ATTIC AIR CHANGE TESTING:
PROTOCOL DEVELOPMENT

Final Report

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BLP File No. 2458
October, 1989

EXECUTIVE SUMMARY

This report describes the development of a procedure for tracer gas field testing of attics.

During the course of developing the field test protocol, nine tests were conducted in two phases. The testing was done on two houses of similar size. Test House A had gable and soffit vents and test House B had ridge and soffit vents.

The first phase of tests involved twelve time-averaged sampling locations and four injection locations. This protocol was used for four tests on House A and one test on House B.

For the second phase, an alternative manifold injection system was used. The number of sampling locations were reduced and the injection locations were increased.

The time-averaging pumped-sample methodology employed for the research proved to work well but further refinement of the injection system is needed.

DISCLAIMER

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1.0 INTRODUCTION

Years of building inspections have indicated that attics are continually plagued by moisture problems. Empirical testing has found that, in many cases, increased ventilation can alleviate the problem. The present requirement in the National Building Code of Canada for a free area of venting related to attic area was implemented as a result of these empirical evaluations. However, the lack of actual scientific research into the magnitude and effects of ventilation indicates that a better understanding of the processes of ventilation is required. In fact, some recent discoveries suggest that ventilation may be counter-productive.

This report describes the development of a procedure to field test the magnitude and effect of ventilation in attics using a tracer gas.

Fundamentally, the procedure incorporated a constant injection tracer gas methodology. Time-averaged sampling for tracer gas concentration was achieved by using small pumps in the attic to transfer sampled air to a sample bag. Samples for analysis were drawn from these bags.

The development process began with a test set-up comprised of a large number of sample locations (thirty) and four injection locations in the attic. Based on the results of the initial tests done on the two houses, it was judged that field test protocols could be done with fewer samples but particular care was required with the injection process.

2.0 TEST METHODS

2.1 Phase I: Initial Testing

2.1.1 Basic Test Set-Up and Procedure

The injection set-up involved injecting one hundred per cent SF_6 into four locations in the attic space. The flow of SF_6 from the cylinder was controlled by a rotameter-type flow meter and needle valve. Tubing connected to the flow meter was split into four lines and connected to four additional rotameters and needle valves. This allowed equal amounts of SF_6 to be injected at each injection point.

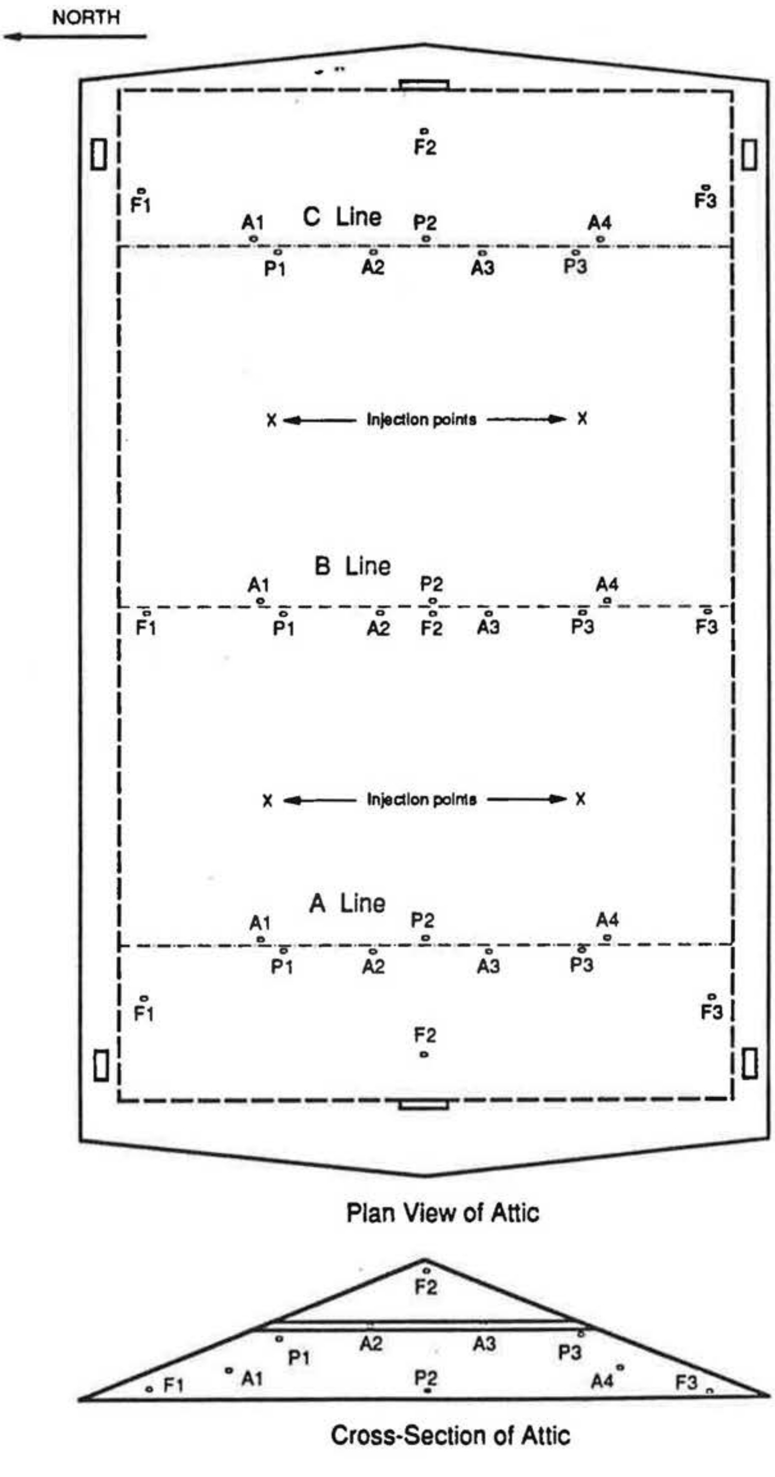
Sampling pumps were installed at each of thirty sampling locations. Small aquarium air pumps that pump air at approximately 1 L/min were used. The thirty samplers were divided into three lines with ten samplers per line. The sampling lines were located at the center of each third of the rectangular attic plan area (see Figures 2.1 and 2.2). The vertical location of each sampling pump along each sampling line is illustrated in the cross sections. The sampling locations were divided into three categories: "F" or flow samples were taken at each corner of the triangle (eave, ridge, eave), "P" or periphery samples were taken near the sheathing and floor of the attic and four "A" or average samples were taken approximately midway between the flow and periphery samples. Each category of sample locations had a purpose:

- The "flow" sample locations were intended to assist in detecting where air was entering the attic (the tracer gas would be more diluted than the average) or where there might be a "short circuit" of injected tracer gas out of the attic (higher concentration);
- The "average" sample locations were intended to be those which would be used for calculating the Air Change Rate;
- The "periphery" sample locations would help to determine if there was a stratification of the sampled tracer gas concentration or if the ventilation pattern along the joists or rafters was substantially different from the internal enclosed air volume of the attic.

Depending on the vent arrangements, the flow samples located at the ridge (F_2A, F_2C) were moved closer to the gable vent or the ridge vent.

Clear plastic tubing was connected to each sampling pump and the other end was brought down through the attic hatch to the living area and connected to a sampling bag. This enabled a thirty minute sample to be taken, the pump shut off, the full sample bags to be replaced with empty bags and the next

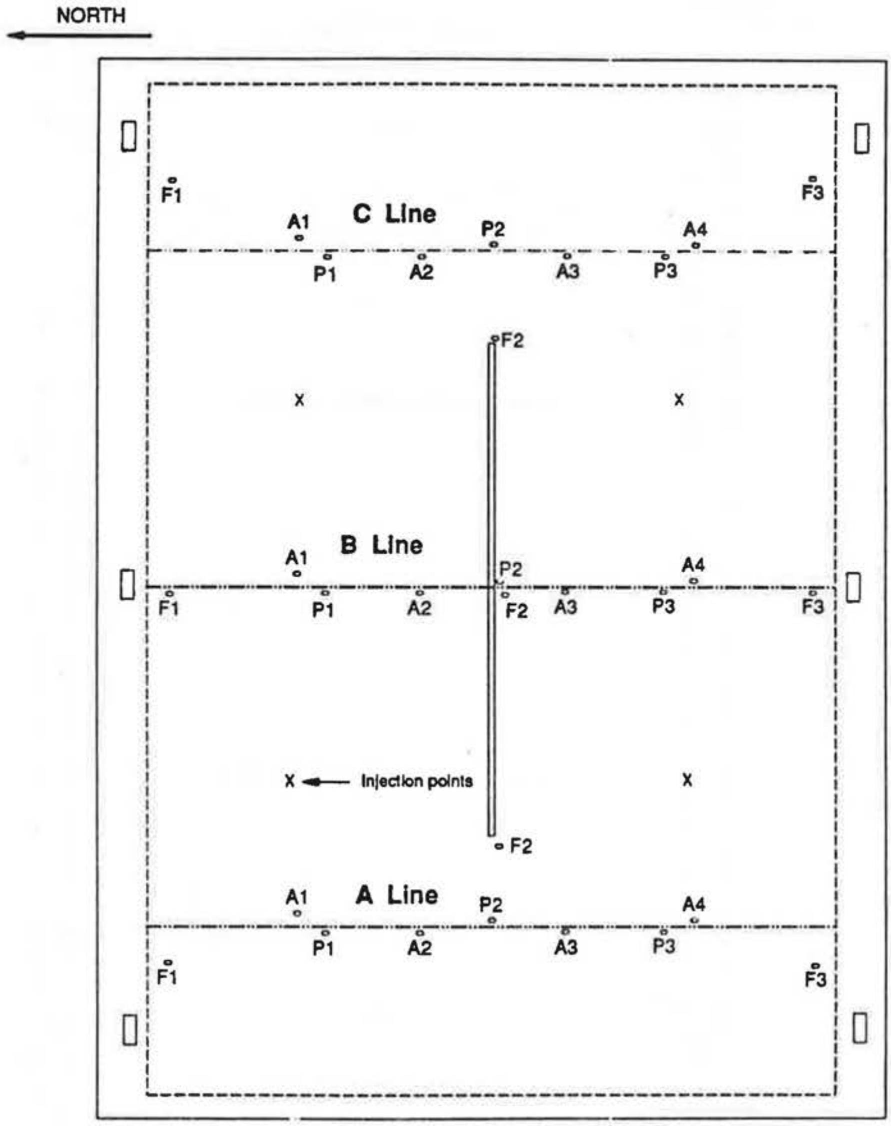
Figure 2.1 HOUSE A INJECTION AND SAMPLING LOCATIONS
Phase I, Test 1, Soffit, Soffit and Gable, and Gable Venting Configurations



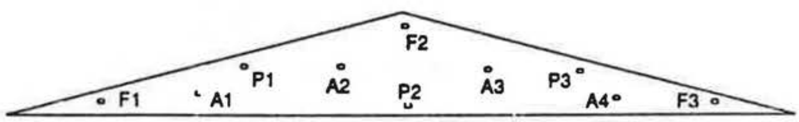
Plan View of Attic

Cross-Section of Attic

Figure 2.2 HOUSE B INJECTION AND SAMPLING LOCATIONS
Phase I, Test 1, Soffit and Ridge Venting Configuration



Plan View of Attic



Cross-Section of Attic

thirty minute sampling period to be initiated. Using a syringe, 15 cc samples were drawn from the full sample bags and injected into a 10 cc vacutainer.

A duplicate sample was taken from one series of samples for each attic configuration. This provided the analysis lab with a set of non-critical samples to use in determining the approximate range of the SF_6 concentration in order to establish the dilution requirements.

One hundred per cent SF_6 was used for the testing and this resulted in high concentrations of tracer gas in the attic. It was recognized that, once the venting characteristics of some attics could be defined, it would be preferable to inject gas at a rate that provided SF_6 concentrations in the attic of 0 - 200 ppb, the normal range for analysis by gas chromatography (GC).

