FIELD TESTS OF REMEDIAL MEASURES FOR HOUSES AFFECTED BY HAZARDOUS LANDS

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Prepared for:

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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.

Abstract

Remedial measures to prevent soil gas infiltration have been implemented on many buildings affected by intrusion of radon, water vapour, methane and other volatile organic compounds (VOCs). The success of these measures has been well documented for gases such as radon; however similar detailed documentation was not readily available for methane or other VOCs. The objective of this study was to evaluate the effectiveness of four different remedial solutions installed on houses. All houses tested in this study had the potential of methane intrusion. Nine houses were tested as part of this study.

The four different remedial measures which were evaluated included: a liner with a subslab passive vent system; an active venting fan connected to a foundation perimeter gas collection pipe; a passive vent connected to a foundation perimeter gas collection pipe; and a liner system only. Each of these four systems were installed in four separate communities across Canada. Based on long-term monitoring, none of the nine houses tested were identified as having significant methane concentrations indoors due to soil gas entry. Although the remedial measures installed may have had an effect on the limited amount of methane detected indoors, other factors such as low methane generation rates, and diffusion controlled sources also had significant influence. In fact, at some houses, the control systems likely were not necessary because of these factors.

Further short-term tracer tests were carried out on one of the systems to evaluate the integrity of the remedial measure. Based on a limited number of houses tested, the results suggested that the amount of gas could be limited by as much as four orders of magnitude.

Contents

Appendixes

Tables

Figures

Executive Summary

Soil gas infiltration into buildings located on or near hazardous lands is a growing problem in Canada, especially as more developments encroach on former swamps, landfills, or industrial sites. Based on a recent study initiated by CMHC, the most common incidents of soil gas entry in Canada are related to the influx of hydrocarbons from petroleum products, methane from landfills or other organic sources (e.g. woodlots), and volatile organic compounds (VOCs) from previous industrial activity. Soil gases which infiltrate into houses/buildings can pose two potential problems: explosion hazards or health concerns. These concerns have made the redevelopment of urban lands extremely difficult and costly in the last several years.

In order to solve the problem of soil gas entry, solutions typically have used two strategies: source-control or house-based control. Source-control strategies are normally implemented where the soil gas is generated, or in the pathway between the source and potentially affected buildings. House-based controls are typically used when the source of gas is directly adjacent to the house, where source controls are not practical, or where source controls have not been effective. Many of the house-based solutions currently used for gases such as methane are quite similar in design to those systems used for the mitigation of radon or water vapour entry (i.e. gases not necessarily associated with hazardous lands). Although house-based controls have been well documented for radon gas over the past five years, similar detailed documentation was not readily available for pollutants such as methane and other VOCs. The purpose of this study was to evaluate the effectiveness of four different remedial measures installed on houses near hazardous lands. If the effectiveness of the remedial measures is verified, the technologies could be used at sites scheduled for redevelopment.

The four different remedial measures evaluated included: a liner with a subslab passive vent system; an active venting fan connected to a foundation perimeter gas collection pipe; a passive vent connected to a foundation perimeter gas collection pipe; and a liner system only. Each of the four systems were installed in four separate communities across Canada. The pollutant of concern in all cases was methane. Based on long-term monitoring, none of nine houses tested were identified as having significant methane concentrations indoors due to soil gas entry. Although the remedial measures installed may have had an effect on the limited amount of methane detected indoors, other factors such as low gas generation rates, and low permeability soils also had significant influence.

Based on a limited number of houses tested, the test results suggested that the remedial measures could limit the amount of gas infiltration by as much as four orders of magnitude. These results could be very helpful for the specification of performance standards of alternative building technologies for the purpose of limiting soil gas entry.

Résumé

L'infiltration des gaz souterrains dans les bâtiments situés sur l'emplacement même ou à proximité de terrains à risques devient un problème croissant au Canada, surtout depuis que l'aménagement gagne de plus en plus ce qui était auparavant des marécages, des décharges ou des établissements industriels. Selon une étude menée récemment par la SCHL, les cas les plus fréquents d'infiltration de gaz souterrains mettaient en cause des hydrocarbures de produits pétroliers, de méthane issu de décharges ou d'autre source organique (terres à bois, par exemple) et de composés organiques volatils attribuables à une activité industrielle antérieure. Les gaz souterrains qui parviennent à l'intérieur des maisons ou des bâtiments peuvent poser deux problèmes : des risques d'explosion ou des préjudices pour la santé. De telles préoccupations ont rendu le réaménagement de terrains urbains très difficile et coûteux depuis plusieurs années.

Dans le but de remédier à l'infiltration des gaz souterrains, les solutions ont généralement fait appel à deux stratégies : l'élimination à la source ou l'élimination à la maison. Les stratégies axées sur l'élimination à la source se mettent normalement en oeuvre là où se produisent les gaz souterrains, ou sur leur trajet entre la source et les bâtiments risquant d'être touchés. Par ailleurs, les mesures d'élimination à la maison s'emploient habituellement lorsque la source des gaz est toute proche de la maison, lorsque l'élimination à la source s'avère peu praticable ou n'a pas donné de résultats efficaces. Bon nombre de ces solutions couramment utilisées notamment pour le méthane s'apparentent aux systèmes auxquels on a recours pour réduire la concentration de radon ou la diffusion de vapeur d'eau (c'est-à-dire les gaz non nécessairement associés aux sols à risques). Quoique les techniques d'élimination à la maison aient été bien documentées à l'égard du radon depuis cinq ans, pareille documentation détaillée n'était pas accessible pour les polluants comme le méthane et les COV. La présente étude a pour objet d'évaluer l'efficacité de quatre différentes mesures correctives dont ont fait l'objet des maisons implantées près de terrains à risques. Si l'efficacité des mesures correctives est établie, les techniques pourront être destinées à des sites appelés à être réaménagés.

Les quatre mesures correctives évaluées faisaient appel à : une membrane et un système de ventilation passif sous la dalle; un ventilateur d'extraction relié à un tuyau collecteur disposé au pourtour de la fondation; une colonne de ventilation passive reliée à un tuyau collecteur disposé au pourtour de la fondation; et à une membrane seulement. Chacune de ces mesures a été pratiquée dans quatre collectivités différentes du Canada. Dans tous les cas, le méthane constituait le polluant préoccupant. D'après un contrôle à long terme, on a relevé dans aucune des neufs maisons testées une concentration de méthane appréciable à l'intérieur, imputable à l'infiltration de gaz souterrains. Malgré que les mesures correctives adoptées aient pu exercer un effet sur la quantité limitée de méthane relevée à l'intérieur, d'autres facteurs tel un faible taux de production de gaz et la faible perméabilité du sol ont pu jouer.

Selon un nombre limité de maisons testées, les résultats indiquent que les mesures correctives pourraient restreindre la quantité d'infiltration de gaz par jusqu'à quatre ordres de grandeur. Ces résultats pourraient se révéler très utiles pour l'établissement de normes de performance d'autres techniques de bâtiment visant à contrer l'infiltration de gaz souterrains dans les bâtiments.

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Section 1
Introduction

Soil gas infiltration into houses located on or near hazardous lands is a growing problem, especially as more developments encroach on former swamps, landfill or industrial sites. In view of this concern, Canada Mortgage and Housing Corporation carried out a survey to assess the situation across Canada. One conclusion reached as a result of this survey was that relatively few communities across Canada had identified or recorded major soil gas problems which affected the indoor air quality of houses. However, the importance of the issue is growing steadily. This is primarily due to advances being made in the area of sampling methodology, knowledge of soil gas entry mechanisms, and better awareness of indoor air quality issues. The most common incidents of soil gas entry were related to influx of hydrocarbons from petroleum products, methane from landfills or other sources, and a few cases of other volatile organic compounds.

In order to solve the problem of soil gas entry, solutions typically have used two strategies: source control or house-based control (CH2M HILL, 1992). Source control strategies may be implemented where the soil gas is generated, or in the pathway between the source and potentially affected buildings. House-based controls are typically used where the source of the soil gas is directly adjacent to the house, where source controls are not practical, or where source controls have not been effective. If a problem is anticipated prior to construction, these controls may be incorporated in the original building structure; if not, retrofit measures may be used.

Many of the house-based solutions are quite similar to solutions used for the mitigation of radon and water vapour entry. However, in contrast to solutions used for radon entry, whose effectiveness has been well publicized in the last five years, those for other gases are not. The goal of this research project is therefore to evaluate the effectiveness of commonly used solutions for non-radon gases.

Objectives

To achieve the goal of evaluating the effectiveness of house-based solutions for non-radon gases, several objectives were developed, including:

- To locate four or more locations where houses have remedial measures against soil gas infiltration from hazardous lands.
- To interest a sample of householders in permitting gas monitoring in their dwellings.

- To undertake such measurements during worst case conditions, if necessary, by artificial creation of those conditions.

- To evaluate the effectiveness of the remedial measures in place.

Scope

As part of the evaluation of the remedial measures, the following information was acquired (and required) as part of this work:

- A history of the site and its problems

- A description of the remedial measure installed, as designed and as operated

- A description of the gas source, including existing monitoring records, as well as site soil gas measurements

- A description of the houses, including data on their building performance (e.g. internal pressures, air change rates, etc.)

- Test results on the effectiveness of the remedial measure at keeping the soil gas out of the indoor environment

Section 2
Methodology

Selection of Homes

Four different locations were chosen for this study. At each location, a different remedial technology was implemented. Table 1 summarizes the location of homes selected for testing, the gas type and source, the type of system installed, and some physical or monitoring features at each location. The location of each area was kept confidential to protect the rights of the homeowners. Testing was carried out in two provinces: in Ontario by CH2M HILL ENGINEERING LTD., and in British Columbia by Sheltair Scientific Ltd. A brief discussion of each area and the reason for its inclusion is provided below.

Area A Background

During the construction of a residential subdivision in southern Ontario, methane soil gas was discovered at explosive levels. The residential area was located near to or on a poorly drained area, i.e. a swamp. In view of this discovery, the contractor hired an environmental engineering company to determine the extent of the methane problem and devise solutions.

As part of the investigation, the local geology was first characterized. Two to five metres of organic fill (silty clay and wood pieces) was found to overlie loose sand and gravel, and a layer of fill. The bedrock, located at 12 metres, was a black shale which may also have had petroliferous content. During the initial investigation, twenty-three boreholes and gas probes were installed. The gas probes were installed at various depths between 3.0 and 12.8 metres below ground surface. The probes were monitored for methane content on a weekly basis during the first month and then on a monthly basis during the remainder of the one year monitoring program. Monitoring was also conducted during frozen ground conditions during the year. Methane concentrations were generally discovered to be quite low, spanning from non-detect readings to 18 percent methane per volume. Out of a total of 174 numerical readings, 143 readings (or 82.7 percent) were recorded as non-detect.

Following the termination of the monitoring program, the consulting firm concluded, firstly, that the methane gas concentrations within the boundary of the former swamp exceeded the lower explosive limit at two probes, both located at the southern perimeter of the poorly drained area. From this result, it was concluded that methane was slowly being generated from the organic soft soils found in the area defined by the former swamp. Secondly, lateral migration in the subsurface from the soft soils and swamp to the native soils was minimal, resulting in non-detectable methane concentrations outside of the former swamp area. Thirdly, structures located on native soil were shown to be unaffected by the methane gas. Fourthly, gas probes drilled to bedrock

Table 1
Homes Selected for Soil Gas Testing

Location/Investigator	Gas Type/Source	Type of System Installed	Physical/Monitoring Features
Area A/CH2M HILL	• Methane • Located on petroliferous bedrock, sands and gravels, and organic matter	• Sub-floor passive gas collection • Back-up CPE liner	• No significant monitoring • Membranes only covered area under slab
Area B/CH2M HILL	• Methane • Refuse buried on the site	• Active venting systems connected to large diameter collection pipes around footings • Gas alarms • Long-term monitoring probes	• Installation completed in 1985 • Additional testing until 1987 revealed that a number of fans were disconnected, alarms not working • No consideration was given to environmental factors
Area C/CH2M HILL	• Methane • Located near refuse, sandy soil in area (good for transmission)	• Weeping tile tied into passive venting arrangement	• High gas concentrations • Consistent monitoring
Area D/Sheltair Scientific	• Methane • Located on organic matter	• Single layer of CPE as a liner • Bentonite seal around utilities	• Concentrations in excess of 40% by volume in some areas

did contain methane at reduced levels (below lower explosive limit) and did not present a concern.

It was recommended that investigation of the methane problem should continue regardless of the low concentrations recorded. Passive venting systems were proposed for 28 houses possibly affected by the methane gas. The as-built passive venting system is shown on Figure 1. As shown on Figure 1, the gas interceptor system consisted of subfloor and perimeter piping placed in a granular envelope, inlet and outlet pipe connections, as well as a backup 20 mil CPE liner. The system was intended to operate in a passive mode; however, the system could be converted to an active system if required. All homes were equipped with methane alarms.

Monitoring subsequent to construction revealed no detectable concentration of methane in any of the gas interceptor systems or the basements. A monitoring program spanning one year revealed no detectable gas in the system or the buildings, but revealed concentrations of up to 66 percent at depth in a nearby gas probe. Despite this occurrence, monitoring was discontinued at the completion of one monitoring year. Based on discussions with homeowners, the indoor methane alarms have never sounded with the exception of being activated by other indoor sources. Homeowners are now responsible for maintaining the equipment.

Area B Background

In the process of construction of a Southern Ontario subdivision, refuse was discovered during basement excavation operations. Due to this discovery, construction was halted until an assessment of the situation could be made. Several boreholes were drilled and soil gas monitoring wells were installed.

Depending on the level of methane gas concentrations observed and the delineation of onsite refuse, various gas control measures were implemented at this site. The developers were required to install various types of systems. Those houses most threatened by methane infiltration were equipped with the most elaborate systems, including several methane monitors, large diameter weeping tiles around the foundations, and a blower system. Sixteen homes were eventually equipped with active blower systems. Four of these homes also had long-term monitoring probes installed on their respective properties. An additional twenty-six homes were equipped with single port gas alarms; no active venting systems were required.

Each active system was equipped with a locked starter. All fans were located in the area of each building in locked weatherproof housings. Since active venting was occurring, the developers were required to obtain a Certificate of Approval (Air) from the Ministry of Environment and Energy (MOEE). Conditions of the certificate were generally vague; it stipulated that if any contaminant emissions in the stacks exceeded health, odour, or safety guidelines/standards, corrective action must be taken. Addition to the stack monitoring, indoor methane levels were also to be measured over a specified testing period.

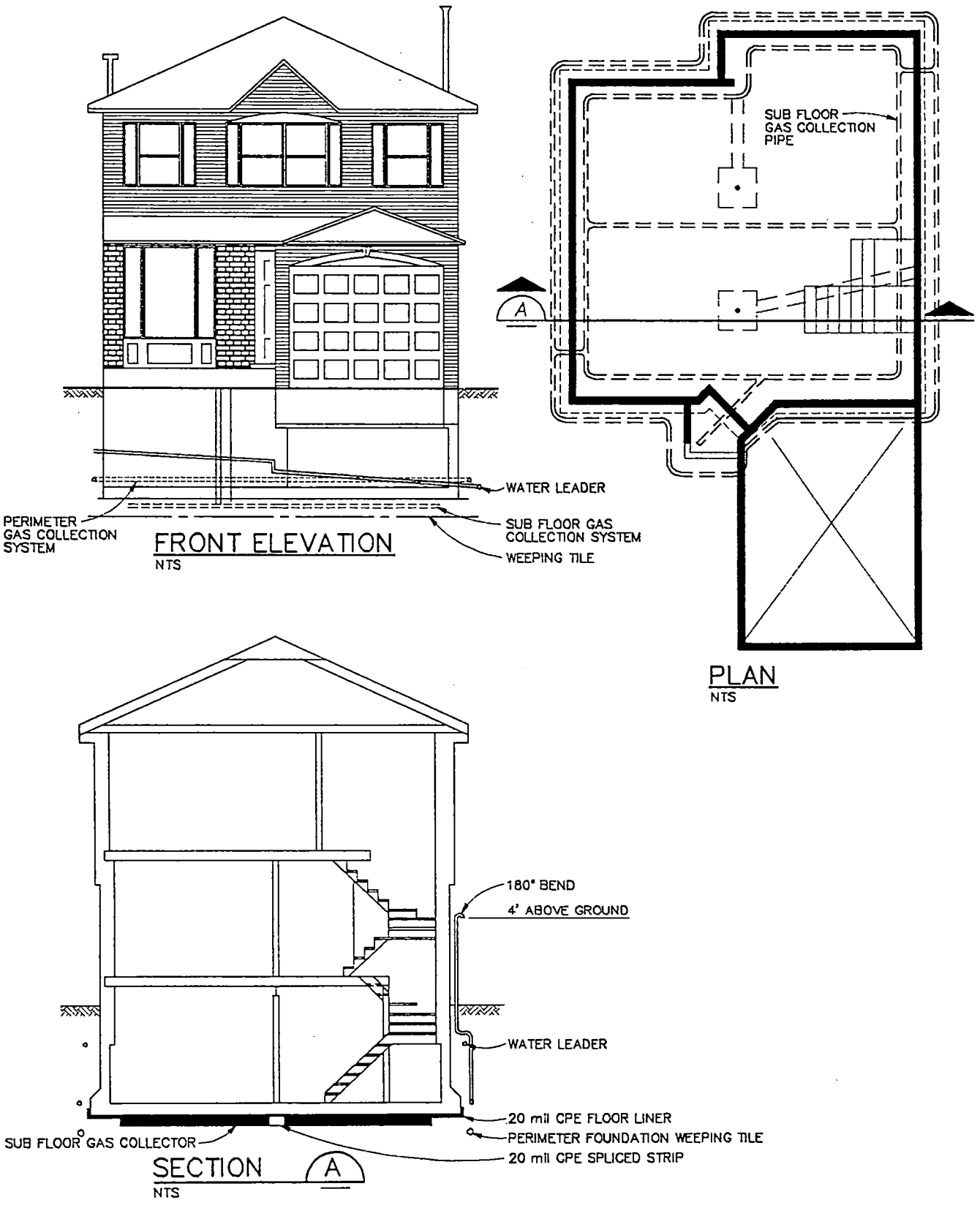

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FIGURE 1
SCHEMATIC OF PASSIVE VENTING SYSTEM

The homes in the subdivision were monitored approximately seven times by an independent consultant between September 1984 and February 1989. Indoor methane monitoring was completed in each of the four corners of the basements in the houses designated by the MOEE. All measurements taken indoors and outdoors were measured with an explosimeter (typically operating in the LEL range). Although it was recommended that a more sensitive measurement be conducted with regards to indoor methane measurements, such a plan was never implemented.

During the monitoring program no combustible levels of methane were ever detected indoors (i.e. the explosimeter never exceeded 0 percent LEL). The reports did not state whether or not calibration was routinely carried out as part of the monitoring protocol. Based on telephone records at the time, the MOEE was concerned only if indoor methane levels exceeded 2 percent LEL (or 1,000 ppm). Values greater than 2 percent LEL would have "caused concern".

Testing outdoors was less extensive than the indoor monitoring program. In the initial monitoring event (September 18, 1984), a total of twelve gas probes were checked for methane. Results indicated that methane existed in the subsurface in volumes of 0 percent to 40 percent by volume. Table 2 summarizes the results from the September 1984 monitoring round.

Table 2
Test Results from September 1984 (Area B)

Soil Gas Monitor No.	% by Volume	Soil Gas Monitor No.	% by Volume
87R	0	102R	24
90R	0.9	102F	5.0
92R	40	105R	0.4
94R	40	97F	0.4
96R	0	102F	4.0
98R	34	122F	2.0

During the remaining five monitoring events, significantly less locations were tested. Only four soil gas probes were checked. Concentrations ranged from 0 percent to 5.0 percent LEL.

Following the monitoring by the independent consultant from September 1984 to February 1989, the following conclusions were reached. Since no methane was recorded indoors at any of the homes, there was no threat of a methane danger. Of all the homes where methane alarms were installed, by July 1986, seven alarms were no longer operational. By October 1987, 21 alarms were no longer working. Because of noise problems, by October 1987, six occupants of the houses with active systems had turned off their fans. After the February 1989 monitoring period, no further testing has been completed. Following the testing, some homeowners inquired with the developer

about turning the fans off; the developer did not reply. By late 1993, only a couple of homeowners continued to operate their exhaust fans.

Area C Background

The third subdivision to be investigated was located adjacent to a former landfill area. The area where the subdivision is located, once consisted of low lying swamps and a meandering creekbed. The geology is composed of glacial till or outwash sand in intervening depressions. Part of the site where houses are now existing was used for landfilling from the period of 1957 to 1960. Cover soils which were used for capping the refuse were also used to build up other typographical lows. The location of the landfill site relative to the subdivision is shown on Figure 2.

The area where the subdivision was eventually built was first investigated for methane in 1969. As part of an audit of "marsh gases" within the municipality, various areas were investigated by an independent consultant. Drive points were hammered into the soil to maximum depths of approximately 1.0 metre; soil gases were then sampled. The consultants reported that "marsh gases were present in the entire area. Concentrations of gas for the most part were low ranging from 5 to 10 percent" (per volume is assumed).

At the time of the investigation (1969), construction had already begun on one new house located some 150 metres away from the active landfill. In the immediate vicinity of that house however, no subsurface gas was present. The consultant anticipated that the construction of future houses would not be affected unless construction proceeded at least within 60 metres of the landfill boundary. Further recommendations were given by the consultant for future development within the 60 metre buffer zone. Houses within the 60 metre buffer zone were located within the shaded area shown on Figure 2. Subsequently, these recommendations were incorporated as part of "special requirements" set out by the municipal building department. By 1975, the subdivision was completely built.

The "special requirements" set out by the municipal building department were intended for all new structures or major renovations in "urban renewal areas". The "special requirements" are detailed below.

> "In the case of building sites located on or within 60 metres (200 feet) of land which has been filled with material made up of or containing a significant percentage of garbage or other organic material which generates or is likely to generate methane gas:
>
> (a) so far as possible all organic material shall be removed from the area to be covered by building and replaced with suitable material and properly compacted;

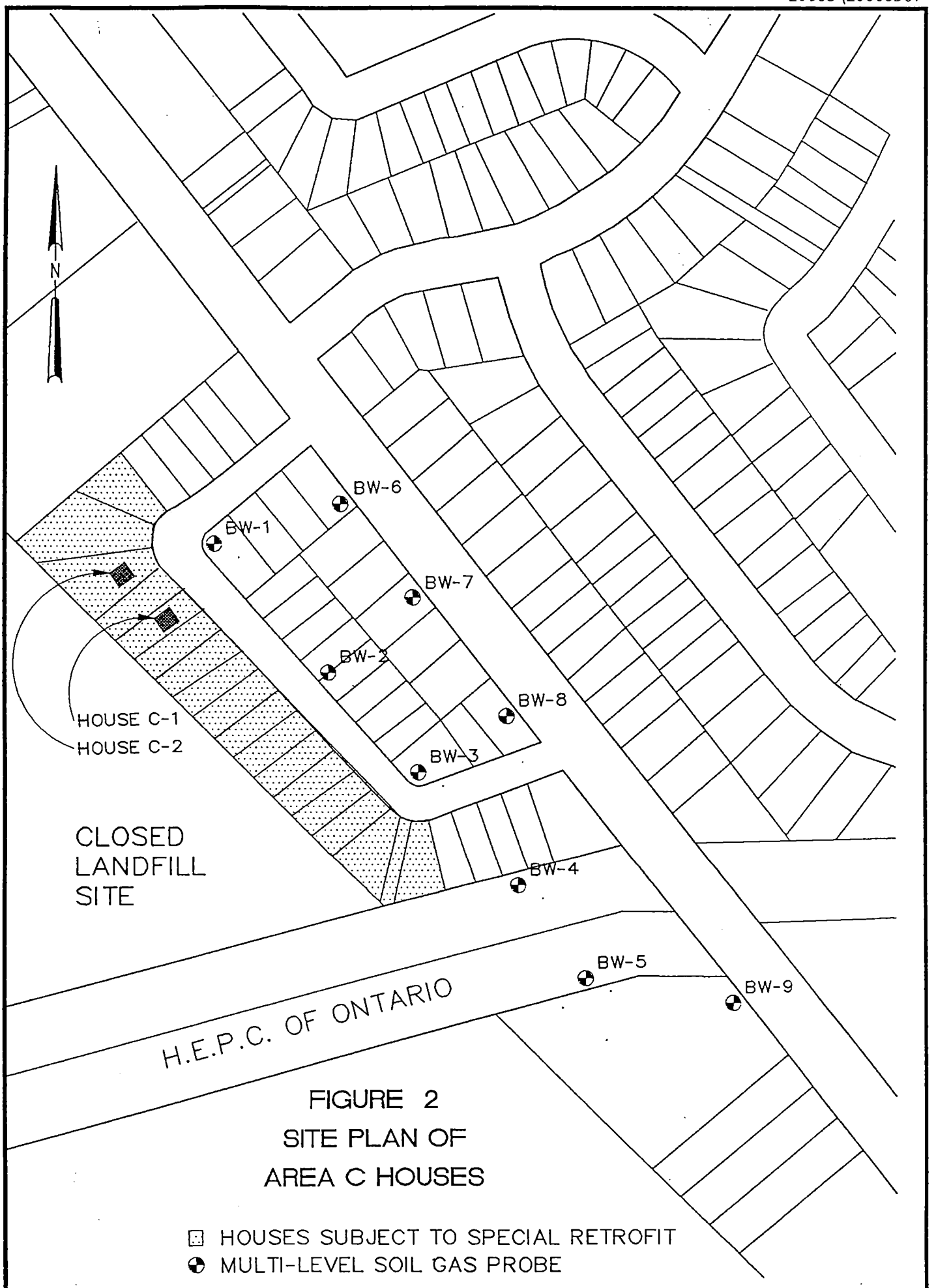

FIGURE 2
SITE PLAN OF
AREA C HOUSES

CH2MHILL

(b) The weeping tiles around the foundation shall be connected to the sanitary sewer in such a way that one or more traps prevent the entry of gas from the weepers into the building;

(c) A venting barrier consisting of a gravel trench with a 0.15 metre (6 inch) pipe extending at least 0.15 metres above the eavesthrough level, shall be provided in addition to the foundation weepers;

(d) when indicated, test inserts shall be inserted in the basement floor to enable tests to be made for build-up of gas;

(e) when indicated, basement floor and walls shall be painted with an epoxy paint or other suitable sealant."

One row of houses immediately adjacent to the landfill (within 60 metres) were subject to the "special requirements" outlined above. Conditions (d) and (e) were not applied.

