RESEARCH REPORT

Study Of Houses Affected By Hazardous Lands

Canada

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STUDY OF HOUSES

AFFECTED BY

HAZARDOUS LANDS

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ABSTRACT

CH2M HILL ENGINEERING LTD., at the request of CMHC, has undertaken a study to identify, document and analyze incidents where Canadian homes have been affected by soil gas infiltration. This database of case studies has been used to analyze trends in types of contaminants found, remedial measures taken, and (where possible) the relative success of these measures.

CH2M HILL solicited information from various levels of government and private groups, primarily through telephone interviews and through the analysis of reports.

Three major soil gas problems were identified including petroleum hydrocarbon vapours, methane and miscellaneous VOCs. Common sources for these contaminants were respectively: fuel storage tank leaks, landfill sites or swampy areas, and local spills.

Remedial measures were grouped into two strategies: source control and house-based control. The success of the individual measures was dependent upon many factors but benefited from a good initial assessment of the problem, collection of all pertinent data, and testing after the remediation.

A number of problem areas were identified in the documentation of site conditions and success of remediation. In many cases authorities did not complete the above tasks or were unable/unwilling to give further information. Deficiencies were also highlighted in the following areas: investigation protocol, jurisdictional responsibility, and guidelines for remedial measures.

DISCLAIMER

This study was conducted by CH2M HILL ENGINEERING LTD. for Canada Mortgage and Housing Corporation under Part IX of the National Housing Act. The analysis, interpretations, and recommendations are those of the consultants and do not necessarily reflect the views of Canada Mortgage and Housing Corporation or those divisions of the Corporation that assisted in the study and its publication.

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EXECUTIVE SUMMARY

Soil gas infiltration into homes is recognized as a contributing factor to the degradation of indoor air quality. Homes on or near hazardous lands may experience an influx of volatile organic compounds (VOCs) from current or past industrial activities, or methane from peaty lands or landfill sites. The occurrence of soil gases entering homes will likely be more common in the future, especially as housing is being proposed for sites near landfills or former areas of industrial activity. While radon has been well studied and publicized in the past five years, those for other gases are not.

The objectives of this study were to: identify incidents in which Canadian homes have been contaminated through soil gas infiltration, document how this soil gas had affected air quality (or safety), and document remedial measures and analyze their relative success. A comprehensive coverage of soil gas entry problems across Canada could be used to determine trends in and identify problems with : types of soil gas contamination, remediation strategies protocol, and results. The primary method of retrieval was by means of telephone interviews with environmental, health, and municipal officials. The analysis of reports from these and other groups also provided information.

In many cases a lack of knowledge, confidentiality issues, lack of mandate among officials for indoor air quality, and biases imposed by budget constraints limited the quality of the survey results. Nevertheless a good representation of the types of soil gases typically encountered and how they were dealt with is presented.

This survey identified three major types of soil gases from hazardous lands which were found infiltrating into the indoor air environment including: petroleum hydrocarbon vapours, methane, and other miscellaneous volatile organic compounds (VOCs). The most frequently identified soil gas problem was due to spillage of gasoline and home heating fuel. Indoor air contamination was easily recognizable by the odours created and therefore remedial efforts were implemented quickly. As such, high-dose, long-term exposure of petroleum hydrocarbons was typically rare. Methane soil gases may have been present due to either natural sources such as swamps or man-made sources such as landfill sites. Methane has long been recognized as a potential safety hazard, and as such many well documented studies exist. The infiltration of miscellaneous VOCs was the least common type of soil gas identified indoors. The presence of VOCs indoors was typically a result of offgassing of contaminated groundwater, local spills, or from the migration of trace gases from landfill sites.

Concentrations of soil gases indoors are a function of pressure dependencies across the building envelope, source production rates, subsurface travel pathways, leakage areas, ventilation rates as well as possible storage mechanisms. In order to perform thorough and accurate assessments of soil gas problems for the evaluation of risks or for recommending the need of remedial measures, consideration should be given to the above factors. Typically however, many of the above factors were not addressed in the

majority of soil gas investigations. Investigations involving petroleum hydrocarbon vapours normally treated indoor air problems as secondary compared to groundwater concerns. Frequently, investigations tended to measure contaminant concentrations with no regard for air flow dynamics, and often used equipment which was incapable of taking readings at "appropriate" levels or identifying the specific contamination involved. Accurate risk assessments using such protocol were impossible to achieve. Some studies involving methane infiltration, on the other hand, at times gave more consideration to the variability discussed above. Typically, more measurements were taken over a longer time period, and in some cases environmental factors were documented. Studies involving miscellaneous VOCs often took more care in the analytical procedures for measurement of contaminants, however, rarely reported on the variability of concentrations or environmental influences.

Many different types of remedial measures were implemented. They can essentially can be grouped into two categories: source control, and house-based control. Source control measures, as defined in this text, are primarily aimed at reducing or impeding the migration of soil gases at the source. Typical source control measures for methane include: passive and active venting, pressurized air curtains, and liners installed in geologic pathways. In cases involving petroleum hydrocarbons or VOCs, active venting and other soil and groundwater remediation techniques were typically used. The success of the various remedial measures was dependent on a good analytical approach in the initial definition of the problem, collection of all pertinent data, and testing after remedial measures were implemented. If the above requirements were met, success could normally be achieved; however, not all investigations were that thorough. In addition, as the systems age, some degradation can be expected. Long-term monitoring and maintenance were often neglected. Data indicates that remedial measures such as house-based control strategies implemented generally have been successful, based on normally limited monitoring. Longer-term monitoring is needed for verification.

Despite the success of many remedial technologies at least on a short-term basis, there is a need for standardized performance criteria for remedial technologies, acceptable indoor air criteria, and allowable soil contamination. Although there is some guidance for indoor methane levels developed by some municipal and provincial governments, such criteria is not universally accepted. Guidance for the implementation of technologies is non-existent and therefore decisions concerning the choice of one technology over another is based on the subjective opinion of the designer. Finally, criteria for both indoor and outdoor soil VOC concentrations is required.

Section 1
INTRODUCTION

STATEMENT OF THE PROBLEM

Soil gas infiltration into houses located on or near hazardous lands is a growing problem, especially as more developments encroach former industrial or landfill sites. In view of this concern Canada Mortgage and Housing Corporation was interested in assessing the situation across Canada through a survey carried out by CH2M HILL ENGINEERING LTD.

While remedial measures for radon had been well-publicized in the last five years, those for other gases were not. Solutions may well differ for each contaminant. Prior to this study, CMHC had located a number of municipalities where high levels of pollutants had been measured in houses, and municipal officials had encouraged correctional actions and the ensuing air quality was checked. Unfortunately, for various reasons, information on such investigations or corrective action was not easily available.

OBJECTIVES AND SCOPE

The objectives of this study were as follows:

- To identify incidents in which Canadian houses have had difficulties with soil gas infiltration;
- To document how this soil gas infiltration has affected air quality (or safety);
- To document remedial measures and analyze how successful the remedial measures have been; and
- To draft a guide for municipal officials on how to deal with the problems.

The scope of work essentially involved three tasks:

- the data collection phase,
- the analysis of the collected data, and
- reporting on the two activities above.

Since the occurrence of specific types of soil gas entry is widespread, this study emphasized particular types of problems. Cases which were reviewed focused on:

- housing structures (rather than industrial or commercial),
- non-radon type gases,
- Canadian case studies, or
- unique or well documented cases of soil gas entry from outside the country.

The problem of soil gas entry is not uniquely a Canadian problem. For example, in the United Kingdom, numerous cases of soil gas entry have been reported in conjunction with housing near old industrial or mine sites. Although these experiences provide useful information to the Canadian scene, the construction detailing of Canadian homes and climatic conditions may not make such information directly applicable. Canada's housing stock typically can be characterized by the tight above-ground envelopes and the common use of basements. Consequently, the data collected in this study included primarily cases from Canada with a minor emphasis on problems identified in the northern United States. Cases from the northern U.S. may be regarded as having similar construction detailing and climatic conditions.

Despite the restrictions of this study to non-radon type gases in Canadian housing structures, on occasion a particularly unique remedial technology or an innovative analytical (or investigative) approach was identified. Documentation of such cases was carried out.

Section 2
METHODOLOGY

RETRIEVAL PROCESS

This study was an empirical study based on the collection of information from actual cases of where hazardous lands have affected nearby homes. Hazardous lands in the context of this report include:

- Landfill facilities where methane is seeping into houses,
- Peat bogs where methane is a problem,
- Gasoline spill sites where odours or organics have caused problems in nearby homes,
- Industrial/commercial facilities,
- Rail yards that have spilled chemicals,
- Fuel storage facilities,
- Etc.

This study involved two separate but complementary data collection components: the collection of general data of soil gas entry problems and remedial measures, as well as the collection of more detailed data for homes where more accurate or thorough information was available.

The general data collection was intended to get as much information with minimal effort on a large number of case studies. Its basic purpose was to provide general information on the type of soil gas problem encountered, the methods of detection, the remedial method implemented, and if possible, the regulatory or administrative programs pertaining to the case studies. Soil gas cases in the general data collection effort were not limited to those incidents where remedial methods or a positive identification was noted, but also included cases where soil gas entry was strongly suspected but not confirmed.

The primary method of collection was by means of telephone interviews. Interviews were conducted by environmental abatement officers in every region across Canada, health engineers, medical officers of health, municipal building inspectors, citizen's environmental groups, environmental consulting groups, and others.

Other information retrieval systems were also utilized: database searches through two major newspaper networks, through related journals, research reviews, and information supplied by CMHC Research Division.

The second data collection component involved the acquisition of more detailed information of selected cases where either unique solutions had been implemented or more analytical data was required. Follow-up of some of this data required personal interviews or visits to offices where information was being stored. Some site visits were also included. At the end of this search, conclusions were completed based on the information which was gathered.

Personal contracts made as part of this study are summarized in Appendix E. In all of the data collection efforts, the voluntary cooperation of individuals within municipalities, provincial and federal governments was heavily relied upon. Without the cooperation of those individuals, this study would not have been possible.

All contacts were carried out by CH2M HILL ENGINEERING LTD. in association with a number of other consulting firms across Canada. The country was subdivided into three geographical areas. An eastern region encompassed the Atlantic provinces and Quebec, the central region included Ontario and Manitoba, and the western region detailed case studies in Saskatchewan, Alberta and British Columbia. Each of these geographical areas are documented in Appendix A, B and C, respectively. A fourth geographical area, the United States, is documented in Appendix D.

LIMITATIONS OF RESULTS

Although the aim of this study was to provide a comprehensive coverage of all cases of soil gas entry across Canada, due to various limitations, this was not completely possible. Several limitations prevented the complete collection of data and consequently the thorough analysis of the situation. Limitations were inherent for several reasons, including:

- Lack of definition in the mandate for indoor quality among regulatory officials
- Lack of knowledge of the problem
- Confidentiality issues
- A great deal of similar case studies
- Bias due to population density

One major problem which certainly affected the quality of the results was the lack of definition in the mandate for indoor air quality. Most soil gas problems were identified through the environmental abatement officers. In many cases of soil gas entry, environment officials indicated that their mandate did not allow them to have jurisdiction over indoor air quality problems. In some cases, referral was made to local health officials. However, when health officials were contacted, researchers in this study were referred back to environment officials. Ironically, in other cases, environment officials presided over indoor air problems. This confusion in the jurisdictional boundaries caused difficulties in identifying appropriate parties.

The lack of knowledge of indoor air problems was also another difficulty which had to be overcome. Based on the initial contacts within each geographical region, the contact's knowledge about such potential problems was critical. If the initial contact was informative, then further follow-up was made with other parties or agencies. Conversely, if the initial contact was either new in the position or poorly informed, limited follow-up was possible. In some cases, problems were cited; however, follow-up with other parties proved unsuccessful. Information retrieval was not always successful due to retirements, transfers, closed files, etc.

