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TRACER GAS MEASUREMENT SYSTEMS COMPARED IN A MULTIFAMILY BUILDING

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ABSTRACT

The more complex building poses additional challenges to air infiltration measurement, especially the case of multiple zones and rooms. Today's technology has provided us with a number of measurement choices which include: the constant concentration single tracer gas system; multi-tracer gas systems using the mass spectrometer; and perfluorocarbon multi-tracer systems both passive and active. This paper will compare simultaneous field measurements in a Princeton area multifamily building using each of these tracer-gas based air infiltration systems. Personnel from Princeton University, Lawrence Berkeley Laboratory, and Brookhaven National Laboratory were involved in the air infiltration measurement studies.

Air Infiltration rates in the various zones in each building are compared as well as the ease of implementation of the various approaches in these comprehensive measurements. Sources of errors using the various techniques also will be discussed.

Keywords: airflow, infiltration, tracer gases, multiple zones, measurement systems.

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INTRODUCTION

During the past decade there have been major advancements in the measurement of airflows in buildings. Because of energy considerations, efforts have often concentrated on air infiltration documentation for the building as a whole, since these natural airflows may typically represent 20-40% of the heating load in residential buildings. Today, concerns extend beyond air infiltration into the building and place new emphasis on multiple zones and airflow between zones since both contaminant movement and energy use must be evaluated. To provide such airflow documentation has required the development of new instruments and measurement concepts.

Although airflow measurement systems have probed a variety of ventilation questions, and a variety of tracer gases have been compared (1), unfortunately there has been limited emphasis on addressing the questions of how the measurement systems and techniques compare with each other (for example, Ref. (2)). This study is directed at providing for such initial comparison testing, in a multifamily building, so as to more fully evaluate the capabilities of each measurement approach, and to determine what are the relative strengths and weaknesses of the methods.

SITE OF THE COMPARISON TESTS

The building site chosen for the tests was the Hibben Apartments on the Princeton University campus in Princeton, New Jersey. This eight story building has been housing junior faculty and staff since 1965. Ninety-six families occupy two-story apartments in the building. An unoccupied apartment in the lower level of Hibben was used as one of the areas for the air flow measurements and also housed the variety of equipment during the weeks of the study which took place in February and March of 1988.

Choices for the measurement zones were based on building accessibility and the capabilities of the measurement equipment. Within the test apartment there was a kitchen-living zone and a bedroom-bathroom zone. On floors one and two of the building there was an apartment with ventilation measurement access to the upstairs and downstairs zones. Next to the basement apartment there was a storage room as well as the mechanical services room, where the latter had mechanical exhaust 24 hours each day. From these spaces one had access to four or more zones for the test comparisons. The zones are outlined in Table 1 below.

TABLE 1 - DETAILS OF THE TEST ZONES

Zone	Description	Volume (m^3)
1	Upstairs Apartment	200
2*	Bedroom/Bath Downstairs Apartment	59
3*	Living Rm/Kitchen Downstairs Apartment	111
4*	Basement Storage Room	152

*Mixing fans used to increase room circulation

THE MEASUREMENT SYSTEMS

Each of the laboratories involved in these tests has developed distinctly different tracer gas approaches to the measurement of air infiltration/ventilation, and these are described in the following paragraphs and shown in Figure 1. Table 2 provides some insight to the strengths of these individual approaches. Also described are the analysis methods used. These are not full descriptions but rather are provided to convey the analysis concepts.

TABLE 2 - ATTRIBUTES OF THE VARIOUS TRACER GAS SYSTEMS

CCTG:

1) Real-time
2) May be used in many (10 or more) zones to determine infiltration (i.e., airflow from outside)
3) Automated for unattended operation after set up, modem communication

PFT-CATS

1) Quickly installed
2) Determines interzonal flows
3) Low-Cost for long-term application

MTMS:

1) Real-time system
2) Determines interzonal flows
3) Insensitive to rapidly changing conditions.

Constant Concentration Tracer Gas (CCTG) - Method

The constant concentration tracer gas system (CCTG) employed by Princeton University depends upon careful maintenance of a target tracer gas concentration in each of up to 10 zones to be measured(3,4). The present equipment uses a single tracer, sulfur hexafluoride, together with 10 tracer injection valves and sequenced sampling. Injection takes place at the circulating fan or at that place in the individual room where natural air currents will help distribute the dilute tracer gas mixture. This is a "closed loop" control operation since the system uses (or feeds back) information of the measured concentration and estimated infiltration in order to maintain zone concentrations at the target value. The digital optimal adaptive proportional control algorithm used to compute the injection rate is carefully designed to minimize deviation from the target concentration(3). Readings of just how closely the tracer gas target concentration has been achieved is an excellent indication of measurement system performance.