2.1.2 Test Houses

House A

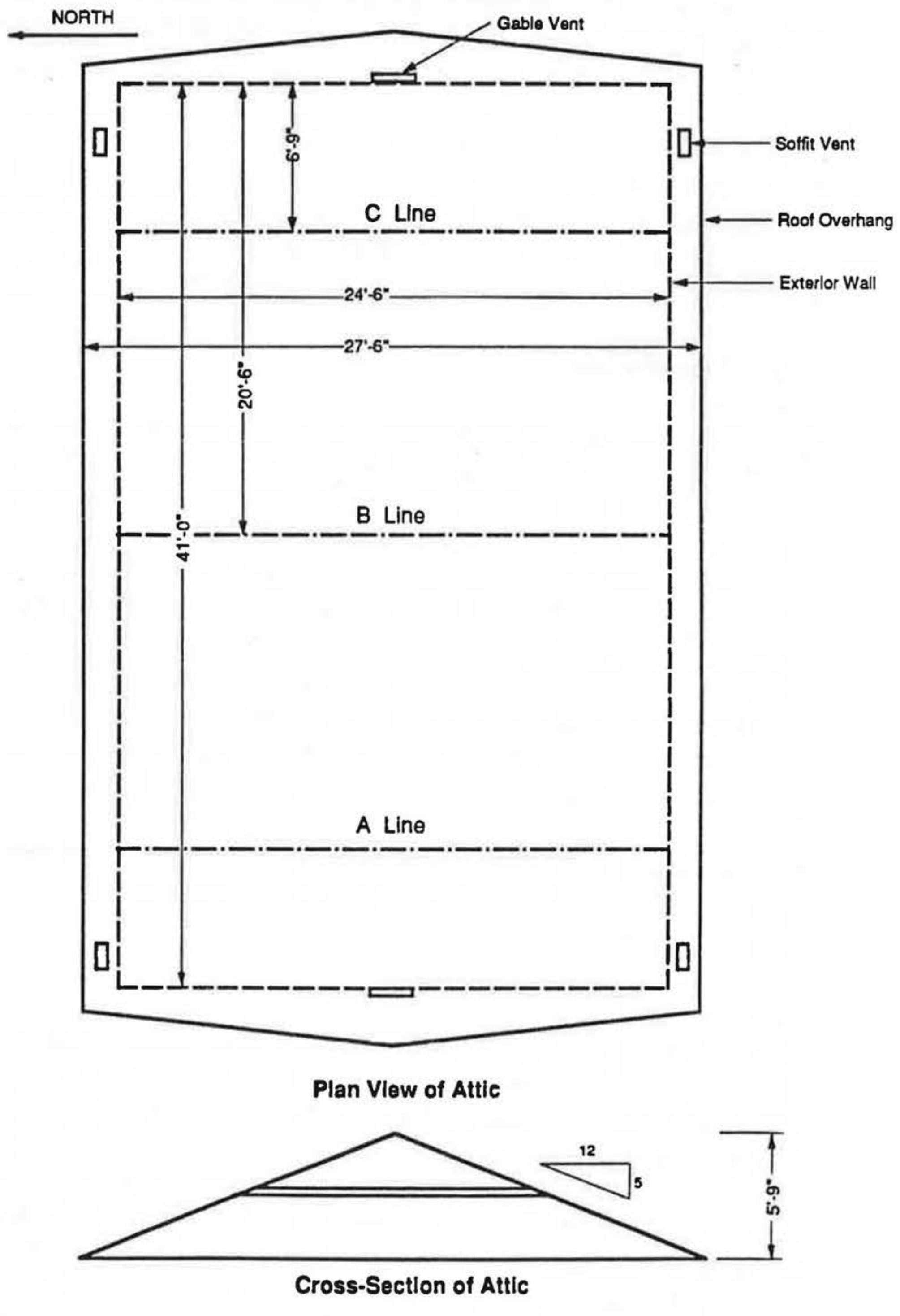
The pilot test was performed on a 1960 bungalow, with outside dimensions of 12.5 m x 7.5 m (41' x 24'6") (see Figure 2.3). The attic was of rafter construction, with a single 38 mm x 140 mm (2" x 6") horizontal cross-bracing. The roof had a 5 in 12 pitch with a 460 mm (18") overhang on the sides and a varying overhang of 300 mm to 760 mm (12" to 30") on the front and back. Attic venting was comprised of four soffit vents and two gable vents. Each soffit vent was 150 mm x 360 mm (6" x 14") and was located 610 mm (24") from each end. The estimated free area at the vents was 90 per cent. The total soffit venting area was 0.19 m^2 (2.1 ft^2). The two gable vents, one located at each end of the building, had a total free area of 0.14 m^2 (1.5 ft^2). The attic volume was 91,800 litres (3,240 ft^3).

The ratios of vent to attic area were approximately 1 to 280 with all vents open, 1 to 490 with only the soffit vents open and 1 to 670 with only the gable vents open.

House B

House B was a newer bungalow with outside dimensions of 12.5 m x 8.38 m (41' x 27.6') (see Figure 2.4). The attic was of truss construction with a roof pitch of 3.5 in 12. The roof overhang was 300 mm (12") on the sides and 610 mm (24") on the front and back. The volume of the attic was 82,285 L (2905 ft^3). Attic venting consisted of six soffit vents and a ridge vent. Each soffit vent was 150 mm x 300 mm (6" x 12") with a free area of 90 per cent yielding a total soffit venting area of 0.25 m^2 (2.7 ft^2). The ridge vent was 6.1 m (20') long with a free width of approximately 80 mm (3") yielding a ridge venting area of 0.46 m^2 (5 ft^2). The ratio of total vent area to attic area was approximately 1 to 150.

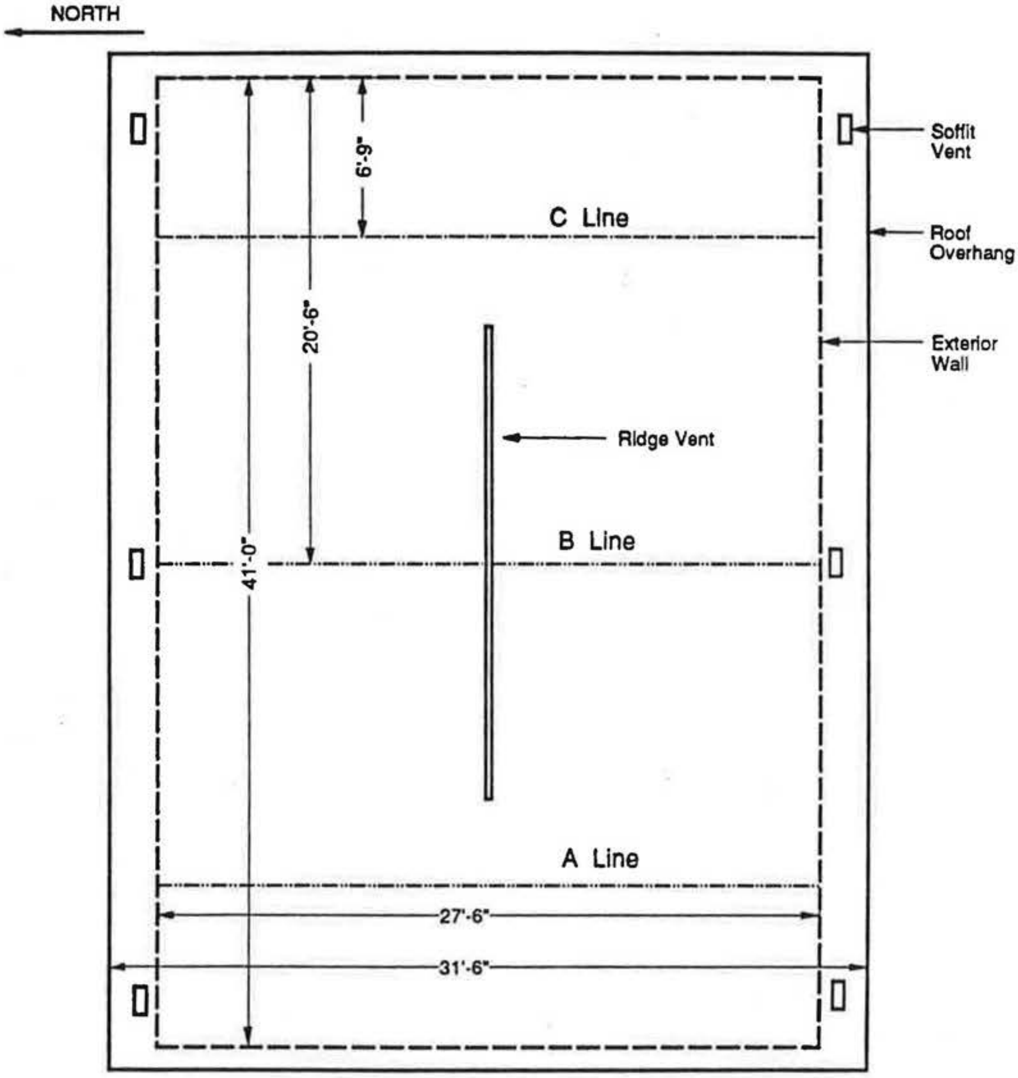
Figure 2.3 HOUSE A ATTIC LAYOUT



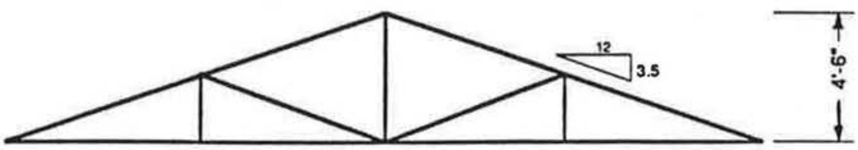
Plan View of Attic

Cross-Section of Attic

Figure 2.4 HOUSE B ATTIC LAYOUT



Plan View of Attic



Cross-Section of Attic

2.2 Test Descriptions

House A - Test 1, Three Different Venting Configurations

A series of three different venting configurations were tested on House A on April 21, 1989. The first configuration tested involved taping over the gable vents, leaving only the soffit vents operational. For the second configuration tested, both the soffit and gable vents were left open and the third involved taping over the soffit vents. By only changing the status of the vents (open/closed) and using the same structure with fixed parameters (attic volume, injection points, sampling locations and house orientation), the three tests would be more comparable.

Soffit testing was undertaken first with the gable vents sealed over. The test began by injecting the SF_6 at a measured rate of 11.4 L/hr. A thirty minute stabilization period was allowed before the sampling pumps were activated. After a thirty minute sampling period, the full bags were replaced by empty bags and the process was repeated. Three sets of samples were taken.

The gable venting was opened for the next test. The measured injection rate of SF_6 was 12.6 L/hr. With both the soffits and gables open, the attic was left to stabilize for thirty minutes before the pumps were again activated. Three sets of samples were taken under this configuration.

The soffit venting was sealed and a thirty minute stabilization period allowed before the pumps were activated again. A measured injection rate of 14.3 L/hr was maintained for this third test. A series of three sample sets were taken under this set-up as well.

House B - Test 1

The first test on the ridge and soffits configuration was performed on May 26, 1989. the injection and sampling locations are the same as in House A (see Figure 2.2) with the exception that the sample F_2A and F_2C were taken at the ends of the ridge vent rather than at the gables.

One hundred per cent SF_6 was injected at a rate measured to be 11.7 L/hr. An eighty minute stabilization period was allowed before the sampling pumps were activated. Two sets of samples were taken under this configuration.