Although it was not certain whether monitoring was completed from 1975 to 1984, partial public records exist from 1984 to 1989. Records on individual houses are confidential and are the sole property of the home-owner and the municipality. As far as it is known, due diligence monitoring has taken place since 1984 and is currently being conducted on a monthly basis. Weekly monitoring occurs only when landfill gas control systems are malfunctioning. Based on the partial monitoring summary (1984 to 1989) of the houses equipped with methane preventative measures, some methane has been detected indoors. A brief synopsis of indoor monitoring is summarized below:

- Usually non-detect to trace concentrations of methane are present in most residences.

- Seven of the seventeen houses (including House C2 - tested in this study) with control measures had a single-time high methane concentration (7 to 30 percent LEL) in October 1988 with trace to low methane concentrations before and after that month.

- One house had consistently elevated methane concentrations detected over the entire sampling period. Maximum methane concentrations of 20 percent (by volume) were detected in June 1988, however typical ranges were from 10 to 20 percent LEL.

- Another house had consistent elevated methane concentrations prior to July 1986 with the highest reading of 95 percent LEL recorded in July 1986. Since that time trace to low concentrations have been recorded.

- Another house had consistently elevated methane concentrations prior to May 1987 with the highest reading (of 15 percent LEL) recorded in May

1987. Trace to very low concentrations have been reported from 1987 to 1989.

It should be noted that not all homeowners complied with the municipal inspections. Also, maximum readings cited above were in most cases measured at entry points in the basements of the houses, and do not reflect mixed indoor air concentrations.

In view of a concern for extended subsurface methane migration, a further drilling and house monitoring program was initiated by the municipality in 1990 and 1991. A series of borings and gas monitors were installed in the subsurface in a parallel row some 60 metres from the landfill (shown on Figure 2 as BW-1 to BW-5). Methane gas at elevated concentrations (50 - 60 percent by volume) at elevated pressures (700 to 1000 Pa) were measured at four out of five monitors. The methane was however believed to originate at depth approximately 8 to 9 metres below ground surface. Houses located near these monitors (approximately 70 metres from the landfill) were monitored on ten different occasions in the autumn of 1990. No significant indoor methane was detected.

In the autumn of 1991, the houses located 85 metres from the landfill were similarly monitored. No significant indoor methane was recorded. Some of these homes were some of the first houses built in 1969. Subsurface methane monitors also installed in 1991 (BW-6 to BW-9) showed only marginal methane concentrations (< 1 percent by volume).

Area D Background

The last of the sub-divisions to be investigated was previously farmland consisting mainly of peat and organic soils. During development of these lands to residential use, some landfill was also added to the site. The landfill consisted partly of "hog fuel" containing organic lumber wastes such as bark and small branches. The concerns related to methane production from the soils were first raised by the public health division in the municipality.

The houses in the subdivisions are a mixture of crawl space and slab-on-grade foundation types. The actual foundation and soil-gas barrier construction were identical for both types of foundation. With the exception of one multiple family development in subdivision D1, all of the dwellings are single family. The oldest houses in the developed areas were constructed in 1990.

Houses were selected for monitoring purposes in two subdivisions. The test houses were built by separate developers. Methane barriers were constructed differently in each case and are described briefly below.

In subdivision D1, the older of the two subdivisions, a flexible 30 mil CPE liner had been installed below each house foundation. A 350 mm layer of granular sand was sandwiched between the PVC liner and the minimum 100 mm floor concrete slab. In all houses, including crawl space houses, the concrete slabs were strengthened with steel

mesh and designed with concrete stiffening groves on the underside of the slab for increased strength. Any penetrations through the slab into the occupied space were supplied with special fittings such as boots and sleeves. Hose clamps were used to tighten the liner around drain pipe risers, and other plumbing.

The second subdivision, also employed a system based on a 30 mil CPE liner. However, the 350 mm granular layer was omitted upon recommendations from an American engineering firm. They contended that such a permeable layer potentially allows any soil gas leaking through pin holes in the liner to move freely to the nearest available crack or opening. They theorized that eliminating the granular layer would trap any gas leakage in a localized area, reducing infiltration.

Monitoring Equipment

Monitoring as part of this program was conducted for several parameters which are influential for the influx of soil gases indoors. Indoor and subsurface methane concentrations, indoor and outdoor temperatures, soil gas pressures, and air exchange rates were all measured as part of this program. The monitoring equipment used as part of this program is summarized on Table 3. All measured data with the exception of subsurface methane concentrations were recorded continuously with dataloggers.

Table 3
Summary of Monitoring Apparatus

Equipment	Parameter	Range
Valtronics Model 2010 RT Methane Monitor	indoor methane	0 - 50,000 ppm (or modified) 0 - 1,000 ppm
Heath GMI Methane Detector	subsurface methane	10 - 700 ppm 0% - 100% LEL 0% - 100% GAS
Omega Px 163 Pressure Transducer	soil gas pressure	-1,244 - 1,244 Pa
National Semiconductor 163	temperature	-5°C to 30°C
Dwyer inclined Manometer	pressure	0 - 62 Pa
Gastec Solid Sorption Tubes	CO_2	various ranges
Dwyer 60 Pa Pressure Transducer	Crawl space to outdoor differential pressure	0 - 60 Pa
AD 590 IC Temp Transducer	Average Indoor Temperature and Outdoor Temperature	0 - 400 K
Mitsubishi HS-7	Crawl Space Absolute Humidity	0 - 30 gm/kg (dry air)

The monitor which was used to measure indoor methane concentrations was the Valtronics Model 2010 RT methane monitor. The monitor is an infrared device which

measures the response of the C-H stretch of the methane molecule. Infrared techniques were viewed as more favourable over other measurement techniques for this study. Stand-alone monitors especially those based on electro-chemical cells can be influenced by other ubiquitous gases, e.g. carbon dioxide. Although the Valtronics Model 2010 RT methane monitor was not as stable and accurate at low ppm concentrations as monitors based on flame ionization detection (FID), it was viewed as being far more portable and did not require daily refuelling.

Subsurface methane concentrations outside the houses were measured to determine source strength. The instrument used was a Heath GMI. Based on a catalytic detection sensor, this instrument is portable and rugged for outdoor use. Although this instrument may suffer in accuracy in higher CO_2 environments, the measurement is normally a good approximation of the actual methane concentration.

In addition to the measurement of methane, soil gas pressures immediately outside the building envelope were also recorded. Elevated soil gas pressures can be a significant driving force for the influx of soil gas contaminants into the indoor air. Soil gas pressure differentials (between the soil gas and the indoor air) can be increased by: barometric fluctuations, compression of gases due to precipitation wetting fronts, wind or stack effects, and mechanical ventilation or heating systems. The barometric record was obtained from local airports and compared to the results.

Indoor and outdoor temperatures were also measured as indicators for the stack effect.

Monitoring Protocol

Area A

Monitoring was first undertaken at one house in Area A (House A1) from early October 1993 to the end of December 1993. Initially indoor methane concentrations were recorded for a period of two weeks with a Valtronics Model 2010 RT methane monitor set at a sensitivity of 0 ppm to 50,000 ppm. Initial results for this period of time indicated non-detectable concentrations of methane. In view of these measurements, the instrument was rewired to increase its sensitivity in the 0 to 1000 ppm range. Beginning on October 29, 1993 until December 22, 1993, methane concentrations were recorded at the lower more sensitive range. Later in March 1995, when monitoring was again taking place in the area, house A1 was monitored for indoor methane only.

An outdoor soil gas monitor was installed on October 25, 1993. The soil gas probe was installed to a depth of approximately 3.1 metres at a horizontal distance from the house of 3-4 metres. The monitor was installed at such a distance so that soil gas pressure would not be affected by the passive vent system installed within the building envelope. The geology was consistent with earlier descriptions given by previous investigators.

Organic fill composed of mainly moist silty clay with some wood chips were found in the top three metres of soil. The soil gas was measured initially for methane, carbon dioxide, and oxygen. Methane concentrations were low (0.1 percent LEL), carbon dioxide, and oxygen were typical of atmospheric conditions. Subsequently only methane measurements were undertaken. A datalogger installed nearby continuously recorded soil gas pressures and outdoor temperatures. A second monitor installed by previous investigators was also sampled for soil gases. This monitor was installed at a depth of 4.5 metres below ground surface at an approximate distance of six to seven metres from the building envelope. Continuous monitoring was carried out at this probe in the latter stages of this investigation. Barometric fluctuations as recorded four times daily at a nearby airport were obtained and compared to the results.

As will be presented in the next section of this report, methane concentrations indoors were generally very low, in the non-detectable range. In view of this result, a pump test on the house was completed on March 1, 1995 to test the integrity of the subslab liner. The integrity of the liner was tested by injecting sulphur hexafluoride (SF_6) into the indoor air, and creating a negative pressure in the subslab venting system. A negative pressure of approximately 700 Pa was maintained for a 45 minute period on the subslab ventilation piping. Exhaust gases were periodically monitored for methane; gases were also sampled for SF_6 throughout this time period. Indoor air was sampled periodically for SF_6 for the determination of the air exchange rate. Directly after the pump test, a natural air exchange test was carried out.

The second house (House A2) tested in Area A was instrumented for monitoring during March 1995. A soil gas monitor was installed in the backyard approximately six metres from the house; the depth of the monitoring interval was 5 to 5.5 metres. Although initially the monitor had a minimal supply of soil gas (i.e. the soil permeability was very low), within weeks water flooded the monitor. The supply of methane declined.

Similar to House A1, indoor methane was generally low, in the non-detectable range. A pump test, similar to that completed on House A1, was carried out on March 1, 1995. Using SF_6 as a tracer gas inside the house, with a negative pressure in the subslab venting system of 700 Pa, the integrity of the liner was evaluated. Exhaust gases were periodically monitored with an Organic Vapour Analyzer for methane; SF_6 was also sampled in the indoor air and exhaust gas. Directly after the pump test, a natural air exchange test was carried out.

Area B

Testing of the houses in Area B began in early November 1993 and were completed by the middle of April 1994. As detailed in Section 2, methane was present at various levels in the subdivision. Homes were selected where previously elevated methane concentrations in the soil gas were detected. Monitoring was carried out in the first house from November 1993 to February 1994. The second house was monitored in

December 1993 and January 1994. A third house was investigated in late January 1994 to mid-April 1994.

Initially when monitoring began in the first house in Area B, the Valtronics Model 2010 RT methane monitor was set to a sensitivity of 0 to 50,000 ppm. Initial results indicated non-detectable levels of methane. In early December 1993, a new monitor rewired for the 0 to 1000 ppm range was installed. The other two houses were installed with methane monitors set at the lower more sensitive range.

Soil gas monitors were installed in the backyards of each of the houses. Soil gas monitors were installed to a depth of 3.0 to 4.0 metres below ground surfaces; each monitor was located approximately 4.0 metres from the basement foundations. The subsurface geology consisted of mainly silty till combined with some construction or fill material. Occasional thin sandy zones were also present at a depth of two to three metres below ground surface. Soil gas monitors were installed to a depth of 3.1 metres. Soil gas pressures and ambient temperatures were continuously recorded. Periodic measurements of methane in the soil gas were also taken. Each house was visited a minimum of five times during the monitoring period.

Area C

Testing of the houses in Area C began in late November 1994 and were completed by the end of February 1995. Indoor methane concentrations were measured in both houses in Area C with the Valtronics Model 2010 RT methane monitor set at a sensitivity of 0 to 1000 ppm.

Outdoor soil gas monitors were installed 4 to 5 metres away from each house. The screened measurement depth was approximately 3 to 4 metres below ground surface. The geology was found to consist of mainly silty till (0-1 metre) overlying a silty grey sand. At house C2, some refuse was also encountered at a depth of 2.5 to 3 metres. Odour was quite intense at both monitoring locations (in the rear of houses C1 and C2). Each house was visited a minimum of five times during the monitoring period.

Area D

The testing in Area D was carried out from mid March 1993 to the beginning of June 1993. Monitoring of the two sites began during the same week in March and visits were made to the sites monthly. Valtronics RT 2010 Methane Monitors were set to a sensitivity of 0 to 50,000 ppm during the period. All pressure, humidity, temperature, and RT 2010 monitors were spot calibrated and/or zeroed at the beginning of testing, during the monthly visits, and at the end of the monitoring periods. The RT 2010 sensors were zeroed by placing them in a well ventilated area on the main floor of the house and assuming this to be at zero methane concentration at this location.

Prior to, and concurrent with the installation monitoring equipment, rod probe tests were carried out at the four corners of the building lots. The procedure used for gas concentration measurement was as follows. A 2 m x 19 mm diameter iron rod was driven into the ground at the test hole site to a depth of 1.25 m. The rod was then removed and immediately the gas analyzer probe was lower into the test hole to an intermediate depth (0.65 m) and a reading was taken of the methane level. The rod was then replaced in the same test hole and the procedure was repeated for depth up to 1.75 m. The above steps were repeated for each of the four test holes. The entire procedure was then repeated using new test hole locations, adjacent to the original test hole. This was done four times during the monitoring period.

Initially soil gas pressures were monitored for an initial test period. Because the soil gas pressures were essentially non-detectable in the subsurface at Houses D1 and D2, the cross-envelope pressure was monitored instead.

Weather conditions at the time of each site test were also recorded. It was anticipated that significant downward swings in barometric pressure would effectively intensify the release of methane from the soil due to depressurization.

Section 3

Results and Discussion

The results of monitoring in Areas A, B, C, and D are presented in Appendixes A to D. Methane concentrations indoors were compared to indoor and outdoor temperatures, soil gas pressures in nearby probes, and atmospheric barometric fluctuations.

Area A

House A1

The monitoring results in House A1 obtained during the months of October, November, and December 1993 are listed as Figures A.1, A.2, and A.3. As seen on these figures, continuous monitoring results were available from October 29 to November 22, 1993 and from December 6 to December 23, 1993 for indoor methane concentrations. For a brief period from November 22 to December 6, 1993, the continuous methane monitor indoors experienced excessive zero drift problems such that a continuous record of methane concentrations was not available for that period. Subsequently this drift problem was attributed to startup of the monitor.

A continuous record of soil gas pressures was obtained from October 25 through to November 28, 1993 at a soil gas monitor located approximately 4.0 metres from the basement foundations. Methane was measured at this monitor on four occasions; the largest concentration of methane was 0.1 percent LEL. In view of the low soil gas pressures and methane concentrations measured, the datalogger was removed and relocated to the second soil gas probe located approximately 7.0 metres from the building. The second probe, screened at a depth of 4-5 metres below ground surface, had significant pressure relative to the atmosphere; measurements were forced offscale. Methane concentrations measured from early December to January, 1994, were observed to be between 35 and 66 percent by volume.

Methane indoors generally varied between 0 and 150 ppm (during the time period of October to December 1993) with a great degree of scatter within that range. Much of the scatter experienced by this instrument was a result of the low signal to noise ratio, i.e. the instrument was extremely susceptible to other influences such as temperature. Despite the interference problem related to temperature, the detection of excessive indoor methane was still possible. Based on laboratory calibration tests conducted before and after the field exercises, the instrument responded well to excessive methane (i.e. greater than 150 ppm). Therefore if elevated methane concentrations were present in the field, such levels could be recorded.

Several conditions were present during field testing when increased methane infiltration would have been expected. For example, several large declines in the barometric pressure occurred on October 29, November 5, November 19, December 10, and December 23. Despite these ideal conditions for soil gas infiltration, no significant rises in indoor methane concentrations were noticeable. The long-term monitoring data suggested that no significant methane problem was experienced indoors at this house.

Over the monitoring period, the house was visited five times to calibrate the continuous monitors, download data, and manually measure indoor methane levels with portable equipment. On no occasion were indoor methane levels, as measured by portable instruments, above 40 ppm; such measurements can be attributable to instrument drift, and are therefore not significant.

In view of the signal drift problems experienced initially, indoor methane concentrations inside House A1 were again monitored during March 1995. The more recent data was filtered of the majority of temperature effects. The results are shown in Figure A.4. As shown here, methane concentrations were below 50 ppm. Weekly monitoring by means of spot checks with an Organic Vapour Analyzer confirmed that low indoor concentrations were present; concentrations typical of background (1.0 to 1.5 ppm) were recorded on all occasions.

The pump test results for House A1 are shown in Figure A.6. Concentrations of the SF_6 tracer gas declined over time; concentrations in the vent pipe remained fairly stable ranging from 0.1 to 0.3 ppb. By assuming the subfloor space under House A1 behaves like a continuous flow stirred tank reactor (CFSTR), the flowrate through the liner may be evaluated. The material balance for a CFSTR is well known:

$$\textit{Accumulation} = \textit{Inflow} - \textit{Outflow}$$

OR

$$\frac{dC_o}{dt} V = Q_i C_i + Q_s C_s - Q_o C_o$$

where:

$\frac{dC_o}{dt}$	= 0, since C_o is constant at 0.3 ppb
V	= volume of reactor
Q_i	= flowrate from inside the house
C_i	= SF_6 concentration inside the house
Q_s	= flowrate from soil pore space
C_s	= SF_6 concentration in soil pores
Q_o	= flowrate from fan
Q_o	= SF_6 concentration from fan

Averaging indoor concentrations of SF_6 over the 45 minute pumping interval at 60 ppb, the CFSTR equation reduces to:

$$O = Q_i\ (60\ ppb) - Q_o\ (0.3\ ppb)$$

where: Q_o had an average value of 4.33 m^3/min (72.2 L/s)

Using the equation given by Yuill and Associates (1991) for flow through a slab,

$$Q_i = C\ \Delta\ P$$

where: Q_i = flowrate (L/s)
C = flow coefficient (L/s • Pa)
ΔP = pressure difference across floor (Pa)

the flow coefficient can be calculated. The experimental ΔP of 700 Pa and Q_i = 0.36 L/s results in a flow coefficient of 5.1×10^{-4} L/s • Pa. In comparison with laboratory studies, this flow coefficient was equivalent to single crack in a floor (with a width of 1.5 mm) supplemented by lapped and uncaulked polyethylene liner. The liner arrangement used on House A1 appears to be in very good condition and capable of minimizing soil gas entry.

Methane measurements which were also taken during the pump test by an Organic Vapour Analyzer revealed typical background concentrations (1.0 to 1.5 ppm). This suggested that little or no methane had accumulated under the structure nor was there significant methane transport. Low permeability soils and/or limited gas generation capability was likely the cause of limited gas detection.

House A2

Similar to House A1, no significant methane was recorded indoors by the Valtronics methane monitor. As shown on Figure A.5, continuous methane monitoring showed no significant fluctuations during times when optimal soil gas entry should have taken place (i.e. during barometric declines, or during times when stack is strongest). Weekly monitoring also verified the lack of methane indoors; on all visits, methane levels reflected typical background concentrations (1.0 to 1.5 ppm).

During the installation of the soil gas monitoring probe, the methane production capability of the organic soils were evident. Measurements taken on March 1, 1995 indicated concentrations as much as 60% GAS. By the second week concentrations declined to 20% GAS; by week three and five, concentrations only measured 47% and 31% LEL respectively. Much of the decline was attributable to rising groundwater levels within the soil gas monitor. Therefore very erratic pressure fluctuations were noted in the monitor (refer to Figure A.5).

Given the declining concentrations of methane due to groundwater influx into the first soil gas monitor, a second monitor was installed in the shallow soils in the close vicinity. After one week, concentrations of methane peaked at 1.7% LEL. This result indicated that although gas was being produced at depth (i.e. 5-5.5 metres below ground surface), methane in the shallow soils was minimal. This suggested that the vertical flux of methane was negligible at this location. This was confirmed during the pump test when a vacuum of 700 Pa at the house foundations failed to draw significant methane from the subsurface. Methane concentrations in the exhaust gas registered 1.0 to 1.5 ppm.

The SF_6 concentrations as measured during the pump test are shown on Figure A.6. As expected, indoor SF_6 concentrations declined during the pump test from 99 ppb to 42 ppb. In the exhaust gas, the concentration of SF_6 varied between 0.20 ppb at the start of the test to 0.50 ppb at the conclusion. Assuming an average indoor SF_6 concentration of 70.5 ppb and an exhaust concentration of 0.5 pb, the equivalent flow co-efficient C was 7.31×10^{-4} L/s • Pa. The liner installed in House A2 appears to be in similar good condition. The liner appears to restrict flow similar to a liner installed on a cracked slab in a laboratory setup (Yuill and Associates, 1991).

Area B

House B1

The monitoring results for House B1 as recorded from November 10, 1993 to February 18, 1994 are shown on Figures B.1 to B.4. The exhaust fan installed on the house was not operating for the entire duration of the test period. Although measurements were recorded for this period, several complications arose with respect to datalogger failure and zero shift problems in the methane monitor. The most dependable record of indoor methane concentrations occurred from December 7, 1993 to February 18, 1994 with the exception of a zero shift problem in early January.

Pressures were measured in a soil gas probe located approximately 4.0 metres from the basement foundations. Maxima soil gas pressures occurred during periods of barometric declines (e.g. November 18, 28, December 10, 29, January 28, etc.). Conversely, maxima negative soil gas pressures occurred during periods of barometric increases. Based on the pattern observed, the possibility of convective transport of soil gases into the indoor environment were possible. Methane concentrations measured periodically in the probe however were quite low; the maximum soil gas concentration recorded was 3.0 percent LEL (1500 ppm). The maximum soil gas concentration recorded at a gas probe installed in a neighbour's backyard was 11 percent LEL; this probe was located approximately 15 metres from the House B1.

In early December, a methane monitor wired for low methane concentrations was installed. Although the monitor showed relatively low methane concentrations, there was a significant instability in the readings. This instability was a result of electronic

noise or temperature fluctuations, not methane. A large barometric drop on December 10th should have caused large increases in indoor methane. In fact coincident with the large soil gas pressure observed on December 10th, indoor methane was at a minima. A new monitor installed on December 23rd showed similar fluctuations. In any case, readings never exceeded 200 ppm during the monitoring period. On six different occasions, when the house was visited, methane levels indoors and outdoors were comparable. No significant indoor methane was detected.

Based on the concentrations of methane in the soil gas, the low permeability soils, the low or non-detectable methane concentrations indoors was not entirely unexpected.

House B2

The monitoring results for House B.2 as recorded from December 14, 1993 to January 19, 1994 are shown on Figures B.5 and B.6. The exhaust fan installed on the house was not operating during the monitoring period. Although methane concentrations fluctuated between zero and 150 ppm, much of this fluctuation was a result of temperature effects not methane. On every site visit, indoor methane levels resembled background concentrations.

Soil gas pressures were measured in a soil gas probe located approximately 4.0 metres from the basement foundations. The maximum methane concentration recorded at this monitor was 11% LEL. At other times, however concentrations were less than 0.6% LEL. Maxima soil gas pressures occurred during periods of barometric decline (e.g. December 22, 29, and January 13); the pressures however increased only marginally over atmospheric pressure.

The lack of significant indoor methane concentrations was likely due to the low methane readings recorded in the soil gas, the lack of significant soil gas pressures, and the relatively tight soils. Methane concentrations indoors did not even increase during times of barometric declines; this suggested that there was an insufficient methane flux towards the building envelope to cause problems at this house.

House B3

Monitoring at House B3 began in January, 1994 and was terminated by early April, 1994. (Refer to Figures B.7 to B.10). Although the instrumentation was installed in January, 1994, the indoor equipment unfortunately was not turned on until February 12, 1994. Methane concentrations indoors, as shown on Figures B.8 to B.10, indicate that daily fluctuations between 0 and 150 pm occurred during that period. Again as in House B1 and B2, this variation was more related to temperature fluctuations as opposed to indoor methane. Even though falling barometric pressures occurred (e.g. February 13, 24, March 3, 14, 26, and April 2), no significant methane peaks were recorded indoors. Periodic spot checks with a Health GMI confirmed these readings.

On every occasion, the GMI (operating in ppm mode) recorded similar readings indoors as outdoors.

Soil gas pressures as recorded in the soil gas probe in the backyard of House B3 are shown in Figure B.7. Since these soil gas pressures were relatively insignificant, pressure results obtained from the rear of House B1 were presented for the month of February 1994. Finally in March 1994 measurable pressures finally developed in the rear of House B3; these pressures are shown on Figures B.9 and B.10. This period of adjustment may have been related to insufficient hydration of the bentonite seals surrounding the soil gas monitor behind House B3. Although soil gas pressure developed behind House B3, methane concentrations in the soil air were quite low for the entire monitoring period. Methane concentrations never exceeded 0.1% LEL throughout this period.

Given the low soil gas methane concentrations present here, the lack of methane peaks during peak periods was not surprising. A lack of methane in the soil air suggested that an insufficient flux of methane was present to cause problems for the indoor air quality.

Area C

House C1

The monitoring results from House C1 are shown in Figures C.1 to C.5. Monitoring in this house was carried out from November 24, 1993 to March 3, 1994.

Methane concentrations indoors in House C1 showed an extremely erratic pattern throughout the entire monitoring period. The pattern shown on the figures actually fluctuates approximately every hour. When initial results were reviewed, it was conjectured that possibly the methane monitor and/or the datalogger were unstable. The indoor temperature monitor also showed similar fluctuations. Suspecting a faulty monitor and datalogger, new units were installed on December 16, 1994; the fluctuations however continued. Finally in early January, the cause of these fluctuations was determined. The occupant of the house left one or more windows open all day long for the purposes of ventilation. In her opinion, leaving windows open were necessary since people in the house complained of headaches, with the windows closed. Her dog would also become very ill.

Certainly by ventilating, the air exchange rate would be expected to be higher. Based on the SF_6 decay method, the air exchange with only light winds was determined on February 21, 1995. The air exchange rate was calculated at approximately one air exchange per hour. Calculations are shown in Figure C.9.

The fluctuations in indoor methane however remained unexplained. Finally in early February, the Organic Vapour Analyzer was installed in the house and connected to a continuous recorder. Methane was recorded for approximately one week. This monitoring confirmed that hourly fluctuations were indeed happening. The methane fluctuations were traced back to a leaky fitting near the gas furnace. Results on Figures C.1, C.2, and C.3 indicate fluctuations were ± 50 ppm; variations as measured by the Organic Vapour Analyzer were more in the order of ± 20 ppm. Although the indoor methane data was filtered for the majority of the temperature effects, there was still an element of hysteresis in the response of the instrument due to a temperature change. This hysteresis had the effect of exaggerating the amount of methane present in the ambient air. The leaky fitting was repaired by the utility company on February 21, 1994.

After the fitting was repaired on February 21, 1994, apparent methane fluctuations still occurred however on a much smaller scale. The fluctuations were more a result of temperature hysteresis effects. Periodic spot checks confirmed indoor methane levels had declined to 10 ppm or less on the days visited. No significant peaks were identified as a result of possible soil gas entry for the rest of the monitoring period.

As noted in the above discussion, although there was significant short-term fluctuations in the methane concentrations, there was not any distinct recorded event when elevated methane occurred indoors due to advective gas transport. Such conditions existed despite methane concentrations measured between 60 and 70% GAS. (These values were probably somewhat elevated compared to actual soil gas concentrations. The catalytic sensor has an upscale bias due to the presence of carbon dioxide.) Furthermore, despite large barometric declines and corresponding positive soil gas pressures (e.g. November 27, December 9, 28, January 6, 20, 31, February 4, 15, and 20) no significant measurable change was noticed. This suggested that either a limited flux of methane was arriving at the subsurface envelope of the building, or the venting system installed was performing as intended.