The computer performs these functions as well as keeping a running account of each zonal air infiltration rate, which is approximately proportional to the tracer gas requirements for that zone. The actual CCTG measurement system consists of three modules: the gas chromatograph which employs an electron capture detector, molecular sieve columns and backflushing of column flows to achieve a 30-second tracer concentration analysis. The tracer injection module uses a controlled upstream pressure to computer controlled individual solenoid valves and calibrated orifices to provide a variable flow to each zone. The sampling module, programmed for the number of zones or repeat measurements that are all controlled by a microcomputer, which also handles the data acquisition requirements and routinely makes use of a modem to transmit data from the building to the lab.

CCTG - Analysis

For the analysis of the data, each zone is treated separately. It is assumed that the concentration of the airflows between the zones is at the target level. Thus, the tracer injection rate responds only to changes in zone infiltration rate and not interzone rates. Since the concentration in the zone does not stay exactly at the target, the computation method considers both the concentration and injection rate data. This is accomplished by performing a least squares regression analysis of the data over the specified time period, normally one hour. Instrument error has generally proven to be of the order of 2.5% for the detector. The uncertainty of the gas concentration is ± 2% and the calibration gas uncertainty is ± 1%. Injection rate uncertainty is ± 1/2% with good mixing, and typical air infiltration variation ± 5% errors are typical.

Multiple Tracer Measurement System (MTMS) - Method

Lawrence Berkeley Laboratory's Multiple Tracer Measurement System (MTMS) injects a unique tracer gas into each zone(5). One injection and one sample tube are required for each zone, and both have continuous flow. Air sampled from each zone is sequentially introduced into a Residual Gas Analyzer (RGA, i.e., a quadrapole mass spectrometer), which measures the intensity of selected peaks that uniquely identify and quantify the concentration of all the tracers in each zone. At present five tracer gases have been used successfully, and a capability of eight has been demonstrated in the lab. In order to keep concentrations within acceptable limits, MTMS attempts to keep the concentration of each gas at a constant value in the zone in which it is injected. Since (in contrast to the CCTG system) the analysis is not dependent on holding constant concentration, the control is optimized for stability rather than fast response using basically the same algorithm as that employed by the CCTG.

MTMS-Analysis

The analysis of the data uses the full multizone continuity equation, which includes both interzonal flows and uses the time derivative of the concentration. The matrix of continuity equations is integrated over a user-selected time constant and then solved for the individual flowrates. Next, any flowrates, which are physically impossible, are adjusted to minimize the disallowed terms. The uncertainties are then calculated. This procedure is repeated consecutively to produce time-series data. The accuracy of the RGA is approximately 0.05 ppm with a linearity of better than 1%. The mass flow controllers are calibrated to approximately 1/2% of full scale. The combined instrument error is approximately 2%, but the estimated flowrates from of any such tests are rarely that good because of incomplete mixing. The uncertainties in the concentration and flowrates associated with the mixing in the room will dominate the error, and will be the same for all the techniques. In this four zone study each of the 16 concentrations were measured every four minutes. The time constant in the analysis was set to 1/2 hour.

Perfluorocarbon Tracer Measurement Techniques (PFT) - Method

The ventilation measurement technology employed by BNL involves the release and measurement of multiple perfluorocarbon tracers (PFTs). The PFTs are emitted at a steady rate by miniature permeation sources with a different PFT being emitted into each well-mixed zone of the building. Three methods are currently available for measuring the PFT concentrations in the building zones: (1) passive adsorbent tubes known as CATS (Capillary Adsorption Tube Sampler), (2) BATS (Brookhaven Atmospheric Tracer Sampler), a programmable, pumped device which automates the collection of air onto 23 adsorbent tubes, and (3) a real-time instrument which both collects and analyzes sampled air for PFTs with a resolution of about five minutes. Samples collected using either CATS or BATS are returned to the laboratory where they are analyzed using gas chromatographic separation and electron capture detection. A more detailed description of these measurement techniques can be found elsewhere (6,7). All three of the above sampling devices were used for this intercomparison with both the BATS and the real-time analyzer collecting samples every 15 minutes and the CATS collecting integrated samples over the entire six hour test. The results reported in this paper for the test period are from samples collected on the BATS.