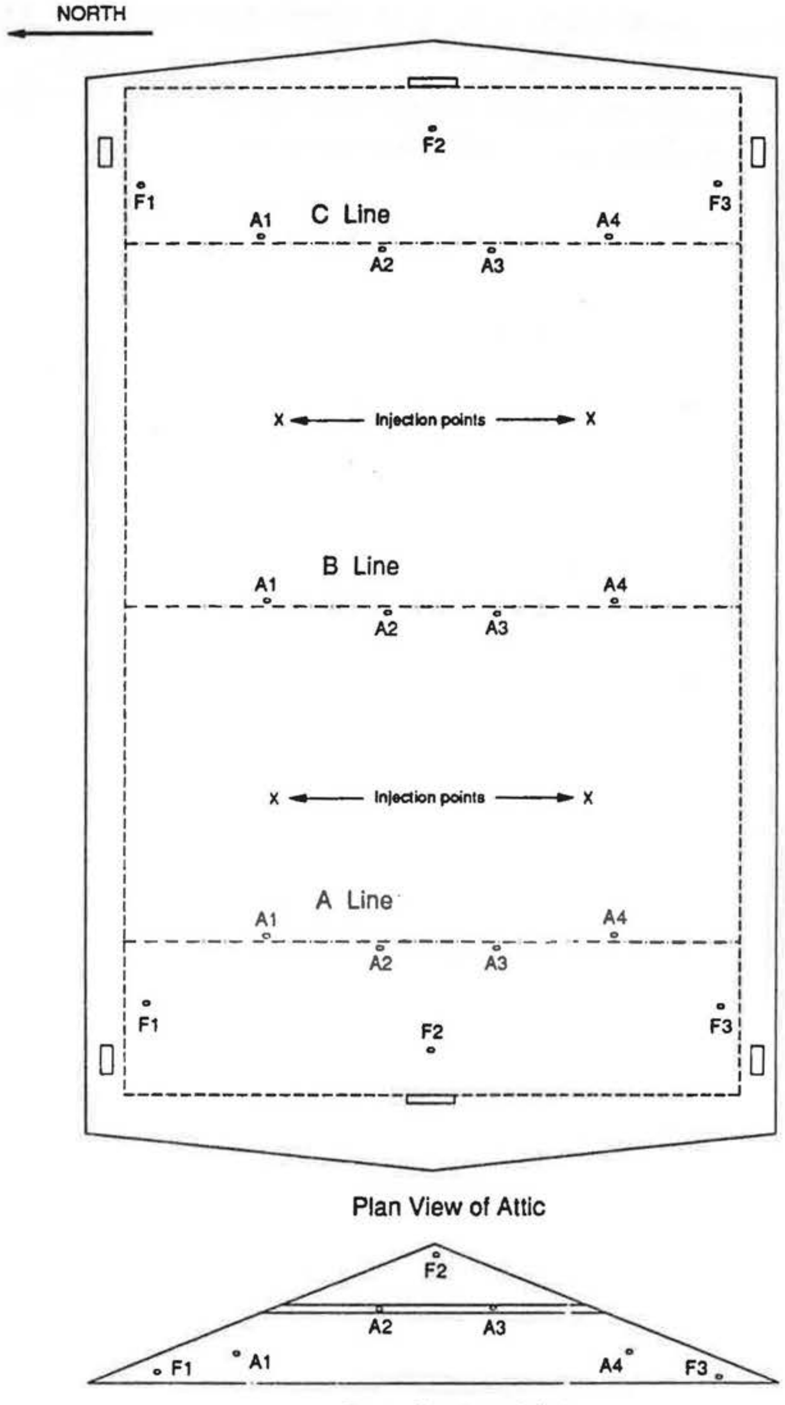
House A - Test 2

The preliminary round of testing on House A showed the redundancy of some of the samples. The "P" samples showed virtually identical concentrations as the "A" samples. It was also judged that the "F" samples which were not taken near a vent were redundant.

A second test was carried out on House A using the same injection system and approach as previously noted but with a reduced number of sample locations (see Figure 2.5).

This test was performed on June 7, 1989 commencing at 11:15 am. The SF_6 was injected at a rate measured to be 12 L/hr. A stabilization period of 65 minutes was allowed before the sample pumps were activated. Two sets of samples were taken under this configuration.

Figure 2.5 HOUSE A REVISED INJECTION AND SAMPLING LOCATIONS
Phase I, Test 2, Soffit and Gable Venting Configuration



Cross-Section of Attic

3.0 ANALYSIS OF PHASE I

The main goals of the Phase I tests were:

- To determine the variation in attic SF_6 concentration with both time and location in order to determine the number of samples that would be required for a field test.
- To determine if there were flow patterns which would indicate short circuiting of injected SF_6 out of the attic.
- To determine the length of the stabilization period required between the start of injection and testing.

The chronology and results of the five venting configurations tested under Phase I are presented in Tables 3.1 through 3.6.

The first tests of three different venting configurations were examined during the same day on House A.

The first item of note in these tests was the relative consistency of the SF_6 concentrations during the sampling period. Particularly, samples that were taken from the periphery (the "P" samples) were consistent with the concentration of those samples that were placed to determine average concentrations in the attic (the "A" samples). Furthermore, the "F" samples did not indicate significant short circuiting of SF_6 out of the attic.

One factor is evident in Table 3.2. The concentrations of gas taken during the first test period were significantly lower than in later tests. It appears that for field testing, a stabilization period of at least one hour is required.

Some variation in concentrations were evident which could be attributable to flow patterns through the attic. In general the results indicate a rise in the concentrations of SF_6 from low on the west side (Line A) to high on the east side (Line C).

The attic of House A was under-ventilated by modern standards. House B had both a higher vent area and a soffit/ridge vent arrangement. In House B, a higher level of ventilation and probably a greater variation in concentrations that could be attributed to flow pattern would be expected. This was borne out in the test data shown in Table 3.4. The south side, which was windward, had lower concentrations than the north side. But, again, the difference in the mean of the "A" samples and the "P" samples was not significant.

Table 3.1 HOUSE A CHRONOLOGY AND FIELD CONDITIONS
Phase I, Test 1, Soffit, Soffit and Gable, and Gable Venting Configurations

Time	Action	Injection Rate (cc/min)	Airport Weather Outdoor Temp °C	Wind Speed	Wind Direction
8:20	Start SF6 Injection	190			
	Soffits Open				
9:00	Start Pumps First Set		4	3 kph	SW
9:30	Stop Pumps First Set				
9:42	Start Pumps Second Set				
10:00			7	5 kph	NW
10:12	Stop Pumps Second Set				
10:24	Start Pumps Third Set				
10:54	Stop Pumps Third Set				
11:00	Open Gable Vents		9	11 kph	SW
	Soffits & Gable Open				
11:24	Start Pumps First Set	210			
11:54	Stop Pumps First Set				
12:00			10	19 kph	NW
12:04	Start Pumps Second Set				
12:34	Stop Pumps Second Set				
12:45	Start Pumps Third Set				
1:00			11	22 kph	NW
1:15	Stop Pumps Third Set				
1:23	Seal Soffit Vents				
	Gable Open				
1:53	Start Pumps First Set	238			
2:00			11	35 kph	NW
2:23	Stop Pumps First Set				
2:32	Start Pumps Second Set				
3:00			12	33 kph	NW
3:18	Stop Pumps Second Set				
3:20	Start Pumps Third Set				
3:50	Stop Pumps Third Set				
4:00	End Test		10	28 kph	NW

Table 3.2 HOUSE A SAMPLE CONCENTRATIONS
Phase I, Test 1, Soffit, Soffit and Gable, and Gable Venting Configurations
(Concentrations in parts per million)

SOFFIT VENTS OPEN

LOCATION	FIRST SAMPLING SET A	B	C	SECOND SAMPLING SET A	B	C	THIRD SAMPLING SET A	B	C
F 1	15.0	13.8	17.8	20.4	24.3	30.6	0.3	28.8	29.7
F 2	*	16.9	20.5	27.4	23.0	29.0	28.0	32.8	28.6
F 3	8.5	18.6	17.7	15.8	19.7	30.8	45.8	29.0	33.6
A 1	15.1	16.7	18.2	19.9	29.1	27.0	27.6	24.6	27.5
A 2	16.0	14.6	11.8	23.5	25.7	31.7	29.2	29.2	28.3
A 3	16.0	19.7	16.2	20.2	28.3	32.5	29.5	31.9	36.5
A 4	7.4	16.2	31.0	12.9	23.9	34.2	17.6	29.3	34.1
P 1	14.0	30.5	19.7	24.6	28.8	15.7	21.1	30.3	26.9
P 2	4.1	17.6	23.3	17.3	24.2	28.4	22.4	24.6	30.5
P 3	13.8	19.1	26.2	24.4	24.4	33.8	28.6	29.2	35.6
Ave. of Lines A,B & C Samples A1 to A4		16.6			25.7			28.8	

SOFFIT AND GABLE VENTS OPEN

LOCATION	FIRST SAMPLING SET A	B	C	SECOND SAMPLING SET A	B	C	THIRD SAMPLING SET A	B	C
F 1	15.5	17.0	18.5	22.3	12.7	12.2	11.5	9.1	8.0
F 2	19.9	18.1	22.0	16.3	14.5	18.5	14.1	14.1	15.4
F 3	18.1	18.3	22.8	12.0	14.2	19.4	11.4	12.6	16.9
A 1	17.7	18.8	17.7	13.1	16.2	9.8	12.9	12.9	11.8
A 2	28.8	20.8	20.6	31.4	18.0	17.0	30.2	15.5	14.0
A 3	23.5	22.4	23.1	18.4	19.5	18.6	17.3	15.6	14.4
A 4	13.0	18.3	19.5	9.5	16.4	16.7	9.9	13.6	14.5
P 1	19.8	17.0	20.7	16.6	14.6	15.0	16.2	12.6	11.3
P 2	15.7	17.1	12.9	13.5	12.9	16.1	11.6	13.3	14.4
P 3	23.2	20.8	21.9	18.3	15.5	22.9	16.4	16.0	17.3
Ave. of Lines A,B & C Samples A1 to A4		20.4			17.0			15.2	

GABLE VENTS OPEN

LOCATION	FIRST SAMPLING SET A	B	C	SECOND SAMPLING SET A	B	C	THIRD SAMPLING SET A	B	C
F 1	13.5	8.7	10.1	15.4	7.1	9.2	12.1	5.9	6.9
F 2	13.1	12.6	13.1	14.7	15.4	13.9	17.2	15.4	15.6
F 3	11.0	12.4	14.5	14.7	11.2	17.7	11.3	13.5	15.9
A 1	7.9	12.6	12.4	15.8	18.4	10.8	13.5	13.2	*
A 2	36.3	13.2	10.9	25.7	13.4	13.5	33.6	13.5	*
A 3	12.6	12.9	6.1	15.8	13.5	14.2	16.6	11.5	*
A 4	12.8	12.7	13.2	12.4	13.6	12.2	13.3	*	13.6
P 1	15.7	12.9	10.3	15.9	14.0	8.9	13.4	11.9	10.3
P 2	12.9	11.7	12.9	12.2	14.0	12.5	12.7	13.2	11.5
P 3	16.3	16.4	15.1	15.1	11.3	21.9	18.6	15.7	15.0
Ave. of Lines A,B & C Samples A1 to A4		13.6			14.9			15.2	

Note: * indicates invalid sample

Table 3.3 HOUSE B CHRONOLOGY AND FIELD CONDITIONS
Phase I, Test 1, Soffit and Ridge Venting Configuration

		Attic	On Site Weather		Airport Weather		
		Temp	Wind	Wind	Outdoor	Wind	Wind
Time	Action	(°C)	Speed	Direction	Temp °C	Speed	Direction
1:30	Start SF6 Injection	20	Light	SE			
2:00					18	9 kph	S
2:50	Start Pumps First Set	20	Light	SE			
3:00					18	6 kph	SW
3:30	Take First Set Samples	22	6 kph	S			
4:00	Take Second Set Samples	24			20	9 kph	SW
4:40	End Test	25	6 kph	S			

Table 3.4 HOUSE B SAMPLE CONCENTRATIONS
Phase I, Test 1, Soffit and Ridge Venting Configuration
(Concentrations in parts per million)

	FIRST SAMPLING SET			SECOND SAMPLING SET		
LOCATION	A	B	C	A	B	C
F 1	19.5	17.9	7.6	20.5	14.3	6.5
F 2	16.5	18.3	12.0	15.3	15.4	9.9
F 3	6.6	12.5	1.8	11.7	8.8	4.0
A 1	20.7	18.2	7.7	15.1	17.8	8.0
A 2	18.2	16.9	9.7	19.2	15.8	11.2
A 3	14.8	15.6	12.6	19.7	16.6	17.3
A 4	6.9	6.0	4.3	8.6	7.4	8.1
P 1	16.7	19.5	7.7	15.9	15.2	10.6
P 2	13.5	18.0	7.7	12.9	19.4	8.7
P 3	14.2	14.4	11.6	20.4	12.0	16.5
Ave. of Lines A,B & C Samples A1 to A4		12.6			13.7	