To understand more fully the implications of methane flux through the soil, a simplified analytical model was used to assess methane concentrations indoors. The analytical model used here was derived by Little et al. (1992). The model assumes a contaminant flux originating from a landfill and travelling through the subsurface under the influence of a pressure gradient. The calculated attenuation factor α represents the dilution of subsurface gases reaching the indoor air.

$$\alpha = \frac{C_{indoor}}{C_{outdoor}} = \frac{k}{\mu}\left(\frac{P_s - P_b}{L}\right)\left(\frac{A}{Q_b}\right)$$

where:

C_{indoor}	= concentration indoors
$C_{outdoor}$	= concentration in the soil gas
k	= soil gas permeability (m^2)
μ	= dynamic viscosity of the soil gas
P_s	= pressure of the source
P_b	= pressure of the building (assume zero)
A	= effective contaminant flux area

Values for k were determined experimentally by coring a 2.5 cm diameter hole near the soil gas probe. A soil gas packer was installed and a steady flowrate was removed at a given probe pressure. The value of permeability was calculated using the expression given by Garbesi (1988),

$$k = \frac{Q\mu}{4\pi rP}$$

where:

Q	= steady state flowrate
r	= radius of hole
P	= probe pressure

A permeability of 10^{-10} m^2 was calculated using experimental soil gas pressures of approximately 0.1 kPa. The permeability estimate calculated here was reasonable for values typical of sand and silty/sand (Freeze and Cherry, 1979). With an effective flux area of 120 m^2, an air exchange rate of 1 hr^{-1}, the corresponding α was calculated at 1.7 x 10^{-5}. Setting $C_{outdoor}$ = 600,000 ppm (60% GAS), C_{indoor} would be 10 ppm. Such an increase would not have been measurable using the current equipment setup. Although the numbers reported here could easily be out by an order of magnitude, the values calculated here suggest that the soil permeability was a major inhibitor to soil gas migration. The venting system may in fact be working, however the flux of methane was likely low due to low soil permeability.

House C2

The monitoring results from House C2 are shown in Figures C.6 to C.8. Monitoring in this house was carried out from December 22, 1994 to February 28, 1994.

Although some fluctuations occurred, methane concentrations indoors were generally quite stable. Methane concentrations were always below 50 ppm at times of high and low influx. Periodic spot checks with the Organic Vapour Analyzer confirmed very low levels of methane. The highest methane reading was recorded at the end of the monitoring period on February 28 and again on March 3; indoor methane concentrations on those days registered 10 ppm. At the beginning of the monitoring program, values were typically in the range of 1.0 to 5.0 ppm.

Soil gas pressures in the monitoring probe were generally quite low, typically ± 10 Pa. Only on one occasion were higher pressures recorded, in mid-January (Figure C.7).

Melt waters caused by higher than normal temperatures were believed responsible for these inconsistencies. Methane concentrations in the soil gas probe ranged from 40% GAS to 0% GAS when water filled the probe at the end of the monitoring period.

The soil permeability was determined experimentally as per the method described for House C1. Because of the presence of abundant water in the soil pores, the permeability was an order of magnitude lower (i.e. 10^{-11} m^2). This would suggest an even lower potential for soil gas transport. This appeared to be confirmed by the lack of methane indoors in House C2. The presence of water in the soil pore space likely inhibited significant movement of subsurface soil gas towards House C2.

Area D

House D1

Shown on Table 4 are the subsurface methane concentrations as recorded at House D1 during the monitoring period in 1993. Concentrations of methane varied considerably around the perimeter of the house with the most significant gas concentrations in the southeast corner of the building (at 44% GAS).

Table 4
Rod Probe Methane Measurements - Area D

Location/ Depth of Probe (m)		Sampling Date					
		March 16, 1993		March 31, 1993		April 16, 1993	
House D1	House D2	House D1	House D2	House D1	House D2	House D1	House D2
SW/1.37 m	SW/1.22 m	NA	5% Gas	9% LEL	10-31% Gas	50-65% LEL	25% LEL
	SW/1.37 m		NA		30% Gas		35% LEL
SE/1.22 m	SE/1.22 m	NA	30-85% LEL	35% Gas	15% Gas	44% Gas	30% Gas
NE/1.22 m	NE/0.76 m	NA	0% LEL	25-32% Gas	0.4% LEL	36% Gas	
	NE/1.37 m		40% LEL		11% LEL		
NW/1.22 m	NW/0.91 m	NA	0.1% LEL	15-20% LEL	0.4% LEL	1% LEL	0.1% LEL
NW/1.37 m	NW/1.22 m	NA	0.1% LEL	25% LEL	0.7% LEL	1% LEL	0.1% LEL
	NW/1.52 m		20% LEL		8% LEL		20% LEL

The results of the long term monitoring for House D1 are presented graphically in Appendix D as Figures D.1 through D.4. Figures D.1 to D.4 represent 2 months of monitoring data. The data implies that methane levels were barely detectable to the sensors. The sensors range was set at 0 to 50,000 ppm (100% LEL).

The highest daily swing for House D1 was about 94 ppm. These trace amounts are only 0.1% of the sensors full scale and were not considered reliable. The data for House D1 was corrected for zero-drift using a polynomial curve fit. The corrected data

shown in Figure D.1, showed the peak day of March 23, 1993 coincides with higher outdoor temperature after days of low temperature and cloud. The 94 ppm change was seen as a steady increase that follows the weather trend.

Some very high envelope pressures (instantaneous maximums of over 30 Pa, 15 in average of 10 Pa) were recorded for some periods during midday. This was related to high winds that developed each day. Pressure from winds were recorded despite some efforts to average out the pressures using multiple pressure tubes and a pressure damping box. The location of the damping box was in a shielded area under a concrete staircase which was partly open to outdoors, and they had been susceptible to the high wind pressures. There was no definite correlation made between methane levels and high pressures but there was indication that the concentrations decreased slightly during the high stack pressure periods. Although the results were limited in view of sensor sensitivities, the reduction could be due to increased infiltration and crawl space air change rates.

House D2

As can be seen from the Table 4, the highest levels were found in Southwest and Southeast corners of the lot at up to 30 percent methane at depths of 5 ft (1.6 m) below the grade line. The detected levels ranged from 0.005 percent GAS to as high as 30 percent gas concentration. In general, a trend was observed in the data towards increasing concentrations in the soil from the beginning of the monitoring period. However, site measurements that were made when the data loggers were removed after the end of the monitoring period in July 1993, indicated a decreasing trend in the summer. This data was not included in this report. This implied that the source strength may have been at a maximum in late spring. In general, the results indicated a high concentration of methane in the soil adjacent to the houses. From this it can be inferred that testing beneath the slab of the house would have produced similarly high concentrations.

The results of the long term monitoring for House D2 are presented in Figures D.5 through D.8. It can be seen from Figure D.5 that sensor zero-drift was a continuous problem. The sensors, despite efforts to stabilize them, were allowed to drift freely over the period and relative changes in the methane levels from day to day were used as "indicated" instead of "absolute" levels. As mentioned previously, the methane levels were compared to outdoor levels (assumed to be zero) on at least 4 occasions over the monitoring period. Again, during those checks no significant rise in methane was detected when the sensors were returned to the crawl spaces.

In both Houses D1 and D2, the flux of methane into the indoor air was minimal. The output of the Valtronics meter showed some correlation with respect to humidity and outdoor temperature. On the other hand, no measurable increases in the output was recorded when cross-envelope fluxes were expected to be the greatest (i.e. stack effects, barometric declines). It was reasonable to conclude that methane influx into these houses were minimal.

Section 4
Conclusions

House-based solutions for soil gas entry problems have been implemented at numerous houses which have the potential of being affected by soil gas intrusion. The objective of this study was to evaluate the effectiveness of four different solutions for reducing methane infiltration. Conclusions with regards to each solution is presented below.

Liner with a subslab passive venting system. The houses tested with this remedial measure were located on or in the close vicinity of a former swamp. Soil gas concentrations measured in a monitor approximately 6 metres from the building envelope approached 66% methane by volume. Closer to the building, no significant methane was detected in the soil gas. Therefore evaluation of the system by means of methane migration was inconclusive. Consequently a tracer gas experiment was conducted to evaluate the integrity of the liner. Based on the results of the test, the liner system had a bulk calculated flow coefficient in the range of 10^{-4} L/s • Pa. Similar values of flow coefficients were obtained by laboratory experiments for a cracked concrete slab supplemented with a liner. This suggested that the liner was operating as intended. If such results can be verified for a larger sample, the performance specifications of such technology could be very useful for future risk assessment studies aimed at commercial lands considered for residential redevelopment.

Active venting fan connected to a foundation perimeter gas collection pipe. The source of methane in the second area tested, originated from a small landfill located in the rear of the houses. Methane monitoring was conducted on three houses located closest to the highest historical subsurface methane concentrations. Unfortunately during testing, the highest subsurface concentration recorded was only 11 percent of the lower explosive limit of methane. Although the systems were in good repair, no conclusive evaluation could be completed on the installed systems because of the lack of methane in the soil gas.

Passive vent connected to a foundation perimeter gas collection pipe. The houses equipped with this remedial technology were located to a well developed methane source (i.e. within 25 metres of a closed landfill). The houses tested during this program were two of seventeen houses equipped with similar measures. One of the two houses tested at one time had excessive methane concentrations indoors (7-30% of the lower explosive limit) based on historical data. Methane was consistently elevated in the soils of both test houses C1 and C2. Indoor methane in both houses were below 100 ppm throughout this monitoring period. Although the monitoring data suggested that the passive venting system was working as intended, the low soil gas permeability measured at this site would restrict the amount of methane migrating to the building envelope. Much of the lack of indoor methane at these sites likely is due to the diffusion-limited source.

Liner system. The soil gas concentrations measured in the subsurface around the houses outfitted with CPE liners only had recorded maximum methane concentrations of 44 and 30 percent by volume respectively. However, non-detectable soil gas pressures were recorded during the initial stages of monitoring. Given that a lack of measurable soil gas pressure existed, limited advective transport of gases due barometric pumping or methane buildup could occur. Other factors which could influence advective transport such as wind loading and stack effect also created no appreciable increases in indoor methane. Under the given conditions, the liner performed well; no significant methane was recorded indoors.

Section 5
References

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Appendix A

MONITORING RESULTS FOR AREA A

- Figure A.1 House A1 - October 1993
- Figure A.2 House A1 - November 1993
- Figure A.3 House A1 - December 1993
- Figure A.4 House A1 - March 1995
- Figure A.5 House A2 - March 1995
- Figure A.6 House A1 and A2 - SF6 Tracer Tests
- Figure A.7 House A1 - Forced Air Exchange Test
- Figure A.8 House A1 - Natural Air Exchange Test
- Figure A.9 House A2 - Forced Air Exchange Test
- Figure A.10 House A2 - Natural Air Exchange Test

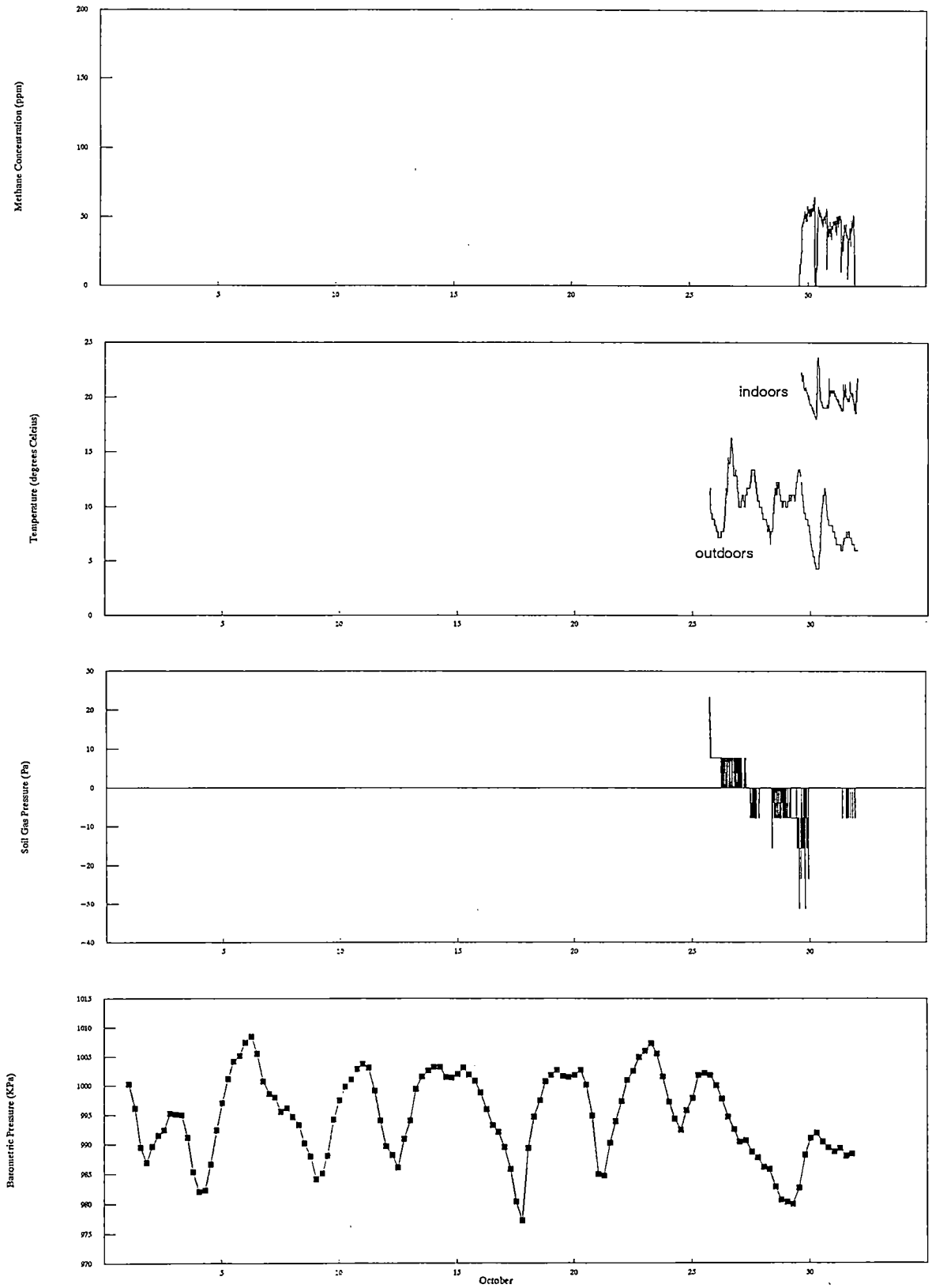

Methane Concentration (ppm)
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
October

Figure A.1

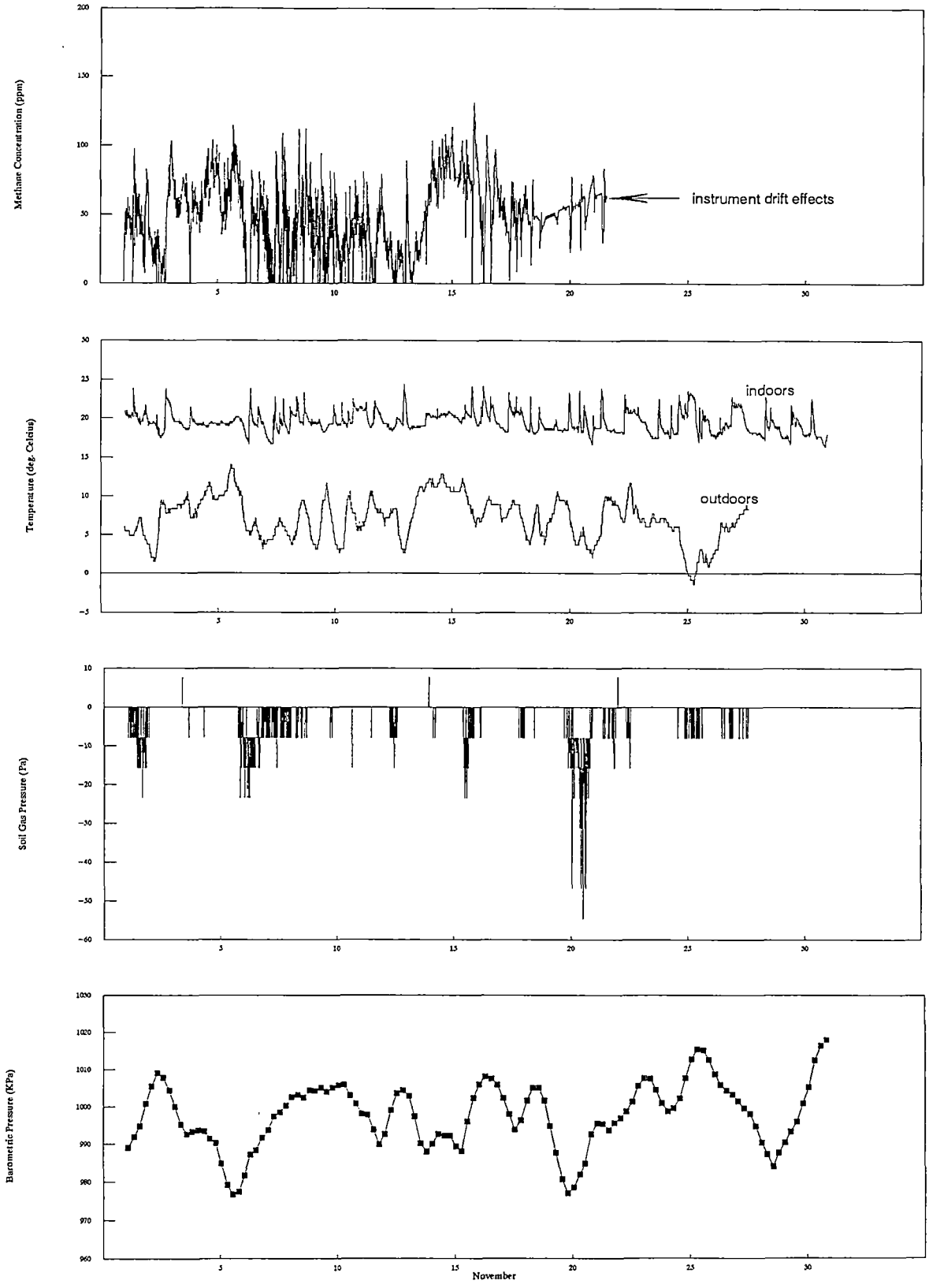

Methane Concentration (ppm)
instrument drift effects
Temperature (deg. Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
November

Figure A.2

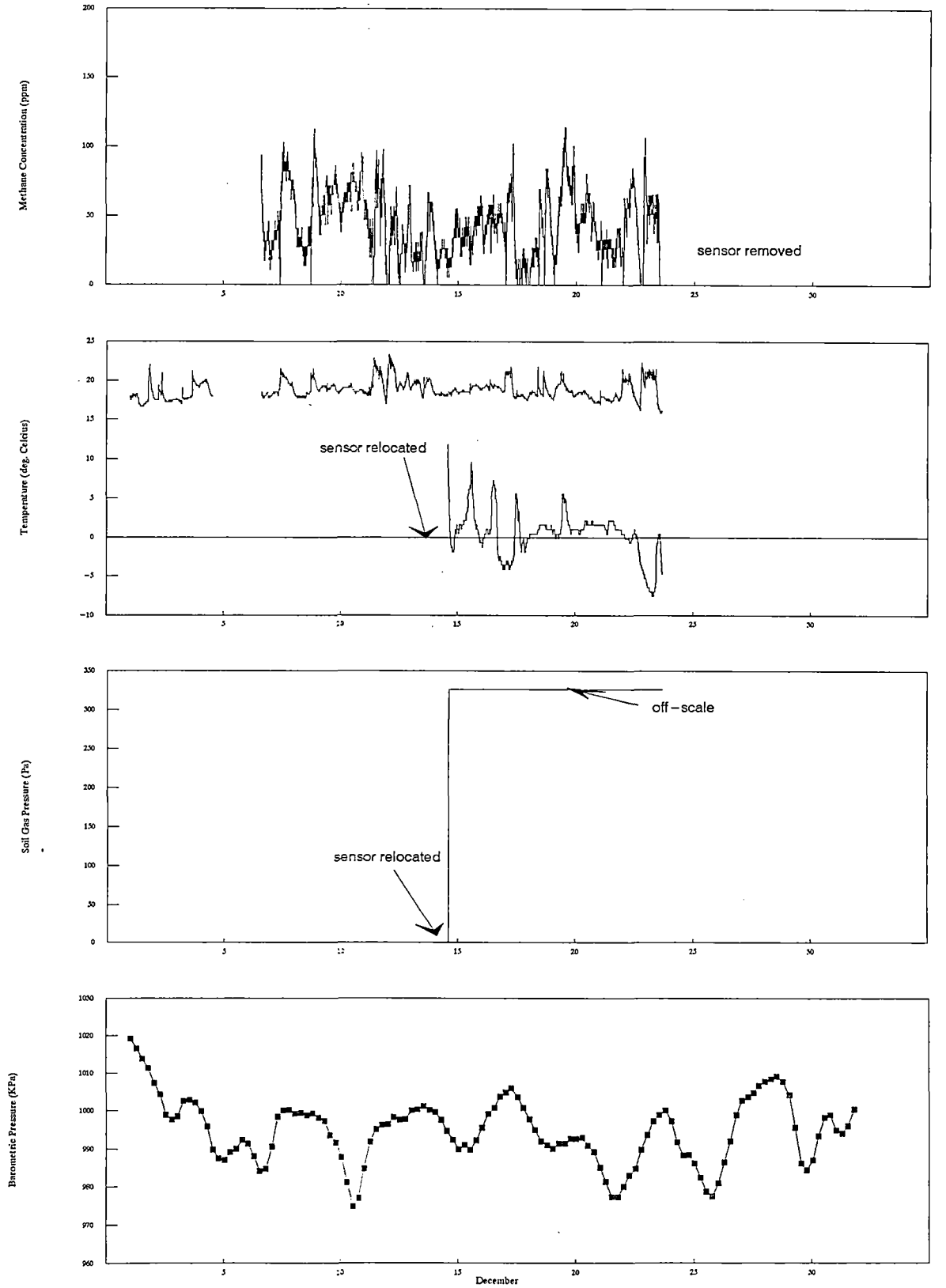

Methane Concentration (ppm)
sensor removed
Temperature (deg. Celcius)
sensor relocated
Soil Gas Pressure (Pa)
off-scale
sensor relocated
Barometric Pressure (KPa)
December

Figure A.3

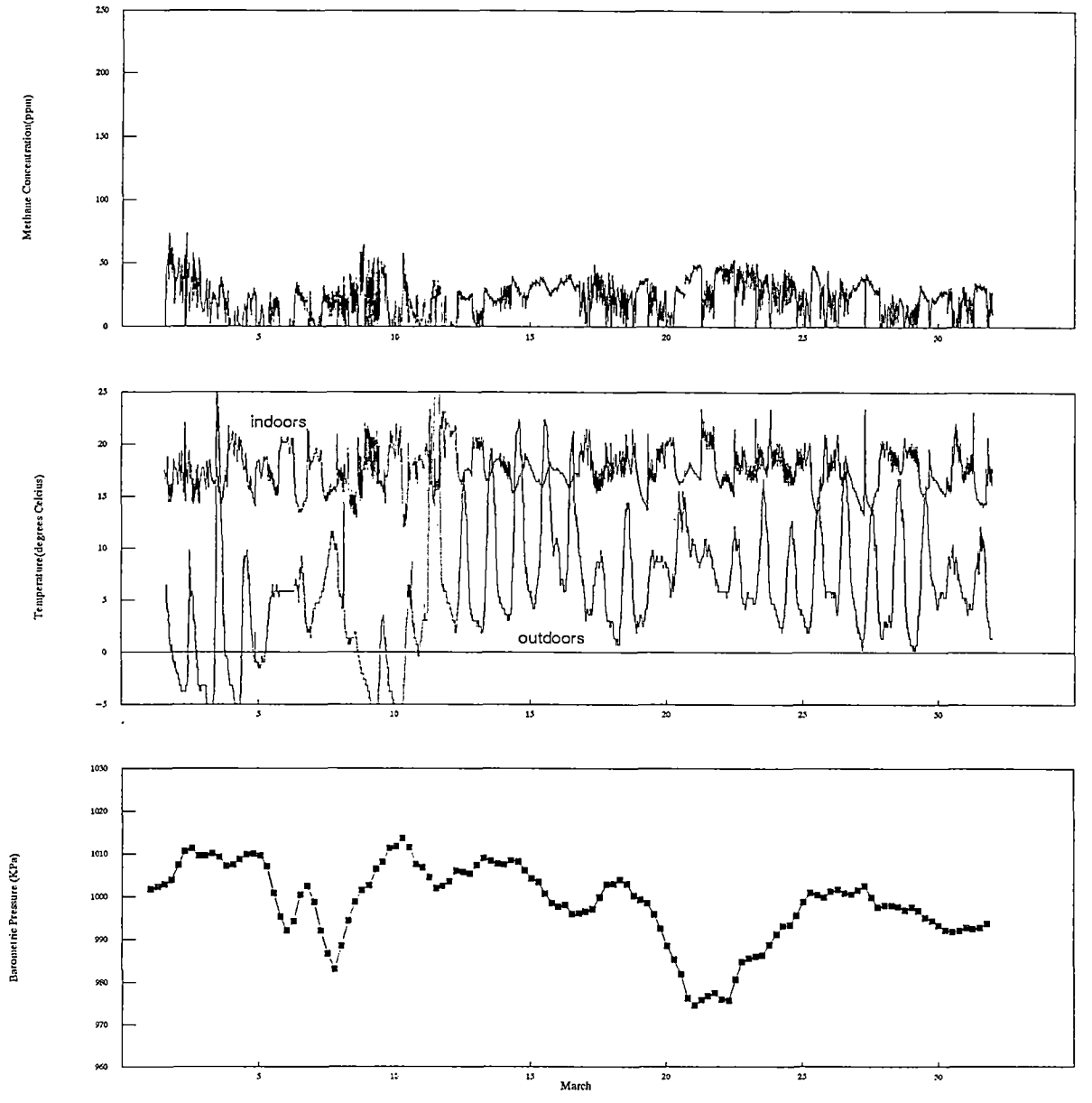

Methane Concentration(ppm)
250
200
150
100
50
0
5
10
15
20
25
30
Temperature(degrees Celcius)
25
20
15
10
5
0
−5
indoors
outdoors
Barometric Pressure (KPa)
1030
1020
1010
1000
990
980
970
960
March