The issue of confidentiality was another difficulty encountered in this study. During the course of the study, a great number of landfill sites were implicated with soil gas migration problems. Unfortunately, the most informed parties in such cases were normally municipal officials. Although many officials cooperated very positively, others did not. Many officials were clearly nervous about possible litigation or were worried about people's personal property. In such cases, officials were willing to only vaguely discuss problems; however, they frequently did not support such comments with documentation. Where remediation efforts were successful, reports were more easily obtained. Case studies involving the intrusion of gasoline vapours was one particular type of problem which was often clouded in confidentiality. Petroleum companies or their consultants were sceptical about releasing such information due to concerns for litigation.

In order to minimize the concern for confidentiality, assurances were given in this study that information was intended purely for scientific purposes. As such, identifying information concerning the location of various residences, individual's names, etc. has been omitted when requested. In a few cases, identifying information relayed to the consultant was deleted. It is the intent of this study to limit such information, since it is beyond the scope or purpose of this study.

A fourth limitation in the results of this study had a somewhat minor impact. As this study was conducted, a great number of case studies involving the influx of soil gases from petroleum spills were encountered. Since many of these spills had very limited indoor air quality data, and many of these spills were handled in a similar fashion, only select case studies were cited for each region across Canada. Case studies presented in each region were typical for that specific region.

The fifth limitation was introduced by the investigators of this study. As this study progressed, it became apparent that significantly more soil gas problems were encountered in areas of higher population densities. Consequently, a bias was introduced since a significant effort was aimed at soil gas problems within major centres. This resulted in several areas of the country not being investigated thoroughly. The Northwest Territories and the Yukon were included in this category. Although some effort was made to obtain information of soil gas entry, no cases were identified. However, given the preferred construction practices of crawl spaces as opposed to basements, and the presence of permafrost, the possibilities for soil gas entry were limited. As such, it is felt that a bias in the search towards urban centres was warranted.

METHOD OF ANALYSIS

The concentrations of soil gases indoors can vary significantly over time and space within any building structure. In fact there is very little consistency in concentrations at any one location. This variability in concentrations is in part due to pressure-dependencies across the building envelope, source production rates, subsurface travel pathways, leakage areas, ventilation rates, as well as possible storage mechanisms. Or simply, to state it another way, the assessment of indoor air is simply not just a matter of taking a set of isolated readings indoors and making an assessment. It also requires a recognition of other factors such as a temperature difference, precipitation events, indoor activity, geological considerations, etc. These factors can influence both the production and entry rates of gases towards the indoor environment.

During the retrieval stage of this project, the project team attempted to obtain as much indoor air data as possible. By collecting as much data as possible, it was hoped that some description of the variability could be documented. Unfortunately, very few studies had sufficient amounts of readily available indoor data. There was even a greater dearth of information related to the other factors (listed above) which could have influenced soil gas entry. This lack of data made it difficult to either substantiate the assessment of the problem or the occasional recommended remedial method.

The discussion about the results given later in this text will evaluate the results with respect to the above considerations. Although this approach may in fact unjustly discredit or raise uncertainty with respect to either the analytical approach applied, or the recommended remediation schemes, valid conclusions cannot be reached without consideration for the above factors.

Section 3
STUDY RESULTS

PROVINCIAL OVERVIEW

The types and occurrences of soil gas infiltration and the resulting indoor air quality problems varied across the country. The most abundant soil gas problem reported was due to petroleum spills (whether it was gasoline or heating oil), followed by problems related to gases from landfill sites. The jurisdictional authority (or investigating parties) also varied. Although fire marshals and health officials typically had legal jurisdiction in terms of eviction for health and safety reasons, their involvement in many soil case intrusion cases was often limited or non-existent. Table 1 is a summary of the most frequent types of soil gas entry encountered in each province and the various agencies which have been involved in soil gas entry problems. A commentary on the types of soil gas infiltration common to each province and how such problems are handled are described in greater detail in Appendix F. A brief description of the common soil gas types with respect to the regions within Canada is given below.

EASTERN CANADA SECTOR

The most common soil gas entry problem identifies in the eastern sector (encompassing the Atlantic provinces and Quebec) was related to the spillage of petroleum hydrocarbons. As seen on Table 1, soil gas infiltration of gasoline and home heating fuel vapours, were common to nearly all provinces within the eastern region. Estimates vary from province to province, however there are a reported 100-150 gasoline and 400-500 domestic fuel oil spills annually in Nova Scotia alone (P. Nunn, personal communication, 1990). Although not all spills have affected indoor air quality, many spills may cause vapours to enter the weeping tile, or sewer systems, and through holes or cracks in the foundation. Whenever a spill occurs, the Department or Ministry of the Environment is normally the first jurisdictional body to investigate. Air monitoring is normally completed by the potentially responsible party or their consultant under the direction of environment officials. Typical instrumentation may include explosimeters, photoionization detectors, and occasionally flame ionization detectors. If explosive concentrations are encountered, the Fire Marshal's office may be informed; the fire marshal has the jurisdiction to evacuate residents. Health concerns are normally referred to the Department of Health, however in this survey, very few cases were identified where health officials were involved.

Solutions to indoor air quality problems due to petroleum hydrocarbon spillage typically centre on source control. Source control of a hydrocarbon spill may include soil excavation, installation of drainage ditches and the flushing of sewers. Excavated soil is normally disposed of at a local landfill and used as daily cover. In some cases, remediation by soil vacuum extraction, bioremediation, and groundwater pumping has been implemented. In other cases where remediation is more difficult, such as

Table 1
Types of Soil Gas Problems
Identified by Province

Province	Most Common Soil Gas Problem(s)	Other Types of Soil Gas Problems	Jurisdictional Authority
Newfoundland/ Labrador	• gasoline spills	• heating oil spills • landfill • industrial backfill • chemicals from groundwater • chemicals in backfill	• Department of the Environment and Lands • Ministry of Health • Fire Marshal's Office
Nova Scotia	• heating oil spills • gasoline spills	• landfill • pesticide dumping • coal gases	• Department of the Environment • Department of Health and Fitness • Fire Marshal's Office
New Brunswick	• gasoline spills	• heating oil spills • chemical spill in sewer	• Department of the Environment • Municipalities • Fire Marshal's Office
Prince Edward Island	• gasoline spills	• heating oil spills	• Department of the Environment • Department of Health
Quebec	• gasoline spills • landfills	• toxic landfills	• Ministry of Environment • Ministry of Energy and Resources • Municipalities
Ontario	• gasoline spills • landfills	• toxic wastes • radioactive wastes	• Ministry of Environment • Ministry of Health • Ministry of Labour • Municipalities • Fire Marshal's Office • Ministry of Natural Resources
Manitoba	• gasoline spills • landfills		• Department of the Environment • Municipalities
Saskatchewan	• gasoline spills	• landfill	• Department of Environment and Public Safety • Muncipalities
Alberta	• gasoline spills	• methane from natural sources • coal gases	• Alberta Environment • Fire Departments
British Columbia	• gasoline spills • methane from organic matter	• landfills	• Ministry of Environment • Ministry of Health • Municipalities

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contaminated soil underneath the building, petroleum companies will consider purchasing the building. This option is viewed as acceptable due to public pressure and legal considerations. Standards used for effective cleanup appear to be motivated by either olfactory evidence or groundwater issues. In the case of home heating oil spills, sometimes environment officials are not even notified.

Soil gas infiltration due to methane from landfill sites, particularly in the Atlantic provinces is very limited. One landfill in St. John's, Newfoundland, and another site in Kentville, Nova Scotia has/had methane migration potential into nearby buildings. The reason for the low number of landfill problems is the lower demand for land. Quebec, on the other hand, has several sites where methane from landfills has been found to be of concern. In the City of Montreal, several landfills have caused the City or individual owners to implement remedial measures.

One other type of methane problem was caused by soil gases emanating from previous mining activities. Two cases were documented in Nova Scotia where fractures in the bedrock underneath several buildings were confirmed or suspected of allowing the migration of methane.

CENTRAL CANADA SECTOR

The Central Canada Sector includes the provinces of Ontario and Manitoba. As indicated on Table 1, gasoline spills were cited as common sources of soil gas entry. In Ontario, there are hundreds of gasoline spills yearly. In Manitoba, there are approximately 125 hydrocarbon spills yearly. In both of these provinces, the Ministry or Department of the Environment are normally the first jurisdictional bodies to be contacted, although officially these departments do not preside over indoor air quality. Whenever such a soil gas problem is encountered within a municipality, municipal officials may also play a major role. Municipal officials will become involved in a gasoline spill, especially when entry through the sewer system is suspected. Health agencies may also play a minor role whenever health concerns are raised. Their involvement is however limited. Investigations where gas fumes are present commonly centre on source cleanup. Typical source control measures such as soil gas venting, bioremediation, and excavation of contaminated soil are routinely practised.

Landfill-based soil gas problems, another common source in Central Canada, are often found in municipalities where inner-city landfill sites exist, e.g. Hamilton, Ottawa, Kitchener, Sault Ste. Marie, Mississauga, Woodstock, Oshawa, and Winnipeg. Several of these centres have implemented source control measures (e.g. landfill gas extraction systems), whereas other centres have implemented controls at the point of impingement (house-based control measures).

Ontario also has a large industrial base. Soil gas problems associated with industry are poorly documented, likely for legal concerns, and are actually not well-known. Other incidents of radioactive gases infiltrating into homes have been identified where radioactive fill has been placed around buildings. Demolition of the structures is normally the action taken.

WESTERN CANADA SECTOR

Similar to the eastern and central Canada sectors, the most common soil gas entry problem identified in western Canada (Saskatchewan, Alberta, and British Columbia) was due to petroleum spills. Depending on the province, complaints of soil gases indoors were handled by various agencies including environmental, fire or health officials. Table 1 summarizes the responsible parties for each province. Although several government authorities enforce cleanups, the investigations are normally carried out by potentially responsible parties (e.g. petroleum distributers) or their agents. Remediation techniques typically employ vapour extraction, groundwater pumping, etc.

Methane infiltration was also identified as a problem in several centres. Methane originating from landfills (in British Columbia), and from natural organic sources, have posed problems for nearby residences. Typical mitigative measures such as active gas extraction systems, passive and air injection systems have been applied. Other house-based mitigative measures such as venting, and/or liners have also been installed on houses to eliminate the infiltration of gases. In Saskatchewan, concern of gas leakage from producing well sites has been cited as a potential problem. However, no cases of affected buildings were identified in this study.

SUMMARY OF TYPES OF SOIL GAS ENTRY

A summary of the various soil gas infiltration problems which were documented in this study are detailed on Tables 2, 3, 4 and 5 for the eastern, central, western Canada and international sectors, respectively. The summary presented on these tables is only a representation of different types of soil gas intrusion problems identified and does not represent a statistical occurrence of such problems within each region. Essentially there were three predominant groups of problems encountered including those related to petroleum hydrocarbons, methane sources, and miscellaneous volatile organic compounds. Although there were similarities in how such gases may enter homes, the measurement of the problem, the frequency of occurrence, and solutions implemented were slightly different.

PETROLEUM HYDROCARBONS

Although petroleum spills represent the greatest number of reported cases of soil gas entry, only a few cases are presented in Tables 2, 3, and 4, due to the similarity of approach. The degree of analytical effort involved in most hydrocarbon infiltration studies was generally minimal, stressing the identification of entry pathways and to a minor degree source concentrations. Influx of petroleum fumes occurred either from leaks of underground storage facilities or from home heating fuels.