Table 3.5 HOUSE A CHRONOLOGY AND FIELD CONDITIONS
Phase I, Test 2, Soffit and Gable Venting Configuration

		Attic Temp	On Site Weather		Airport Weather		
Time	Action	(°C)	Wind Speed	Wind Direction	Outdoor Temp °C	Wind Speed	Wind Direction
11:00					18	7 kph	SW
11:15	Start SF6 Injection	26	Light	West			
12:00					20	5 kph	SW
12:20	Start Pumps First Set	30	Light	West			
12:55	Take First Set Samples	34	Light	West			
1:00					23	7 kph	SW
1:25	Take Second Set Samples	36	Light	SW			
2:00	End Test	38	Light	SW	24	10 kph	SW

Table 3.6 HOUSE A SAMPLE CONCENTRATIONS
Phase I, Test 2, Soffit and Gable Venting Configuration
(Concentrations in parts per million)

	FIRST SAMPLING SET			SECOND SAMPLING SET		
LOCATION	A	B	C	A	B	C
F 1	35.8	n/a	18.6	35.3	n/a	16.5
F 2	37.3	n/a	21.4	36.4	n/a	26.3
F 3	35.1	n/a	20.1	23.3	n/a	22.3
A 1	30.8	34.8	25.7	33.5	29.2	22.1
A 2	34.3	42.8	26.7	39.3	34.4	26.9
A 3	34.6	35.3	22.5	41.6	33.1	25.8
A 4	18.5	45.5	21.0	13.2	31.7	24.9
Ave. of Lines A,B & C Samples A1 to A4		31.0			29.6	

Note : n/a means not applicable since samples not taken

In the second test conducted on House A with the soffit and gable vents open, there was a significant variation in the sample results. The concentrations in the southwest corner were significantly lower than average. On this day, the winds were light and varying between west and southwest. This could account for part of the difference but there was some concern that this location was upstream from the injection points and could be skewing the results.

The raw results provided some guidance in the development of a field protocol.

First it appears that the number of samples could be greatly limited, but not to the point that flow patterns could not be detected. Four sample locations are suggested with the sampler placed at the centroid of each quadrant of the attic. There is no apparent need to take samples at the "periphery" as in the protocol development. The "flow" samples were taken primarily as a check against short circulating patterns. For "survey"-type field testing, these could be eliminated. It may be desirable to retain them for more detailed studies such as repeated tests on the same attic in different conditions.

With such a limited number of sample locations, particular attention must be paid to the injection system. It should provide as wide a dispersion as practical without raising concerns about the close proximity of injection points to sample locations.

As mentioned earlier, a stabilization period of at least one hour between the start of injection and the sampling is suggested. As well, a minimum of two (and possibly more) rounds of sampling should be done. This introduces some redundancy, however, if weather has remained consistent, it is useful to assess whether or not a steady state has been achieved.

3.1 Calculated Air Change Rate

The air change rate of the attic can be calculated by the equation:

ACH = injection rate/average concentration/attic volume.

The results indicate that the average tracer gas concentration in the attic can be reliably determined. A comparison of the results of the Phase I and Phase II testing, however, raised a concern about the accuracy of the measured injection rates in Phase I. Follow-up calibration work indicated that there was, in fact, a significant problem with the rotameter and injection system used.

For the Phase I testing, the prime injection rate reading was obtained from the Matheson 602 rotameter used to measure total flow rate prior to splitting to the four separate balancing flow meters (Model 600's). It was noticed at the time of initial analysis, that the readings for the prime flow meter did not match the sum of the four secondary ones. However, this was attributed to the fact that the inlet pressure of the secondary meters was not known and, since a rotameter is a volume flow measurement device and therefore dependant on inlet pressure, a variation could be expected.

A different injection method was used for the Phase II testing with a different rotameter. The calculated air change rates for those tests were significantly different than for the Phase I testing. This prompted some additional analysis assessing the validity of the Phase I results.

It was found that there was a significant problem measuring the flows in the Phase I injection system. There were a number of potential sources of error including:

- Pressure regulator and pressure gauge problems causing the real pressure and stability of the system to be unknown.
- A specific problem with the rotameter.
- Leaks in the lines between the measurement device and the attic so that not all the measured SF_6 was entering the attic.

By the time the problem was suspected, it was impossible to assess the relative contributions of these possible errors. It is known, however, that the rotameter was not accurate when calibrated through a bubble meter. There was also reason to suspect a problem with the regulator.

For the record, Table 3.7 presents the air change rates calculated two ways:

- Based on the primary flow meter reading (model 602) using the SF_6 calibration chart for the inlet pressure measured at 20 psi. Subsequent laboratory testing indicates these figures are incorrect.
- Based on the injection rates of the four secondary meters (model 600 x 4) assuming a near atmospheric inlet pressure. Subsequent laboratory testing substantiates the near atmospheric pressure, however, the actual inlet pressure was not known.

Table 3.7 SUMMARY OF PHASE I TESTS

Venting Configuration	Test No.	House Type	Test Date	Attic Volume (litres)	Average Concentration (ppm)	Calculated Air Changes per Hour (ACH) ***		Injection Rate		# of Sampling Locations	# of Injection Locations	# of "A" Sample Locations
						602	600 x 4	100% SF6 L/hr	1% SF6 L/hr			
Soffit	1	A	21-Apr	91800	28.8**	4.30	1.90	11.4	/	30	4	12
Soffit & Gable	1	A	21-Apr	91800	15.2**	9.00	4.50	12.6	/	30	4	12
Gable	1	A	21-Apr	91800	15.2**	10.20	3.60	14.3	/	30	4	12
Soffit & Ridge	1	B	26-May	82285	13.2*	10.80	4.50	11.7	/	30	4	12
Soffit & Gable	2	A	7-Jun	91800	30.3*	4.30	2.10	12	/	18	4	12

Note: * denotes average of all sets
** denotes average of last set only
*** Absolute values known to be inaccurate, use for relative comparisions only

The absolute values for the air change rates in this table cannot be relied on. Useful information, however, can be gained from the relative values.

The difference in air change rates between the three tests performed on House A in one day are as would be expected based upon the venting patterns tested. When only the soffit vents were open, the air change was lowest and was measured at less than half the number of air changes as when both the soffit and gable vents were open. Sealing the soffit vents made relatively little difference to having both vent-types open but winds during this test were higher than with the other tests.

The repeat test with the soffit and gable vents open showed values to be significantly lower than during the first day of testing. Winds during this test were lower but caution should be taken in drawing conclusions from this considering the uncertainty in the injection rate.

The ridge/soffit vent arrangement of House B displayed the highest air change rate.

4.0 PHASE II TESTING

The Phase I testing demonstrated that the sampling patterns could be significantly simplified. The four point injection system, however, could use some improvement, particularly if the solution would not greatly add to the complexity of the field set-up.

Ideally, a large number of injection points would be desirable in order to approximate injection over the entire surface of the attic floor. Increasing the number of injection points and relying on flow meters and needle values to balance the flow was judged to be too complex and expensive for field testing. As a result, experimentation was undertaken to develop a manifold-type system using orifices to balance the flow. With this set-up, a single flow meter could be used.

A number of types of "injectors" were assessed, notably propane torch nozzles and injector nozzles for oil-fired furnaces. The latter proved to provide the most consistent flow patterns in lab testing. At a line pressure 10 psi, the flow through seven nozzles ranged from 289 to 366 cc/min. This was judged to be adequate for the purpose.

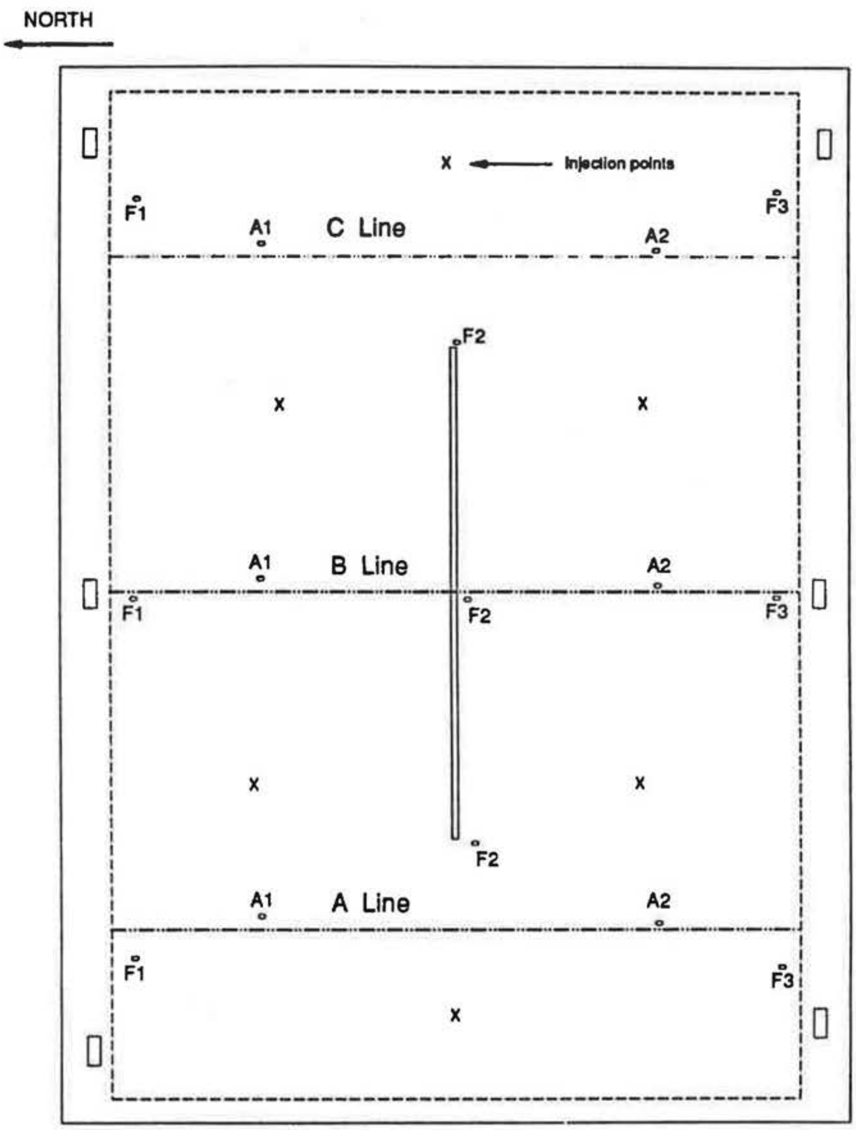
A new injection system was fabricated for the Phase II testing consisting of a single rotameter and line going to the attic. This was Y-split into a number of different nozzles. Tests were carried out using six nozzles and eight nozzles.

To maintain line pressures so that line losses were insignificant in comparison to the pressure drop through the nozzle, higher flow rates than those used for the Phase I testing were required. This implied a higher capacity rotameter, a Matheson model 604. As well, the decision was made to inject one per cent SF_6 rather than the 100 per cent SF_6 used for the Phase I testing.

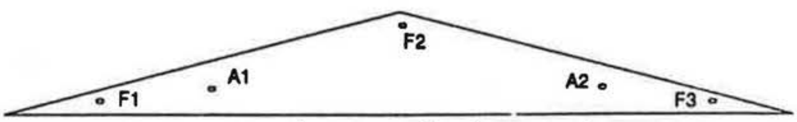
Using this injection system and the sampling locations illustrated in Figures 4.1 through 4.3, the Phase II testing consisted of four tests. The two tests performed on House B consisted of virtually identical procedures, except that the number and location of injection nozzles increased from six to eight. These tests were carried out on July 18 and 20, 1989, respectively. Two tests were carried out on House A on the same day with different venting formats, one with only the soffit vents open and one with the soffit and gable vents open.