Figure A.4

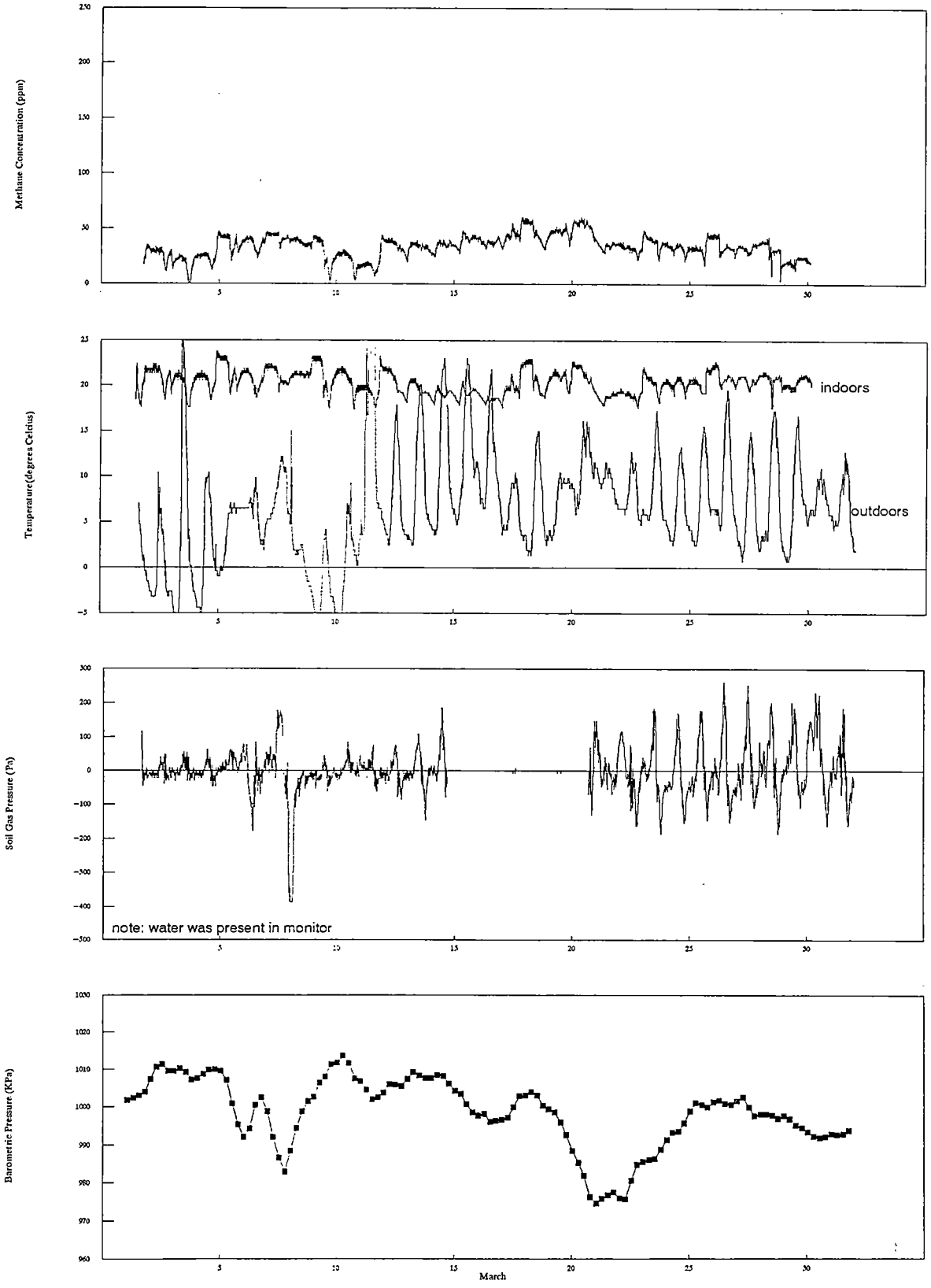
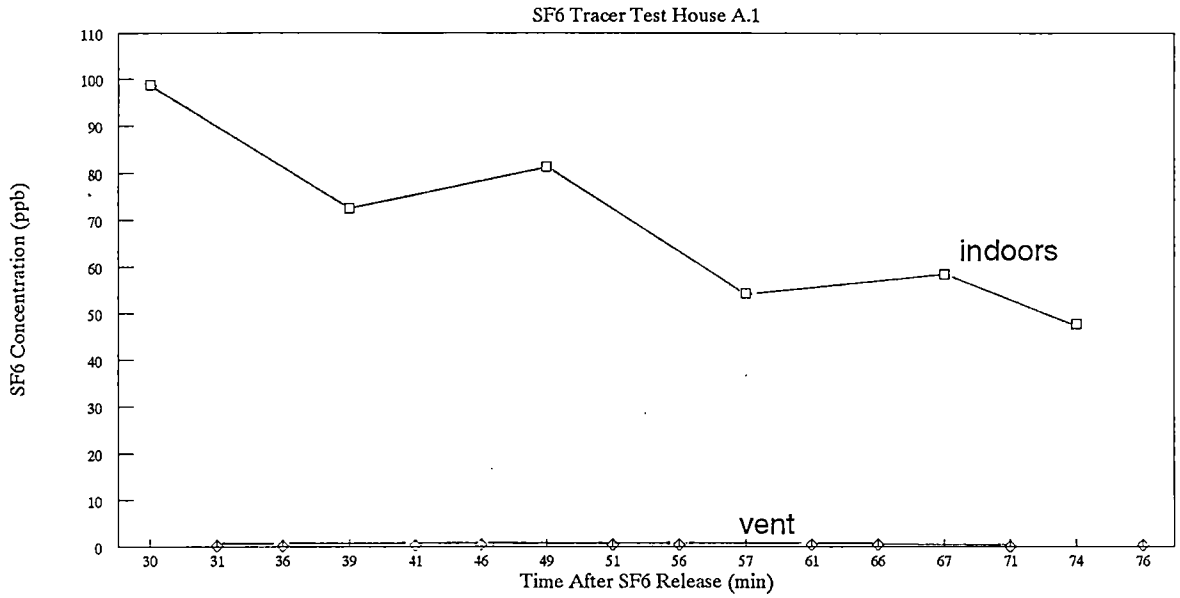

Methane Concentration (ppm)
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
note: water was present in monitor
Barometric Pressure (KPa)
March

Figure A.5


SF6 Tracer Test House A.1
SF6 Concentration (ppb)
110
100
90
80
70
60
50
40
30
20
10
0
indoors
vent
30
31
36
39
41
46
49
51
56
57
61
66
67
71
74
76
Time After SF6 Release (min)

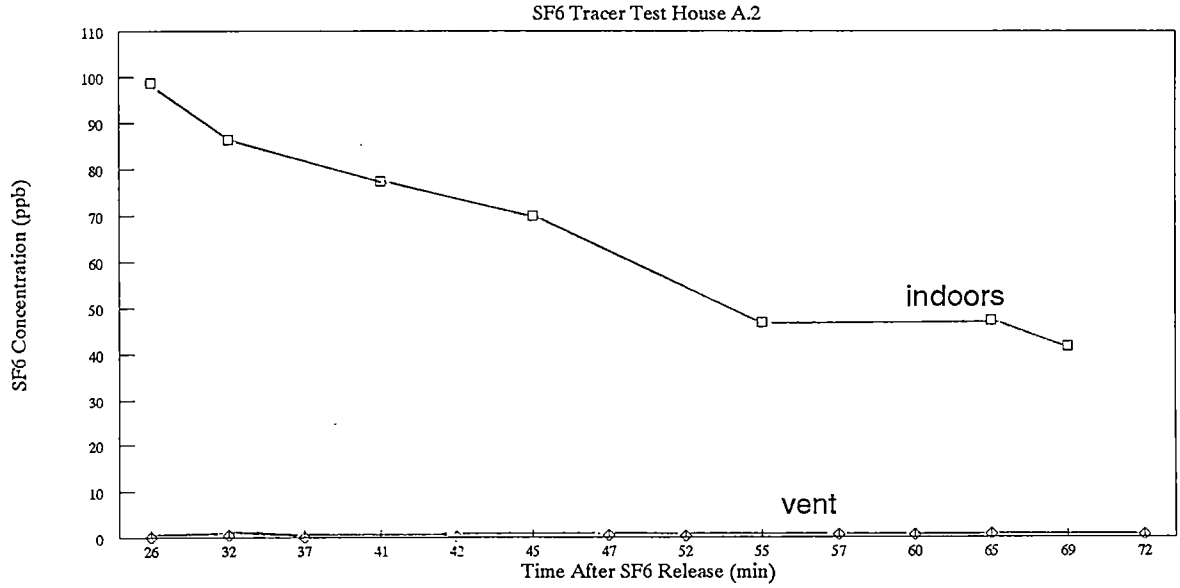

SF6 Tracer Test House A.2
SF6 Concentration (ppb)
110
100
90
80
70
60
50
40
30
20
10
0
indoors
vent
26
32
37
41
42
45
47
52
55
57
60
65
69
72
Time After SF6 Release (min)

Figure A.6

FORCED AIR CHANGE CALCULATION - March 1,1995.
House A.1

ORIGIN ≡ 1
i := 1 ..6

$$t := \begin{bmatrix} 30 \\ 39 \\ 49 \\ 57 \\ 67 \\ 74 \end{bmatrix} \qquad c := \begin{bmatrix} 98.8 \\ 72.5 \\ 81.4 \\ 54.4 \\ 58.4 \\ 47.8 \end{bmatrix}$$

(c-vector is the SF6 concentration)
(t-vector is the time after injection)

Define the fitting function

$$cc(t,\alpha,ß) := ß \cdot \exp(-\alpha \cdot t)$$

$$SSE(\alpha,ß) := \sum_i \left[c_i - cc\left[t_i, \alpha, ß \right] \right]^2$$

Initial guess for parameters
$\alpha := 0.015$ $ß := 55$

Given
$SSE(\alpha,ß) \approx 0$

$1 \approx 1$

$$\begin{bmatrix} \alpha \\ ß \end{bmatrix} := Minerr(\alpha,ß)$$

Parameters for best fit

$\alpha = 0.015$
$ß = 144.344$

Mean squared error

$$\frac{SSE(\alpha,ß)}{4} = 80.494$$

Plot of fit:

tt := 1 ..150

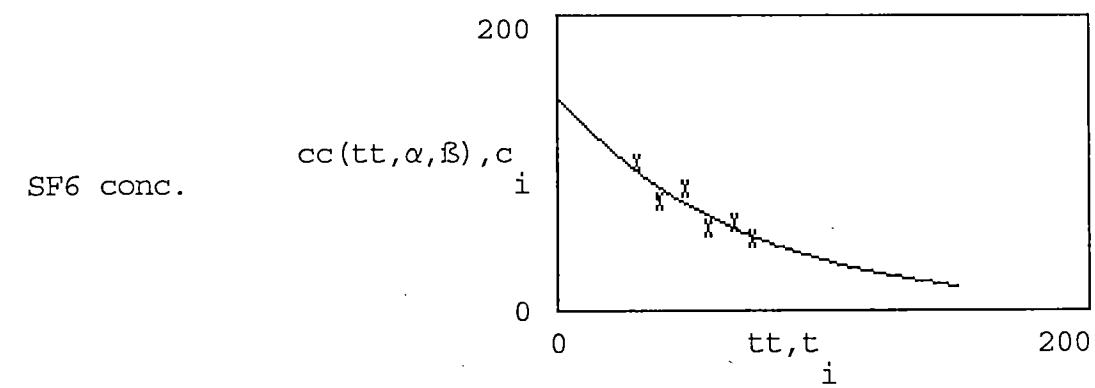


Figure A.7

NATURAL AIR CHANGE CALCULATION - March 1,1995.
House A.1

ORIGIN ≡ 1
i := 1 ..8

$$t := \begin{bmatrix} 15 \\ 24 \\ 39 \\ 54 \\ 69 \\ 84 \\ 99 \\ 111 \end{bmatrix} \qquad c := \begin{bmatrix} 103 \\ 93.6 \\ 66.7 \\ 59.8 \\ 50.4 \\ 41.2 \\ 36.3 \\ 33.4 \end{bmatrix}$$

(c-vector is the SF6 concentration)
(t-vector is the time after injection)

Define the fitting function

$$cc(t,\alpha,ß) := ß \cdot \exp(-\alpha \cdot t)$$

$$SSE(\alpha,ß) := \sum_i \left[c_i - cc\left[t_i ,\alpha,ß \right] \right]^2$$

Initial guess for parameters
α := 0.015 ß := 55

Given
SSE(α,ß) ≈ 0

1 ≈ 1

$$\begin{bmatrix} \alpha \\ ß \end{bmatrix} := \text{Minerr}(\alpha,ß)$$

Parameters for best fit

α = 0.013
ß = 122.337

Mean squared error

$$\frac{SSE(\alpha,ß)}{4} = 23.805$$

Plot of fit:

tt := 1 ..150

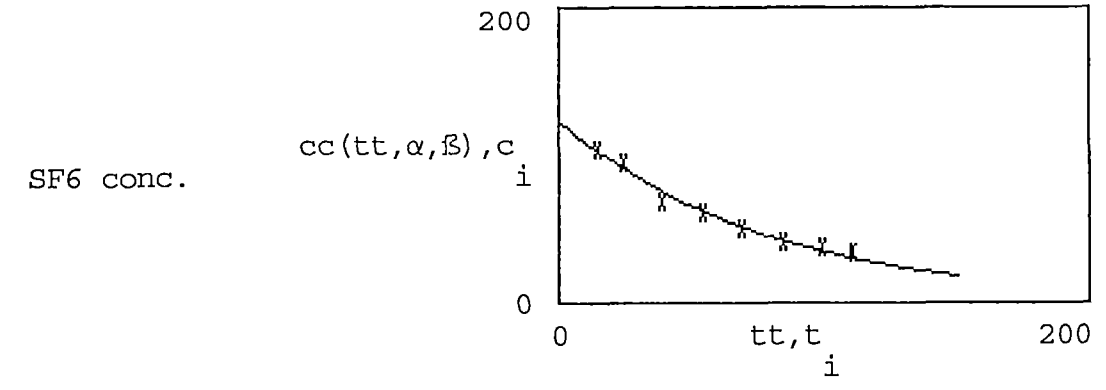


Figure A.8

FORCED AIR CHANGE CALCULATION - March 1,1995.
House A.2

ORIGIN ≡ 1
i := 1 ..7

$$t := \begin{bmatrix} 26 \\ 32 \\ 41 \\ 45 \\ 55 \\ 65 \\ 69 \end{bmatrix} \qquad c := \begin{bmatrix} 98.8 \\ 86.4 \\ 77.3 \\ 69.9 \\ 46.8 \\ 47.3 \\ 41.7 \end{bmatrix}$$

(c-vector is the SF6 concentration)
(t-vector is the time after injection)

Define the fitting function

$$cc(t,\alpha,ß) := ß \cdot \exp(-\alpha \cdot t)$$

$$SSE(\alpha,ß) := \sum_i \left[c_i - cc\left[t_i, \alpha, ß \right] \right]^2$$

Initial guess for parameters
$\alpha := 0.015$ $ß := 55$

Given
$SSE(\alpha,ß) \approx 0$

$1 \approx 1$

$$\begin{bmatrix} \alpha \\ ß \end{bmatrix} := \text{Minerr}(\alpha,ß)$$

Parameters for best fit

$\alpha = 0.02$
$ß = 166.77$

Mean squared error

$$\frac{SSE(\alpha,ß)}{4} = 24.925$$

Plot of fit:

tt := 1 ..150

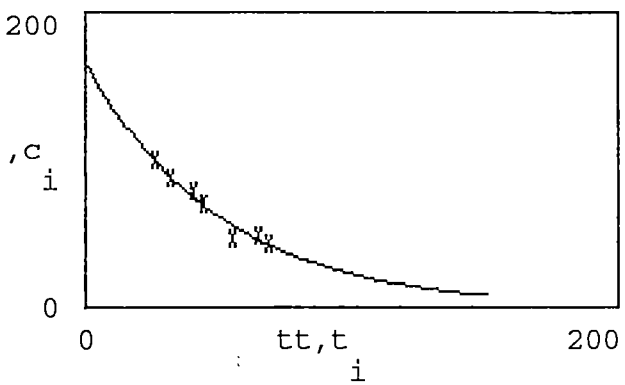


Figure A.9

NATURAL AIR CHANGE CALCULATION - March 1,1995.
House A.2

ORIGIN ≡ 1
i := 1 ..7

$$t := \begin{bmatrix} 21 \\ 38 \\ 54 \\ 69 \\ 84 \\ 99 \\ 114 \end{bmatrix} \qquad c := \begin{bmatrix} 58.9 \\ 64.9 \\ 39.5 \\ 33.7 \\ 30.5 \\ 22.7 \\ 18.3 \end{bmatrix}$$

(c-vector is the SF6 concentration)
(t-vector is the time after injection)

Define the fitting function

$$cc(t,\alpha,ß) := ß \cdot \exp(-\alpha \cdot t)$$

$$SSE(\alpha,ß) := \sum_i \left[c_i - cc\left[t_i ,\alpha,ß \right] \right]^2$$

Initial guess for parameters
$\alpha := 0.015$ $ß := 55$

Given
$SSE(\alpha,ß) \approx 0$

$1 \approx 1$

$$\begin{bmatrix} \alpha \\ ß \end{bmatrix} := Minerr(\alpha,ß)$$

Parameters for best fit

$\alpha = 0.013$
$ß = 84.721$

Mean squared error

$$\frac{SSE(\alpha,ß)}{4} = 53.429$$

Plot of fit:

tt := 1 ..150

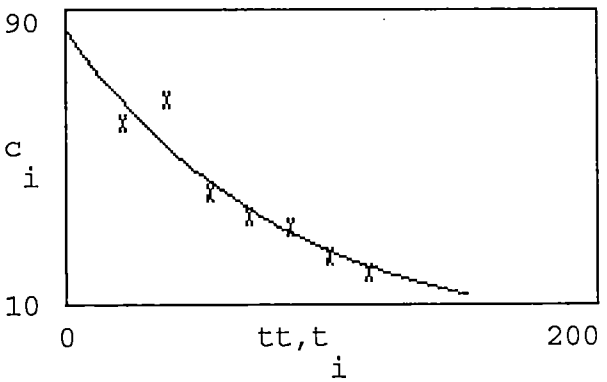


Figure A.10

Appendix B

MONITORING RESULTS FOR AREA B

- Figure B.1 House B1 - November 1993
- Figure B.2 House B1 - December 1993
- Figure B.3 House B1 - January 1994
- Figure B.4 House B1 - February 1994
- Figure B.5 House B2 - December 1993
- Figure B.6 House B2 - January 1994
- Figure B.7 House B3 - January 1994
- Figure B.8 House B3 - February 1994
- Figure B.9 House B3 - March 1994
- Figure B.10 House B3 - April 1994

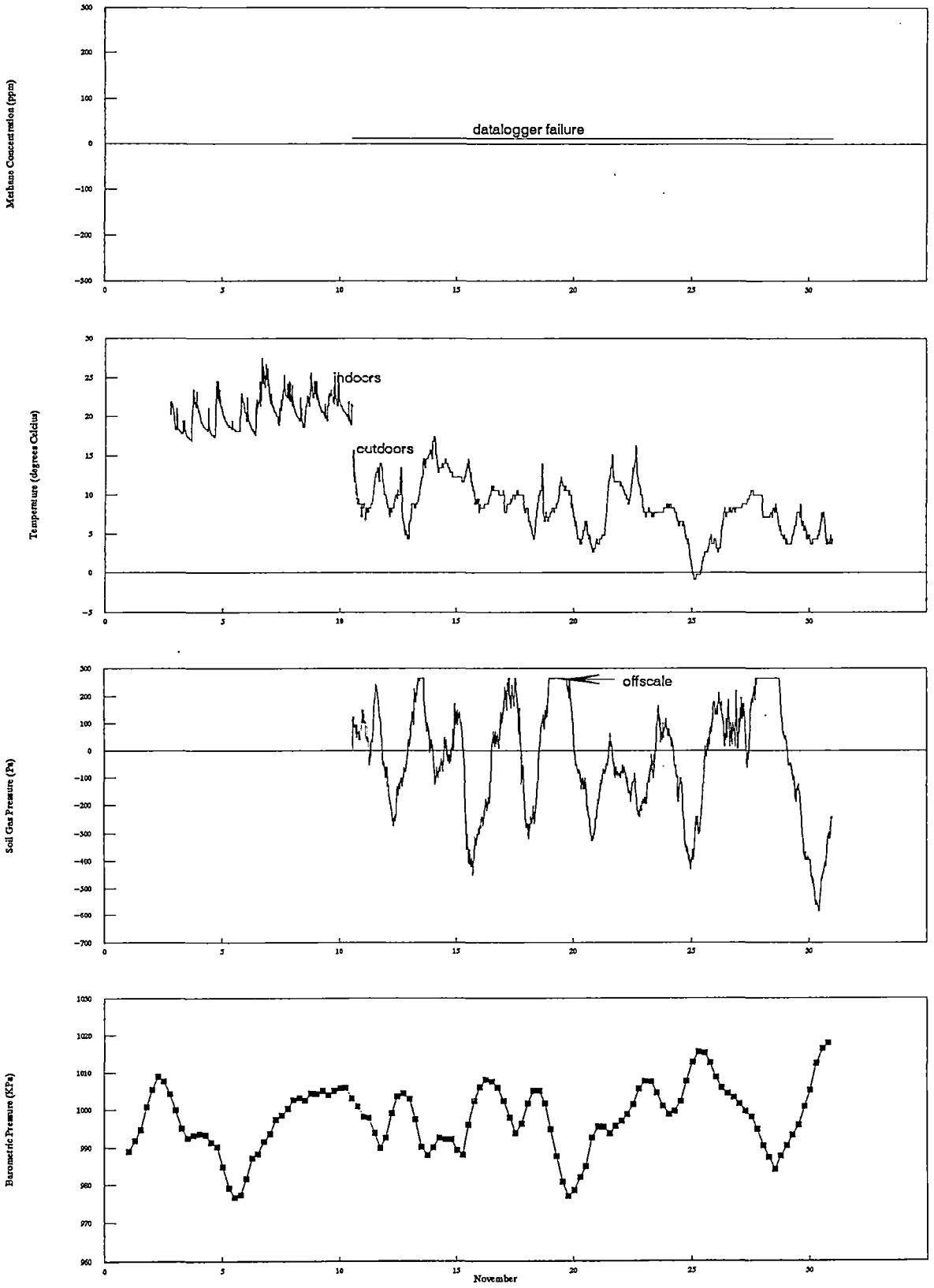

Methane Concentration (ppm)
datalogger failure
Temperature (degrees Celsius)
indoors
outdoors
Soil Gas Pressure (Pa)
offscale
Barometric Pressure (KPa)
November

Figure B.1

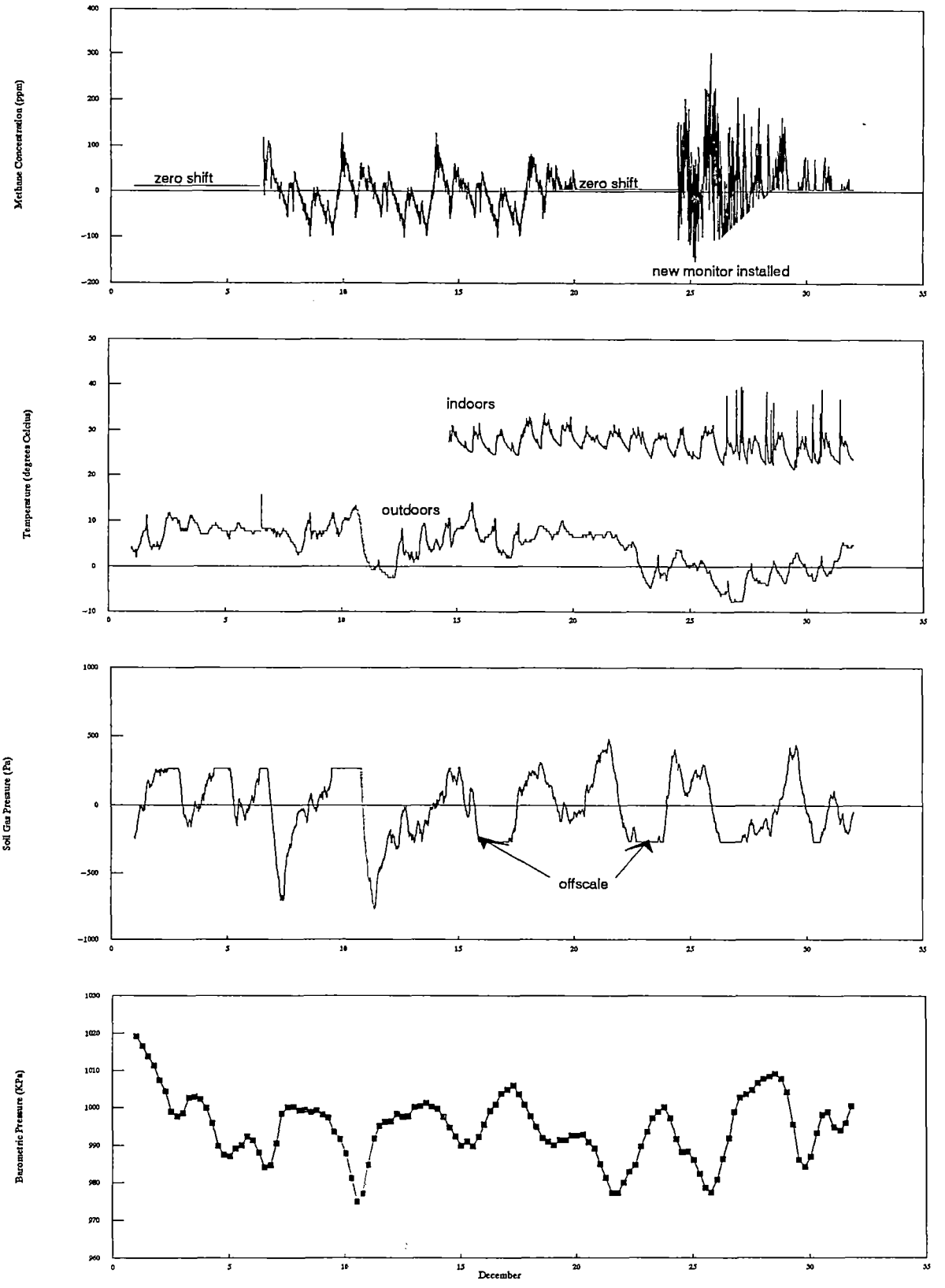

Methane Concentration (ppm)
zero shift
zero shift
new monitor installed
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
offscale
Barometric Pressure (KPa)
December