Table 2
Summary of Eastern Canada Sector
Case Studies

Case No.	Gas Type	Problem Identification – Construction		Suspected Entry Point					Suspected Source/ Pathways	Recorded Source Conditions
		Pre	Post	Sewer	Cracks/ Floor	Open Hole	Weeping Tile	Unknown		
1	gasoline		✓			✓			Leaking UST/gravelly soil, plume near home	
2	petroleum		✓		✓				Leaking UST/snow cover, plume influenced by tides	
3	pesticides		✓				✓		Pesticide disposal/contaminated soil	
4	perchloroethylene		✓	✓					Illegal dumping/sewer source	
5	methane		✓			✓			Bootleg mine shaft/mine gases	
6	methane		✓					✓	Underground mines/fractured bedrock, mine gases	
7	petroleum		✓		✓				Fuel oil spill/pool under building	
8	methane		✓					✓	Nearby landfill/sandy soils	
9	solvent		✓	✓					Illegal dumping into sewer	
10	gasoline		✓					✓	Gasoline spill/sewer	
11	heating oil		✓					✓	Leaking UST/soil	
12	petroleum		✓	✓					Leaking UST/sewer	
13	gasoline		✓						Leaking UST/degassing of tap water, contaminated groundwater	
14	gasoline		✓				✓		Leaking UST/groundwater	
15	radon?		✓		✓		✓		Uranium contaminated backfill	
16	methane	✓							Landfill	
17	paint residues		✓	✓	✓				Paint manufacturer/floor, well cracks	
18	perchloroethylene		✓		✓				Illegal dumping/sandy soil, groundwater	
19	methane, VOCs		✓	✓	✓				Landfill/fractured bedrock	
20	methane, VOCs		✓					✓	Hazardous landfill	
21	methane	✓							Landfill/fractured bedrock	
22	methane	✓							Landfill/fractured bedrock	
23	methane	✓							Landfill	
24	landfill gases	✓							Landfill	
25	gasoline		✓	✓					Leaking gas pipe/sewer	

UST - Underground Storage Tank (for gasoline, heating fuels etc.)

Table 3
Summary of Central Canada Sector
Case Studies

Case No.	Gas Type	Problem Identification		Suspected Entry Point					Suspected Source/ Pathways	Recorded Source Conditions
		Construction		Sewer	Cracks/ Floor	Open Hole	Weeping Tile	Unknown		
		Pre	Post							
1	methane	✓							Built on organic fill	0.1 - 30% GAS (low generarion rate?)
2	methane	✓							Built on organic matter	
3	methane	✓							Landfill/fractured till, frozen surface	ND - 88% GAS
4	methane		✓						Landfill/fractured till, sand	0-65% GAS
5	methane		✓						Landfill	0-90% GAS
6	methane	✓	✓	✓	✓		✓		Landfill	0-30% GAS
7	petroleum, PERC		✓				✓		Leaking UST/sand	
8	gasoline		✓				✓		Leaking UST/road subgrade migration, clay soil	
9	methylnaphthalene		✓					✓	Built on contaminated soil	
10	methane	✓							Landfill	0-40% GAS
11	petroleum		✓	✓					Fuel spills/sewer	
12	methane		✓					✓	Landfill	
13	methane		✓	✓			✓		Landfill/sand and gravel	ND-55% GAS
14	methane	✓							Landfill	high concentrations?
15	gasoline		✓	✓					Leaking UST/sewer	
16	methane	✓	✓						Landfill	
17	methane	✓							Landfill	
18	petroleum		✓		✓		✓		Leaking UST/sand	
19	methane, VOCs		✓		✓		✓		Landfill, illegal dumping	
20	fuel oil		✓					✓	Leaking UST	
21	methane		✓				✓		Decomposing woodchips	
22	trichloroethane		✓						Illegal dumping	
23	methane	✓							Landfill	ND-50% GAS
24	methane		✓	✓	✓				Landfill/utility corridors	.02-80% GAS (high production rate)
25	methane		✓	✓	✓		✓		Landfill/utility corridors	.057-78% GAS (0-250 Pa)

Table 3
Summary of Central Canada Sector
Case Studies

Case No.	Gas Type	Problem Identification		Suspected Entry Point					Suspected Source/ Pathways	Recorded Source Conditions
		Construction								
		Pre	Post	Sewer	Cracks/ Floor	Open Hole	Weeping Tile	Unknown		
26	methane		✓					✓	Landfill/utility corridors	trace - 79% GAS
27	methane		✓					✓	Landfill/fractured till	
28	methane		✓		✓		✓		Landfill	1-75% GAS
29	methane		✓						Landfill/unsaturated sand	ND-7.5% GAS
30	methane		✓						Landfill/clayey silty soils	10-14% GAS
31	methane		✓						Peat bogs	
32	gasoline		✓					✓	Gas spill?/granular base of sewer	
33	methane		✓						Landfill	
34	methane	✓							Former swanp, organic fills	4-66% GAS
35	gasoline		✓						Leaking UST/sand,gravel	
36	radon		✓						Mine tailing backfill	
37	methane		✓		✓				Landfill	up to 40% GAS
38	methane		✓		✓		✓		Landfill/sand	50 Pa (high production rate)
39	methane	✓							Landfill/sand	up to 92% GAS
40	methane	✓							Landfill	
41	heating fuel		✓		✓				Leaking UST/outwash sands	
42	heating oil		✓		✓				Leaking UST	
43	methane		✓						Landfill/sands,gravel	up to 60% GAS
44	methane		✓						Landfill	10% GAS
45	methane		✓					✓	Landfill/sandy soil	up to 35% GAS
46	methane, VOCs	✓	✓		✓				Landfill	ND to 70% GAS (up to 380 Pa)
47	sulphur, VOCs		✓	✓					Hazardous waste landfill/sewer	
48	methane								Landfill/sand	>1.5% GAS?
49	gasoline		✓						Gasoline spill/silty strata	>100% LEL, pooled product
50	gasolinc		✓						Gasoline spill	up to 1500 ppm
51	gasoline		✓						Leaking UST/alluvial sand deposits	

UST - Underground Storage Tank (for gasoline, heating fuels etc.)

Table 4
Summary of Western Canada Sector
Case Studies

Case No.	Gas Type	Problem Identification: Construction		Suspected Entry Point					Suspected Source/ Pathways	Recorded Source Conditions
		Pre	Post	Sewer	Cracks/ Floor	Open Hole	Weeping Tile	Unknown		
1	methane	✓							Peat, organic fill	negligible to 40% GAS
2	methane	✓							Peat	negligible to 2% GAS
3	methane		✓						Peat, wood waste	trace methane
4	methane		✓		✓				Peat, organic matter	>18% GAS
5	methane		✓					✓	Landfill/sand	explosive indoor conc.
6	methane	✓							Landfill	up to 65% GAS
7	methane	✓							Wood wastes, mulch, peat	up to 60% GAS
8	methane	✓							Peat, organic fill	
9	methane	✓							Peat, wood wastes	up to 70% GAS
10	methane		✓					✓	Peat	
11	methane	✓							Landfill	
12	methane		✓					✓	Landfill/sandy soil	high concentration in sewers
13	methane	✓							Landfill	up to 20% GAS
14	methane	✓							Landfill, industrial waste	
15	methane		✓					✓	Landfill	
16	methane		✓						Landfill	
17	methane, H_2S	✓							Marsh lands	
18	odours, H_2S	✓							Former chem. plant-spills?, dumping?	
19	VOCs, methane	✓							Industrial, chem. spills & waste.	toxic compounds present
20	sewage		✓	✓					Sewage organic waste	
21	hydrocarbons		✓					✓	Leaking UST	
22	gasoline		✓		✓	✓			Leaking UST/gravel, silt cap	pooling under buildings
23	gasoline		✓					✓	Leaking UST/gravel	pooling under some buildings
24	gasoline		✓					✓	Leaking UST	large distribution of vapours

UST - Underground Storage Tank (for gasoline, heating fuels etc.)

Table 5
Summary of International Sector
Case Studies

Case No.	Gas Type	Problem Identification: Construction		Suspected Entry Point					Suspected Source/Pathways	Recorded Source Conditions
		Pre	Post	Sewer	Cracks/ Floor	Open Hole	Weeping Tile	Unknown		
1	VOCs, pesticides		✓		✓		✓		Toxic dump/groundwater transport	myriad of toxic wastes
2	methane, CO_2		✓		✓				Landfill	explosive levels
3	methane, VOCs		✓					✓	Landfill/undersaturated aquifers	up to 90% GAS
4	VOCs		✓						Superfund site/groundwater transport	
5	VOCs		✓					✓	Manufacturing facility/groundwater transport	
6	methane		✓	✓			✓		Landfill/sand soil	
7	methane, VOCs		✓					✓	Landfill/fractured bedrock	>5% GAS

The method of entry of soil gases typically travels from the source to the home through the path of least resistance. As seen on Tables 2, 3, and 4, several preferred pathways exist for the migration of petroleum vapours including: sewer systems, or higher permeable geologic pathways such as sand and gravel. Once such gases have entered the building envelope, entry can occur either through cracks (such as floor/wall joints), through the pore space in the concrete, locations where no wall, floor or foundation exists (as in a dug-out basement), or through the weeping tile system (especially when it is terminated at a sump pump indoors). These various entry points (with the exception of entry through the concrete pore space) were cited in many of the gasoline entry investigations. In some cases, the exact point of entry may not have been known or went undocumented; therefore it is indicated as such on the summary tables.

In order to conduct a thorough analysis of indoor air contamination, the nature of the contributing source must be well understood. Unfortunately many investigations concerning the spillage of gasoline products have tended to focus primarily on soil and groundwater contamination; indoor air concerns were normally treated as a secondary issue. Therefore, information on the source conditions of gasoline spills, (i.e. concentration of specific compounds and soil gas pressure), are normally quite vague. Of all of the studies which were reviewed, on no occasion was the soil gas pressure or concentration of specific compounds recorded during the investigative phases of the program. Similarly, influences on the soil gas pressure such as barometric effects, rainfall events, fluctuating water-tables, stack effect, etc. were never documented (or even mentioned). Although individual cases studies which were referenced here likely have more specific information beyond which was retrieved by this study, such information is normally limited and quite frequently in non-useable form for indoor air studies.

Despite the generally limited descriptions of petroleum source concentrations, one trend was nevertheless apparent from the data that was collected. Of the various case studies involving gasoline vapour transport through soil and into the indoor environment (excluding those related to the sewer pathways), most of the studies had either a source of pure-phase product or a severely contaminated groundwater plume near or underneath the building affected by soil gas infiltration. Four of the five eastern sector, five of eight central sector, and three of four western sector petroleum hydrocarbon case studies had some form of plume underneath the building whenever indoor air contamination was identified. Many of the other case studies had insufficient data for comparison.

METHANE

The most documented cases of soil gas entry across Canada dealt with methane intrusion. Methane intrusion has long been recognized as a safety problem, and consequently has been the subject of many investigations. Two main sources of methane have been known to cause problems for buildings. These include man-made sources such as mining activities or landfill sites, and natural sources such as degassing of natural peat deposits or petroliferous bedrock formations.

Throughout this survey, it was discovered there were essentially three types of methane studies carried out. The first type of study was a general audit. Such a study, usually conducted by municipalities, was aimed at documenting any zones of potential methane hazards, and/or investigating homes/businesses where such hazards existed. Typically, such investigations were restricted to areas within jurisdictional boundaries. If problem areas were discovered, the municipality would in turn restrict building permits or implement action plans to remediate the problem. The two other types of studies were typically carried out when a potential problem had been identified. The second type of methane study, carried out by or for developers, was conducted on lands where previously methane had been suspected or confirmed. The objectives of such studies normally centred around determining the potential for subsequent methane build-up, and recommending appropriate preventative technologies to ensure safety of future occupants. The developer was normally forced to satisfy the concerns of other municipal or environment officials before building permits were issued. Table 2, 3, 4, and 5 summarize the cases where the problem was identified prior to construction and preventative measures were consequently implemented. The third type of study was conducted whenever homes/businesses were affected by some methane source. If the methane discovered was due to natural conditions, the owner normally was faced with remediation costs, whereas if man-made actions had caused the problem, the owner of landfill sites was normally held responsible.