These four tests were done during a period of very hot weather. Winds were, in general, light and the attic temperatures were between 40°C and 51°C.

Figure 4.1 HOUSE B 6 POINT INJECTION AND SAMPLING LOCATIONS
Phase II, Test 2, Soffit and Ridge Venting Configuration

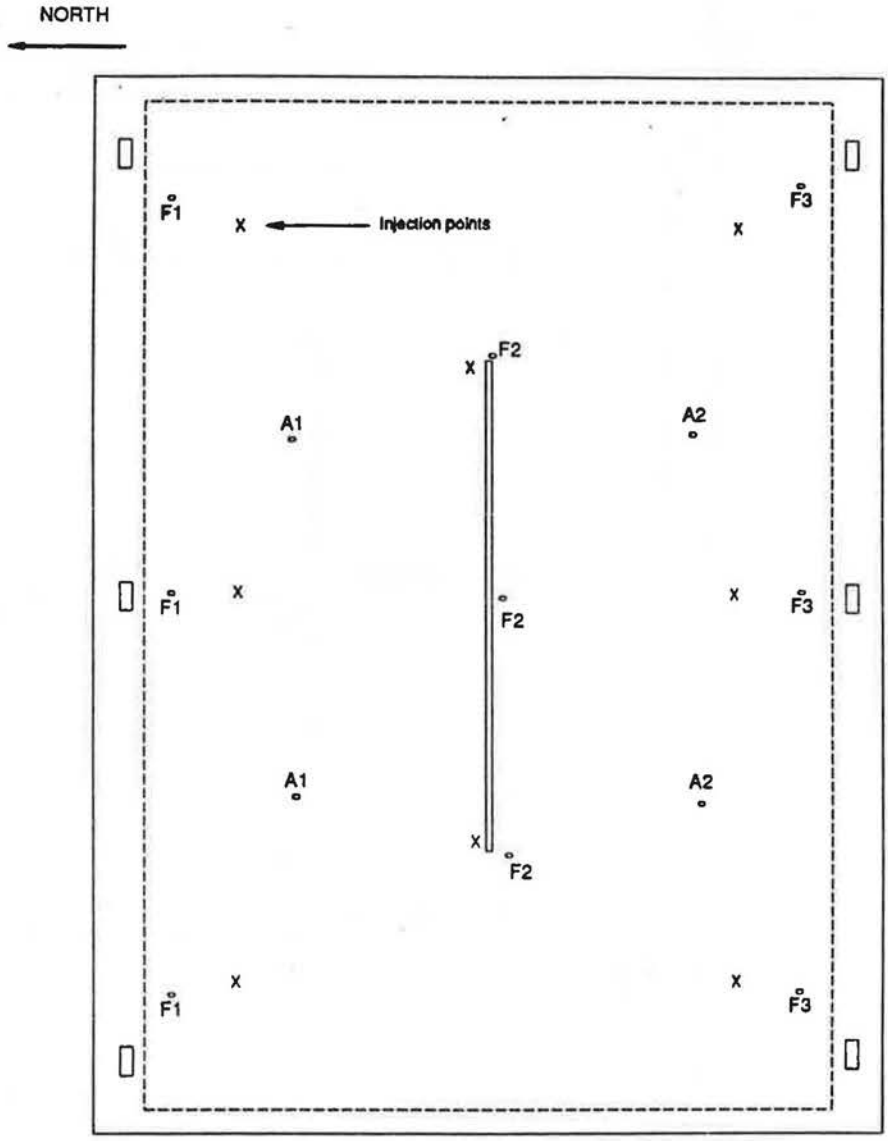


Plan View of Attic

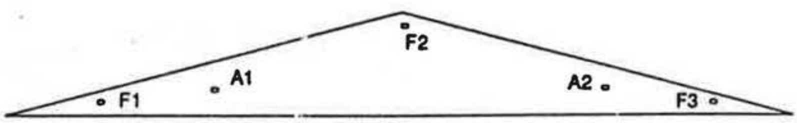


Cross-Section of Attic

Figure 4.2 HOUSE B 8 POINT INJECTION AND SAMPLING LOCATIONS
Phase II, Test 3, Soffit and Ridge Venting Configuration

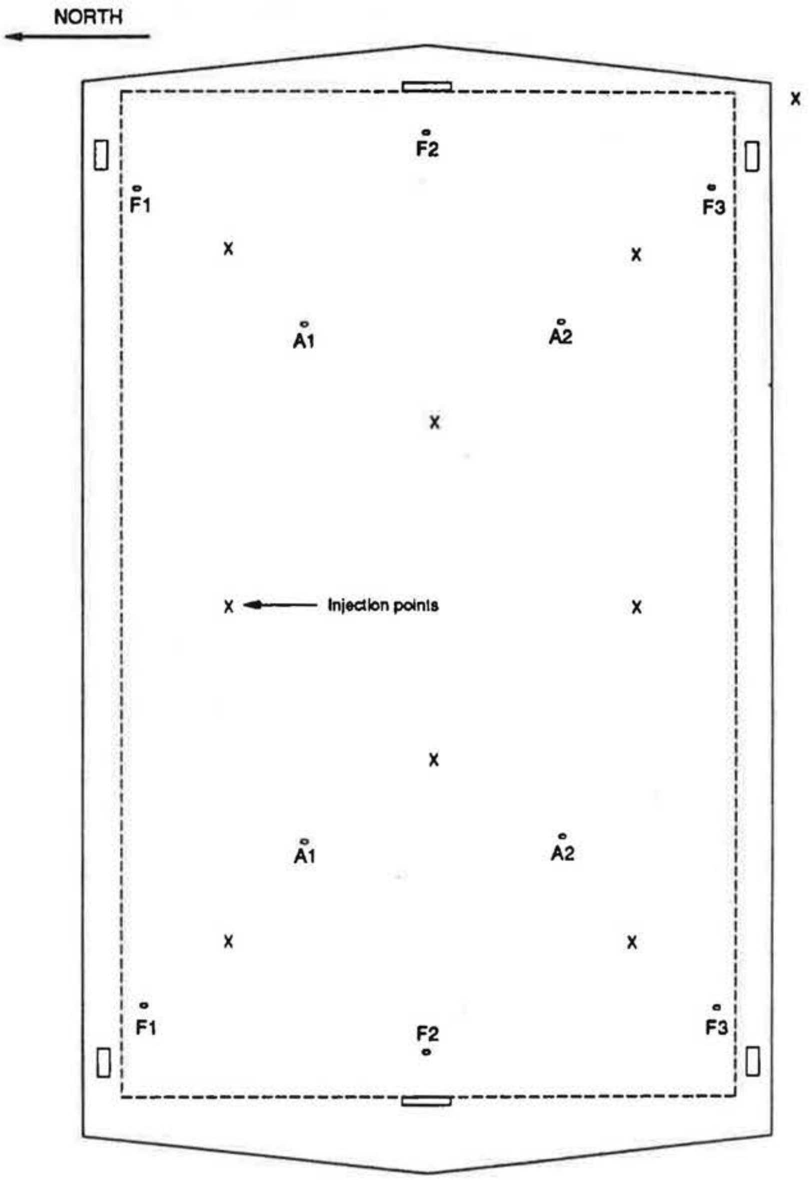


Plan View of Attic

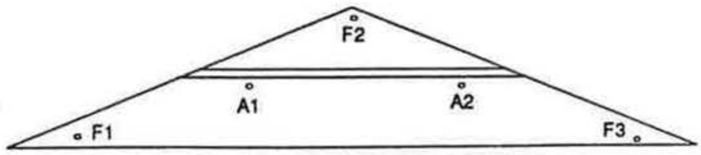


Cross-Section of Attic

Figure 4.3 HOUSE A INJECTION AND SAMPLING LOCATIONS
Phase II, Test 2, Soffit and Test 3, Soffit and Gable Venting Configurations



Plan View of Attic



Cross-Section of Attic

These high temperatures proved significant in defining future field test procedures. During the course of the sampling there were occasions where the flow into some sample bags ceased or was greatly reduced. It would appear that under very high attic temperatures the clear vinyl tubing used for both injection and sampling expanded and softened to the point that connections leaked or came apart entirely. A leak on the sampling side would not result in dilution of the sample since it is under positive pressure. On the injection side, it is possible that there was some leakage at the fittings skewing the injection pattern.

5.0 ANALYSIS OF PHASE II TESTING

Tables 5.1 through 5.3 document the chronology and field conditions of the Phase II testing. The results are illustrated in a plan format in Figures 5.1 to 5.4 to aid in discerning possible flow patterns.

For House A, one average sample result was invalid because sample collection ceased. It was later found that a sample hose was loose at the pump connection.

A comparison of the six nozzle injection system and the eight nozzle injection system was conducted in House B. Using the six nozzle system, a great variation in the SF_6 concentrations of the samples was observed, with the northwest sample having much higher than average readings and the northeast sample being much lower. This same pattern was evident, on a smaller scale, in the second test carried out on a different day using the eight nozzle injection system. While there is a possibility of some kind of sampling or analysis error, particularly with the one northeast sample that had a reading of 0.3 ppm, part of the variation could be attributed to leakage from a relatively high number of connections in the injection lines.

5.1 Calculated Air Change

Table 5.4 summarizes the average concentration and calculated air change rates for the four Phase II tests.

A post calibration of the injection system indicated that the flow meter readings taken during these tests were accurate. The calculated air change rates, therefore, are judged to be valid.

The calculated air change rates exhibited the expected pattern of differences between the varying venting characteristics of the house configurations. The ridge and soffit configuration of House B had the highest air change rates on both days tested and these rates were very similar.

In House A, with the soffit and gable configuration, the venting rates were less than those found with the ridge vent configuration, but substantially more than when the gable vents were closed.

Table 5.1 HOUSE B CHRONOLOGY AND FIELD CONDITIONS
Phase II, Test 2, Soffit and Ridge Venting Configuration
6 Injection Points

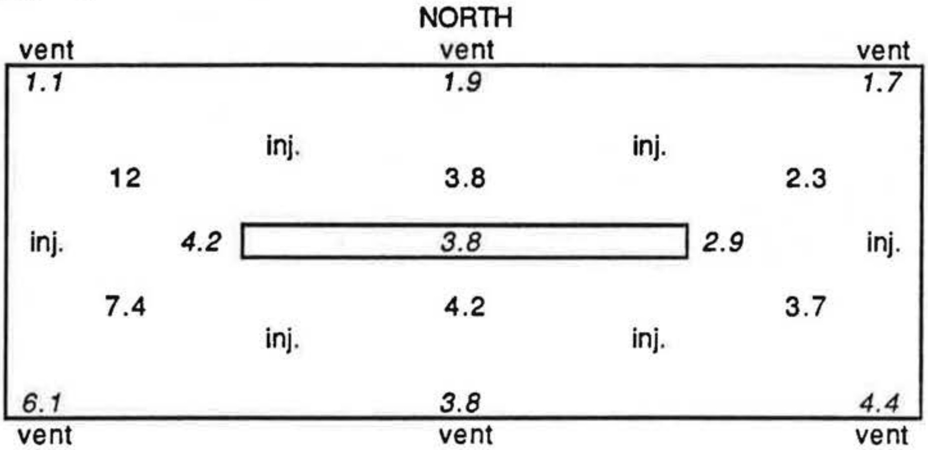
		Attic	On Site Weather		Airport Weather		
		Temp	Wind	Wind	Outdoor	Wind	Wind
Time	Action	(°C)	Speed	Direction	Temp °C	Speed	Direction
11:00					25	13 kph	SW
11:15	Start SF6 Injection	40	Light	West			
12:00	Start Pumps First Set	44	Light	West	26	13 kph	SW
1:00	Take First Set Samples	48	Light	West	28	11 kph	SW
1:50	Take Second Set Samples	48	Light	West			
2:00					29	19 kph	S-SW
2:10	End Test						

Figure 5.1 HOUSE B INJECTION LOCATIONS AND SAMPLE CONCENTRATIONS
Phase II, Test 2, Soffit and Ridge Venting Configuration
6 Injection Points

Top view of house showing injection locations (inj.)
and sample concentrations in ppm