Figure B.2

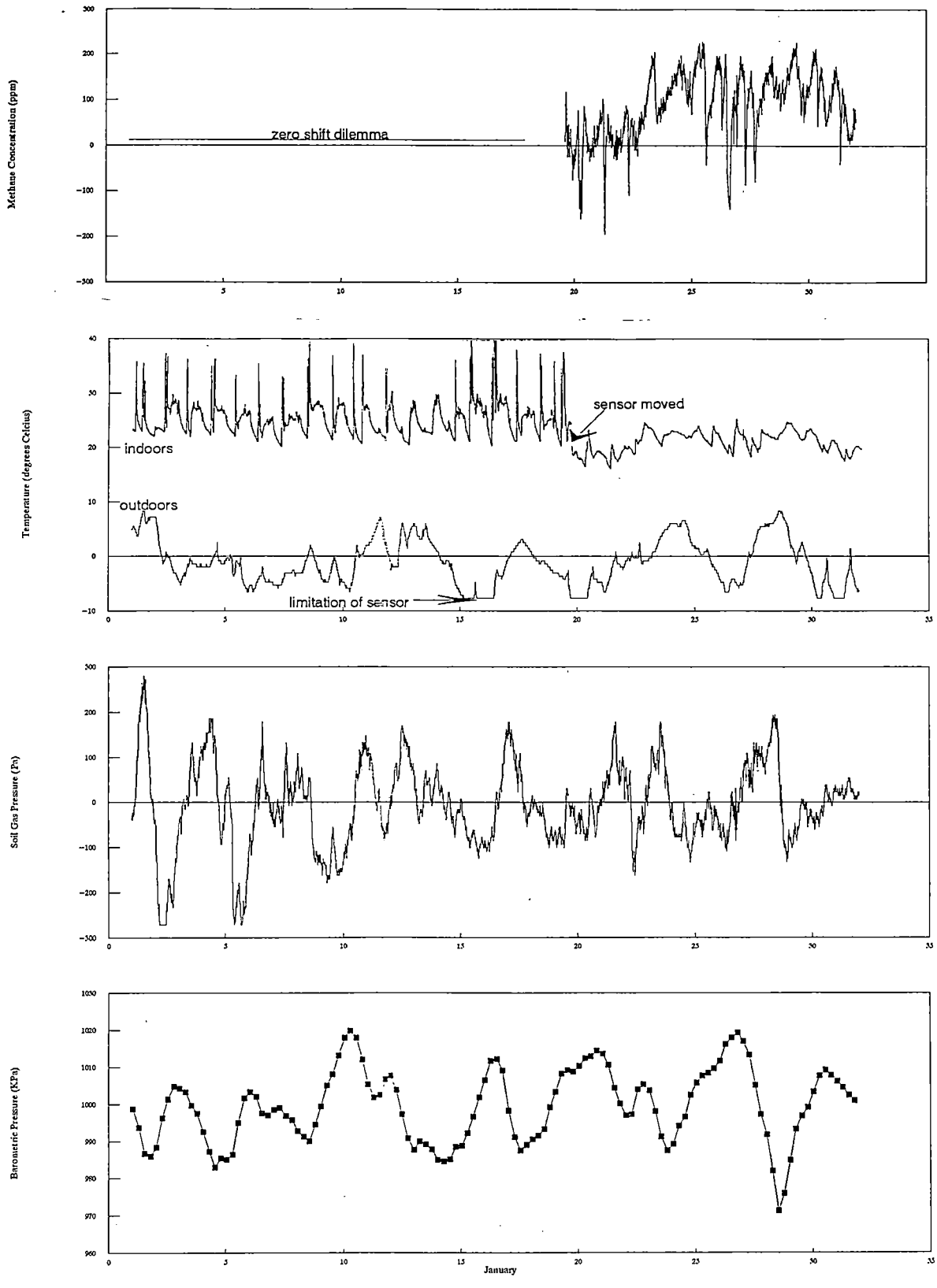

Methane Concentration (ppm)
zero shift dilemma
Temperature (degrees Celcius)
sensor moved
indoors
outdoors
limitation of sensor
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
January

Figure B.3

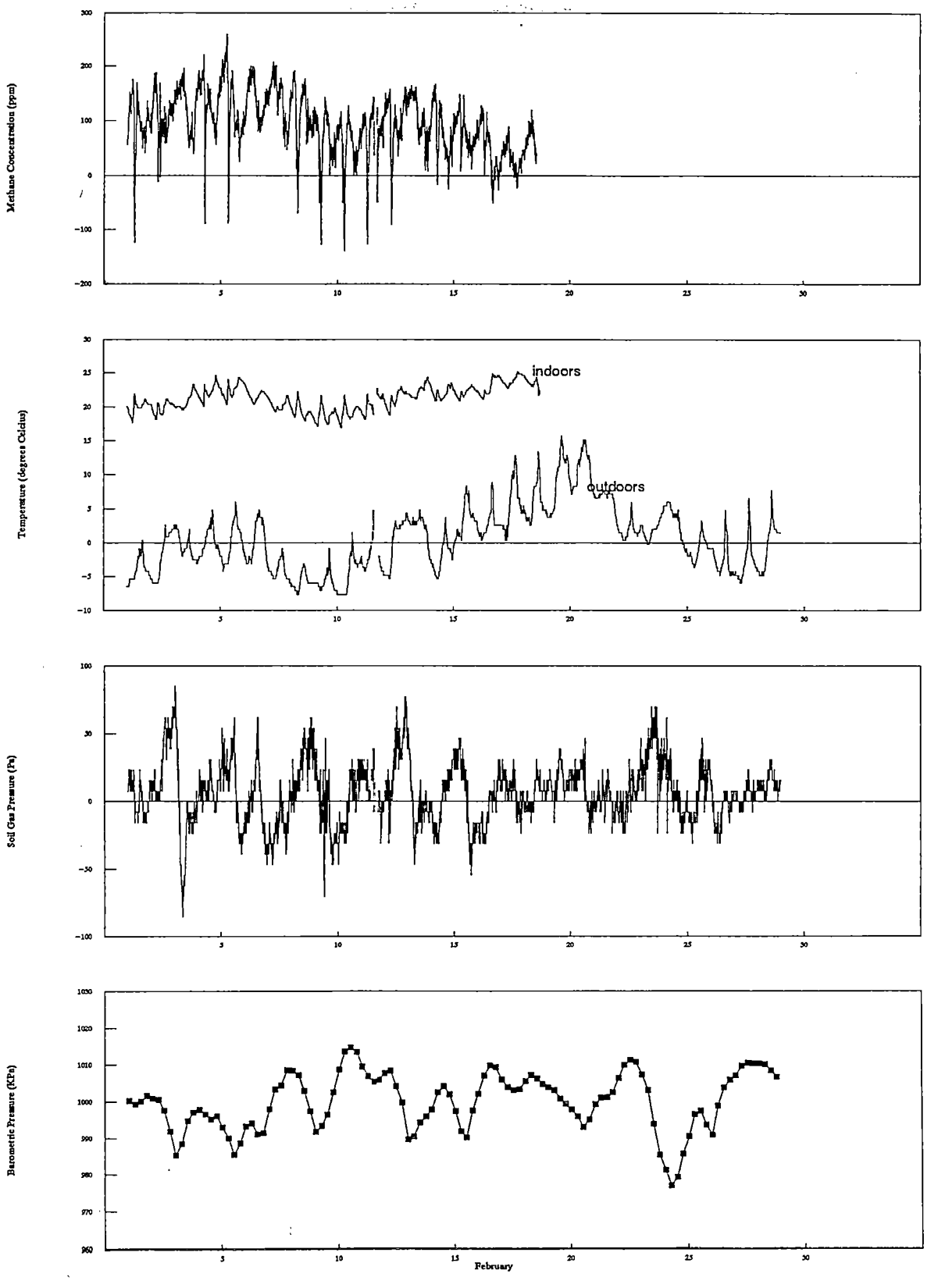

Methane Concentration (ppm)
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
February

Figure B.4

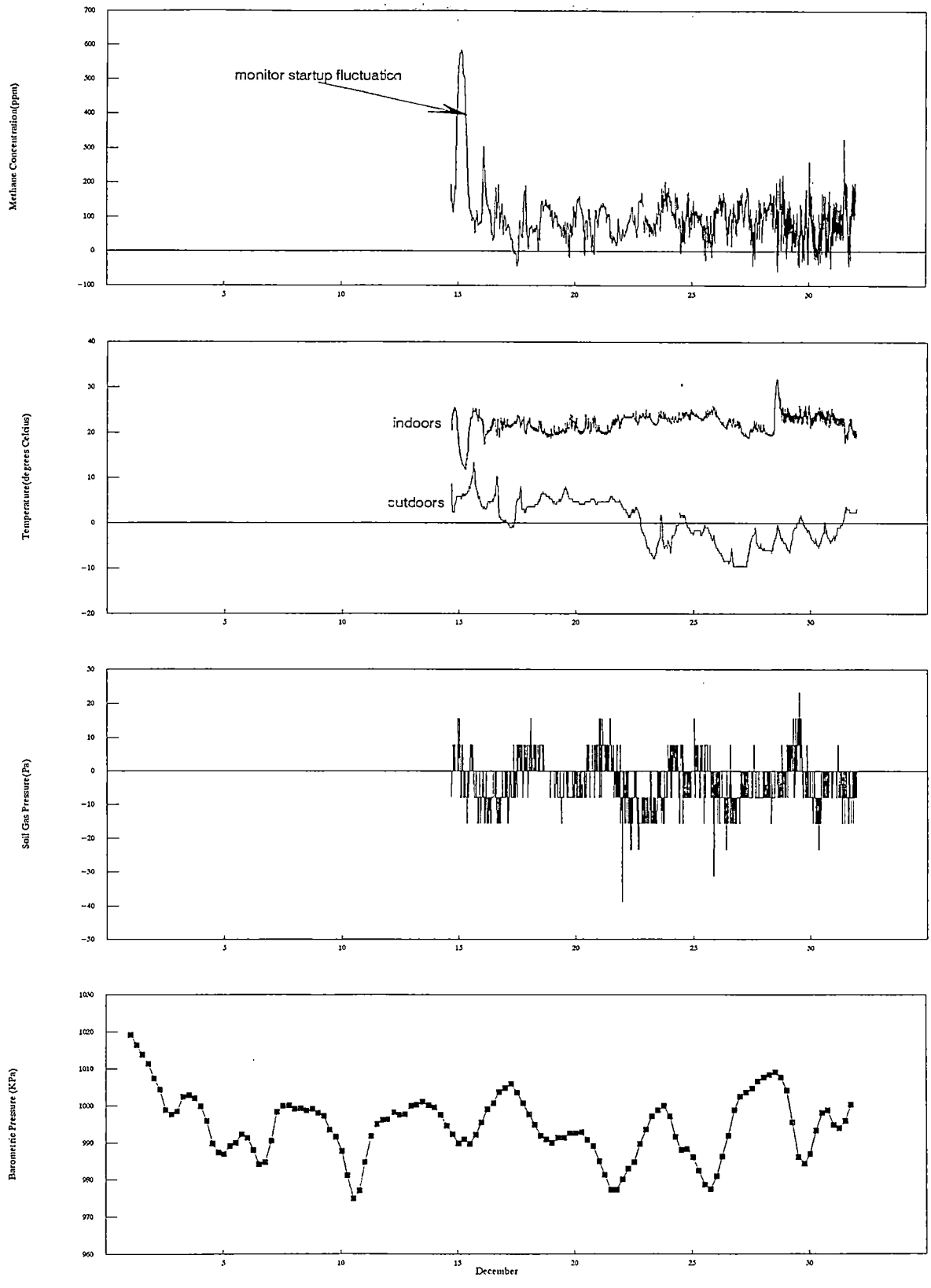

Methane Concentration(ppm)
monitor startup fluctuation
Temperature(degrees Celcius)
indoors
outdoors
Soil Gas Pressure(Pa)
Barometric Pressure (KPa)
December

Figure B.5

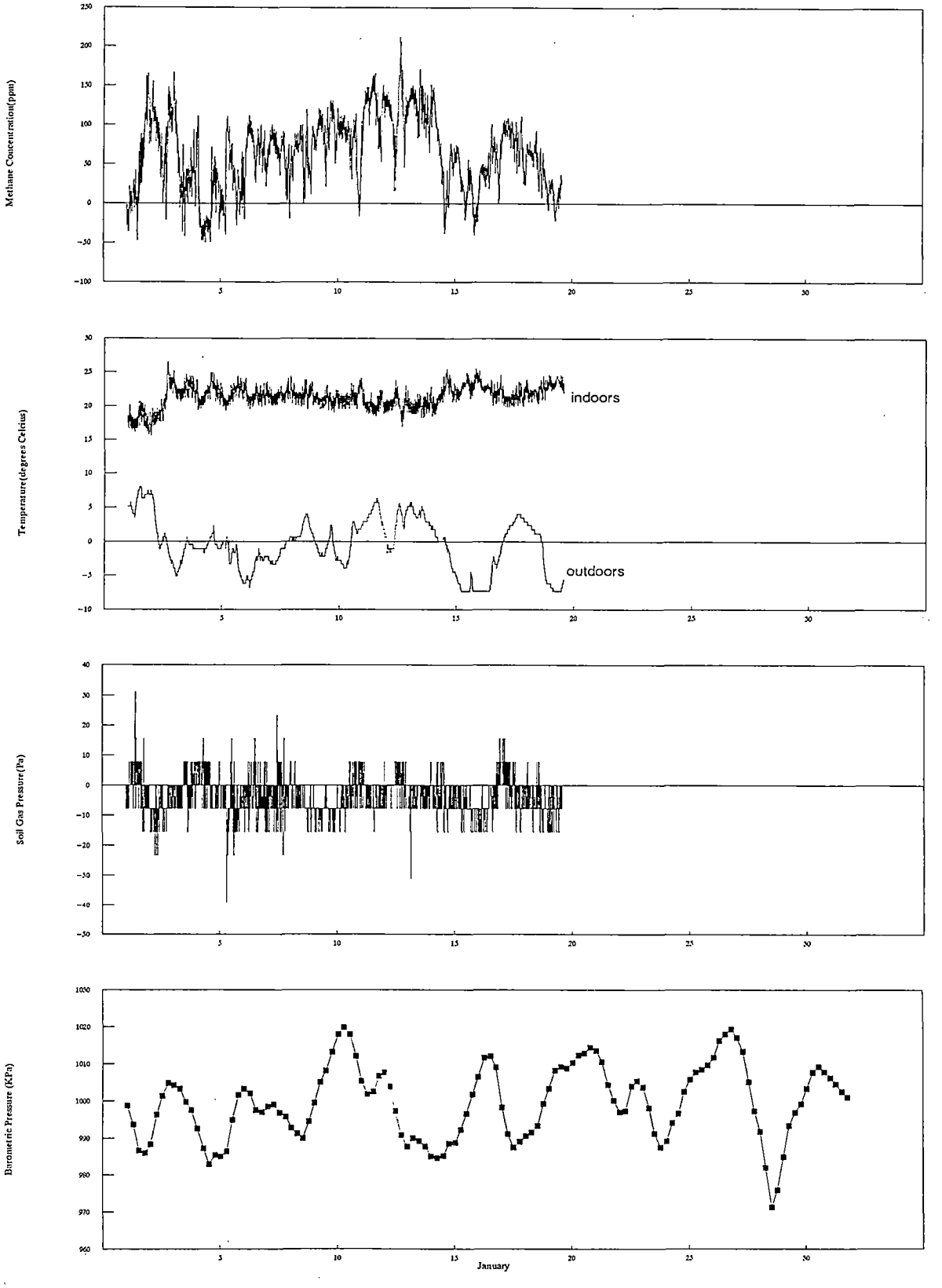

Methane Concentration(ppm)
Temperature(degrees Celcius)
indoors
outdoors
Soil Gas Pressure(Pa)
Barometric Pressure (KPa)
January

Figure B.6

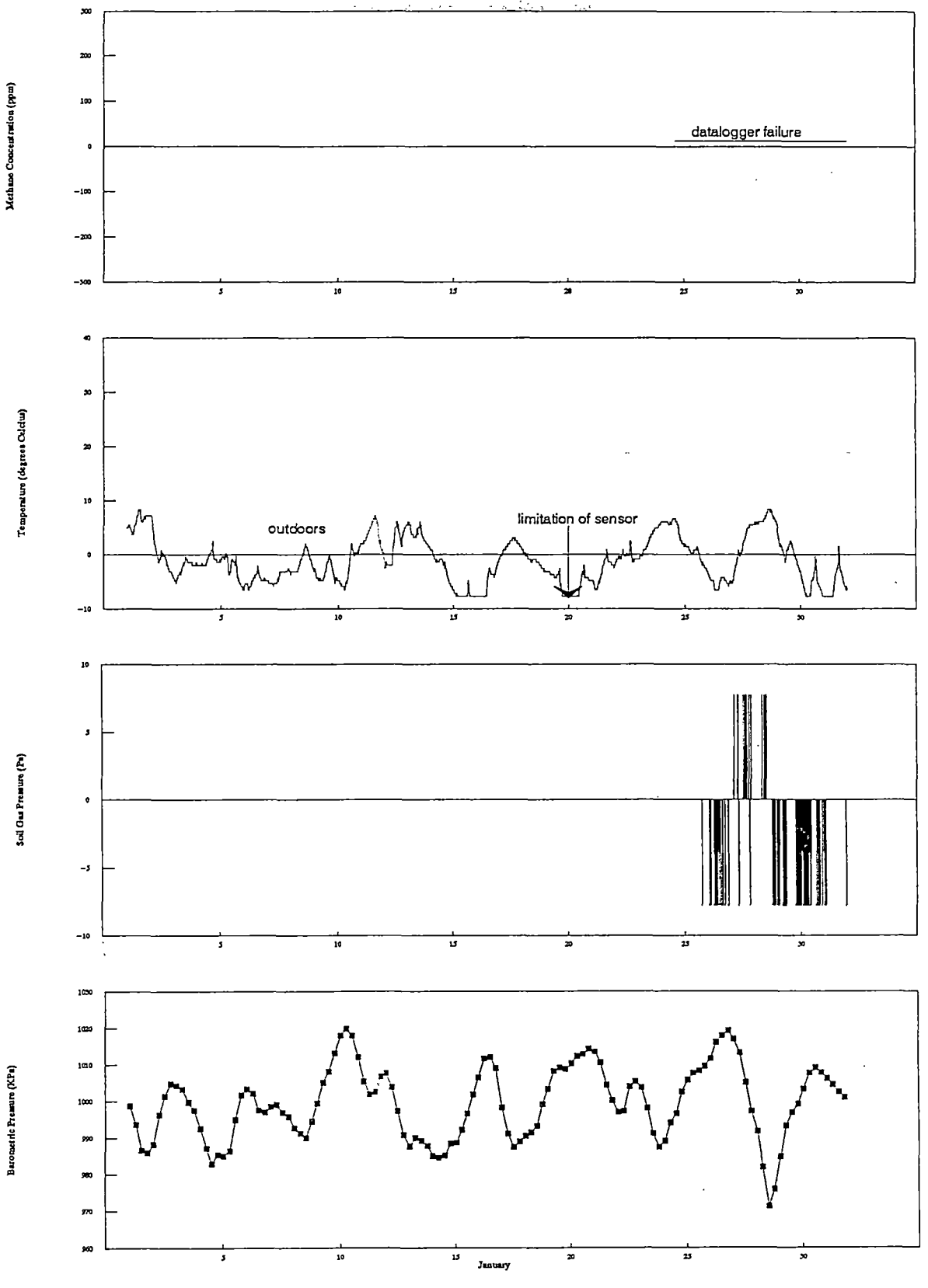

Methane Concentration (ppm)
datalogger failure
Temperature (degrees Celcius)
outdoors
limitation of sensor
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
January

Figure B.7

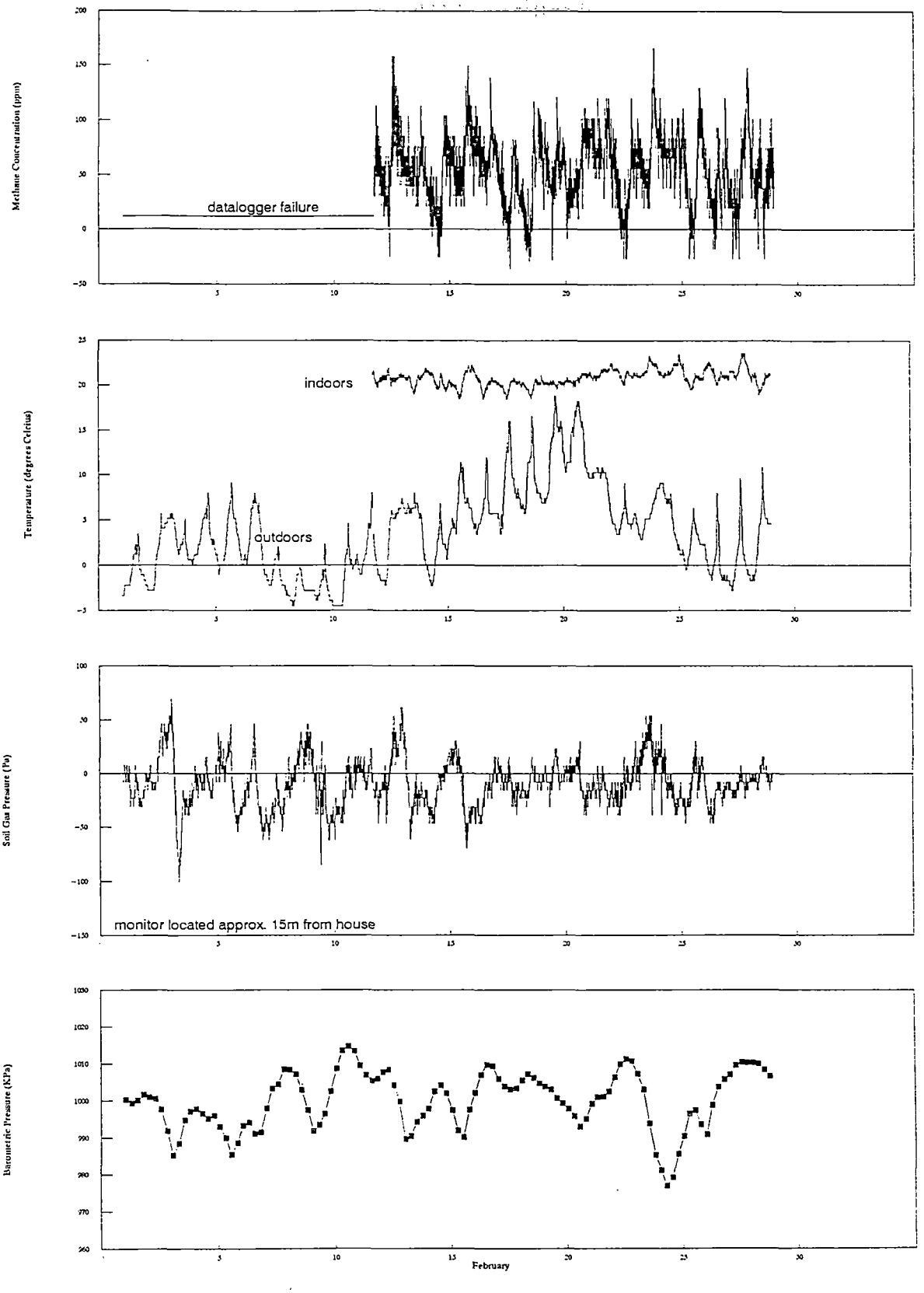

Methane Concentration (ppm)
datalogger failure
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
monitor located approx. 15m from house
Barometric Pressure (KPa)
February

Figure B.8

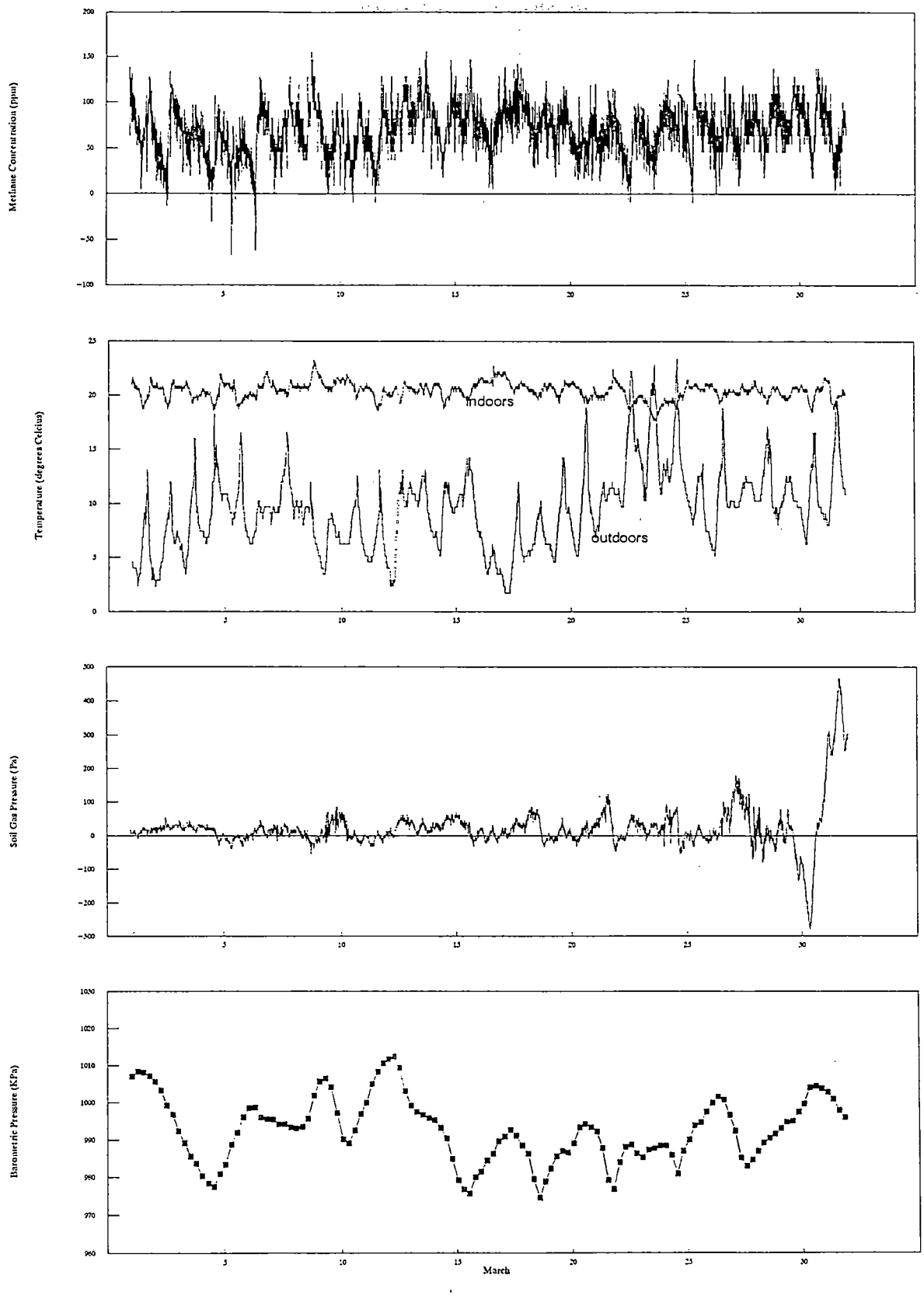

Methane Concentration (ppm)
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
March