The majority of landfill based methane problems was encountered in the more populated centres such as Montreal, Ottawa, Toronto, London, Kitchener, Winnipeg and Vancouver. Previous indiscriminant dumping, and/or the high demand for developable land has resulted in buildings being constructed on or near lands affected by methane gas. Conversely, methane problems related to natural sources such as degassing of peat or petroliferous bedrock is found in both rural and urban settings. Such settings are common in low-lying lands or where gas producing bedrock exists.

As with all soil gases, methane will follow the path of least resistance from the source to the point of impingement. The results of this survey suggested that the length of this pathway could be anywhere from several metres up to 900 m, as in the case of Seattle, Washington. A significant number of homes in this study were identified as being built directly on/adjacent to refuse or organic matter, or the houses were connected to permeable geologic pathways, including fractured rock, fractured till, utility corridors and sand and gravel deposits. Providing that the building envelope intersected such pathways, methane was detected at the most common entry points including sewer or utility lines, cracks in the floor, through the concrete pore space, through open holes, and the weeping tile network.

In contrast to gasoline spill investigations (discussed previously), more effort is typically aimed at understanding soil gas source concentrations. As seen on Tables 2 to 5, most case studies which documented methane intrusion had some degree of source quantification. In most cases, this quantification consisted of methane concentrations in the soil air. Typically, such values were derived from field measurements on portable equipment. Actual values reported on Tables 2 to 5 reflect both spatial and temporal variations of source areas. As shown on Tables 2 to 5, concentrations of methane have been reported from non-detectable to as high as 92 percent methane-in-air. Although a concentration of 92 percent GAS (or methane-in-air) is likely erroneous, it is clear that significant concentrations of methane in the soil air are possible.

Despite the detailed description of soil gas concentrations, significantly less studies documented the soil gas driving force. Although such information as gathered in this survey may have been occasionally been missed or was unavailable, it is still apparent that many investigations have not included such information. Several studies also chose to calculate gas production rates to define the mass balance for methane production. In general, however, such data was not gathered as part of investigative studies.

MISCELLANEOUS VOLATILE ORGANIC COMPOUNDS

The last class of compounds to be reported on here are a group of compounds which will be referred to as miscellaneous VOCs. The types of VOCs discussed here will be defined specifically as those VOCs derived from landfills or any other non-petroleum source. Although the actual travel mechanisms and subsurface pathways are similar to the previous two types of compounds, and although VOCs form the basic building blocks of petroleum fuels, the occurrence of miscellaneous VOCs, as defined here, is much less frequent, and the analytical protocol tends to be much more comprehensive. Since the cases surveyed here typically were of high public profile, the increased effort for a more thorough analytical protocol was warranted. Analytical methods usually included both portable equipment for screening purposes (e.g. photoionization detectors, flame ionization detectors, explosimeters, solid adsorption tubes, etc.) and sampling pumps, cartridges, evacuated canisters for more precise laboratory measurements. Investigations involving other types of gases identified above, (i.e. hydrocarbons and methane), rarely included such comprehensive methods.

Indoor air contamination by miscellaneous VOCs resulted from soil gases migrating from three different sources:

- spills into the sewer system
- contamination from nearby commercial/industrial activity
- landfills which accepted industrial wastes

Tables 2 to 5 summarize the various case studies where the miscellaneous VOCs were documented. With the exception of one case study (western sector case #19), all problems were identified after the buildings were in place.

MONITORING

Given the spatial and temporal fluctuations and differences of soil gas intrusion, one of the most important facets in a soil gas investigation is a good monitoring protocol. This fact is true for investigative phases, and also for the long-term performance evaluation. The type of protocol used will vary depending on the type of soil gas present. Two types of monitoring will be discussed here: monitoring for methane gases; and monitoring for organic gases (which includes petroleum hydrocarbons and the miscellaneous VOCs). The information presented in this section will reflect information presented in Appendixes A, B, C, and D as well as additional documentation and telephone records obtained as part of this study.

METHANE MONITORING

Since methane infiltration has been recognized as a long-term often unpredictable problem, most municipalities which have known methane hazards are directly or indirectly involved in some longer-term monitoring program(s). Municipalities which are directly involved in a monitoring program typically administer such programs through the city/regional engineering departments or fire departments. Some municipalities which conduct their own monitoring include: Montreal, Ottawa, Toronto, Kitchener, Winnipeg, Seattle, and Madison, whereas others such as London, Calgary and Woodstock, have employed consultants to design and administer the programs.

Monitoring programs are used for several reasons. Programs are used for investigative programs, as a stand-alone tool (as opposed to remediation), as an interim measure until a physical control facility can be installed or repaired, or to ensure that control facilities are functioning properly.

Protocol

Different monitoring protocols have emerged due to variations in local conditions as well as the availability of funds. Although a complete treatise of this topic has not been undertaken here, since this is beyond the scope of this study, two programs will be presented below, including a program designed and implemented by Heath Consultants (1991) for the cities of London, Woodstock and Calgary, and a second monitoring program implemented by the City of Seattle.

The Heath program is broken down into two components: interior and exterior investigations. Interior monitoring programs would include: all buildings adjacent to a fill or natural producing methane site, the interior atmosphere of manholes or confined spaces where methane could collect, and ambient and point concentrations such as at floor cracks, well cracks, drains, conduits, etc. Exterior monitoring programs would include: all vent stacks located within the municipality, exterior bar test and grid patterns (carried once a year at known landfill and naturally occurring methane areas) and measurement of soil gas probes for pressure and methane content.

The frequency of monitoring may be conducted on a yearly, monthly, or weekly basis depending on the severity of gas infiltration at each location. Historical data on the combustible gas readings becomes the primary basis for determining the frequency of monitoring. The number of homes involved in this monitoring program changes form year to year and from season to season.

The yearly monitoring program is viewed as the minimum frequency for all buildings and manholes located adjacent to fill sites. Criteria used to assess if a house should be included in the yearly monitoring program are: proximity of the building or manhole to a methane producing site, insignificant parts per million of combustible gas readings found in the interior of the building or the atmosphere of a manhole, and low combustible gas readings detected in the soil at or near the property line for a building or adjacent to a manhole location.

The monthly monitoring program is usually conducted only during the "peak seasonal point" for methane gas migration. This program normally starts when heavy rains or a frost cap has developed, sealing off the ground from surface ventilation. Buildings which are identified as having constant gas infiltration are considered more at risk during the peak time from November to April. The frequency is therefore increased to once per month during this critical time period.

Where consistent gas readings are observed, or at locations extremely close to sources of soil gas, the monitoring frequency is increased to once or twice weekly. Locations where low methane gas concentrations exist in the interior of a building but high exterior combustible concentrations are found at foundation walls or adjacent to man-hole chimneys, a monitoring frequency of once a week is used. Locations where high L.E.L. to percent GAS readings are found in floor or wall cracks, conduits, drains, and in the ambient indoor air, the buildings are monitored twice weekly. These locations are closely watched, especially during heavy rains, wet snow, or days of low atmospheric pressure. Most of these locations are scheduled for installation of ventilation systems when money becomes available.

If during monitoring high methane gas concentrations are encountered, a stabilization program is implemented. For buildings with concentrations over 1,000 ppm (2 percent LEL), venting is accomplished by opening windows or by using emergency purge points. Purge points are drilled wells placed along the sides of a building. These points act as areas of least resistance when a negative pressure is applied. Experience has shown that a temporary purge can completely eliminate methane gas from around structures in minutes. Elimination of gases from manholes is accomplished with the use of explosion-proof exhaust fans. Municipal officials are informed of any unusual situations encountered during monitoring. The City Engineer is called in if ventilation is required.

The second monitoring program employed in Seattle Washington was implemented in response to methane infiltration problems encountered near the Midway Landfill (international case study #3). The program was established by several jurisdictional bodies including representatives from Seattle King Country Department of Public

Health, Washington Department of Ecology, the Kent Fire Department, and the Solid Waste Division of City of Seattle Engineering Department. The criteria for action were based on gas levels (highest concentrations found in a building) found inside individual homes/businesses. The gas action levels are summarized in Table 6.

Table 6
Summary of Gas Action Levels Inside Homes/Businesses
(Seattle, Washington)

Gas Level	Action
0-50 ppm	Consider ambient air; normal condition
50-100 ppm	Monitor as frequently as staff size permits
100-500 ppm	Monitor daily
500 ppm and up	Monitor daily, seal cracks, highlight home on data sheet, request owner to ventilate
1,000 ppm and up	Verify with 2nd meter and methane unit, seal cracks, install alarm, fan, monitor daily, notify Health Department and Kent Fire Department
5,000 ppm and up in atmosphere	Evacuate, call 911
10,000 ppm and up in wall or small confined space	Evacuate, call 911
40,000 ppm and up	Point source, evacuate, call 911

The decision to evacuate a home/business is viewed as far more serious than other decisions. On such occasions, the Health Department (business hours) or the Fire Department (after business hours) are called. The inspector would explain the situation and describe any mitigating circumstances. Therefore, at any point, the Health or Fire Department could make a decision. If the decision is made to evacuate, a uniformed Fire Department employee could be called by the investigator. The evacuees are also given the option of calling the media; a list of media contacts would be provided. Unless told otherwise, names and addresses are kept confidential. The above protocol are viewed as giving the field staff definite guidelines for interpreting methane data and give the authorities flexibility to reach a decision.

It should be noted that the two monitoring protocols described above are some of the more comprehensive programs implemented. Many other undocumented programs which are implemented tolerate substantially higher methane levels and do not have imposed action criteria.

Equipment

Some of the most common types of monitoring equipment used for detecting the intrusion of methane from soil gas sources are summarized on Table 7. Additional tools not listed may include plunger bars, monometers and pressure gauges. Of the instruments shown on Table 7, the combustible gas indicator is by far the most common measurement tool used. Monitoring equipment based on the flame ionization detector (FID) is

Table 7
Summary of Monitoring Equipment Commonly Used in Soil Gas Entry Assessments

Type of Equipment	Measurement	VOCs Investigation	Methane Investigation	Principle of Operation	Limitations
Combustible Gas Indicator	ppm, %LEL, %GAS, (±40%)	✓	✓	Combustible gases change electrical resistance of a wheatstone bridge	• cannot be used in presence of silicones, fuming acids, leaded gasoline vapours, silanes • not accurate in low oxygen or high CO2 environment • relative humidity 10-90% • zero shift problem in ppm range • non-selective
Colourimetric Detector Tubes	ppm, %GAS, (±5% to 40%)	✓		Chemical reaction to produce a colour change	• difficult to assess unknown atmospheres • high humidity can affect results • interferences
Photoionization Detector	Typically 0 to 2000 ppm	✓		Electrons are ionized by ultraviolet light and measured	• high humidity will affect results • non-selective • response not necessarily liner • radio frequency interference
Flame Ionization Detectors	0 to 10, 0 to 100, 0 to 100 ppm	✓	✓	Vapours are burned and ionization occurs, ions are measured electronically	• different response to volatile compounds • when used in GC mode, there is no temperature control • non-selective in survey mode
Oxygen Meter	0 to 25% GAS	✓	✓	Atmospheric O_2 measured on a galvanic cell	• corrosive environments may damage some cells • barometric pressure will affect readings • relative humidity 10 to 90%
Carbon Dioxide Meter	0 to 5000 ppm, 0 to 10% GAS, 0-100% GAS		✓	Infrared adsorption	• different instruments may be required for both indoor and outdoor applications
Portable Gas Chromatograph	ppb, ppm	✓	✓	Column with FID, PID or ECD	• for accurate ppb measurement calibration gas required

also used, but to a much lesser degree; a portable gas chromatograph is hardly ever used.

