FRLI	Federal Register of Legislative Instruments	
FUDS	Formerly Used Defence Sites	
g/100g	Grams per hundred grams	
g m ⁻³	Grams per cubic metre	
GC/ECD	Gas chromatography/Electron Capture Detection	
GC/FID	Gas Chromatography/Flame Ionisation Detection	
GC/MS	Gas chromatography/Mass Spectrometry	
HI	Hazard Index	
g/100g	Grams per hundred grams	
HIL	Health Investigation Levels	
HNF4a	A transcription factor	
111NI 4a		

LIST OF ABBREV	IATIONS, ACRONYMS AND SYMBOLS (CONTD.)
HQ	Hazard Quotient
Ι	Average air exchange rate
IABR	International Association for Breath Research
IARC	International Agency for Research on Cancer
IAQ	Indoor Air Quality
Indoor_Temp_0C	Indoor temperature variable
IPCS	International Programme on Chemical Safety
IRIS	Integrated Risk Information System
ITRC	Interstate Technology and Regulatory Council
J&E	Johnson and Ettinger
JEM	Johnson and Ettinger Model
JRC	Joint Research Centre
KD	Distribution coefficient
kg	Kilogram
Kg	Henry's Constant
K _{OC}	Organic carbon partition coefficient
L	Depth (of contamination in modelling)
L	Litre
LBW	Low Birthweight
LEL	Lower Explosive Limit
LME	Linear Mixed Effects
lnC	Natural logarithm of carbon dioxide concentration
Location	Location variable (R1/1_IN to R5/5_IN)
LOR	Limit of Reporting
m	Metre
m ²	Metre squared
m ³	Metre cubed
m d ⁻¹	Metres per day
mBar	Millibar
AHTA	Massachusetts Department of Environmental Protection
MfE	Ministry for the Environment
m g ⁻¹	Metre cubed per gram
$m^2 d^{-1}$	Metre squared per day
$m^3 g^{-1}$	Metre cubed per gram
$m^{3} m^{-3}$	Metre cubed per metre cubed
mg m ⁻³	Milligram per cubic metre
mg kg ⁻¹ d ⁻¹	Milligram per kilogram per day
ml	Millilitre
mm	Millimetre
ms	Millisecond
m s ⁻¹	Metres per second
MTBE	Methyl-t-butyl ether
Ν	North
NASA	National Aeronautical Space Administration

NATA National Association of Testing Authorities NE North-east NEE North-easteast NES National Exposure Standard NEPC National Environment Protection Council NEPM National Environment Protection Measure ng nanogram NIOSH National Institute of Occupational Safety and Health NJDEP New Jersey Department of Environment Protection NMDR Non-Monotonic Dose Response NNE North-north-east NNW North-north-west NRC National Research Council NSW New South Wales NSW EPA New South Wales Department of Environment, Climate Change and Water NT EPA North-west NWW North-west NWW North-west NWW North-west NWW North-west NYSDOH New York State Department of Health 02 Oxygen OEH Office of Environment and Heritage OEH Office of Solid Waste and Emergency Response Out	LIST OF ABBREV	IATIONS, ACRONYMS AND SYMBOLS (CONTD.)	
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ppb Parts per billion ppm Parts per million	Po-214		
ppm Parts per million	Po-218	Polonium 218 isotope	
	ppb	Parts per billion	
	ppm	Parts per million	
PIFE Polytetrafluoroethylene	PTFE	Polytetrafluoroethylene	
Q _{CD} Volumetric flow rate from subfloor to dwelling interior	QCD	Volumetric flow rate from subfloor to dwelling interior	
QLD EPA Queensland Environment Protection Authority		Queensland Environment Protection Authority	
R1 Radiello location 1 inside, same as 1_IN	R1	Radiello location 1 inside, same as 1_IN	
R2 Radiello location 2 inside, same as 2_IN	R2	Radiello location 2 inside, same as 2_IN	
R3 Radiello location 3 inside, same as 3_IN	R3		
R4 Radiello location 4 inside, same as 4_IN			
R5 Radiello location 5 inside, same as 5_IN			
Relative_Humidity Relative humidity variable			
Resultc Passive sampling results corrected for outdoor concentrations			
RfC Reference Concentration			