Figure B.9

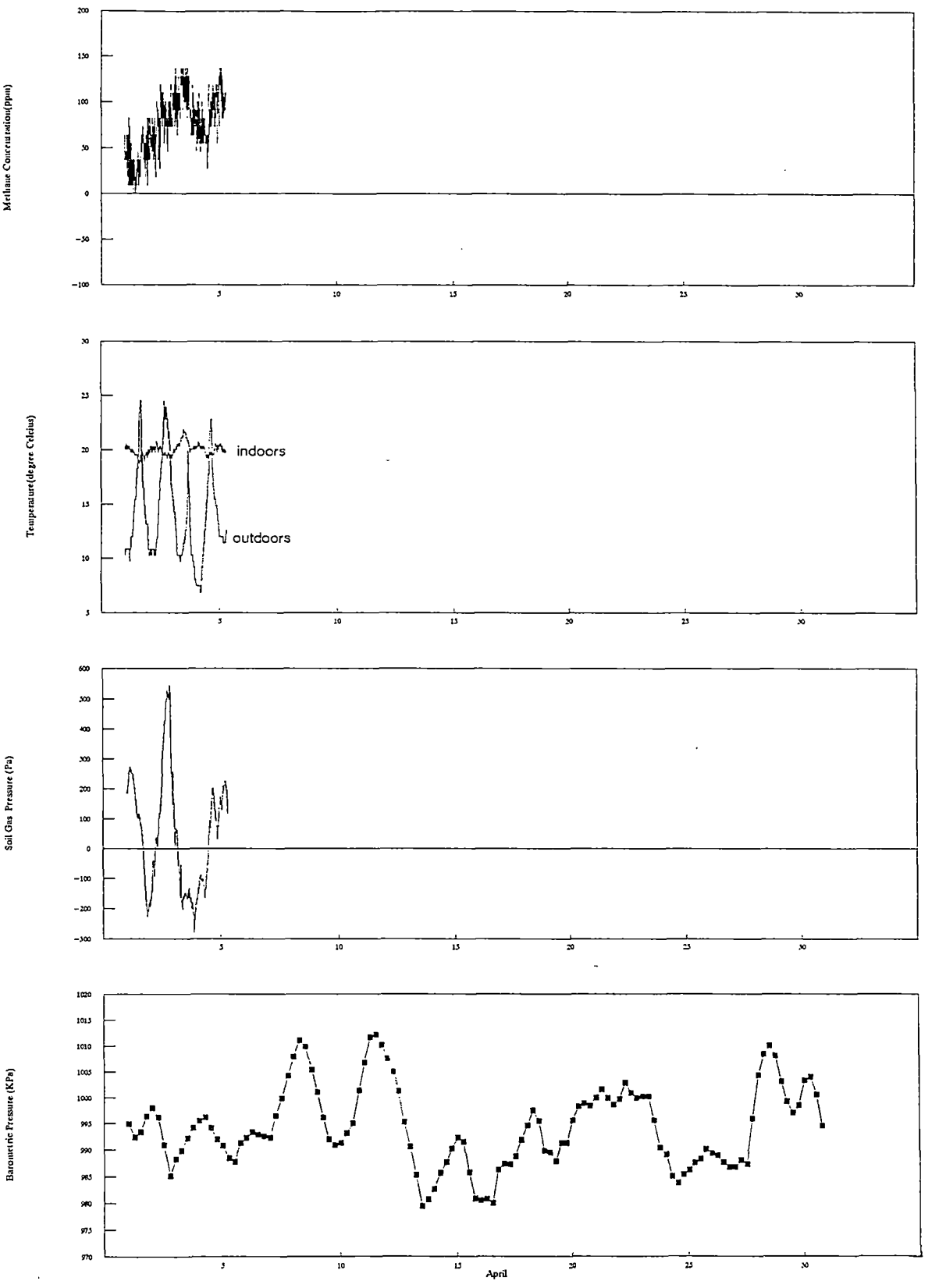

Methane Concentration(ppm)
Temperature(degree Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
April

Figure B.10

Appendix C

MONITORING RESULTS FOR AREA C

- Figure C.1 House C1 - November 1994
- Figure C.2 House C1 - December 1994
- Figure C.3 House C1 - January 1995
- Figure C.4 House C1 - February 1995
- Figure C.5 House C1 - March 1995
- Figure C.6 House C2 - December 1994
- Figure C.7 House C2 - January 1994
- Figure C.8 House C2 - February 1994
- Figure C.9 House C1 - Natural Air Exchange Test
- Figure C.10 House C2 - Natural Air Exchange Test

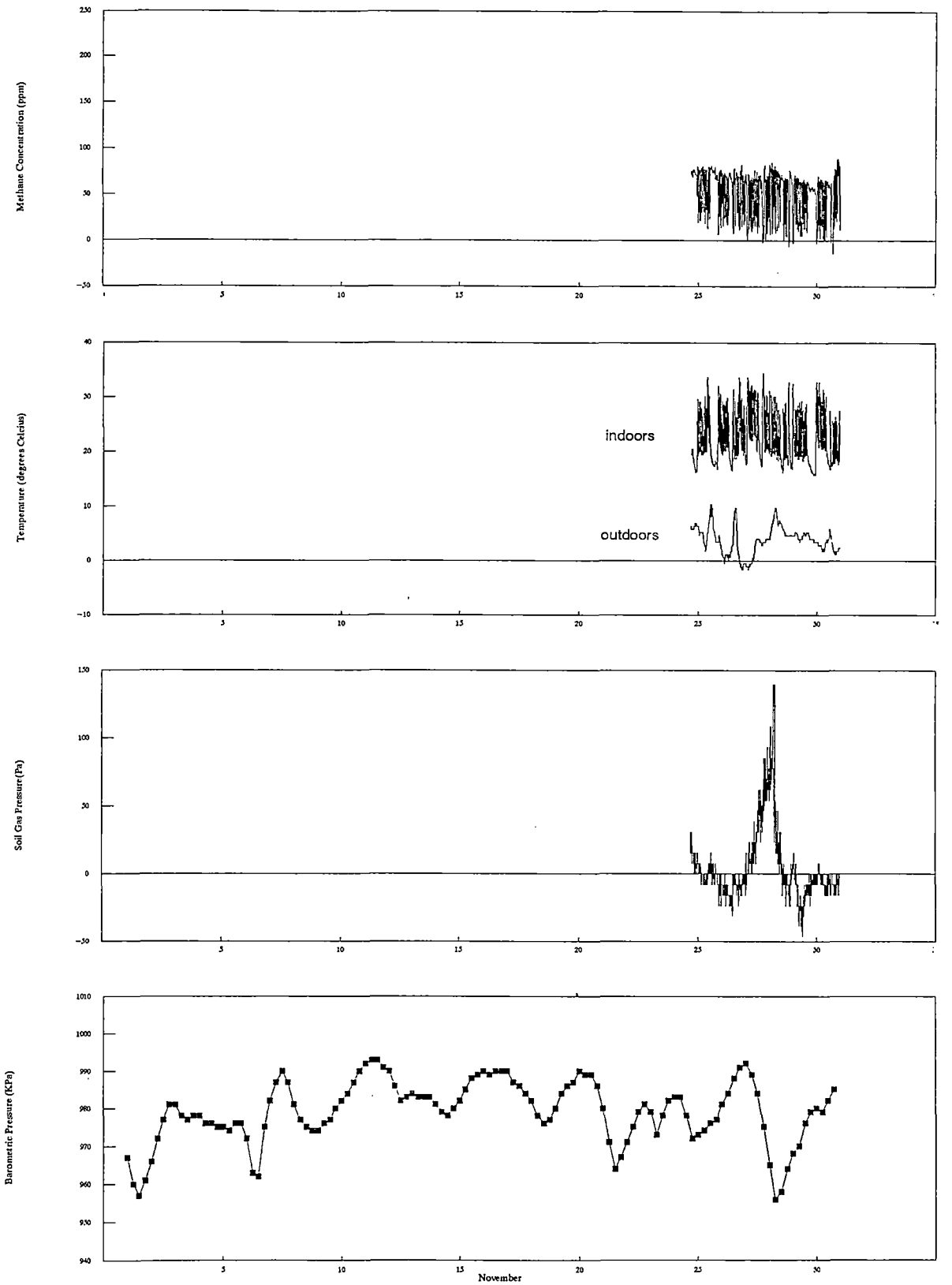

Methane Concentration (ppm)
250
200
150
100
50
0
-50
Temperature (degrees Celcius)
40
30
20
10
0
-10
indoors
outdoors
Soil Gas Pressure (Pa)
150
100
50
0
-50
Barometric Pressure (KPa)
1010
1000
990
980
970
960
950
940
5
10
15
20
25
30
November

Figure C.1

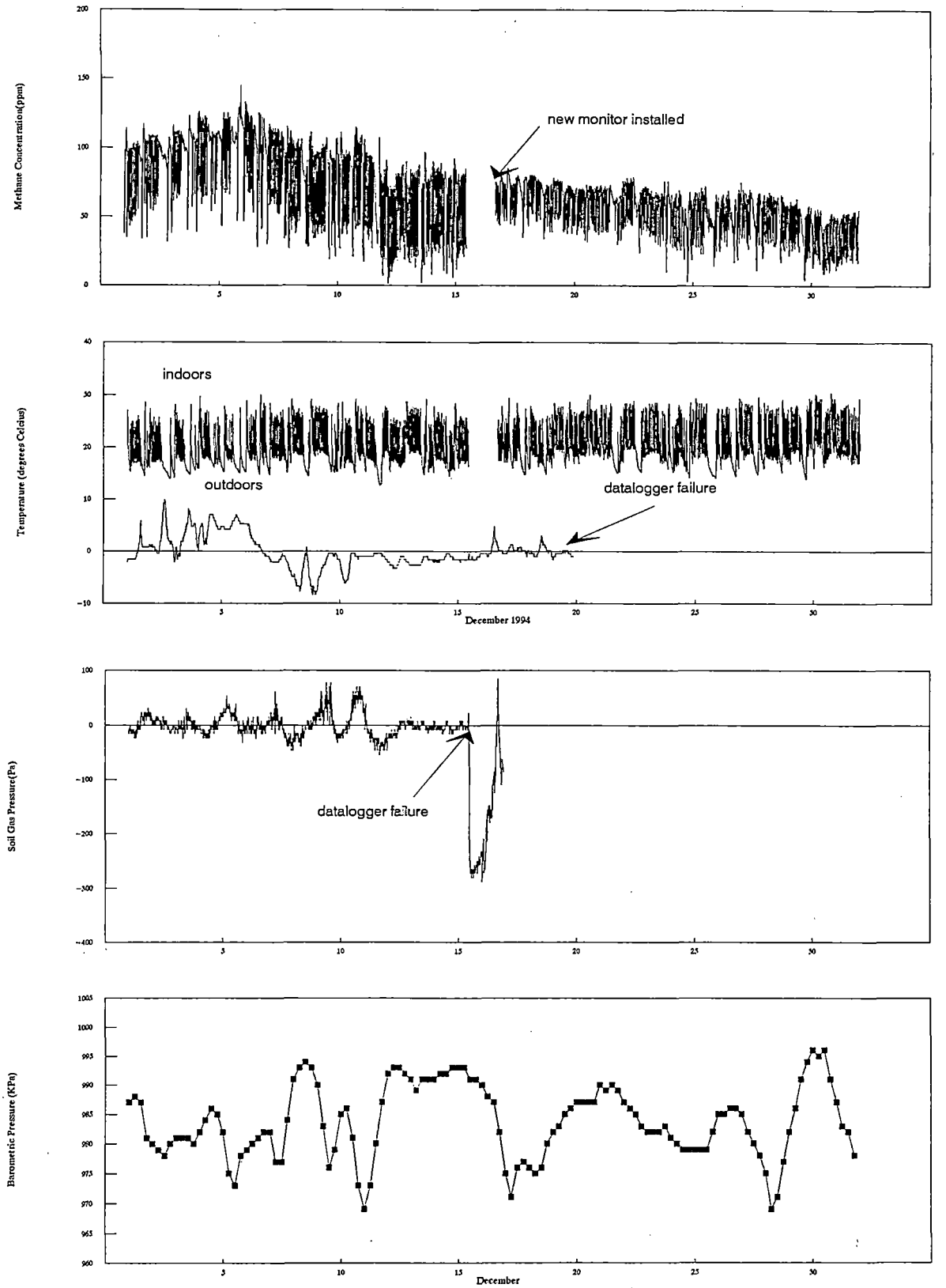

Methane Concentration(ppm)
new monitor installed
Temperature (degrees Celcius)
indoors
outdoors
datalogger failure
December 1994
Soil Gas Pressure(Pa)
datalogger failure
Barometric Pressure (KPa)
December

Figure C.2

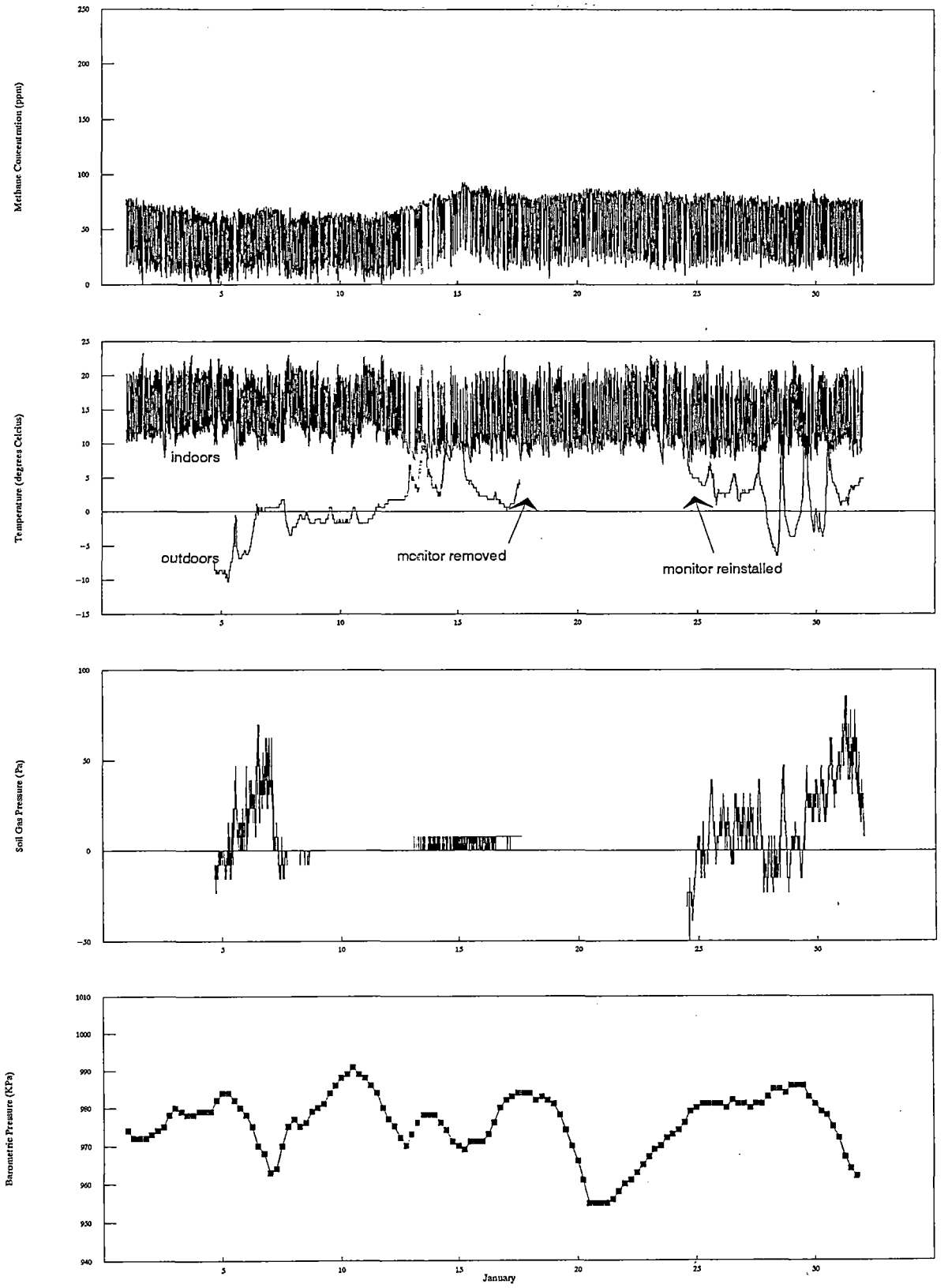

Methane Concentration (ppm)
Temperature (degrees Celcius)
indoors
outdoors
monitor removed
monitor reinstalled
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
January

Figure C.3

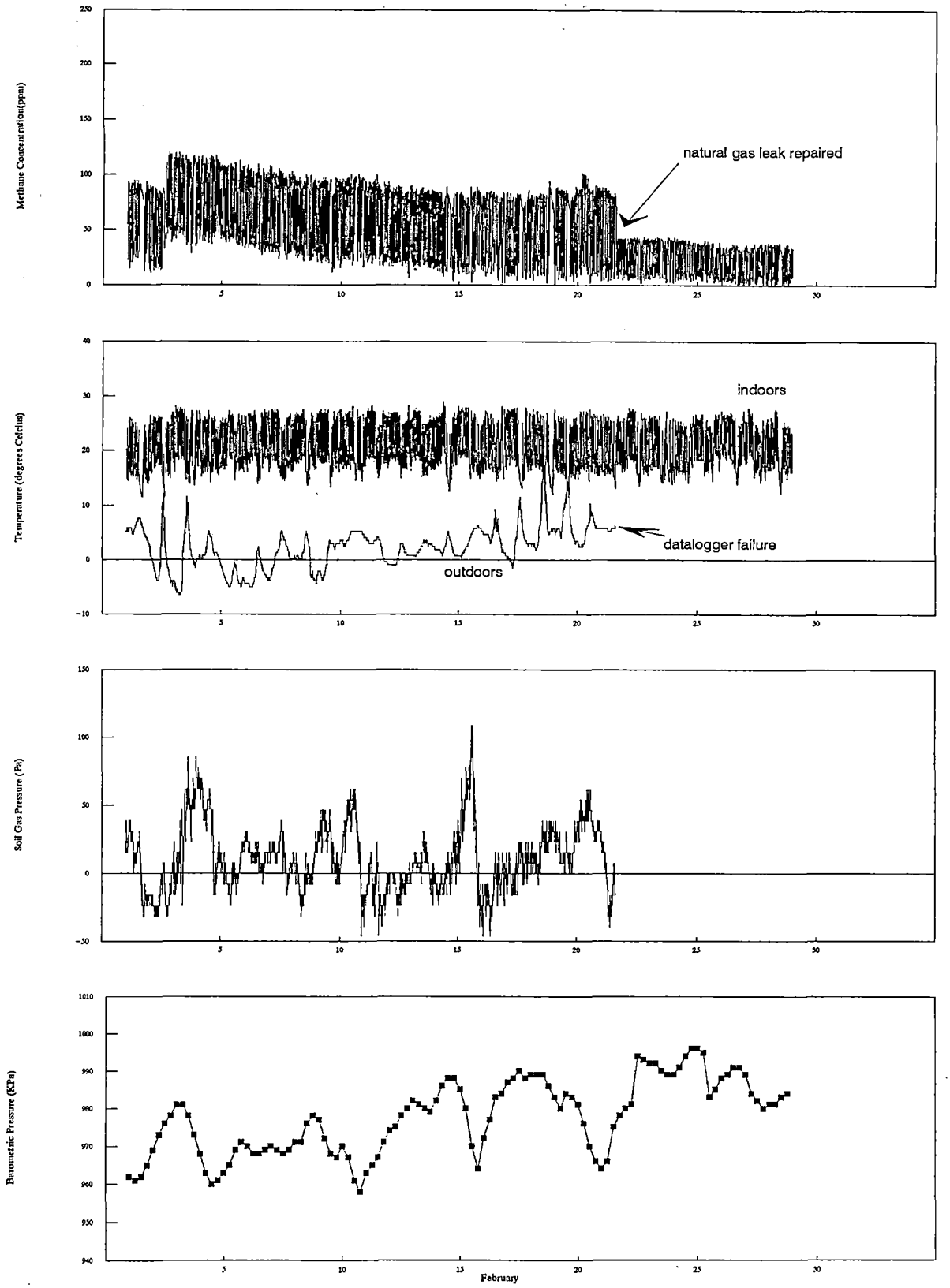

Methane Concentration(ppm)
natural gas leak repaired
Temperature (degrees Celcius)
indoors
datalogger failure
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
February

Figure C.4

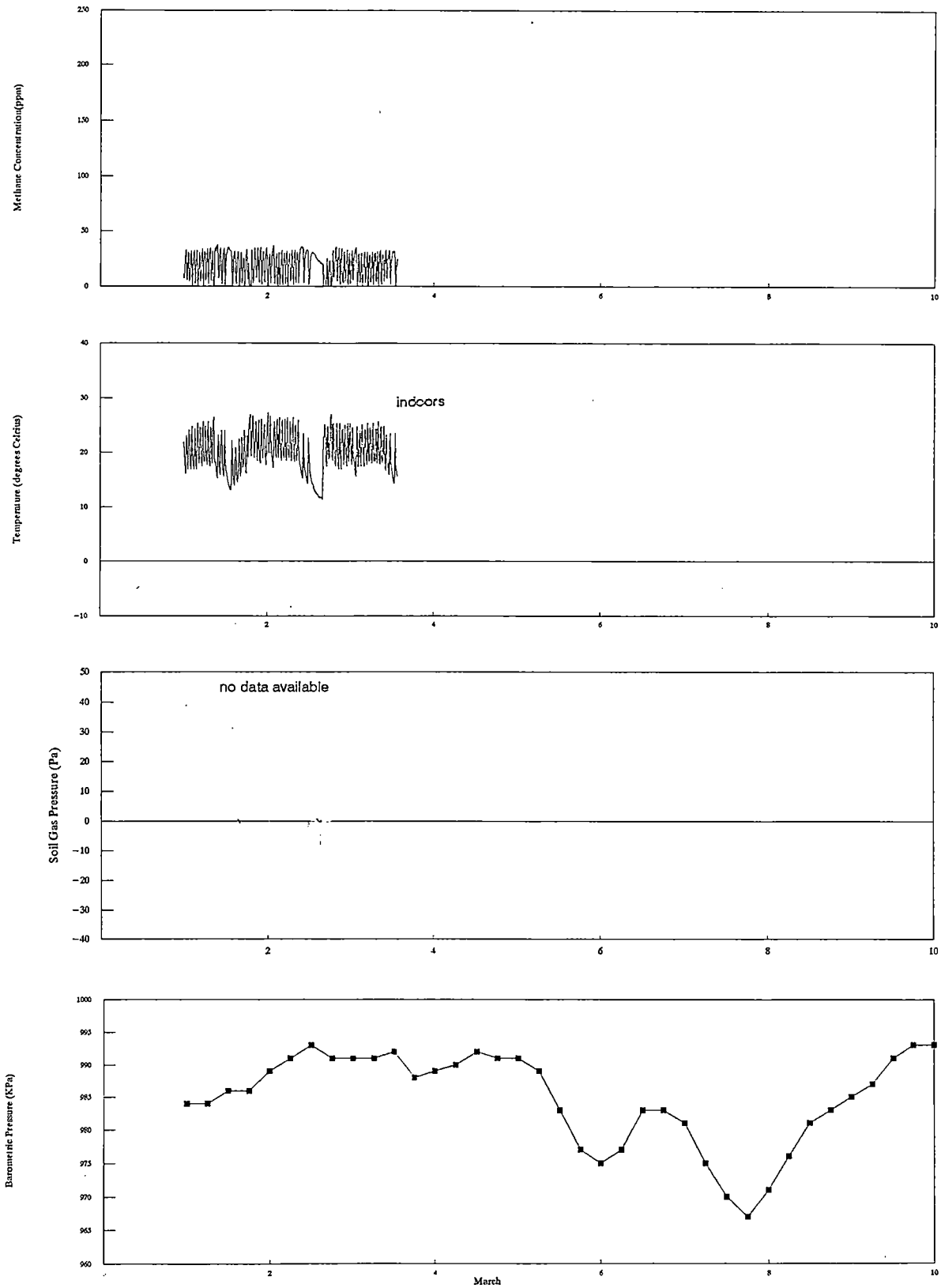

Methane Concentration(ppm)
250
200
150
100
50
0
2
4
6
8
10
Temperature (degrees Celcius)
40
30
20
10
0
−10
indoors
Soil Gas Pressure (Pa)
50
40
30
20
10
0
−10
−20
−30
−40
no data available
Barometric Pressure (KPa)
1000
995
990
985
980
975
970
965
960
March