The combustible gas indicator (CGI) has many advantages. Not only is the instrument portable and easy to use, the newer instruments frequently offer multiple ranges (i.e. ppm, percent LEL, percent GAS) for both indoor and outdoor use. In view of these advantages, many agencies and consultants have widely used this instrument for monitoring purposes. The combustible gas indicator has for the most part provided adequate results in many monitoring programs especially where no specific action levels have been specified. However, when stringent action levels are specified, such as in the case of Seattle, Washington (refer to Table 6), the use of the CGI can suffer from some serious limitations.

The most serious limitations are experienced with the CGI when low gas concentrations are present. Based on testing commissioned by the Washington Department of Ecology (1986), the CGI can experience zero shift problems as much as 200 ppm, and a strong upscale response due to elevated carbon dioxide and moisture. Such limitations make the use of such an instrument unreliable, especially when measurements of less than 50 ppm become significant (e.g. background as defined on Table 6).

Criteria

As part of this survey, an effort was made to obtain information pertaining to criteria used for indoor air assessments. In the case of methane, this criteria related primarily to potential safety hazards. Of the cases reviewed, very few cases actually had any documented criteria; in several instances, such criteria was only based on the recollection of individuals involved. In most cases, however, criteria was derived or negotiated on an individual basis.

Table 8 is a summary of the available criteria applied for both methane and volatile organic compounds. As seen on Table 8, six methane case studies had reference to some target criteria. As seen on Table 8, five cases underwent evacuation. A common criteria applied for evacuation purposes was 10 percent LEL or 5,000 ppm. This criteria was referenced in eastern sector cases #5, #6, central sector case #46, and international sector case #3 (refer to description of monitoring for Seattle, Washington, above). In discussing the criteria used in the eastern sector cases with the Fire Marshal, he indicated that a similar criteria was used in the mining industry. The 10 percent LEL standard used in eastern sector cases #5, #6 was based on the mining criteria. In the case of central sector case #10, a monitoring program was designed to evaluate the remediation scheme. The standard used was based on 1,000 ppm indoors when active/passive venting was occurring. Based on telephone records at the time, environment officials "would be concerned" about any concentrations indoors of 1,000 ppm. It was not apparent what action would have ensued.

Table 8
Summary of Criteria Used for Indoor Air Assessment

Gas Type	Sector	Case No.	Evacuation	Criteria
Methane	eastern	5	✓	10% LEL
		6		10% LEL
	central	10		1000 ppm
		46	✓	10% LEL
	international	3	✓	<1000 ppm for 2 week period at low barometric pressure
		7	✓	methane >5% GAS (adjacent to homes)
Petroleum	eastern	1	✓	Occupational TLV standards
		10	✓	10% LEL
	central	11	✓	fumes dissipated
		18	✓	C=0.238 x 1/SF x TLV (SF = safety factor) SF for benzene = 1000 SF for toluene = 100 SF for gas vapour = 100 comparison with typical indoor data
		42		0.1 ppm of total petroleum distillates
		49	✓	ambient air quality criteria (Reg 308, Ontario)
VOCs	eastern	20		Comparison with control houses
	central	46		ambient air quality criteria (Reg. 308, Ontario)
	international	1	✓	comparison with houses in a similar neighbourhood
		4		comparison with TEAM data
		5		comparison with TEAM data
		7	✓	10 ppb vinyl chloride (ambient air quality criteria)

The fifth criteria referenced on Table 8 was enforced in Seattle, Washington. Based on the description of the monitoring protocol above, evacuation would occur if a level of 5,000 ppm was recorded indoors. As it turned out, several homes and businesses were evacuated. As gas extraction wells were installed and operated, "acceptable" levels were once again established. However, as a safety precaution, additional criteria agreed upon by the Seattle-King County Department of Public Health (1986 a & b) and the Seattle Engineering Department was applied.

1. Evacuated homes/businesses could only be reoccupied after methane (taken from the highest concentrations found in a building) were controlled to levels of 1,000 ppm for at least a two-week period during which the barometric pressure dropped to 100.9 KPa or below on at least two occasions. Methane readings were required to be taken when the barometric pressure was at or below 100.9 KPa as locally measured.

2. Affected homes were also required to undergo further monitoring for methane per established action levels until the highest concentrations found in the building remained at or below 100 ppm over at least a two-week period under atmospheric and monitoring conditions previously referenced.

It should be stressed that the above criteria was not an initial evacuation standard but rather a reoccupation standard for those homes/businesses which demonstrated a significant problem.

The last case which had some form of criteria referenced was international sector case #7. The criteria applied here was somewhat uncertain because of the added presence of vinyl chloride. During the investigations, several homes around the BKK Landfill had methane concentrations around the homes in excess of 5 percent GAS. As well, inside the homes, vinyl chloride concentrations exceeded the ambient air quality criteria of 10 ppb. Evacuation of the homes was carried out immediately. The actual criteria for methane may have been overruled by the vinyl chloride standard. No further details were obtained.

During the survey, discussions were also carried out with several officials from various offices of the Fire Marshal. Based on these conversations, it was clear that the Fire Marshal has legal jurisdiction to evacuate when he/she perceives that a danger to occupants and property may occur. However, the safety criteria (i.e. 10 percent LEL) is neither documented in either the provincial or national fire codes. One official did make reference to a particular case study where a value of 20 percent LEL underneath the building was applied. This value is consistent with the value recommended by the Ontario Ministry of the Environment in a document "Guideline for Assessing Methane Hazards from Landfill Sites (MOE, 1987). This document states that "when barriers and control systems are required for protection of specific buildings, the system must ensure that methane is removed or prevented from entering the area outside the foundation and below the basement floor of the structures so that the concentration present is less than 20 percent of the lower explosive limit.

ORGANIC GASES MONITORING

The monitoring of organic gas indoors is commonly performed with a great deal less structure as compared to methane monitoring described above. The need for monitoring organic vapours has arisen in situations where petroleum vapours have migrated, where VOCs have degassed from contaminated groundwater, or where VOCs have been found migrating from landfills or dumps. Monitoring of these gases typically has been completed with the use of explosimeters, detector tubes, flame ionization detectors, photoionization detectors, portable gas chromatographs, or with stainless steel canisters, passive and active sampling on adsorbent material for later laboratory analysis.

Very few structured programs such as twice weekly, once monthly, etc. which is implemented for methane have been conducted for VOCs. The primary reason for the often limited level of effort involved in monitoring soil gas VOCs is the expense involved. This is especially true when precise measurements at low detection levels are required. Monitoring with precise instruments is normally much more expensive than the use of a portable handheld explosimeter. The drawback which results is that an accurate assessment of soil gas influx is difficult to achieve because of variable concentrations levels indoors in both time and space.

A second difficulty encountered in monitoring VOCs indoors is the problem of indoor sources. The emissions of building materials, and activities of occupants is well documented in the literature as contributing factors to the degradation of indoor air quality with respect to VOCs. White et al (1988) and Pellizzari et al (1987) have found that many indoor sources have many similar compounds as might be expected in soil gases originating from gasoline contaminated soil, or typical landfill components.

Despite the above mentioned difficulties in making an accurate assessment of soil gas contamination, the need for some form of decision has forced some investigators to use various practical approaches. One approach is based on establishing concentrations gradients between the subfloor, basement ambient air, and first or second floor living space. As long as the contaminant concentrations are elevated, a portable photoionization detector has proven adequate to establish migration of contaminants into the indoor air. In those particular cases, severe gasoline contamination was evident below the buildings, and reduced, but still elevated, levels were evident in the basement and main floor living areas. One other study (international case #5) although having significantly reduced indoor contaminant levels, also showed this trend.

Another approach commonly used depends on source identification. Once selected indicator compounds are found, sampling of indoor air and analysis for such compounds is carried out (Garbesi and Sextro, 1989). This approach can be successively used for assessment purposes when the subsurface flowpaths and pressure gradients are well defined, as shown by Garbesi and Sextro. However when subsurface mechanisms are not well defined (as in most indoor air assessments) or when concentrations have severely decayed or been influenced by retardation processes (Chiou and Shoup, 1985), chemical reactivity and biological degradability, the flux of gases has proven to be far more difficult to evaluate. Currently research aimed at resolving this problem is being undertaken; the results are expected shortly (CH2M HILL, 1990).

Equipment

With the increase in awareness of environmental problems and investigations, a great deal more equipment with increased precision capability has been introduced to the market. Some of the portable equipment used in measuring VOCs is listed on Table 7. Although most of these instruments lack the specificity for compounds detectable by laboratory analysis, they require less operator proficiency, provide more rapid results, are less costly, and have been shown to be reasonably effective in delineating subsurface soil gas and indoor air contamination.

Most all of the instruments shown on Table 7 have been used in VOC investigations at one time or another. The CGI and the photoionization detector (PID) are two types of portable equipment which are frequently used in the most common VOC entry problem, gasoline vapours. A third piece of equipment, the FID is also used but less frequently. In recognition that much of the equipment referred to above is used extensively for vapour investigations, several studies have documented the performance of such equipment (Robbins et al, 1990a & b). Although this equipment performed well for the most part, several limitations were discovered. A brief summary of these limitations documented by Robbins et al are summarized on Table 7.

Other equipment such as portable GCs may be helpful in limiting the above-mentioned problems. However, a limited number of studies have implemented the use of a portable GC primarily due to expense. No studies identified by this survey used a portable GC. Other methods of collection such as sorption tubes, etc. are described elsewhere (Lewis and Wallace, 1989). Although such methods offer precision, the availability of real time results are not possible.

Criteria

The criteria used for the assessment of indoor VOCs varied greatly. As documented on Table 8, the criteria used for the assessment of indoor air quality was based on olfactory evidence, occupational TLV standards, explosive concentrations, comparison with other typical indoor air concentrations, ambient air quality criteria, unknown criteria, and comparison with control houses or houses from a similar selected neighbourhood. With the exception of eastern sector case #10, and perhaps central sector case #11, all other criteria used were based primarily on health considerations. The wide variability in the approaches presented underscores that there are no relevant guidelines from either Provincial, State, or Federal health or environmental agencies.

One basis for indoor air criteria which have been used are based on TLV standards derived by the American Conference of Governmental Industrial Hygienists. As seen on Table 8 and elsewhere (e.g. Williams et al, 1990), both TLV or adjusted TOV standards (0.238 x TLV) for deriving 24-hour, seven-day a week exposures have been used. However, the applicability of using TOVs adjusted or not, are questionable since these standards apply only to occupational settings. The use of such standards do not apply to pregnant women or children.

Likely, in view of this concern, the regulatory agencies involved in central sector case #18 applied some additional adjustments based on a formula presented in Table 8. The use of safety factors of 1,000 for benzene, 100 for toluene, and 100 for total hydrocarbons may have provided the necessary protection for indoor air. Nevertheless, the regulatory agency involved eventually declined from enforcing such a strict standard. As detailed in Appendix B, the levels of contaminants measured eventually dropped to concentrations well within the range of typical homes. As such, the regulatory agency reversed their decision; the evacuation order was lifted.

Another group who also grappled with the use of adjusted TLVs were investigators at the Love Canal site (international sector case #1). After debating the issue of acceptable contaminant concentrations in the Love Canal Emergency Declaration Area, investigators rejected the use of "adjusted TLVs". This approach was judged to be inappropriate for two reasons. There was no generally accepted procedure for making this adjustment; therefore, the resulting value would be subject to debate and controversy. Secondly, it was felt that any extrapolation performed by the technical review committee would bypass the necessary and proper scientific, administrative, and public reviews that are involved in establishing these guidelines.

Despite the above reasons for not using TLVs or adjusted TLVs, the convenience of well established occupational guidelines will likely be applied well into the future, especially in lieu of the lack of specific indoor standards.

Another less common criteria used was the ambient air quality criteria (e.g. Reg. 308, Ontario). Primarily, ambient air quality criteria is used for the purposes of assessing outdoor air away from a specific source point. Although the implementation of this criteria may provide a safe environment for all individuals, it still suffers from the same limitations identified above for the TLV standards.