LIST OF ABBREV	IATIONS, ACRONYMS AND SYMBOLS (CONTD.)	
RfD	Reference Dose	
RAGS	Risk Assessment Guidance for Superfund	
RCRA	Resource Conservation and Recovery Act	
R _G	Partition coefficient	
RI	Response Index	
RIVM	Dutch National Institute for Public Health and the Environment	
RR	Rate ratio	
RT	Response Time	
RT ₁₀₀	100ms increase in Response Time	
S	Second	
S	South	
SA EPA	South Australian Environmental Protection Authority	
Sagittal	Sagittal plane which divides the body into left and right	
SAQP	Sampling and Analysis Quality Plan	
SE	South-east	
SGV	Soil guideline values	
SI	Sensitivity Index	
SI _{0.1}	0.1 unit decrease in Sensitivity Index	
Solar radiation	Solar radiation variable	
SS3	Sub-slab location 3	
SS4	Sub-slab location 4	
SSE	South-south-east	
SSW	South-south-west	
STEL	Short-Term Exposure Limit	
Sub	Submucosal tissue	
SVQGIAQ	Soil Vapour Quality Guidelines for Indoor Air Quality	
SWW	South-west-west	
SV3-2m	Soil vapour location 3 at 2m depth	
SV3-7m	Soil vapour location 3 at 7m depth	
SV3-2m	Soil vapour location 3 at 14m depth	
t	Time	
t ₁	Time one	
t ₂	Time two	
TAS EPA	Tasmanian Environment Protection Authority	
TCA	Trichloroethane	
TCA	Tolerable Concentration in Air	
TCAA	Trichloroacetic acid	
TCE	Trichloroethylene	
ТСОН	Trichloroethanol	
ТМ	Trademark	
ТРН	Total Petroleum Hydrocarbons	
TPHCWG	Total Petroleum Hydrocarbon Criteria Working Group	
TRV	Toxicological Reference Value	
TWA	Time-Weighted Average	

LIST OF ABBREV	IATIONS, ACRONYMS AND SYMBOLS (CONTD.)
UK	United Kingdom
UPSS	Underground Petroleum Storage Systems
US	United States
USA	United States of America
US DOD	United States Department of Defence
US EPA	United States Environmental Protection Agency
UST	Underground Storage Tank
V_L^B	Volumetric soil water flux
VIF	Variance Inflation Factor
VC	Vinyl Chloride
VEP	Visual Evoked Potential
VI	Vapour Intrusion
Vic EPA	Victorian Environment Protection Authority
VEP	Visual Evoked Potentials
VOC	Volatile Organic Compound
V _T	Effective solute velocity
W	West
WA EPA	West Australian Environment Protection Authority
WCA	WorkCover Australia
WHO	World Health Organisation
Wind_direction	Wind direction variable
Wind_directionC	Wind direction variable, by quadrant of 22.5° each (16 quadrants)
W m ⁻²	Watts per square metre
Х	n-by-p fixed-effects design matrix
X _{CS}	Ventilation rate of subfloor space
X _D	Ventilation rate of dwelling interior
у	n-by-1 response vector
Z	n-by-q random-effects design matrix

LIST OF APPENDICES

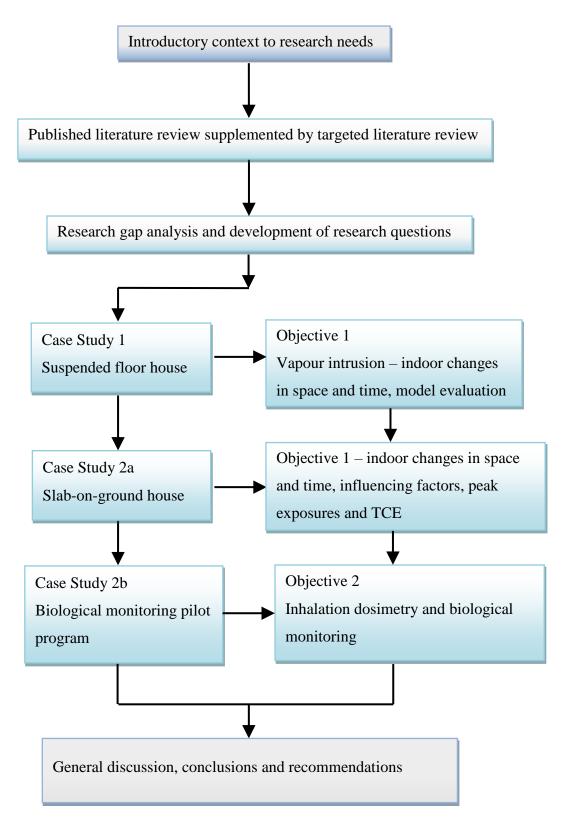
APPENDIX 1 PUBLISHED PAPERS	. 270
APPENDIX 2 PAPER BY TURCZYNOWICZ AND ROBINSON (2001)	. 271
Appendix 3 case study 1 stata® log file	. 272
APPENDIX 4 HOBO U30 STATION TECHNICAL DETAILS	. 273
APPENDIX 5 RADIELLO® ANALYTICAL METHOD	. 274
APPENDIX 6 CASE STUDY 2A EXAMPLE DATA FILE	. 275
APPENDIX 7 SGS LEEDER CONSULTING LABORATORY REPORTS	. 276
APPENDIX 8 CASE STUDY 2A STATA® LOG FILES AND PLOTS	. 277
APPENDIX 9 CASE STUDY 2B ETHICS APPROVAL AND FORMS	. 278
APPENDIX 10 ENVIROLAB SERVICES BLOOD TCE ANALYTICAL METHOD	. 279
APPENDIX 11 BIOLOGICAL MONITORING REPORTS	. 280
APPENDIX 12 EXAMPLE OF BLOOD TCE CHROMATOGRAM	. 281
APPENDIX 13 E-COPY OF THESIS AND DATA ON DISC	282