Figure C.5

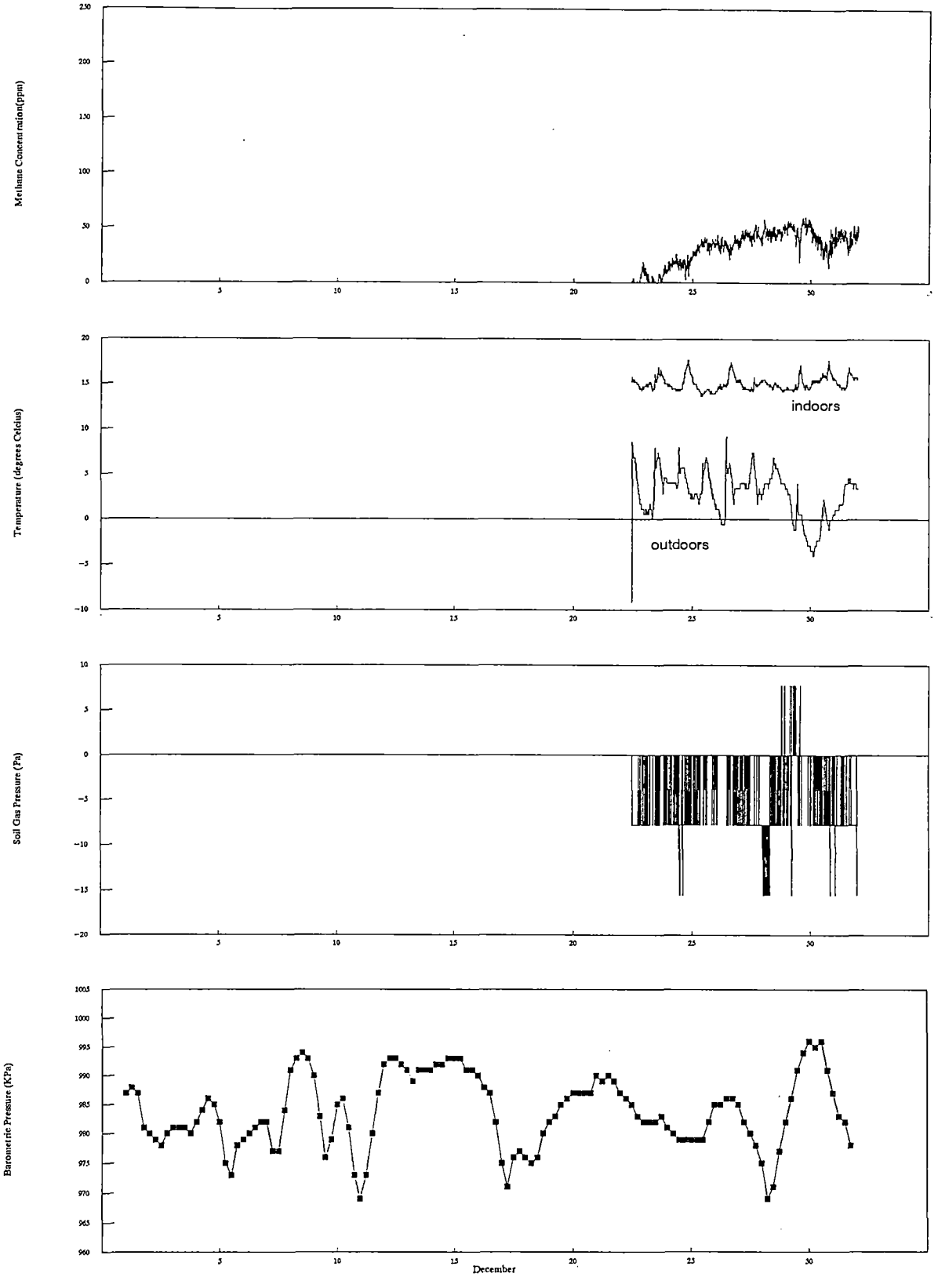

Methane Concentration(ppm)
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
December

Figure C.6

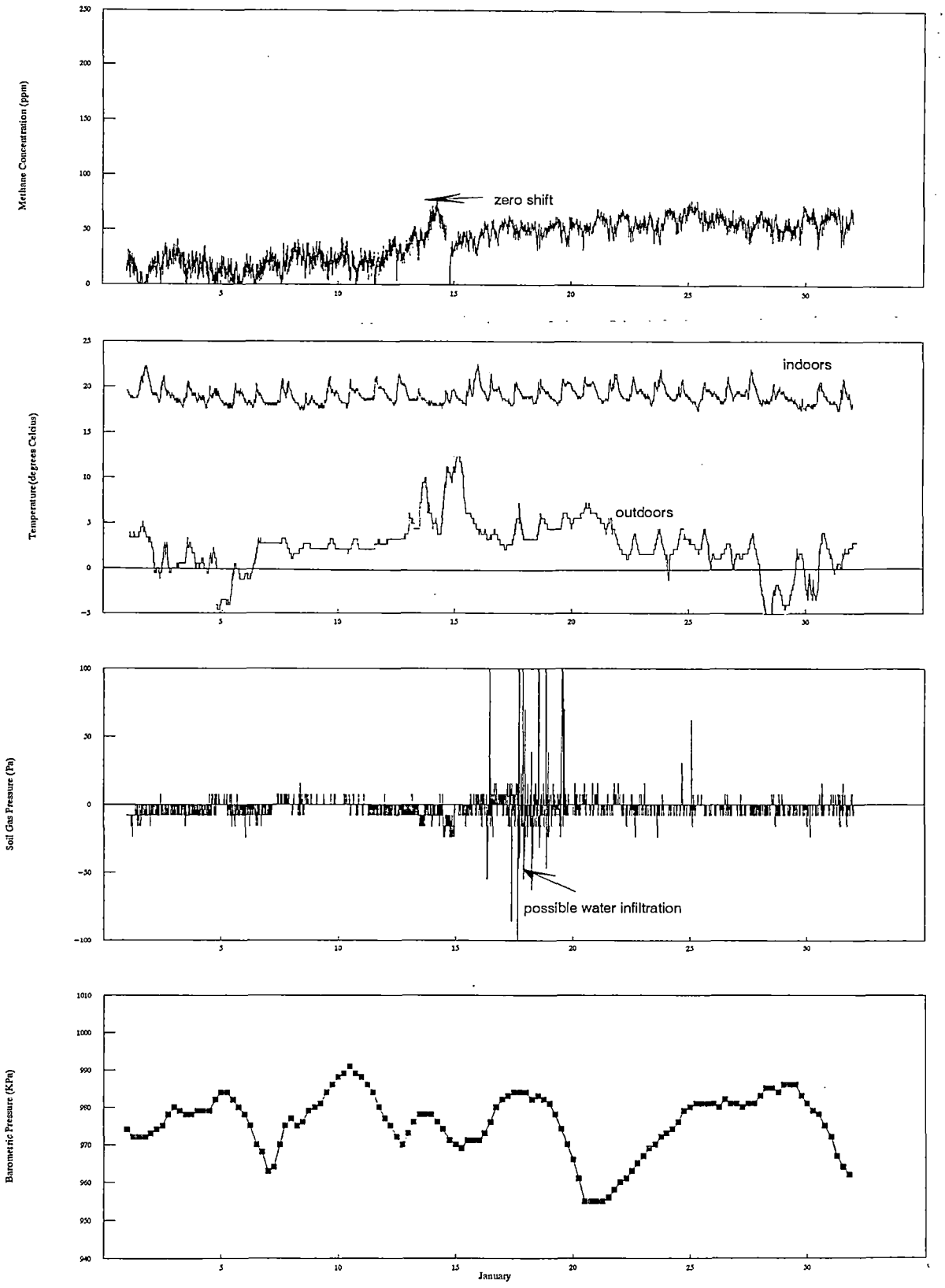

Methane Concentration (ppm)
zero shift
Temperature (degrees Celcius)
indoors
outdoors
Soil Gas Pressure (Pa)
possible water infiltration
Barometric Pressure (KPa)
January

Figure C.7

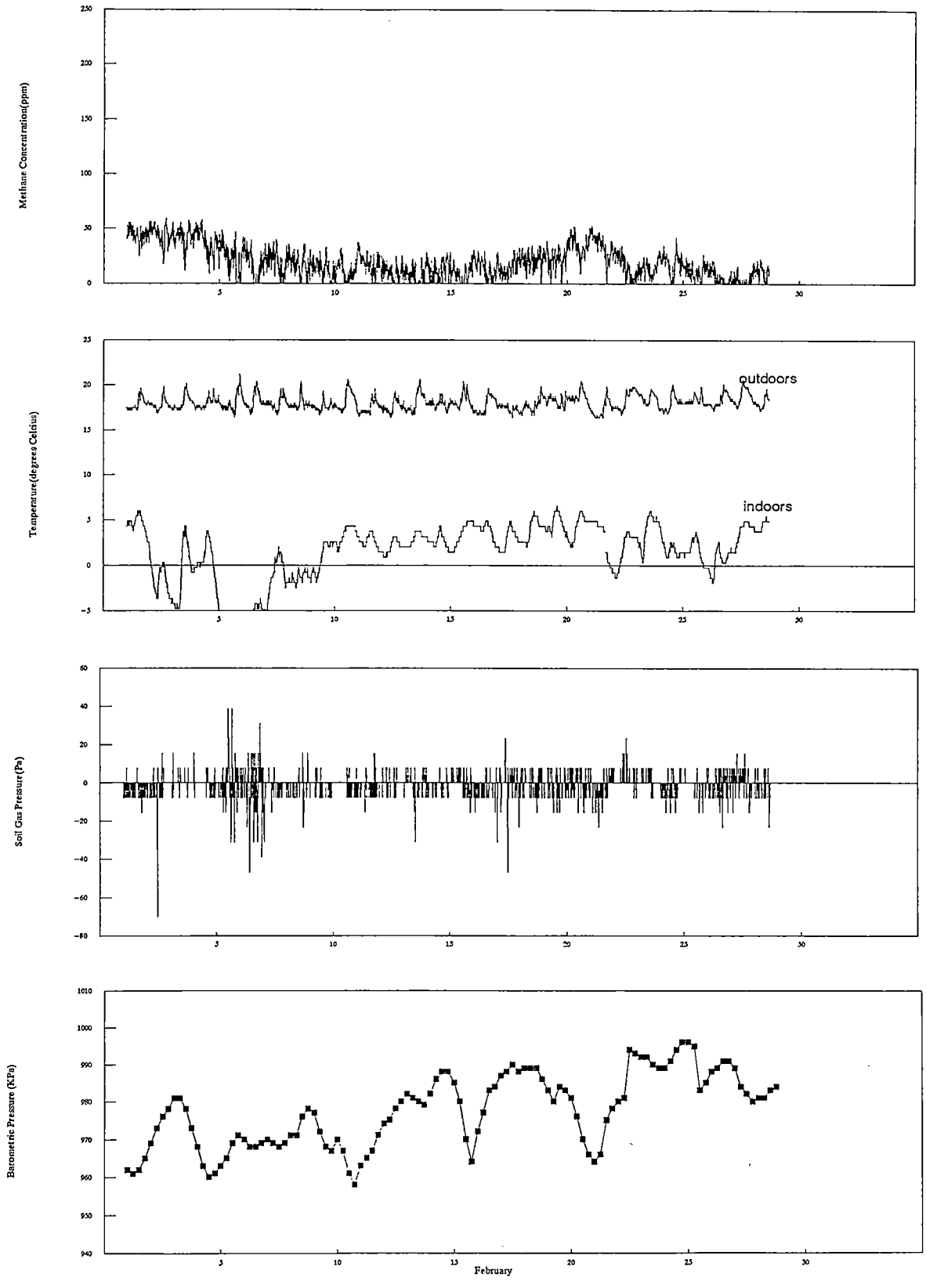

Methane Concentration(ppm)
Temperature(degrees Celcius)
outdoors
indoors
Soil Gas Pressure (Pa)
Barometric Pressure (KPa)
February

Figure C.8

NATURAL AIR CHANGE CALCULATION - February 21,1995.
House C.1

ORIGIN ≡ 1
i := 1 ..8

$$t := \begin{bmatrix} 26 \\ 37 \\ 47 \\ 57 \\ 67 \\ 80 \\ 89 \\ 101 \end{bmatrix} \qquad c := \begin{bmatrix} 22.9 \\ 19.7 \\ 9.7 \\ 12.9 \\ 11.2 \\ 10.7 \\ 8.5 \\ 5.2 \end{bmatrix}$$

(c-vector is the SF6 concentration)
(t-vector is the time after injection)

Define the fitting function

$$cc(t,\alpha,ß) := ß \cdot \exp(-\alpha \cdot t)$$

$$SSE(\alpha,ß) := \sum_i \left[c_i - cc\left[t_i ,\alpha,ß \right] \right]^2$$

Initial guess for parameters
$\alpha := 0.015$ $ß := 55$

Given
$SSE(\alpha,ß) \approx 0$

$1 \approx 1$

$$\begin{bmatrix} \alpha \\ ß \end{bmatrix} := Minerr(\alpha,ß)$$

Parameters for best fit

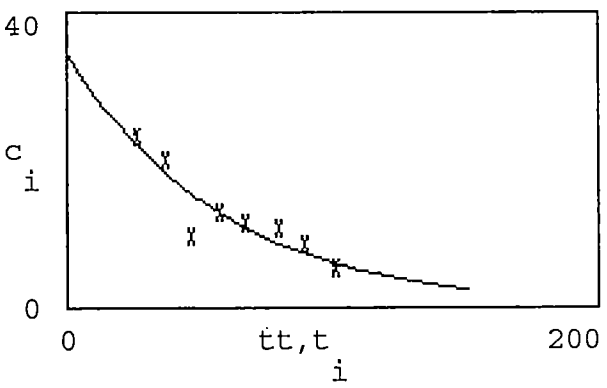
$\alpha = 0.017$
$ß = 34.527$

Mean squared error

$$\frac{SSE(\alpha,ß)}{4} = 10.152$$

Plot of fit:

tt := 1 ..150



SF6 conc.

time in minutes

Figure C.9

NATURAL AIR CHANGE CALCULATION - February 21,1995.
House C.2

ORIGIN ≡ 1
i := 1 ..7

$$t := \begin{bmatrix} 27 \\ 37 \\ 47 \\ 57 \\ 67 \\ 77 \\ 87 \end{bmatrix} \qquad c := \begin{bmatrix} 39.2 \\ 48.7 \\ 33.4 \\ 20.7 \\ 29.4 \\ 32.9 \\ 23.5 \end{bmatrix}$$

(c-vector is the SF6 concentration)
(t-vector is the time after injection)

Define the fitting function

$$cc(t,\alpha,ß) := ß \cdot \exp(-\alpha \cdot t)$$

$$SSE(\alpha,ß) := \sum_i \left[c_i - cc\left[t_i ,\alpha,ß \right] \right]^2$$

Initial guess for parameters
$\alpha := 0.015$ $ß := 55$

Given
$SSE(\alpha,ß) \approx 0$

$1 \approx 1$

$$\begin{bmatrix} \alpha \\ ß \end{bmatrix} := Minerr(\alpha,ß)$$

Parameters for best fit

$\alpha = 0.01$
$ß = 55.284$

Mean squared error

$$\frac{SSE(\alpha,ß)}{4} = 71.029$$

Plot of fit:

tt := 1 ..150

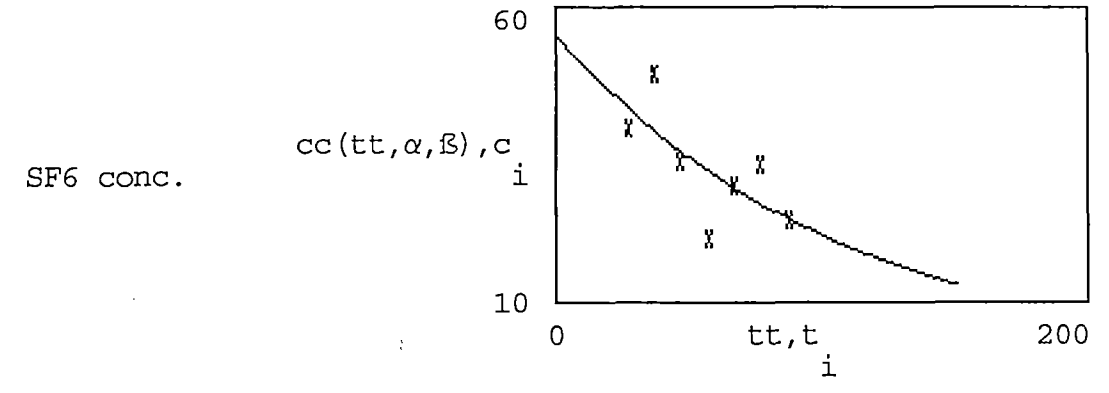


Figure C.10

Appendix D

Monitoring Results for Area D

- Figure D.1 House D1 - March 17 to 31, 1993
- Figure D.2 House D1 - April 1 to 15, 1993
- Figure D.3 House D1 - April 16 to 30, 1993
- Figure D.4 House D1 - May 1 to 13, 1993
- Figure D.5 House D2 - May 17 to 31, 1993
- Figure D.6 House D2 - April 1 to 13, 1993
- Figure D.7 House D2 - April 15 to 27, 1993
- Figure D.8 House D2 - April 29 to May 13, 1993

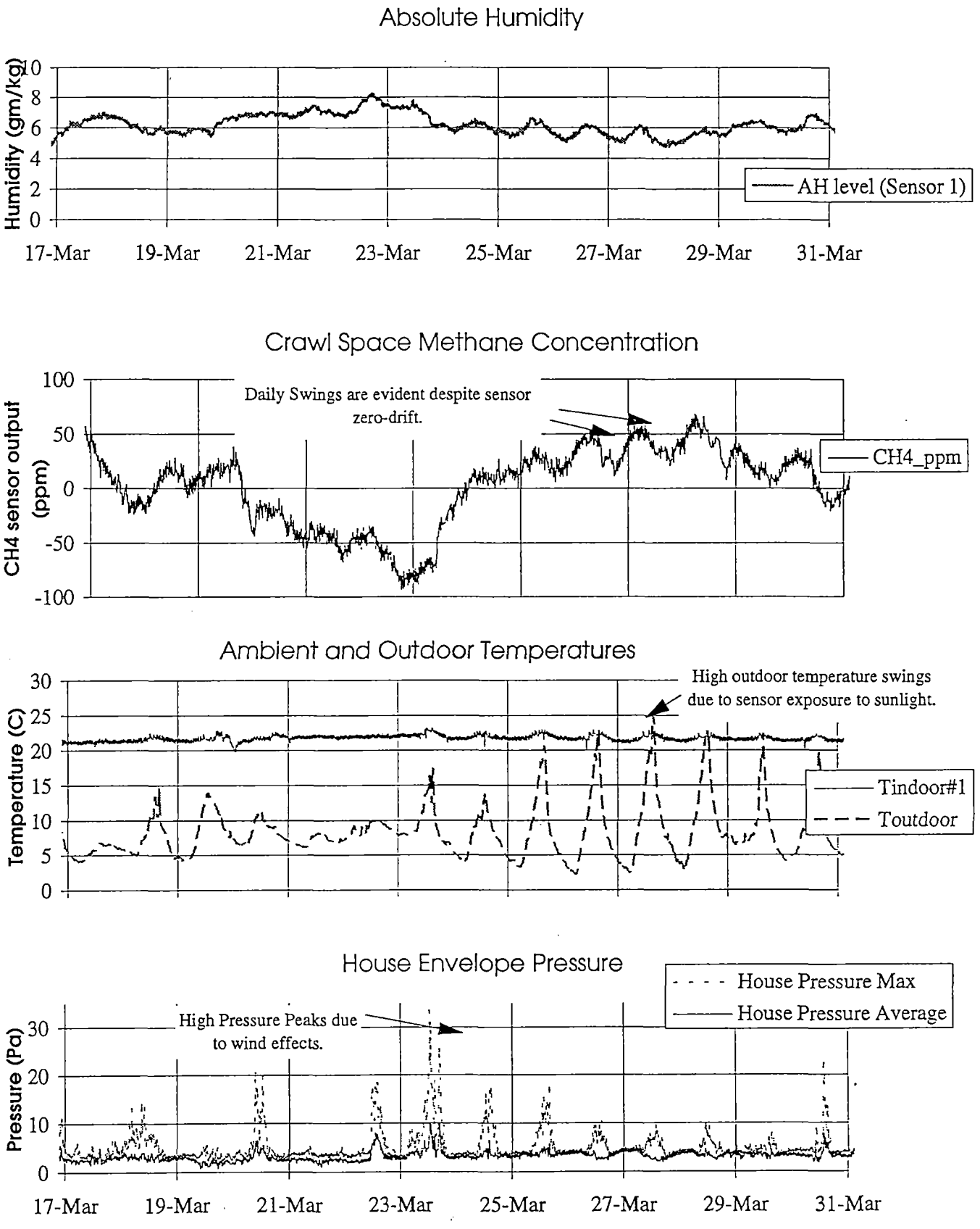
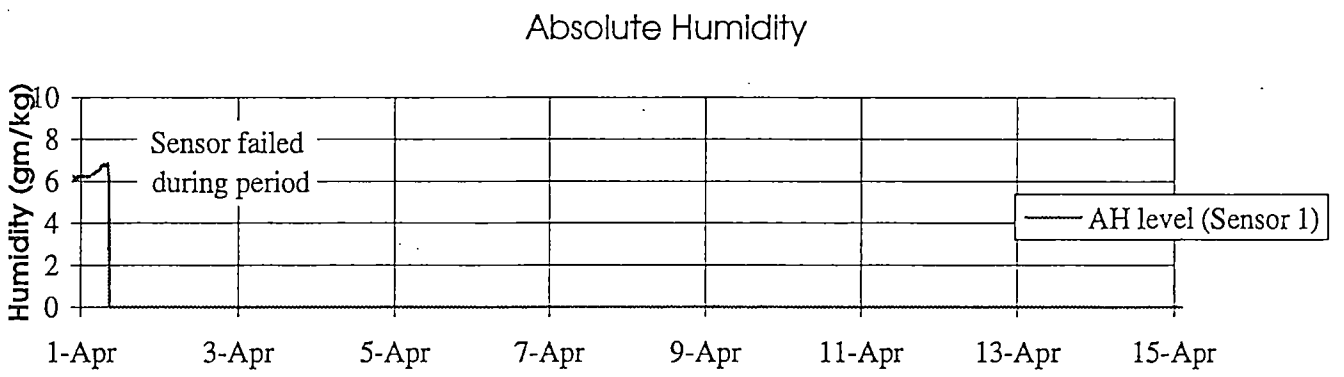
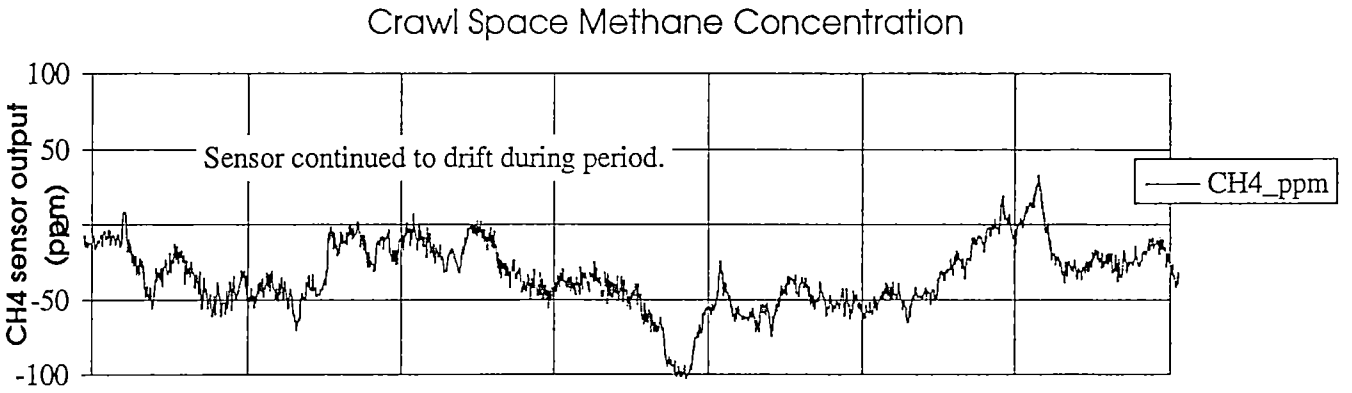
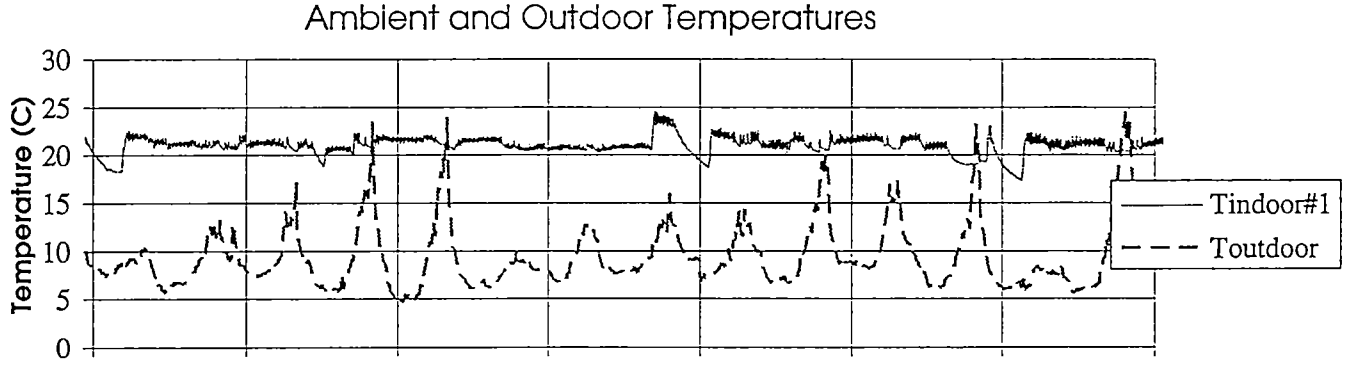

Absolute Humidity
Humidity (gm/kg)
10
8
6
4
2
0
17-Mar
19-Mar
21-Mar
23-Mar
25-Mar
27-Mar
29-Mar
31-Mar
AH level (Sensor 1)
Crawl Space Methane Concentration
CH4 sensor output (ppm)
100
50
0
-50
-100
Daily Swings are evident despite sensor zero-drift.
CH4_ppm
Ambient and Outdoor Temperatures
Temperature (C)
30
25
20
15
10
5
0
High outdoor temperature swings due to sensor exposure to sunlight.
Tindoor#1
Toutdoor
House Envelope Pressure
Pressure (Pa)
30
20
10
0
High Pressure Peaks due to wind effects.
House Pressure Max
House Pressure Average
17-Mar
19-Mar
21-Mar
23-Mar
25-Mar
27-Mar
29-Mar
31-Mar

Figure D.1


Absolute Humidity
Humidity (gm/kg)
10
8
6
4
2
0
Sensor failed
during period
AH level (Sensor 1)
1-Apr
3-Apr
5-Apr
7-Apr
9-Apr
11-Apr
13-Apr
15-Apr


Crawl Space Methane Concentration
CH4 sensor output (ppm)
100
50
-50
-100
Sensor continued to drift during period.
CH4_ppm


Ambient and Outdoor Temperatures
Temperature (C)
30
25
20
15
10
5
0
Tindoor#1
Toutdoor

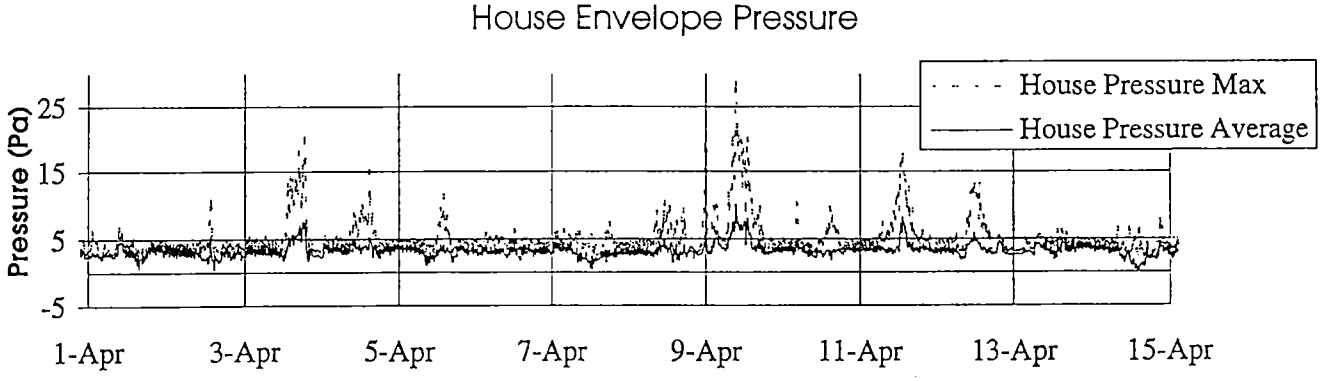

House Envelope Pressure
Pressure (Pa)
25
15
5
-5
House Pressure Max
House Pressure Average
1-Apr
3-Apr
5-Apr
7-Apr
9-Apr
11-Apr
13-Apr
15-Apr