Whenever published criteria is not available, alternative approaches for evaluation of indoor air quality are considered. Comparison with the air quality in other homes was one such method used for evaluation purposes. International sector cases #4 and #5 used data from a USEPA TEAM study (Pellizari et al, 1987) to form an opinion on whether soil gas sources were contaminating indoor air. Although this approach showed some potential, a definitive evaluation of soil gas flux was not always possible, especially when low contamination values are being considered. Furthermore, these comparison techniques do not directly relate potential health issues.

A similar comparison approach was also used at the Love Canal site (international case #1). After a pilot study, however, it became obvious that ubiquitous chemicals not originating from the landfill greatly complicated the interpretation of the results. As such, an alternative approach which relied on identifying any detectable specific Love Canal indicator chemicals was implemented. This resulted in the comparison areas not be sampled. When the revised program was implemented, no indicator chemicals were found.

Two other methods of evaluation also considered at Love Canal were a risk assessment, and an epidemiological study. Both of these approaches were rejected. Because of the myriad of compounds, insufficient toxicological data, uncertainty about interactions, and the threat of new toxicological information, the risk assessment approach was rejected. The latter approach was viewed as inappropriate because it was concluded that it was difficult to detect effects of exposure to low-level environmental pollution in small population groups. Due to the displacement of inhabitants from the Love Canal area, this approach was regarded as inadequately sensitive to detect abnormal health concerns.

One indirect form of criteria not mentioned on Table 8 and in the discussion above, relates to indoor air contamination which occurs specifically due to petroleum spills. As mentioned previously, a major source of indoor air contamination across the country is due to petroleum spills. Whenever cleanup of these spills occurs, cleanup criteria for petroleum contaminated soils has traditionally been expressed in terms of maximum allowable concentrations of gross parameters such as oil and grease, total petroleum hydrocarbons or in some cases combustible vapour concentrations (Williams et al, 1990). In some cases, numerical criteria has been developed for some of the more toxic and mobile motor fuel compounds such as benzene, toluene, ethylbenzene, and total xylenes (BTEX). The derivation of numerical criteria for the above compounds or gross parameters are often based on typical background levels, detection limits, land use, or allowable concentrations in groundwater.

There is a general recognition that the existing approaches to specifying and implementing cleanup criteria for petroleum contaminated soil have a number of limitations. Firstly, whenever gross parameters are used, such as oil and grease, the actual health risk cannot be determined since little is known about the variable composition or mobility of individual hydrocarbons. Secondly, health risks do not account for other relevant pathways such as vapour inhalation. Because of these factors, it is possible that many sites which now have "acceptable" levels of petroleum contaminations in the soil from a groundwater perspective may still have potential health concerns due to the vapour inhalation pathway.

REMEDIATION / PREVENTION TECHNOLOGIES

The term remedial technology, as referred to in this text, refers specifically to a technology which was implemented for the purpose of correcting a situation where soil gas influx was occurring. Such solutions are typically retrofit techniques implemented on houses which have been constructed without consideration for soil gas entry. Prevention technologies, on the other hand, perform similar functions but are normally installed as part of the original structure. Prevention technologies are incorporated either where soil gas had been previously identified or suspected prior to construction. A brief summary of the gas type, initial conditions, the remediation used, and the final reported conditions are shown on a case-by-case basis on Tables 9, 10, and 11. Tables 9, 10, and 11 correspond to case studies in the eastern, central and western sectors as presented in Appendixes A to C. Because of limited detailed housing information for the international sector cases, an additional table for the international sector is not presented here. Nevertheless, the control strategies used in the United States (i.e. international sector) are quite similar to those detailed on Tables 9, 10, and 11.

The various remedial or preventative technologies may be summarized under two strategies: source control or house-based control. Source control essentially attempts to control the soil gas at its source or in the pathway between the source and the building envelope. House-based control strategies are typically implemented within the building envelope.

There are three factors which affect the entry of soil gases: the persistence of the source, the pressure driving force across the building envelope, and the size of the leakage area (White, 1989). By limiting one or more of the above factors, the rate of soil gas influx can be affected. Summarized on Table 12 are the two control strategies, the technologies used, their affect, and limitations. A brief description of the technologies will be given below, however more detailed descriptions may be found in the commentary given in Appendix F.

In some cases identified in this survey, the control strategies described above were not used. In some cases, the demolition or the physical removal of homes, the ventilation of indoor air, or monitoring as a stand alone tool have been used. In general however, few homes are demolished, monitoring strategies are typically used only as stop gap measures, and the climatic conditions in Canada do not make the widespread use of indoor venting economically feasible.

As seen on Table 12, some of the technologies which are regarded as source control measures are also reported under the category of house-based control technologies. For the purpose of this discussion, source control will refer to remedial activities which are removed from the building envelope, at the source or in the pathway between the source and the building envelope. House-based control measures will deal specifically with techniques implemented within the building envelope.

Source Control Strategies

Source control strategies essentially attempt to eliminate the origin of the problem. Depending on the type of source and local conditions, either active or passive venting, liners, pressurized air curtains, groundwater pumping, bioremediation, steam extraction, or soil excavation have been implemented.

Table 9
Summary of Remediation
Eastern Canada Sector

Case No.	Gas Type	Initial Conditions		Remediation/Prevention*	Final Conditions	
		Around Building	In Building		Around Building	In Building
1	gasoline	cont. soil and GW	non-explosive fumes	excavation, venting		TLV objectives
2	petroleum	cont. soil and GW	fumes	tank removal	sludges removed	fumes subsided
3	pesticides	cont. soils	fumes	excavation, sealing		fumes subsided
4	perchloroethylene	cont. sewer	fumes	plumbing corrections	sewers clean	fumes subsided
5	methane	bootleg mine	explosive vapours	filling hole		ND vapours
6	methane	fractured bedrock	ND	no action		
7	petroleum	pooled product	fumes	GW pumping, SVE		
8	methane	60% GAS	ND	homes moved		
9	solvent	cont. sewers	odours	illegal dumping stopped	clean sewers	ND
10	gasoline	cont. sewers		evacuation		ND
11	petroleum	cont. soil	odours	excavation		
12	petroleum	cont. sewers	odours	tank removal	clean sewers	ND
13	gasoline	cont. GW	tap H_2O degassing			
14	gasoline	cont. GW	fumes in well	soil excavation	clean soil	ND
15	radon?	cont. backfill	indoor radiation	backfill removed	clean soil	ND
16*	methane			crawl space venting	landfill methane	ND
17	paint residues	cont. soils, sewers	fumes	investigation phase		
18	perchloroethylene	cont. soils, GW	fumes	excavation		
19	methane, VOCs		some gases	monitoring, GES (ongoing)		
20	methane, VOCs	cont. soils	nothing significant	demolition		
21*	methane			passive venting		effective
22*	methane			passive venting		
23*	methane			passive venting	landfill methane	effective
24*	landfill gases			passive/active venting	landfill gases	
25	petroleum	cont. sewers	explosive vapours			

Note: *Indicates problem was identified prior to construction, as such preventative measures were implemented.
SVE and GES are identical technologies. SVE tends to be cited when VOC cleanup is undertaken.

Abbreviations: GW - groundwater; cont. - contaminated; SVE - soil vacuum extraction; GES - gas extraction system (active); ND - non-detectable

Table 10
Summary of Remediation
Central Canada Sector

Case No.	Gas Type	Initial Conditions		Remediation/Prevention*	Final Conditions	
		Around Building	In Building		Around Building	In Building
1*	methane			passive venting	3,000 ppm	ND in basements
2*	methane			sub-slab venting		no complaints
3*	methane			GES	ND in area	
4	methane	likely ND	ND	passive venting		
5	methane	0 to 63% GAS		active, passive venting	ND (~2.8 kPa of suction)	
6*	landfill	0 to 30% GAS		plumbing corrections		
7	petroleum			active vents, excavation		
8	gasoline			SVE, soil excavation		
9	methynapthlene	cont. soil		demolition		
10*	methane	explosive concentration		passive, active vents	5% LEL	ND
11	petroleum		fumes	excavation		fumes dissipated
12	methane	explosive concentration	ND	monitoring		
13	methane	4 ppm to 16% GAS	detectable	active venting	ND	ND
14*	methane	high concentration		sub-slab venting		ND
15	gasoline		fumes	sewer flushing		ND
16*	methane			passive vents		
17*	methane			sub-slab venting		
18	petroleum		4500 ppm	SVE	negative pressures	>0.6 ppm
19	methane	detectable	detectable	passive vents		detectable
20	fuel oil		fumes	excavation of soil		ND
21	methane		explosive concentration	plumbing vented		
22	trichloroethylene		fumes	soil excavation		ND
23*	methane	20 to 60% GAS				
24	methane	.025 to 80% GAS	up to 58% GAS	demolition, monitoring		no change
25	methane		25 ppm	liner, passive venting		
26	methane			monitoring	1% GAS	ND
27	methane	low concentration		monitoring		

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Table 10
Summary of Remediation
Central Canada Sector

Case No.	Gas Type	Initial Conditions		Remediation/Prevention*	Final Conditions	
		Around Building	In Building		Around Building	In Building
28	methane	15 to 75% GAS	>5% GAS	active venting	trace	
29	methane		ND	monitoring		ND
30	methane	ND		monitoring		
31	methane		ND	passive venting		
32	gasoline		detectable	passive venting		
33	methane		no monitoring	passive venting		
34*	methane			liner, passive vents	ND - 18% GAS	ND
35	petroleum	pooled product	explosive concentration	steam injection		safe levels
36	radon	cobalt in fill	radioactivity	demolition		
37	methane	up to 40% GAS	>5% GAS	active venting	ND	
38	methane		explosive concentration	active venting	ND	ND
39*	methane			liner, air injection		
40*	methane			liner, air injection		
41	heating fuel	60 ppm	fumes	excavation, SVE	clean soil	ND
42	heating oil		0.30 ppm	SVE		<0.1 ppm
43	methane	50 - 60% GAS		active venting	ND (-12 to -203 Pa)	ND
44	methane			monitoring		
45	methane	up to 5% GAS		active venting		
46*	methane	up to 70% GAS	up to 55% LEL	sub-slab venting	~50% GAS	<50 ppm
47	VOCs			sewer flushing		
48	methane	>1.5% GAS		passive venting		
49	gasoline	pooled product	up to 700 ppm	SVE	remediation ongoing	0-40 ppm
50	gasoline	pooled product	10-100% LEL	SVE	15 ppm	0 ppm
51	gasoline		fumes	SVE, Pressurization		acceptable

Notes: *Indicates problem was identified prior to construction, as such preventative measures were implemented.
SVE and GES are identical technologies. SVE tends to be cited when VOC cleanup is undertaken.
Abbreviations: ND - non-detectable GES - gas extraction system (active) SVE - soil vacuum extraction

ONT51/92/rONT9396.021

Table 11
Summary of Remediation
Western Canada Sector

Case No.	Gas Type	Initial Conditions		Remediation/Prevention*	Final Conditions	
		Around Building	In Building		Around Building	In Building
1*	methane			liner	negligible to 40% GAS	ND (short term)
2*	methane			liner	negligible to 2% GAS	
3	methane	trace		passive vents	ND	ND
4	methane	>18% GAS	high concentration (cracks)	sub-slab venting		ND
5	methane		up to 14% GAS	pressurized curtain	ND to trace	ND
6*	methane	up to 65% GAS		sub-slab venting (passive supply)	ND	ND
7*	methane	up to 60% GAS		sub-slab venting	ND	
8*	methane			pressurized sub-slab		
9*	methane	up to 70% GAS		active venting		
10	methane			pressurized, passive		ND
11*	methane			liner		ND
12	methane	high concentration		GES, pressurization	clean	ND (in most cases)
13*	methane			active venting		ND
14*	methane			sub-slab venting, pressurization		
15	methane	detectable		GES, pressurization	ND	
16	methane	high concentration		pressurization	"a reasonable level"	
17*	methane, H_2S			investigation only		
18*	odours, H_2S			polyethene sheet		no odours
19*	VOCs, methane			liners, passive vents		no buildings
20	sewage			no action		
21	hydrocarbons			GW control, pressurization		ND
22	gasoline			passive vents		OK
23	gasoline	pooled product		SVE, ventilation		OK
24	gasoline	high concentration		SVE, sealing		ND