THESIS OVERVIEW

The purpose of this overview is to provide a summary of the key elements of the individual chapters of the thesis. The thesis has been structured in a traditional sense with an introduction followed by a literature review, research questions, methodology, empirical research findings, discussion, conclusions and recommendations. A case study approach has been used, providing an increased understanding and direction for the experimentation undertaken, based on the premise that time-dependence is a key factor in understanding exposure assessment. This commenced with a preliminary program investigating xylene application and site-specific evaluation of an Australian non-steady-state vapour intrusion model in a suspended floor dwelling. This was followed by a more detailed experiment from the knowledge gained which examined a real-life setting where soil and groundwater TCE contamination had impacted a house resulting in occupant evacuation. The empirical investigation included both environmental and biological monitoring and produced information which can lead to an indoor sampling protocol and a non-invasive biological monitoring method.

This thesis comprises six chapters, with a flow diagram of the structure presented in the following figure and the content and key messages presented in the subsequent table.

THESIS OVERVIEW FIGURE



THESIS OVERVIEW TABLE

Chapter	Chapter content	Key messages
1-Introduction.	This chapter provides the background to the international problem of vapour intrusion. It highlights the human health risk assessment process and the public health significance.	Vapour intrusion is a global public health problem associated with site contamination. Its assessment involves the determination of indoor air concentrations in houses above or near contamination. This is achieved through modelling or measurement. Both methods have significant knowledge gaps requiring further development.
2-Literature review.	The literature search objectives are described and search strategy presented. The search outcomes are summarised to present the gaps in knowledge pertaining to spatial and temporal understanding of indoor air exposure from vapour intrusion and current regulatory frameworks. A rationale for the proposed research is presented and the aims and research questions detailed arising from the literature review. Out of scope research aspects are presented.	Vapour intrusion literature is oriented towards subsurface concerns with limited focus on the indoor environment and the inhalation dose. Spatial and temporal concerns more recently raised, highlight the uncertainties, but within-building spatial distribution and temporal aspects of inhalation and dose are not considered. Public health focus is limited with only two papers providing a community impact perspective. Closer examination of these aspects is warranted.
3-Case Study 1. Evaluation of a suspended floor house.	Xylene application to the surface of a suspended floor home was monitored for above-ground xylene decay with ventilation and meteorological factor assessment. An Australian non-steady-state model was evaluated by capturing the necessary site-specific variables.	Xylene diminished in subfloor and indoor air within two weeks. Subfloor xylene levels were greater than indoor air levels with a consistent decline in decay reflected by an order of magnitude difference in air exchange between compartments. Wind speed was associated with subfloor air exchange rates. Diurnal effects were noted with the use of a PID. The model evaluation reported a greater and faster peak and more rapid decline than empirical data suggesting an influence of the diurnal effect. Higher resolution experimentation was a subsequent requirement.
4-Case Study 2. Evaluation of a slab- on-ground house.	A slab-on-ground vacated 4- bedroom home in a TCE affected area was monitored over a period of 14 months using passive sampling methods of varying time- averages (4h, 6h, 12h, 24h and 7d) and durations with concurrent capture of a range of environmental variables including ventilation.	Spatial and temporal changes were observed and seasonal and diurnal effects reported. Indoor air TCE levels were statistically associated with a range of environmental factors. Multivariate modelling reported the most significant factors in order of significance as ventilation, wind direction, barometric pressure and internal temperature.