Figure D.2

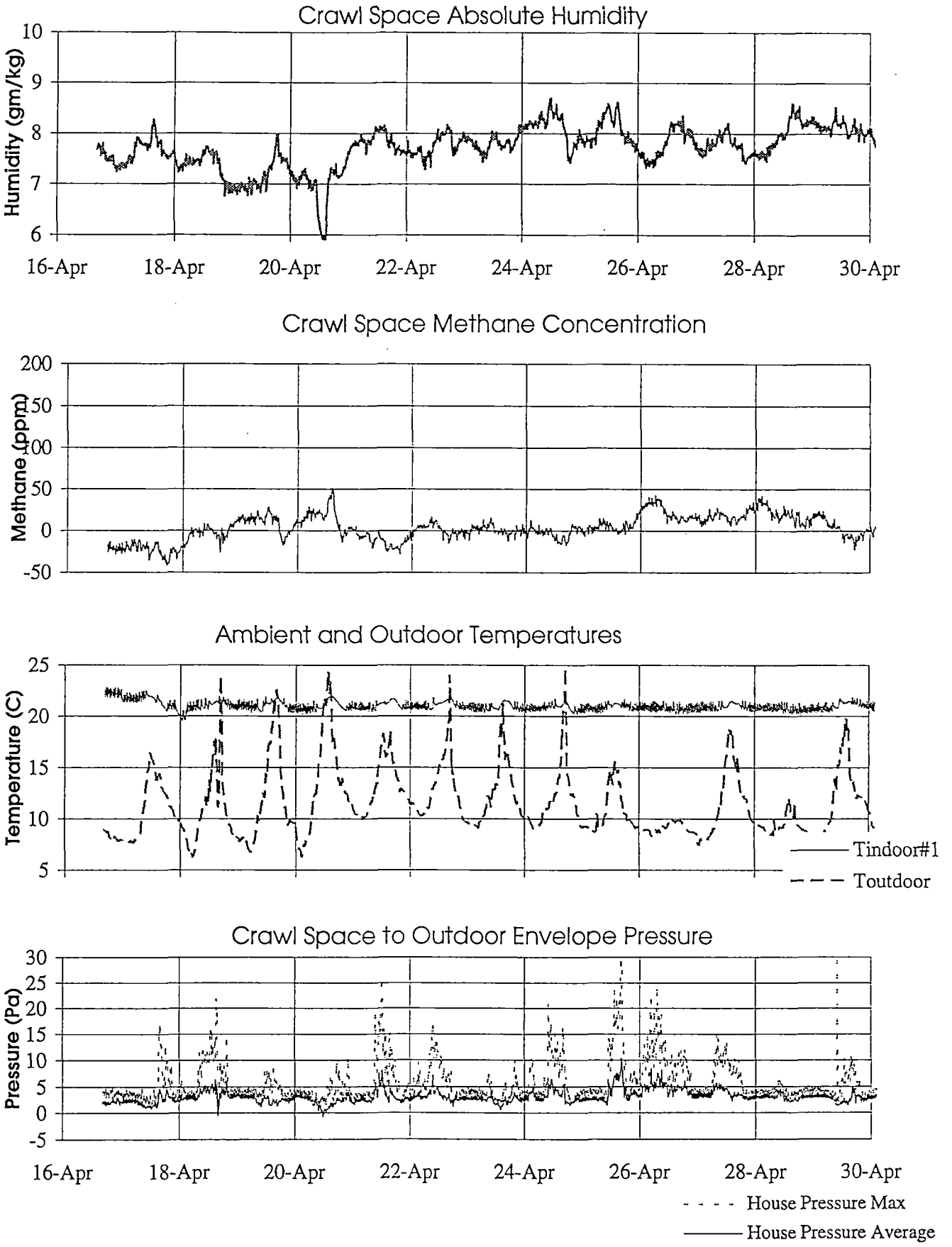

Crawl Space Absolute Humidity
Humidity (gm/kg)
10
9
8
7
6
16-Apr
18-Apr
20-Apr
22-Apr
24-Apr
26-Apr
28-Apr
30-Apr
Crawl Space Methane Concentration
Methane (ppm)
200
150
100
50
0
-50
Ambient and Outdoor Temperatures
Temperature (C)
25
20
15
10
5
Tindoor#1
Toutdoor
Crawl Space to Outdoor Envelope Pressure
Pressure (Pa)
30
25
20
15
10
5
0
-5
16-Apr
18-Apr
20-Apr
22-Apr
24-Apr
26-Apr
28-Apr
30-Apr
House Pressure Max
House Pressure Average

Figure D.3

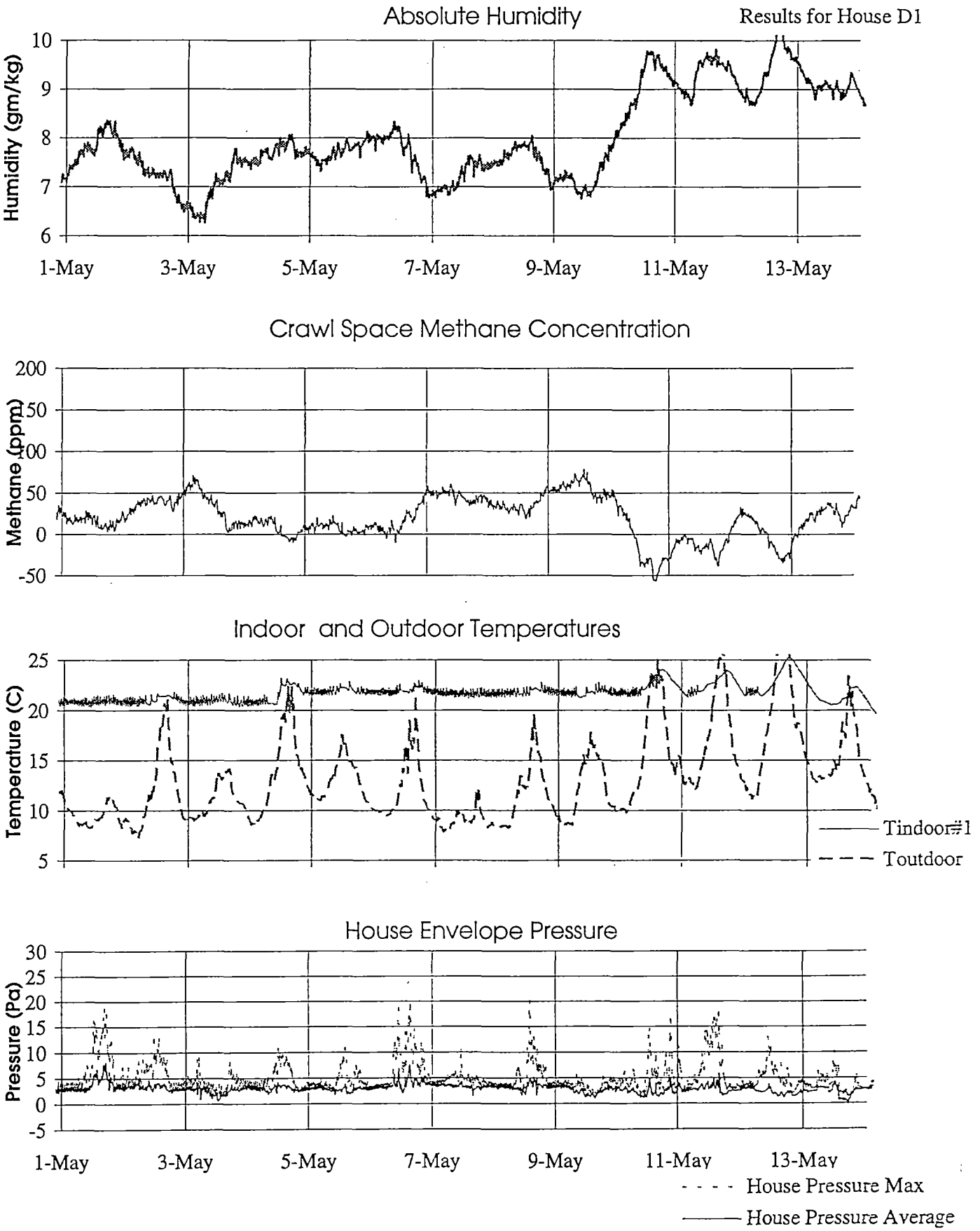

Absolute Humidity
Results for House D1
Humidity (gm/kg)
10
9
8
7
6
1-May
3-May
5-May
7-May
9-May
11-May
13-May
Crawl Space Methane Concentration
Methane (ppm)
200
150
100
50
0
-50
Indoor and Outdoor Temperatures
Temperature (C)
25
20
15
10
5
Tindoor#1
Toutdoor
House Envelope Pressure
Pressure (Pa)
30
25
20
15
10
5
0
-5
1-May
3-May
5-May
7-May
9-May
11-May
13-May
House Pressure Max
House Pressure Average

Figure D.4

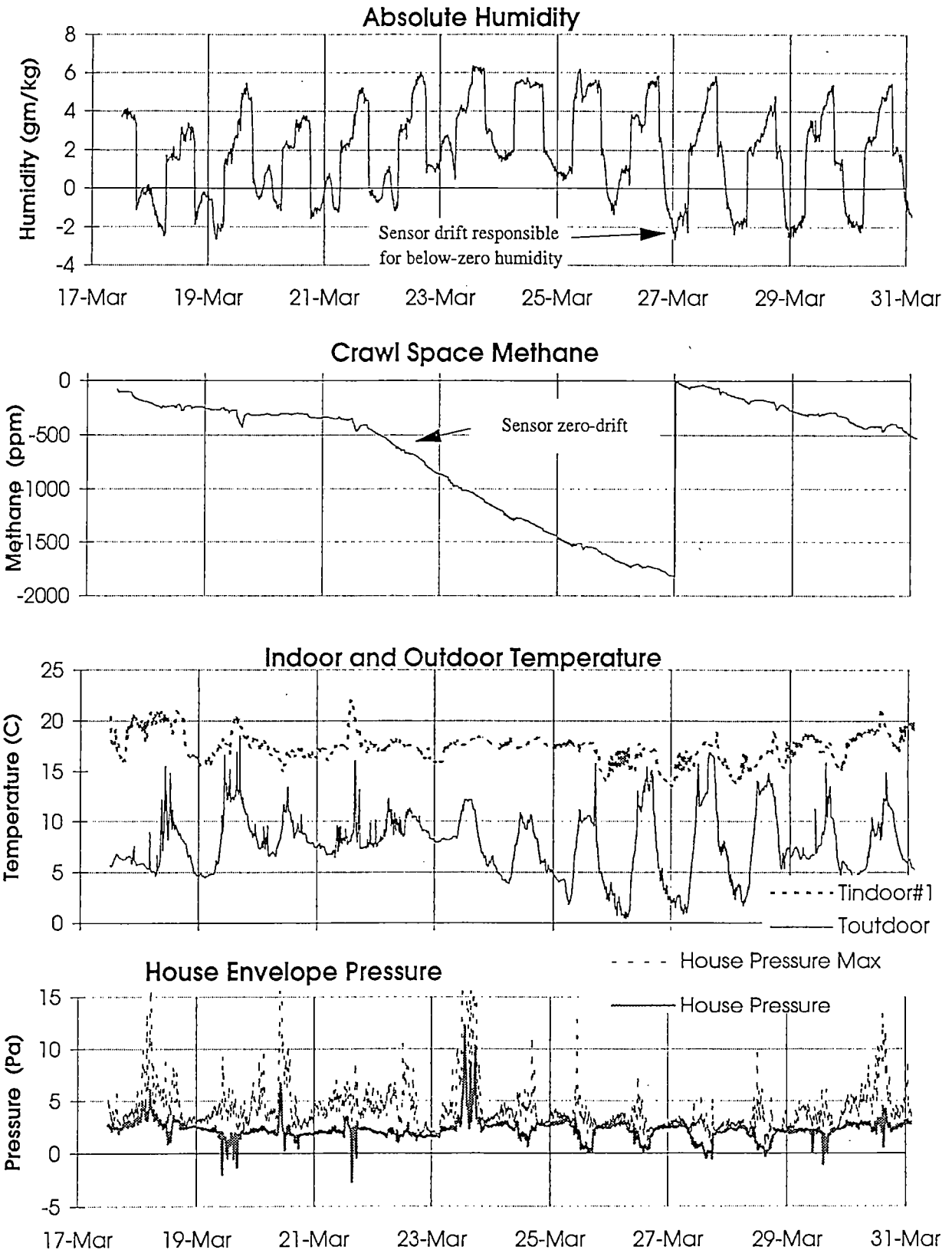

Absolute Humidity
Humidity (gm/kg)
8
6
4
2
0
-2
-4
Sensor drift responsible
for below-zero humidity
17-Mar
19-Mar
21-Mar
23-Mar
25-Mar
27-Mar
29-Mar
31-Mar
Crawl Space Methane
Methane (ppm)
0
-500
-1000
-1500
-2000
Sensor zero-drift
Indoor and Outdoor Temperature
Temperature (C)
25
20
15
10
5
0
Tindoor#1
Toutdoor
House Envelope Pressure
House Pressure Max
House Pressure
Pressure (Pa)
15
10
5
0
-5
17-Mar
19-Mar
21-Mar
23-Mar
25-Mar
27-Mar
29-Mar
31-Mar

Figure D.5

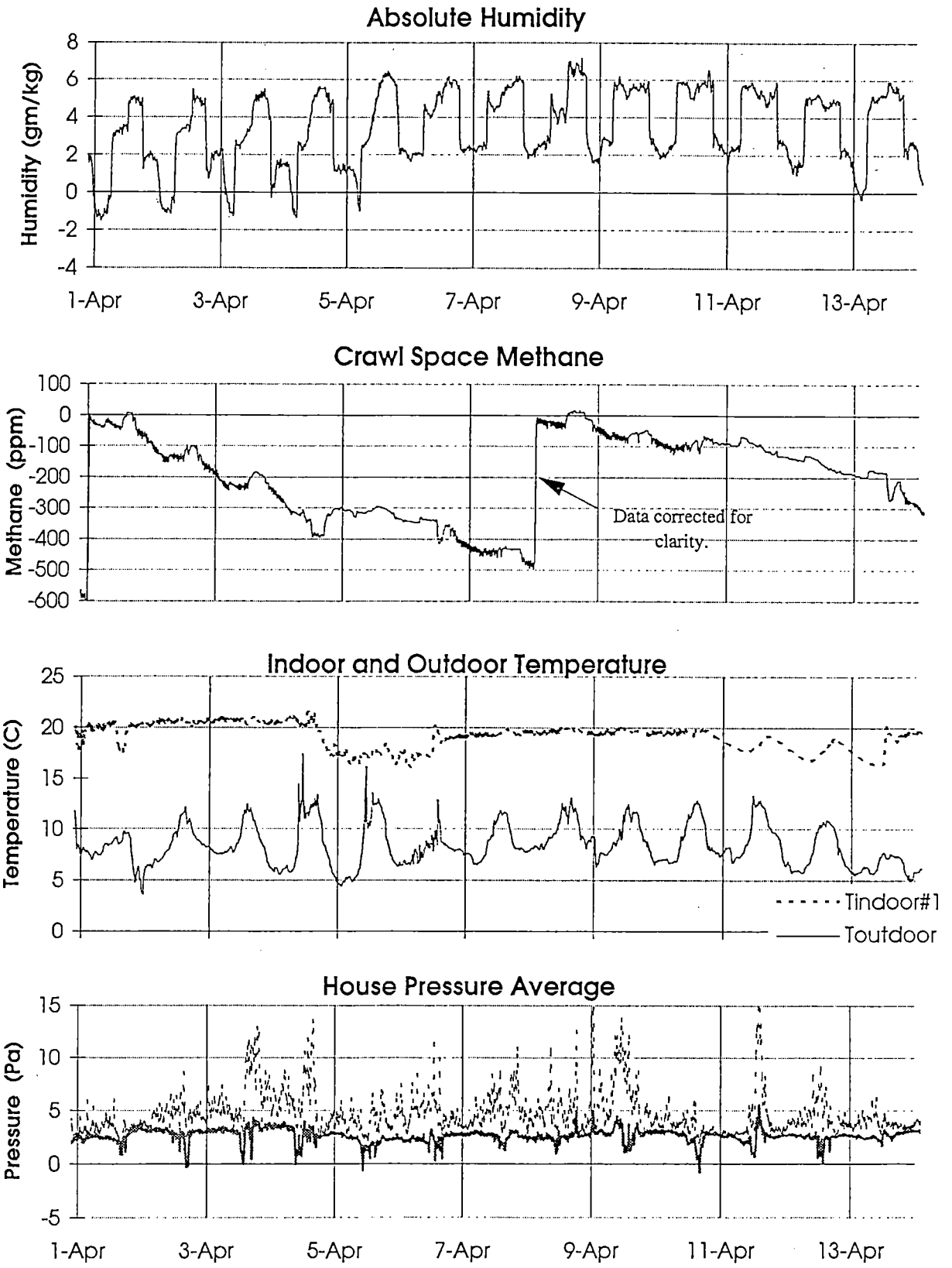

Absolute Humidity
Humidity (gm/kg)
8
6
4
2
0
-2
-4
1-Apr
3-Apr
5-Apr
7-Apr
9-Apr
11-Apr
13-Apr
Crawl Space Methane
Methane (ppm)
100
0
-100
-200
-300
-400
-500
-600
Data corrected for clarity.
Indoor and Outdoor Temperature
Temperature (C)
25
20
15
10
5
0
Tindoor#1
Toutdoor
House Pressure Average
Pressure (Pa)
15
10
5
0
-5
1-Apr
3-Apr
5-Apr
7-Apr
9-Apr
11-Apr
13-Apr

Figure D.6

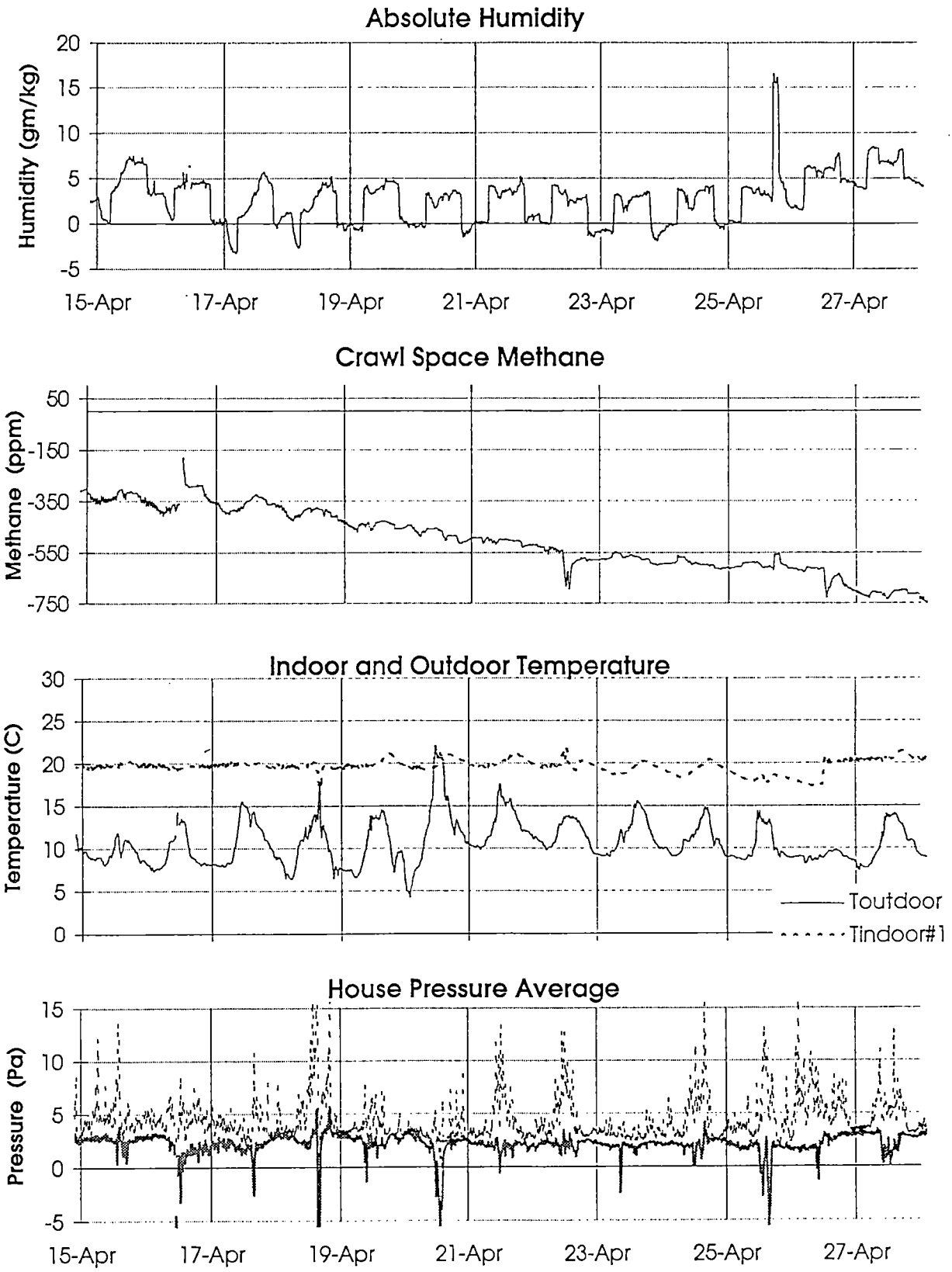

Absolute Humidity
Humidity (gm/kg)
20
15
10
5
0
-5
15-Apr
17-Apr
19-Apr
21-Apr
23-Apr
25-Apr
27-Apr
Crawl Space Methane
Methane (ppm)
50
-150
-350
-550
-750
Indoor and Outdoor Temperature
Temperature (C)
30
25
20
15
10
5
0
Toutdoor
Tindoor#1
House Pressure Average
Pressure (Pa)
15
10
5
0
-5
15-Apr
17-Apr
19-Apr
21-Apr
23-Apr
25-Apr
27-Apr

Figure D.7

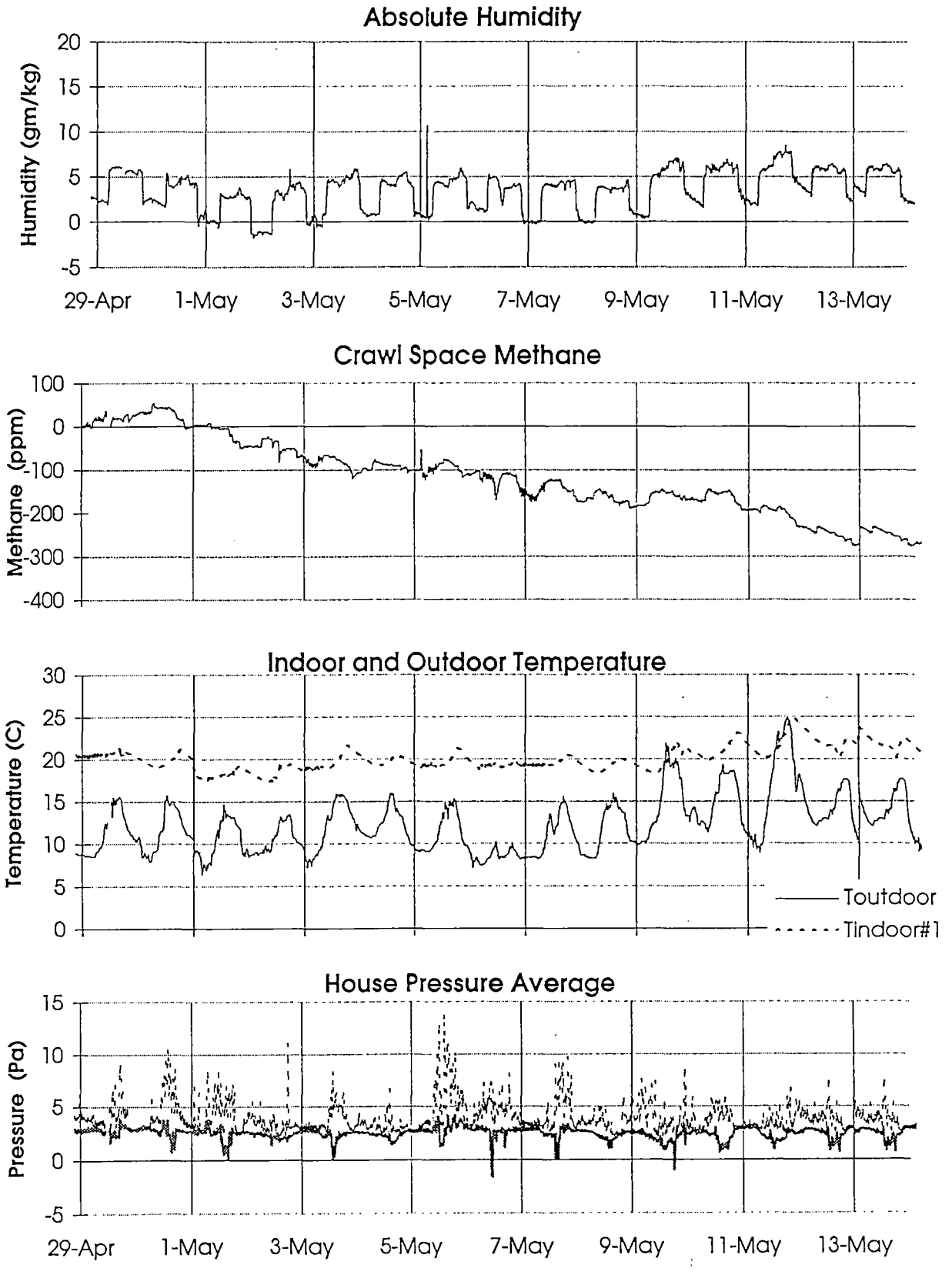

Absolute Humidity
Humidity (gm/kg)
20
15
10
5
0
-5
29-Apr
1-May
3-May
5-May
7-May
9-May
11-May
13-May
Crawl Space Methane
Methane (ppm)
100
0
-100
-200
-300
-400
Indoor and Outdoor Temperature
Temperature (C)
30
25
20
15
10
5
0
Toutdoor
Tindoor#1
House Pressure Average
Pressure (Pa)
15
10
5
0
-5
29-Apr
1-May
3-May
5-May
7-May
9-May
11-May
13-May

Figure D.8