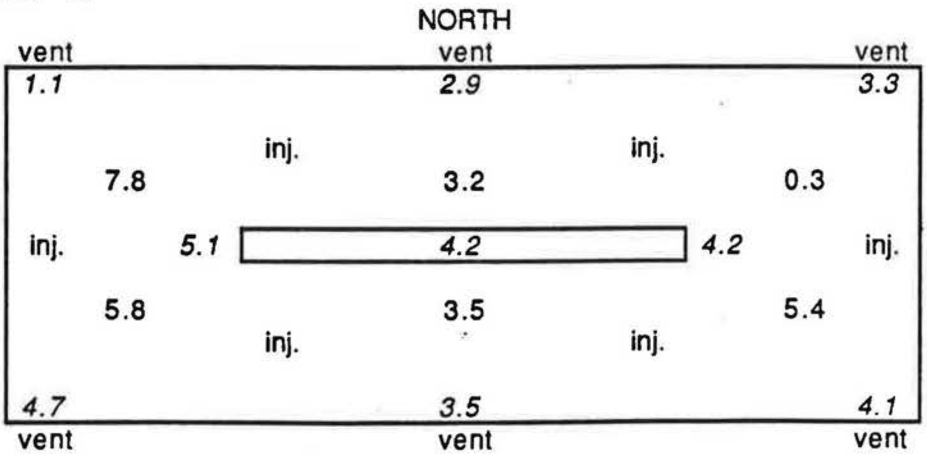
Flow samples in italics were not used to calculate the average concentration

SAMPLE SET 1



Average of "A" samples = 5.6

SAMPLE SET 2



Average of "A" samples = 4.3

Table 5.2 HOUSE B CHRONOLOGY AND FIELD CONDITIONS
Phase II, Test 3, Soffit and Ridge Venting Configuration
8 Injection Points

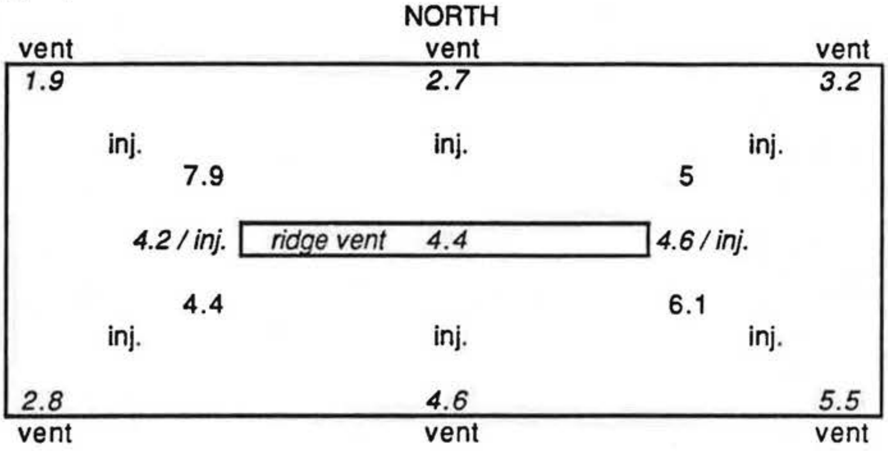
		Attic	On Site Weather		Airport Weather		
		Temp	Wind	Wind	Outdoor	Wind	Wind
Time	Action	(°C)	Speed	Direction	Temp °C	Speed	Direction
12:00					23	11 kph	E
12:10	Start SF6 Injection	41	Light	NE			
12:50	Start Pumps First Set						
1:00					24	9 kph	NE
1:20	Take First Set Samples	45	7 kph	NE			
2:00					24	17 kph	NE
2:20	Take Second Set Samples	46					
2:30	End Test						

Figure 5.2 HOUSE B INJECTION LOCATIONS AND SAMPLE CONCENTRATIONS
Phase II, Test 3, Soffit and Ridge Venting Configuration
8 Injection Points

Top view of house showing injection locations (inj.)
and sample concentrations in ppm

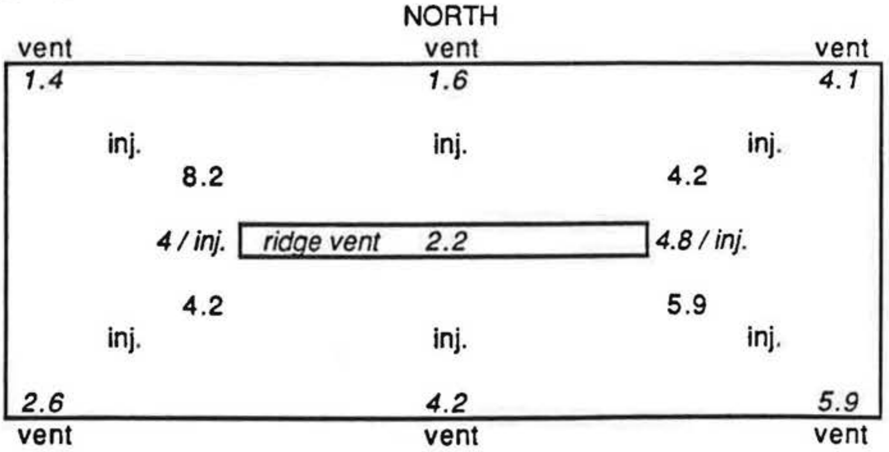
Flow samples in italics were not used to calculate the average concentration

SAMPLE SET 1



Average of "A" samples = 5.9

SAMPLE SET 2



Average of "A" samples = 5.6

Table 5.3 HOUSE A CHRONOLOGY AND FIELD CONDITIONS
Phase II, Test 3, Soffit and Gable, and Test 2, Soffit Venting Configuration

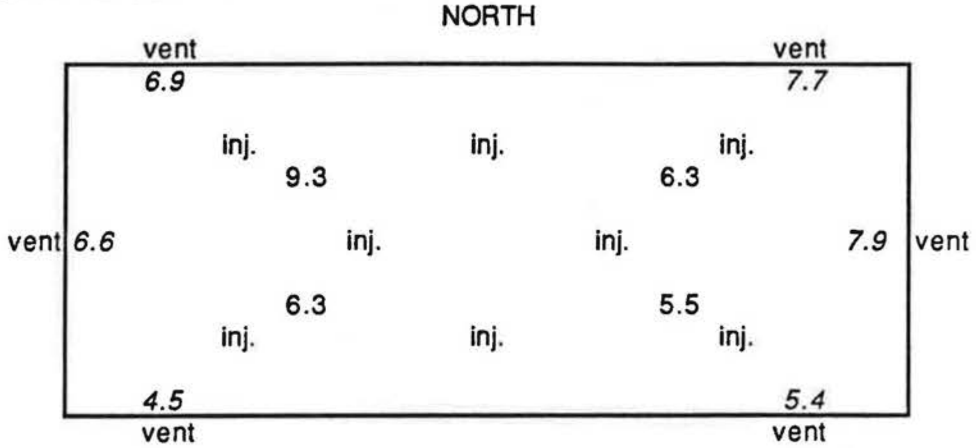
		Attic	On Site Weather		Airport Weather		
		Temp	Wind	Wind	Outdoor	Wind	Wind
Time	Action	(°C)	Speed	Direction	Temp °C	Speed	Direction
12:00					30	15 kph	W
12:05	Start SF6 Injection	45	Light	SW			
	SOFFIT & GABLE, Test #3						
12:45	Start Pumps First Set	46	Light	SW			
1:00					31	11 kph	W
1:15	Take Sample First Set	49	Light	SW			
1:45	Take Sample Second Set						
2:00	Seal Gable Vents	51	Light	SW	33	15 kph	W
	SOFFIT, Test #2						
2:40	Start Pumps First Set						
3:00					33	15kph	W
3:10	Take Sample First Set	54	Light	SW			
3:40	Take Sample Second Set	55	Light	SW			
4:00	End Test				33	17 kph	W

Figure 5.3 HOUSE A INJECTION LOCATIONS AND SAMPLE CONCENTRATIONS
Phase II, Test 3, Soffit and Gable Venting Configuration

Top view of house showing injection locations (inj.)
and sample concentrations in ppm

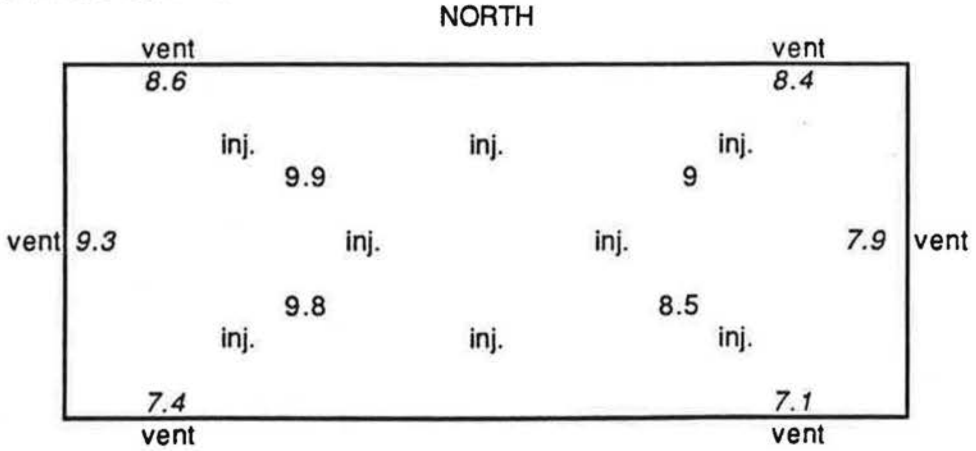
Flow samples in italics were not used to find the average concentration

SAMPLE SET 1



Average of "A" samples = 6.9

SAMPLE SET 2



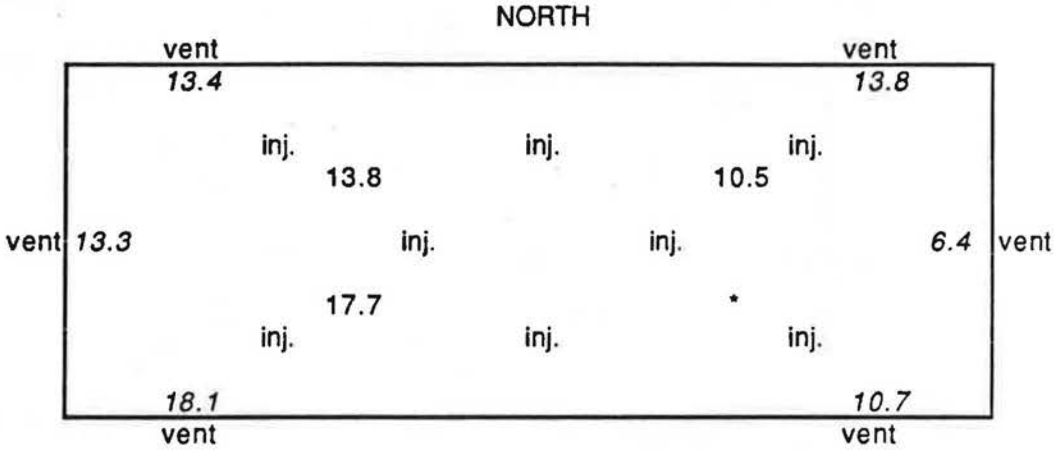
Average of "A" samples = 9.3

Figure 5.4 HOUSE A INJECTION LOCATIONS AND SAMPLE CONCENTRATIONS
Phase II, Test 2, Soffit Venting Configuration

Top view of house showing injection locations (inj.)
and sample concentrations in ppm