Chapter	Chapter content	Key messages
4-Case Study 2. Evaluation	A short-term human exposure	Biological monitoring showed
of a slab-on-ground house	study of 12 hours with biological	mixed results due to a decline in
(contd).	monitoring explored TCE in end-	the indoor air TCE concentrations
	exhaled breath, blood and urine in	but composite end-exhaled breath
	five participants.	and indoor air averages showed
	1 1	general consistency with
		published f values. Blood TCE
		concentrations were below the
		LOR of 0.01µg/L but TCE peaks
		were reported on chromatograms.
5-General discussion.	The novelty and significance of the	The public health focus has been
	research is highlighted and	on exposure assessment hence the
	findings discussed in the context of	assessment of within-building
	international literature.	spatial and temporal variability
	Generalisability is discussed and	was the key determinant not
	the strengths and limitations	considered elsewhere. The
	explored.	qualitative and quantitative nature
		of this evaluation enabled
		statistical model development.
		While the findings are supported
		on the qualitative level the
		literature is limited on the
		quantitative level. For example,
		the quantitative relationships of
		the significant predictors for
		indoor TCE concentrations and
		the evidence of intermittent short-
		term peak elevations in TCE
		exposure. The latter potentially
		being of consequence for a
		substance exhibiting a non-
		monotonic dose-response
		relationship.
		End-exhaled breath TCE sampling
		and analysis show promise for environmental biological
		monitoring.
6-Conclusions and	Conclusions from the research	The application of this knowledge
Recommendations	findings are presented with	will improve confidence in
Recommendations	recommendations for researchers,	exposure assessment.
	government and industry.	This enables development of an
	government and mouse y.	evidence-based "worst case"
		indoor air sampling framework
		which is currently unavailable.
		Recommendations include
		extension research work with
		further time-dependent data
		capture over a year or longer; a
		biological monitoring study using
		end-exhaled breath with more
		robust methods and a
		retrospective epidemiological
		study in TCE-affected areas of
		Adelaide.

General Research Questions

The following questions were developed from the literature review and include:

What spatial and temporal changes are associated with indoor inhalation exposures arising from vapour intrusion and what factors may influence that change?

What inhalation dosimetry understanding is required and what methods of exposure assessment for vapour intrusion need to be considered?

These questions comprise a series of sub-questions structured across three phases of investigation:

- Critical literature review
- Case Study 1 suspended floor dwelling
- Case Study 2 slab-on-ground floor dwelling

Each of these sub-questions are raised at the start of each chapter and addressed at the end of each chapter. They are detailed below.

Specific research sub-questions

Critical literature review

RQ1 How important is it to know the variance in spatial and temporal indoor air concentrations for exposure assessment?

RQ2 How relevant is time-dependent vapour intrusion modelling and exposure assessment to health risk assessment?

RQ3 What are the key elements in the current Australian and international regulatory status on this issue?

In the case of a suspended floor dwelling design:

RQ4 How do subfloor and indoor air exchange rates impact on sub-floor and indoor air concentrations?

RQ5 What are the implications associated with sub-floor housing design for vapour intrusion?

- RQ6 Is there a relationship between wind speed and air exchange rate?
- RQ7 Is there a relationship between wind speed and temperature?
- RQ8 Is there a relationship between wind speed and relative humidity?

RQ9 Is there a difference between the local weather station readings and the Bureau of Meteorology (BOM) station?

RQ10 How does temporality compare with the literature?

RQ11 What assessment protocols (time-averaged or continuous) proved most useful?

RQ12 Is the model output consistent with empirical observations?

RQ13 What were the trends in the empirical measurements of indoor air concentrations?

RQ14 How do the measurements support non-steady-state vapour model improvements?

RQ15 What were the key findings in Case Study1?

In the case of a slab-on-ground dwelling design:

RQ16 Are there any significant differences across indoor testing locations?

RQ17 Are there any differences across seasons?

RQ18 Are there any diurnal differences?

RQ19 Are short-term peak exposures observed?

RQ20 Are short-term peak exposures masked by longer-term average measurements?

RQ21 Which environmental factors were significantly associated with the indoor concentrations?

RQ22 Which environmental factors had the greatest influence on indoor TCE concentrations?

In terms of the biological monitoring pilot program:

RQ23 What are reported TCE concentrations in end-exhaled breath?

RQ24 What are TCE concentrations in blood samples?

RQ25 What indoor TCE concentrations are observed?

RQ26 Are TCE concentrations in end-exhaled breath and indoor air consistent with published data?

RQ27 Is the use of end-exhaled breath as a biological marker for TCE exposure for an environmental setting, a suitable method?

RQ28 What improvements are required to structure a feasible technique?