Notes: *Indicates problem was identified prior to construction, as such preventative measures were implemented.
SVE and GES are identical technologies. SVE tends to be cited when VOC cleanup is undertaken.
Abbreviations: ND - non-detectable GES - gas extraction system (active) SVE - soil vacuum extraction

Table 12
Summary of Remediation/Prevention Techniques

Parameter Controlled	Method of Control	Effect	Soil Gas Type	Limitations
Source control	active venting (gas extraction or soil vacuum extraction)	• source depletion • draw back soil gases	• methane • petroleum hydrocarbons • misc. VOCs	• depends on proper placement relative to gas transmission zone • aerobic conditions may be created, leading to pipe deformation or subsurface fires • proper and consistent monitoring/maintenance required
	passive venting	• limit flow of gas from source	• methane • petroleum hydrocarbons	• most success is achieved in shallow transmission zones • not extremely effective for petroleum based vapours
	liner	• impede gas flow from source	• methane • petroleum hydrocarbons	• may require pressurized air curtains
	pressurized air curtain	• impede gas flow from source	• methane	• proper and consistent monitoring/maintenance required
	groundwater pumping, bio-remediation, steam extraction, soil excavation	• source depletion (not considered as a vapour control)	• petroleum hydrocarbons • misc. VOCs	• not considered as vapour management controls
House-based control	sub-slab venting	• create negative pressure atmosphere below slab	• methane • petroleum hydrocarbons	• requires maintenance • may cause landfill fires due to overpumping
	active venting (soil vacuum extraction)	• create negative vacuum around building envelope	• methane • petroleum hydrocarbons	• requires maintenance • may not be well connected to sub-slab floor space • may cause landfill fires due to overpumping
	passive venting	• depressurize building envelope	• methane • petroleum hydrocarbons	• not sufficient for high subsurface production rates
	pressurized air curtain	• drive gases away from structure	• methane	• limited long-term data
	crawl space venting	• ventilation rate in crawl space exceeds soil gas influx	• methane	• limited performance data • requires maintenance
	liners	• increase resistance of gas flow into buildings	• methane	• limited long-term data
	sealing, caulking	• increase resistance of gas flow into buildings	• methane • petroleum hydrocarbons	• limited success has been documented
	plumbing corrections	• limit gases entering via plumbing or weeping tile network	• methane • petroleum hydrocarbons • misc. VOCs	• will likely only partially address problem
No solution	removal/demolition	• leave source	• radon • methane	• expensive, and frequently unnecessary

Most of the source control technologies implemented have proven quite successful. Whenever active venting is installed at landfills, or in soil contaminated with petroleum hydrocarbons or VOCs in zones where good connection with contaminant has been achieved, effective containment of soil gas sources as well as the depletion of the contaminant within the subsurface typically occurs. Passive venting is normally implemented at sites as a precautionary measure or where low gas production exists. Passive venting has been used for the mitigation of methane and also occasionally for petroleum hydrocarbons. Pressurized air curtains with or without the use of synthetic liners have been used as cut-off walls to impede gas flow from source areas. Effective containment of the source has been claimed providing that all subsurface pathways leaving the source area are intersected. Other source depletion technologies such as groundwater pumping, bioremediation, steam extraction, and soil excavation are widely used to remediate sites contaminated with petroleum hydrocarbons or VOCs. Such technologies are effective means of reducing source concentrations. Although source depletion will affect indoor air concentrations, the process is slow and therefore such methodologies cannot be considered as vapour management controls.

House-Based Control Strategies

Various house-based vapour control strategies have been implemented including sub-slab venting, active and passive venting, pressurized air curtains, liners, sealing, caulking, and plumbing corrections. House-based vapour control strategies attempt to either limit or redirect the pressure across the building envelope, and/or alter the size of the leakage area. Technologies which alter the subsurface pressure regime include: active or passive venting (sub-slab or around the perimeter of the building), pressurized air curtains, and crawl space venting. As long as the zone or pathway of subsurface soil gases is within the radius of influence of the control system, success can normally be achieved. Technologies which limit the leakage area include: liners, sealing, caulking and plumbing. Although all of these techniques have had documented success, with the exception of liners, some negative results have been published (e.g. First et al, 1966). Sealing, caulking and plumbing corrections have had success whenever isolated entry points have been identified, however, overall such methods have not been effective 100 percent of the time. Regardless, some municipal building codes may require sealing of sewer cleanout traps or sump pumps in the vicinity of hazardous lands such as landfill sites (e.g. Madison, Wisconsin). Although sealing cannot guarantee elimination of soil gas infiltration, such procedures are apt to help restrict soil gas entry.

Section 4
DISCUSSION

This section of the text will be devoted to discussing the advances and limitations pertaining to: the methods used for soil gas assessments, the remedial alternatives implemented and the criteria related to soil gas entry in homes. Although some discussion, in the form of specific comments or criticisms, has taken place in the previous results section (i.e. Section 3), here the emphasis will be aimed at an overall analysis of the situation. The following discussion will deal with the three types of indoor soil gases typically encountered within the Canadian context: petroleum hydrocarbons, methane, and miscellaneous volatile organic compounds.

The basis for this discussion will reflect the statements given in the Method of Analysis given earlier in this text (page 7); it will be briefly repeated here. The assessment of soil gas entry problems is complicated by variable time and space dependent contaminant concentrations. This variability is in part due to pressure-dependencies across the building envelope, source production rates, subsurface travel pathways, leakage areas, ventilation rates as well as possible storage mechanisms. In practical situations, a good understanding of all the above factors may not be feasible primarily for economic reasons, however an absolute definitive assessment of a soil gas intrusion problem is not possible without thorough consideration of the above factors.

PETROLEUM HYDROCARBONS

Petroleum hydrocarbons entering the indoor air environment, as seen in the previous section, possibly represents the most common type of soil gas problem encountered in Canada. Problems which are typically reported were found to be associated with: petroleum spills within sewers, vapours which travelled through permeable geologic material, and situations where product had migrated to the building envelope and contaminated water within the weeping tile system or soil adjacent to the structure. As mentioned, inherent in many of the investigations is that very little data is usually collected to provide a basis for an absolute definitive assessment of soil gas entry. Typically, the only parameters which are investigated are: isolated indoor air concentrations, possible entry pathways such as cracks, and some source concentrations. The contaminant concentrations additionally are often measured with equipment capable of determining gross parameter concentrations only. Although such an approach is often appropriate when contaminant concentrations indoors are high, whenever concentrations fall below thresholds imposed by instrument limitations, the evaluation of indoor effects is much more difficult. The lack of data with respect to: the specificity of organic compounds present, the pressure flow regime across the building envelope, the ventilation rate within the building, and the possible contribution of indoor sources make the evaluation of soil gas flux virtually impossible. The above approach is partly due to economic considerations, but is also frequently due to non-appreciation of all of the above factors by both regulatory and investigating personnel.

The impact evaluation of indoor vapours due to hydrocarbons has also likewise been difficult. Evaluations based on the risk assessment approach has two shortfalls. Firstly, due to the typical equipment used, there is generally a lack of definition of the individual hydrocarbon compounds present. Secondly, given the limits of most monitoring programs especially as they relate to temporal changes, an actual dose response function can normally not be determined. Other approaches such as using established criteria like ambient air quality standards, or threshold limit values are also inappropriate for reasons given earlier.

Despite the gloomy prognosis given above with regards to the present state-of-the-art soil gas investigations, there are still some redeeming facts as to how the problems of soil gas entry can be resolved. Whenever significant indoor air contamination results from a petroleum spill, home owners are often alerted by the odorous vapours. This is advantageous, since home owners can alert regulatory officials and are then not subjected to potential safety or long-term health concerns. When notified, regulatory officials and potential responsible parties generally agree to some urgent form of action.

Whenever a petroleum spill occurs, and the product does not find its way to the sewer system, it appeared that the most affected homes were those homes where product was present or near the building envelope. One of the tasks most commonly carried out initially at spill sites is a soil gas survey. The purpose of soil gas surveys is to identify the presence of pure product or contaminated groundwater. If such a survey is carried out properly, the groundwater plume can be determined, and therefore the zone of vapour presence can also be evaluated. There are few occasions where the vapour zone greatly exceeds the area of contaminated groundwater. In contrast, this is much different than the spread of methane where extremely large travel distances are common. Given that contaminant volumes are relatively stable over time due to the typically slow rates of groundwater movement, the zone of potentially affected homes can be generally quickly and accurately assessed.

Another positive aspect occurs when remediation is initiated. Remediation efforts are normally initiated soon after investigations have been completed. Soil vacuum extraction is a proven technology commonly implemented for depleting source concentrations when considerable volatiles are present. The use of such technology also creates a subsurface flow regime which minimizes soil gas entry into homes. Remediation typically continues until some appropriate soil or groundwater criteria is satisfied.

Other remedial methods other than soil vacuum extraction, have also helped to reduce indoor soil gas contaminants. Passive venting has been found to be partially successful in reducing soil gas pressures. This reduction in soil gas pressures will reduce the pressure gradient across the building envelope thereby limiting soil gas entry. Leakage area control methods such as covering of sump areas and sealing cracks has also at times been affective. Both of the above methods have not always been 100 percent effective.

Once the agreed cleanup goals have been reached, remediation is generally halted, leaving relatively low concentrations in the soil. Although in most cases such contamination will likely not have significant effects, there is still some uncertainty about long-term low dose effects of marginally contaminated soil, especially as it relates to vapour inhalation. Williams et al (1990) endorse this fact by suggesting that under typical conditions where the transport of vapours are controlled by building envelope details, a benzene concentration of only 5 ppb is sufficient produce a cancer risk above a commonly acceptable value of 10^{-6}. This health risk calculation was based on an adjusted occupational TLV standard for benzene. As can be appreciated, the typical protocol used for such investigations, as discussed previously, is normally inadequate to answer such concerns.

METHANE

Methane entry was the next most common soil gas problem reported. Sources of methane included both man-made (i.e. landfill sites) and natural sources (i.e. swamps or bedrock formations). The occurrence of methane has long been recognized as a potential safety hazard, and as such, a large number of studies have been conducted. As indicated previously, three types of methane studies were identified during this survey: a general audit, a pre-development assessment, and a post-development problem assessment. Each type of study will now be discussed.

As indicated previously, the general audit was typically carried out by municipalities to identify potentially hazardous areas. Several of such studies carried out across the country had some variations in the methods used. These variations, as seen in this study, may have reflected the state-of-the-art at the time which such studies were conducted, the local conditions, public perception/pressure, budgets, etc. Methods used for the evaluation process varied from comprehensive programs involving the definition of subsurface geologic pathways, installation of permanent monitoring probes, long-term monitoring programs of soil probes, utilities and indoor environments, to short-term programs involving only shallow punch probes with soil gas monitoring. Although the constraint imposed by budgets, etc. is a practical reality which all investigators have to face, the analysis of the results will be greatly affected by the degree of thoroughness exercised in the program. As a result, the interpretations reached would be based more on subjectivity as opposed to hard empirical data. Without hard empirical data, the municipality risks the possibility of a safety hazard.