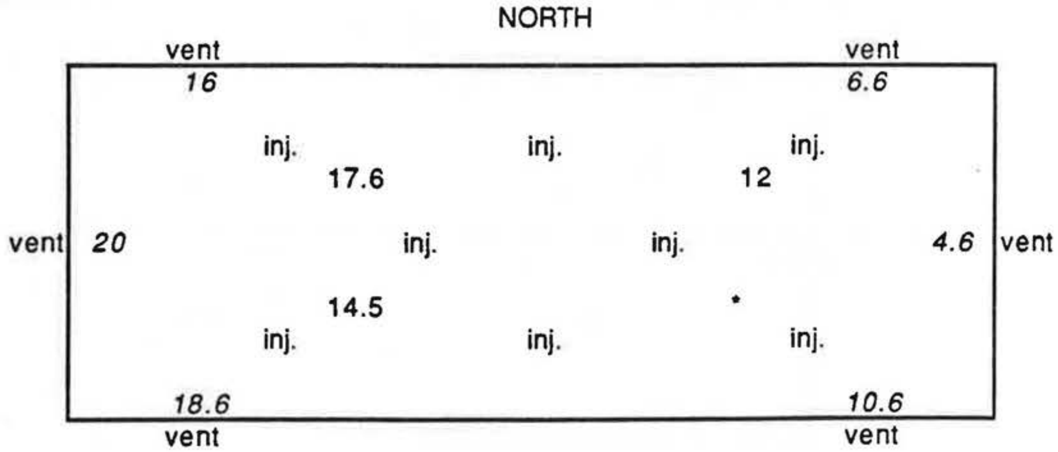
Flow samples in italics were not used to calculate the average concentration

SAMPLE SET 1



Average of "A" samples = 14.0

SAMPLE SET 2



Average of "A" samples = 14.7

* = invalid sample

Table 5.4 SUMMARY OF PHASE II TESTS

Venting Configuration	Test No.	House Type	Test Date	Attic Volume (litres)	Average Concentration (ppm)	Calculated Air Changes per Hour (ACH)	Injection Rate 100% SF6 L/hr	Injection Rate 1% SF6 L/hr	# of Sampling Locations	# of Injection Locations	# of "A" Sample Locations
Soffit & Ridge	2	B	18-Jul	82285	5.0*	2.5	/	102	15	6	6
Soffit & Ridge	3	B	20-Jul	82285	5.7*	2.8	/	132	13	8	4
Soffit	2	A	26-Jul	91800	14.4*	0.96	/	126	10	8	4
Soffit & Gable	3	A	26-Jul	91800	9.3**	1.5	/	126	10	8	4

Note: * denotes average of all sets
** denotes average of last set only

6.0 DISCUSSION OF OVERALL RESULTS

1. Both phases of testing indicated that the time-averaged sampling approach worked quite well. The one field problem found with this approach was that, during periods of very high attic temperatures, the clear vinyl tubing used to draw samples from the sampling pumps in the attic to the bags in the main floor softened and expanded enough to lose the integrity of the connection at the pump. This problem can be corrected by using a pump with a slightly better connecting arrangement than the pumps used in this study. Because the problem can be detected by the inability to draw a sample, it is also possible to use the pumps used in the study. It should be noted that, even if there is a leak, as long as there is some sample drawn, it should provide a valid result because the positive pressure in the sample line minimizes the possibility of contamination by indoor air. However, since there is always a possibility of air being retained in the sample bags, it is desirable to draw as large a sample as possible to minimize the possibility of dilution at this location.

2. As expected, depending upon location, some variation in attic concentrations of the tracer gas were found. The level of variation depended, to a significant extent, on the level of ventilation of the attic. For field sampling, it is therefore suggested that four samples be taken to determine the average. These should be in the centroid of the four quadrants of an attic. This will allow the assessment of any variation due to wind direction and provide some ability to detect problems in the sampling during a test.

3. The greatest problem encountered in the protocol development phase was with the injection systems. This was related to obtaining an even injection to all areas of the attic and the ability to measure and control the tracer gas flow rate into the attic. It is possible to do this adequately based on the following system:

    - The rotameter flow metering and control system used in the development tests created too many areas of uncertainty. It would appear that the devices are not reliable in field service, being quite fragile and sensitive to inlet pressure. A mass flow meter should be specified for use in the field protocol. These are more expensive, approximately $600 - $1000, but, because they are insensitive to pressure, that potential error is eliminated.
    - The manifolded multi-point injection system using oil furnace nozzles as calibrated orifices provided a relatively simple way of achieving the

required distribution control. A weakness in the system used during the development procedures was in the connections and hoses used.

For field testing, a system which consists of a single hose running from the mass flow meter to the attic is suggested. A fabricated metal manifold with positively locking connectors on the inlet and on all outlets connections to the oil nozzle orifices is proposed. This entire system should be prefabricated and tested for leaks. Field-made connections should be minimized.

- During development testing, the concentration of the measured SF_6 in the attic was in parts per million range. SF_6 concentrations that can be directly measured by GC analysis are in the 0 - 200 parts per billion range. Using the higher concentration requires dilution of the sample which could result in some analysis error. Consideration must also be given to the accuracy of measurement of the injection flow rates.

  Based on the air change rates from the Phase II testing, the suggested field test protocol should use a combination of flow rate and SF_6 concentration in the injected gas to arrive at an SF_6 concentration in the attic of 100 ppb at an air change rate of 1.0. With the eight point orifice injection system used in the developmental research, the findings indicate that the total flow through the system should be in the range of 50-100 litres per hour in order to get acceptable distribution from the nozzles. It is proposed that an SF_6 concentration of 0.01% and a mass flow meter of 0 to 200 litres per hour range be used. The Matheson Model 4111-0423 mass flow meter with a range of 0 to 120 L/hr would be capable of meeting this requirement.

- The injection of tracer gas into the attic should start at least one hour before sampling begins and two or more samples of one half hour duration should be taken for each attic.

4. Critical environmental factors to measure during field testing include:
   - ambient temperature
   - attic temperature
   - local wind speed and direction

APPENDIX A

RECOMMENDED PRACTICES
FOR INSTALLING THE TRACER GAS INJECTION SYSTEM
AND THE ATTIC AIR SAMPLING SYSTEM

The procedures detailed here are the recommended practices for the installation of both the tracer gas injection system and the attic air sampling system.

It is important that the integrity of all connections in the injection system be monitored. Leakage can be a source of significant errors.

TRACER GAS INJECTION SYSTEM

The general layout of the injection system is shown in Figure A1. Included in that figure are the specifications for the required equipment. This equipment can all be obtained through Matheson Gas Products Canada.

The basic requirement for injection is to maintain a constant flow through the injection system of approximately 100 L/hr. The target steady state concentration of SF_6 in the attic space is 100 ppb.

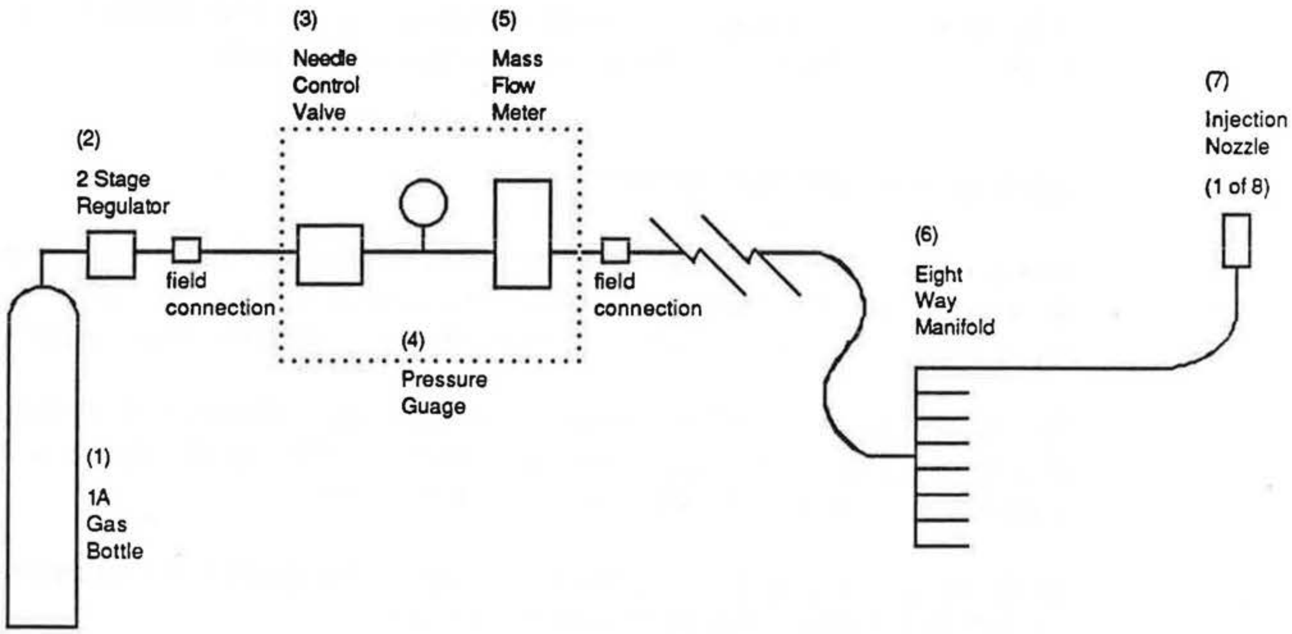
In order to avoid field connections, the injections system is fabricated with all but two connections permanently secured.

The configuration of the flow metering/monitoring module is shown in Figure A2.

Installation Procedure

1. Unpack and lay out all hoses and equipment and inspect for damage.
2. Chose a suitable location for placing the gas bottle and regulator, and the flow measuring/metering module. (This equipment must be located in an area remote from the attic space being tested.)
3. Locate the gas nozzles to provide even distribution in the attic (see Figure A3). Ensure that nozzle caps are removed.
4. Check the security of all connections to the eight-way splitting hose manifold and suitably locate the manifold in the attic.

Figure A1 **INJECTION SYSTEM SCHEMATIC**



LEGEND

	ITEM	SPECIFICATIONS	MODEL #
(1)	1A Gas Bottle	3.8 cum., 0.01 % SF6	
(2)	2 Stage Regulator	0 - 15 psi outlet	3102
(3)	Needle Control Valve	0 - 3,300 scc/m	4174-1505
(4)	Pressure Guage	0 - 15 psi	63-3115
(5)	Mass Flow Meter	0 - 2000 scc/m	4111-0423
(6)	Eight Way Manifold		custom
(7)	Injection Nozzle		custom