Whenever a building lot(s) had been identified as having potential for methane migration, developers or potential responsible parties were faced with providing sufficient provisions to regulatory agencies to ensure protection for future occupants. Normally, site specific investigations carried out may involve measurement of gas production rates, pressures, and methane concentrations. (It should be noted frequently, many of the above parameters are not monitored or evaluated.) Recommendations for remediation, whether they be source control, pressure control, or leakage area control, were normally based on measurements taken in the field. In general, whenever soil gas concentrations were high, active systems and/or liners were recommended. Whenever gas concentrations were low, passive systems and/or liners were recommended. Based on the results presented, such measures generally have good performance records. In many cases (but not all) where methane was identified prior to construction and preventative measures implemented), as shown on Tables 9, 10, and 11, no adverse indoor air quality was documented. Many of the results, however, were based on short-term monitoring programs. Longer-term monitoring results are necessary for a complete assessment.

The third type of methane study involved the site-specific assessment where methane had been found to be infiltrating into buildings after construction. Sources of such methane may have been due to offsite or onsite sources.

Whenever offsite sources were implicated, source control options were normally implemented. Providing that a comprehensive assessment had initially taken place, remedial measures whether they be active or passive venting, pressurized air curtains, liners, or combinations thereof, were generally successful. On the other hand, whenever incomplete assessments were carried out, future problems could develop. Western sector case #12 and international sector cases #3 and #6 are only a few of the sites where initially insufficient details of possible subsurface geologic pathways were retrieved. Subsequent alterations were implemented. The need for thorough initial investigations is evident. Despite the initial success of many source control options, some systems are known to develop problems over time. Active systems require proper maintenance and monitoring since changing subsurface conditions have been known to cause deformation and flooding of subsurface piping. Passive systems, although believed by many to be maintenance free, have frequently been subjected to vandalism. Liners have been known to sag or be susceptible to rodent infestation. Changes such as mentioned above, have resulted in less than the initial design performance of installed systems. It is obvious that all systems require some form of maintenance and monitoring.

Whenever onsite sources have been implemented after construction has taken place, remedial alternatives have incorporated either pressure control or leakage control strategies, or combinations thereof. The principal technologies applied included both active (sub-slab, active, or crawl space venting) and passive measures. Preference of one technology over another was primarily based on gas production (or emission) rates. Sites with high production rates typically implemented active systems; passive systems were normally deemed adequate for sites with low production rates. It is noteworthy, however, that in very few studies gas production rates were actually calculated, nor was it common to find criteria documented as to what was considered high or low in gas production. One rule-of-thumb quoted by one practitioner was that passive systems are implemented when soil gas pressures are less than 125 Pa and methane is less than 50 percent LEL. No specific concern was given to possible temporal changes. This criteria certainly was not practised by all. Another mention of criteria for such decisions was referenced by Emberton and Parker (1987). Emberton and Parker note that an adequate number of air changes are required; however, they stress that no firm guidelines are in fact in place. Given the lack of specified guidelines, it is clear that some subjectivity will result in the analysis of such problems. In fact, some passive systems, as documented in this survey, were changed to active systems when found to be inadequate.

As seen in the above discussion of the three types of studies conducted for assessing and remediating methane soil gas infiltration, a certain degree of subjectivity on behalf of the investigator will normally exist. This subjectivity, whether it is due to the lack of initial thoroughness, inadequate monitoring programs, or specific criteria, is likely most critical in the early assessment phases. Unfortunately, no firm guidelines are currently in place even though guidance may be obtained from the U.K. building regulations where it is suggested that remedial measures may be necessary when methane concentrations in the ground exceed one percent (Emberton and Parker, 1987). Similarly, the Ontario Ministry of the Environment infers an identical guideline (MOE, 1987). Of the studies reviewed, not all homes in fact met such criteria. This is especially true of homes in Ontario assessed prior to the published guidelines.

Whenever remedial measures were implemented, it is obvious from the results of this survey that at least partial success can be achieved. Most of the solutions implemented typically were aimed at influencing one or more of the main factors influencing the movement of soil gas indoors. By influencing one or more of such factors, it is understandable that at least partial success could be expected. The main problem in identifying partial versus complete successes is probably due to the lack of adequate monitoring, and/or unclear or subjective action guidelines when elevated concentrations are encountered.

MISCELLANEOUS VOLATILE ORGANIC COMPOUNDS

The last type of soil gas entry reported in this document and most infrequently occurring was miscellaneous volatile organic compounds. The entry of VOCs into the indoor environment has many similarities with petroleum hydrocarbons especially when discussing appropriate criteria and the monitoring equipment necessary. Soil gas infiltration, as documented in this study, ranged from degassing of contaminated groundwater, vapour transport from a spill, to VOCs travelling with methane gases from a landfill site. The most common situation involving VOCs reported is the mixture of methane and VOCs travelling from landfill sites.

Of the cases reported, very few cases are documented where VOCs have caused significant concern. This partially due to:

- confusion in the interpretation of results due to other indoor sources.

- the adsorption and biogradation of VOCs in and on soil
- the lack of appropriate criteria for the assessment of indoor contamination

Although some work has been done to help quantify the contribution of soil gas to the indoor environment, similar to cases involving hydrocarbon spills, the need for comprehensive impact assessment methods is still outstanding.

Measures implemented for the remediation of VOC entry has included: demolition, excavation of soil, and active venting. Active venting is certainly the most efficient form of remediation and has been found to successfully reduce indoor VOC concentrations to background levels.

Section 5
CONCLUSIONS

The objectives of this study as outlined in Section 1, were to: identify incidents in which Canadian houses have had difficulties with soil gas infiltration; document how the soil gas had affected indoor air quality, and to document remedial measures and analyze the success of the same. The primary method of retrieval was by means of telephone interviews with environmental, health, and municipal officials. Although the aim was to provide a comprehensive coverage of all soil gas entry problems across Canada, limitations due to several reasons made this impossible. Nevertheless, a good representation of the types of soil gases typically encountered and how they were dealt with was presented in the previous sections.

The findings and the discussion of the findings as presented in this report are summarized below:

1. This survey identified three major types of soil gases which entered the indoor environments including: petroleum hydrocarbons, methane, and miscellaneous VOCs. The occurrence of petroleum hydrocarbons in the subsurface soil zone was the result of gasoline spillage or the local spillage of home heating fuel. Methane soil gases may have been present due to either natural sources such as peat bogs or petroliferous bedrock or man-made sources such as landfill sites or mining activities. The presence of VOCs was typically a result of degassing of groundwater plumes, local spills or from the migration of trace gases from landfill sites.

2. There were some geographical trends in the types of gases infiltrating into homes. Indoor air quality problems resulting from petroleum hydrocarbons were evident in all regions across Canada. Entry pathways occurred through the sewer systems, through permeable soil, or utility pathways. Methane problems however, were mainly encountered in major urban centres such as Ottawa, Montreal, Toronto, Kitchener, London, Winnipeg, and Vancouver where landfills were located near housing. These larger centres were frequently faced with requests for building permits on land affected by methane migrations. Those areas where the demand was not as great, such as the east coast, did not have similar problems. Suburban lots located on natural methane producing settings were identified mainly in Ontario and British Columbia. The occurrence of VOCs entering indoor air environments was generally sparse. No real trends could be identified.

3. During the course of the investigation, it became obvious that there was some variations in jurisdictional authority when dealing with soil gas infil-

tration problems. Typically, environment, municipal, health or fire officials provided advice regarding soil gas infiltration. In most cases not all agencies became involved, and not all agencies typically involved claimed jurisdictional authority over indoor air quality problems. Generally, however, health officials regulated health issues, fire officials had authority over safety issues.

4. The concentrations of soil gases indoors is known to vary significantly in both time and space. This variation is in part due to pressure dependencies across the building envelope, source production rates, subsurface travel pathways, leakage areas, ventilation rates, and possible storage mechanisms. In order to conduct a thorough assessment of soil gas impacts indoors, several parameters such as soil gas pressures, barometric effects, rainfall events, etc. are required. Frequently however, in many of the soil gas assessments reviewed, very few of these factors were recorded. Many of the studies conducted for the influx of petroleum hydrocarbons and VOCs neglected to include such factors. Some methane studies performed were reasonably complete, however, many such studies had major omissions.

5. For the assessment of a soil gas problem as well as for the recommendation of remedial alternatives, the implementation of appropriate protocol and equipment is imperative. Not only is the documentation of contributing factors (e.g. soil gas pressures) important, as discussed above, the timing or frequency of monitoring is also critical. Because of the strong influence of barometric pressure, rainfall events, frozen soil surfaces, and stack effects, the inclusion of data which considers these environmental influences is necessary for evaluating worst case conditions. In addition, the use of proper equipment is also necessary to perform such measurements. Although there are variation in possible implemented action criteria (if it exists), some investigating parties have tended to use equipment which is incapable of taking readings at "appropriate" levels or specificity to the contamination involved. This was true both for assessment of methane and petroleum hydrocarbons.

6. Many different types of remedial measures were implemented, but essentially these measures can be grouped into two categories: source control and house-based control. Source control measures, as defined in this text, are primarily aimed at either reducing concentrations or impeding the migration of soil gases at the source area. Typical source control measures for methane include: active and passive venting, pressurized air curtains, and liners installed in subsurface geological pathways. In cases involving petroleum hydrocarbons or VOCs, active venting, excavation of contaminated soil, groundwater extraction, bioremediation and steam injection have been used to minimize source concentrations. Of these

measures only active venting is considering as have a direct influence on soil gases.

The criteria used for making decisions of one technology versus another for methane gases, depends primarily on gas production rates. In general, if production rates are high, active systems are recommended. Conversely if production rates are low, passive systems are normally installed. The difficulty which does exist however, is determining what is an acceptable criteria. In some cases passive systems were installed only to be replaced by active systems when found to be ineffective.

House-based remedial measures implemented on houses have included: sub-slab, active and passive venting, liner systems, sub-slab pressurization, and combination of the above. Most of the systems installed have generally been successful, based on normally limited monitoring. Although no firm guidelines exist, criteria for some form of remediation is normally 1 percent methane in the soil atmosphere. Necessary conditions for active venting typically requires that an adequate number of air changes occur per hour. For liners, no performance criteria exists other than CPE material is recommended.

7. The success of the various remedial measures is in a large part dependent on a good analytical approach in the initial definition of the problem, collection of all pertinent data, and testing after remedial measures have been implemented. Not all investigations complete all of the above. As systems age, some degradation of performance can be expected. Active systems in landfills may develop problems such as warping of plastic pipes (associated with higher temperatures of aerobic degradation), subsurface fires, clogging due to microbial growth, flooding, and failure of mechanical parts. Passive venting may be subject to vandalism or flooding. Some municipalities operate a mobile vacuum unit on passive systems when high migration periods occur. Liners may be subject to sagging or rodent infestation. Active systems installed on houses have been known to create noise problems and therefore, are sometimes turned off. Insufficient long-term data exists on passive and liner systems installed on houses.

8. One of the most difficult tasks in dealing with soil gas problems, has been the implementation of appropriate criteria. Two questions are commonly encountered. What represents an acceptable criteria for indoor air contamination? What is an appropriate level for sub-slab contamination? The problem of assigning appropriate levels of indoor contamination of VOCs (including petroleum hydrocarbons) include: the presence of other indoor sources of pollutants, inappropriate measurement protocol and equipment, and the lack of published regulations. There is however, good guidance for dealing with methane problems indoors. Although not

universally accepted, the City of Seattle has a set of criteria to deal with methane indoors. The criteria established addresses both possible fluctuations typical with soil gas entry as well as assigning action levels for investigating field personnel. A similar protocol with non-specific action levels is used by some municipalities; other municipalities have severally relaxed or non-existent criteria in effect.

The other area of confusion which exists is the question of what is an acceptable concentration in the soil gas. For methane, a level of 1 percent GAS is normally used as a guideline for remediation. There is however, uncertainty whether such a level is in fact necessary. On the other hand, cleanup guidelines for soils contaminated by VOCs which are normally based on groundwater concerns, may be insufficient to provide the necessary protection against vapour inhalation.

Section 6
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