Figure A2 **FLOW MEASURING/METERING MODULE**

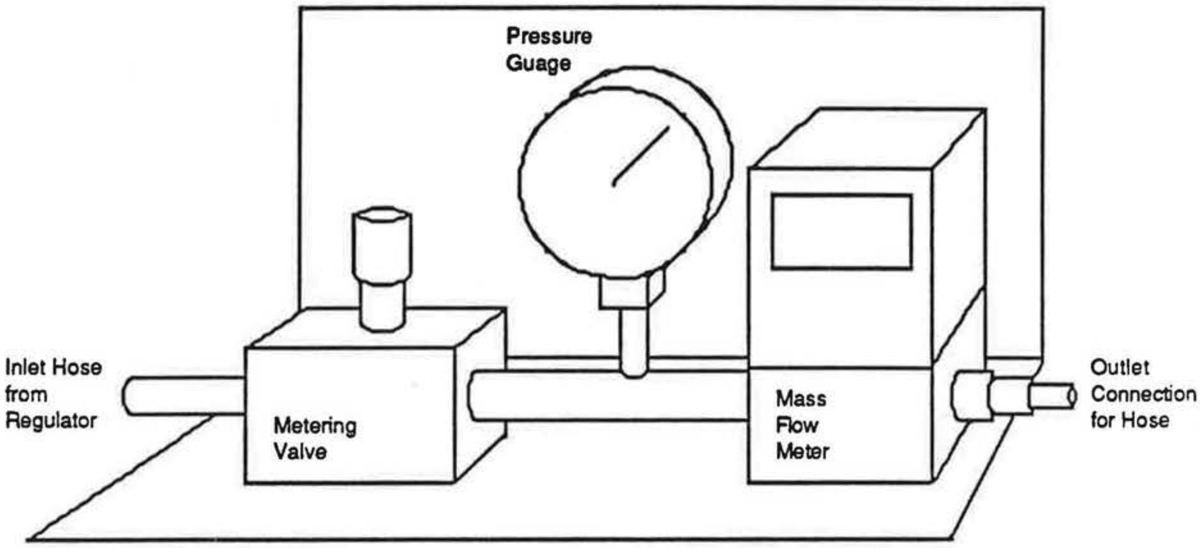
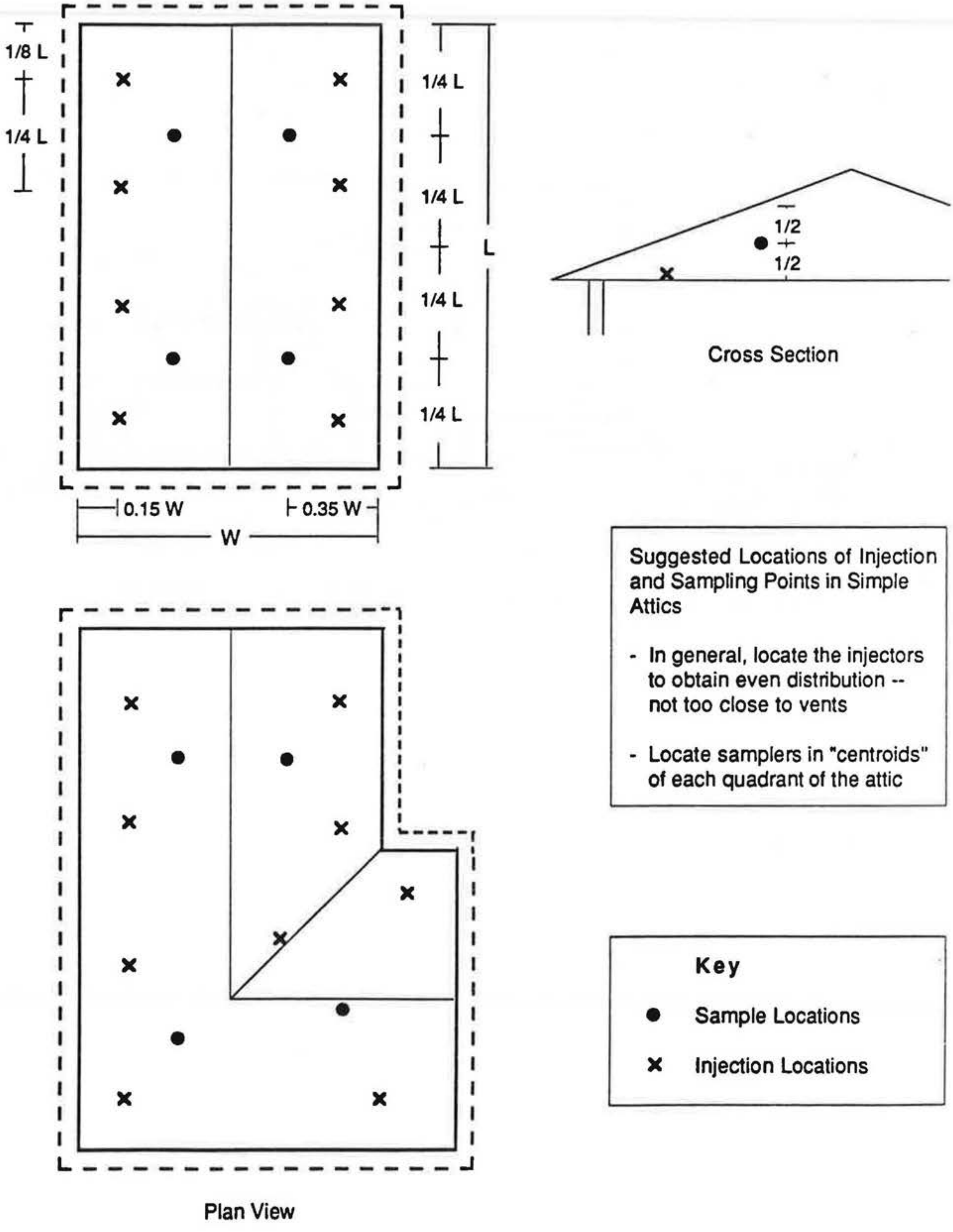


Figure A3 **SUGGESTED INJECTION AND SAMPLING POINT LOCATIONS**



Suggested Locations of Injection and Sampling Points in Simple Attics

- In general, locate the injectors to obtain even distribution -- not too close to vents
- Locate samplers in "centroids" of each quadrant of the attic

Key

● Sample Locations

× Injection Locations

5. Connect the manifold supply hose to the flow measuring/metering module (Figure A2).
6. Connect the flow measuring/metering module supply hose to the regulator assembly.
7. Turn on the regulator and adjust the outlet pressure to 20 psig.
8. Adjust the metering valve to obtain a flow as specified in Table A1.
9. With a soap solution, carefully check the outlet hose connection and the flow measuring/metering module for leaks.
10. Allow SF_6 concentration to stabilize for a period of one hour.

Table A1 INJECTION RATES

Attic Volume (m^3)	Total Flow (L/min)	SF_6 Flow (0.01%) (L/hr)
50 or less	0.83	0.005
60	1.00	0.006
80	1.33	0.008
100	1.67	0.010
120 or more	2.00	0.012

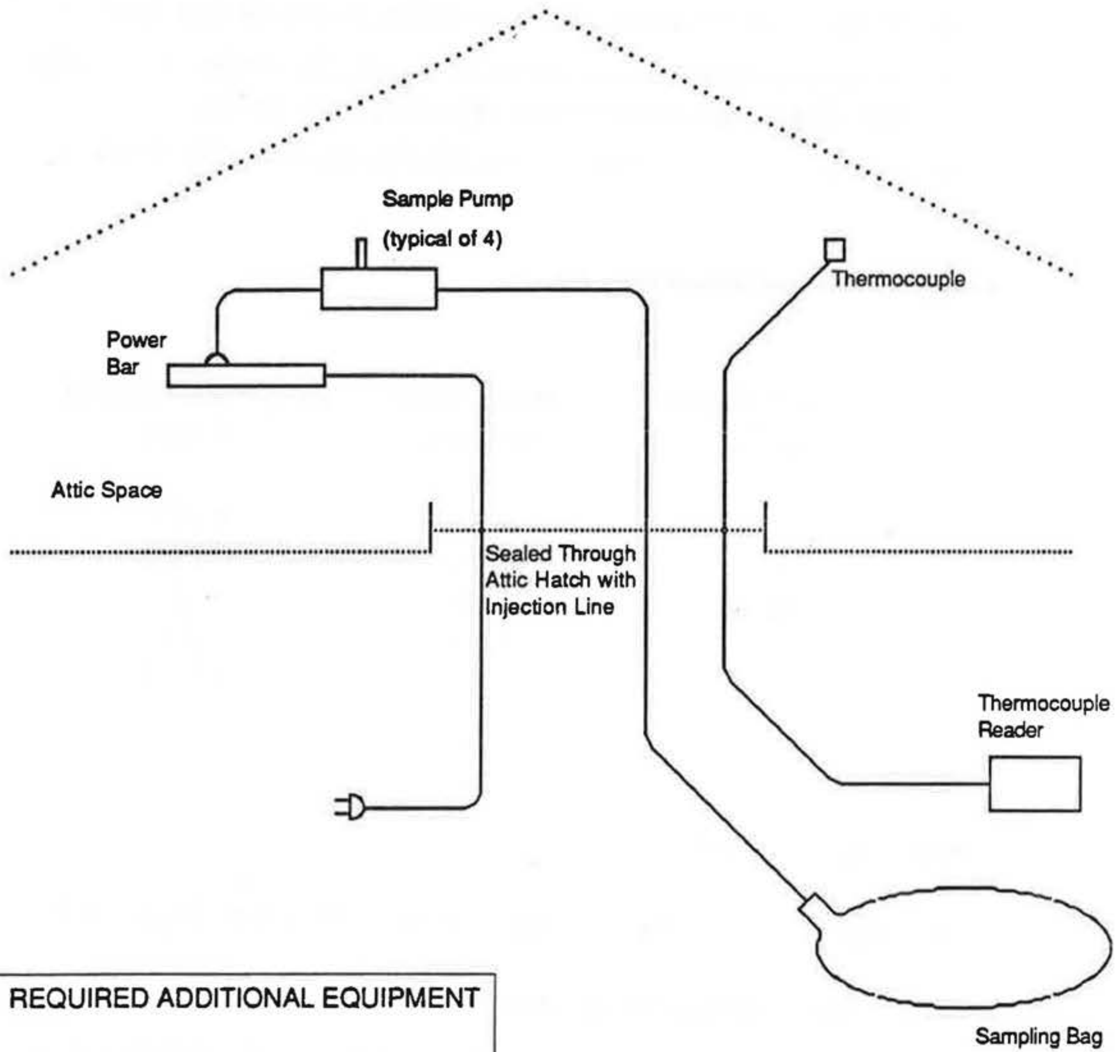
SAMPLING SYSTEM

The schematic for the sampling system is shown in Figure A4.

Installation and Operating Procedures

1. Install pumps in sampling locations as suggested in Figure A3.
2. Plug pumps into power bar and then to single extension cord.
3. Lay out sample hoses to convenient location in house.
4. Seal attic hatch area (around sample hoses, injection hoses and extension cord) and lay out sample bag and sampling equipment.
5. Start injection (See Injection System Installation Procedure).
6. One hour after start of injection, start sampling by:
   - plugging in pumps without sample bags for several minutes to flood sample lines

Figure A4 **SAMPLING SCHEMATIC**



REQUIRED ADDITIONAL EQUIPMENT

10 - Polyethylene Bags
2 - 30 mL Syringes
20 - 10 mL Vacutainer
Anemometer
Compass

- ensure bags are empty of air
- stop pumps and connect sample bags
- start sample pumps and note time.

7. Collect local weather data - windspeed and direction, attic temperature and outdoor temperature.
8. After thirty minutes of sampling:
   - stop pumps
   - remove and cap bags
   - install new (empty) bags
   - restart pumps and note time.
9. Collect samples for analysis by inserting syringe in bag inlet hose, flushing syringe three or four times, drawing a 15 ml sample and injecting entire sample into a 10 ml vacutainer. Note sample number. Take two samples per bag for first test (this provides a duplicate to allow the analysis lab to establish if dilution is required and to verify doubtful results.
10. After second sampling period of thirty minutes stop pump, remove and cap bags and take a single sample from each bag. Take one sample of indoor air.

Analysis

- Locate sample and injection points on plan of attic. Note wind direction and speed, attic and outdoor temperature on data sheets. (Note sample data sheets on pages 43 to 44.) Record sample concentrations on data sheets when received.
- For each sample period calculate air change by using the following equation:

$$AC = \frac{SF_6 \text{ injection rate (L/hr)} \times 10^6}{\text{Attic Volume } (m^3) \times \text{Average Concentration (ppb)}}$$

HOUSE DATA

Address: ____ age : ____ yrs

No. of storeys: 1, 1 1/2, 2, other__________
Roof type: gable hip flat L-shaped dormers other ____________
Slope:____/12 **Sheathing:** plank plywood waferboard other __________
Ext. finish: ash. shingle wood shingle membrane metal other _________
Plan Area: _______(m^2) (to outside of walls) **Volume:** ______(m3)

VENTS

type	soffit	gable	ridge	mushroom	other
location	_______	_______	_______	_______	_______
number	_______	_______	_______	_______	_______
gross area	_______	_______	_______	_______	_______
free area	_______	_______	_______	_______	_______

Total free area: _______(m^2) **Vent area/attic area:** ________

SITE FEATURES

Sketch site showing house, wind shielding, and rough dimensions

TEST DATA

Date: ____________________ **Tester:** ______________________________

ATTIC PLAN: Show *-dimensions*
-injection and sample parts with ref. num.
-wind direction
-attic hatch location

⇑

Cross Section

Time

_____injection start injection rate (raw number) __= ___ 1/hr SF_6
_____first sampling period start wind speed______ dir. ____
_____first sampling period end Temp: Attic_____ Outdoor_____
_____second sampling period start wind speed______ dir. ____
_____second sampling period end Temp: Attic_____ Outdoor_____

SAMPLES

First Test Period			Second Test Period		
Sample no.	Conc	Comments	Samp no.	Conc	Comments
					in house

Average in Attic______ ______________

Calculated ACH ______ ______________