PFT - Analysis

The BNL ventilation flows were computed by inserting the measured tracer concentrations and the known emission rates into a multizone model consisting of N^2 mass balance differential equations and 2N+1 flow balance equations, where N is the number of well-mixed building zones. Derivatives within the mass balance equations were evaluated using a five point numerical technique around the point of interest. In cases where there were known changes in building ventilation (windows shut, doors opened, etc.), derivatives were computed using a five point technique which projects forward or backward from the time of the ventilation change. Errors on the computed flows were estimated using a first-order error analysis technique. These error estimates are not presented in this paper. A further description of the techniques used by BNL to generate ventilation flows and their errors can be found elsewhere (8).

SYSTEM COMPARISON PLANNING

The decision as to the number of tests and when to test attempted to take into account such factors as number of tracers available and the concentration levels employed. In the case of the perfluorocarbon tracers we are talking about concentrations of the order of 1×10^{-12}, yet with the LBL mass spectrometer approach gas concentrations were parts per million, or six orders of magnitude higher. The Princeton constant concentration approach using sulfur hexafluoride was operated at the parts per billion level, or roughly the half-way point of the two other systems. Because of such a spread in concentration levels, the BNL team deployed their system early in the test period to obtain information prior to the presence of high concentrations of other tracer gases so as to evaluate possible tracer interference. Indeed, the real-time measurements of low concentration perfluorocarbon tracers were influenced by the high concentrations of other gases. However, the passive sampler and programmed sampler techniques using the more sophisticated gas chromatographic analysis were able to overcome such interference problems.

To test the response of the three systems, deliberate changes were made in the ventilation in the test apartments. At the start of the test, all windows were closed and the door between zone 2 (bedroom/bathroom) and zone 3 (living room/kitchen) was placed slightly ajar (opened only 8 cm). About 2 hours into the test, at precisely 17:10, a living room window was opened. Then, at 18:25, the door between the two zones was fully opened. Finally, at 19:40, the apartment was returned to its original conditions by closing the window and again placing the door 8 cm ajar. The only other known change in ventilation occurred when, shortly before 16:00 workmen left the mechanical services room and closed its outside doors. The mechanical exhaust fan was then able to create a greater draw on the adjacent test apartment and storage room which was evident from the tracer results.

DISCUSSION

Results from the measurements in the comparison testing will first be discussed using time histories during and prior to the "test period" - February 24, 1988 - covering the hours between approximately 13-14:00 and 19-20:00. All systems were operational during the majority of this period except as noted. Following the test period an additional period, lasting for a number of days, allowed comparison between the CCTG and PFT.

Measured Infiltration into Zone 2 (Living Room/Kitchen, Basement Apartment)

The air infiltration into zone 2 is characterized by two distinctly different periods as shown in Figure 2, an initial period in the ~40-100 m^3h range, followed by a window opening at 17:10 hours, and then rapidly increased air infiltration to the ~150-300 m^3/h level. The actual values of airflow depend on which measurement system is used. The first period finds the air infiltration measurements in good agreement (criss-crossing values, ± 20% maximum disagreement), but the second period finds the CCTG predicting approximately 170 m^3/h and PFT-BATS and MTMS averaging approximately 240 m^3/h (i.e., the CCTG values are 35% lower).

The fluctuations in the PFT-BATS result from 18:25 to 19:40 were because the door between the two zones was opened, causing the two different tracers used in the two zones to become intermixed (and no longer representing a separate zone), which causes the multiple differential equation solution to become ill-defined. This is demonstrated by the PFT

Table 3
Effect of High Interzonal Mixing on Determination of Individual Zonal Infiltration Rates: Test Apartment

(PFT 15-min period results with errors)

Period Start Time	Action*	Infiltration Rate ±Std. Dev. (m^3/h) Bed/Bath(zone2	Liv/kit(zone3)	Test Apt(zones 2&3)+
1510	Door ajar and	30 ± 12	38 ± 37	68 ± 39
1525	windows closed	31 ± 9	76 ± 18	108 ± 20
1540		25 ± 9	118 ± 18	143 ± 20
1555		23 ± 7	128 ± 15	152 ± 17
1610		17 ± 6	131 ± 15	148 ± 16
1625		15 ± 5	134 ± 16	149 ± 16
1640		14 ± 5	129 ± 17	143 ± 18
1655		20 ± 5	129 ± 17	149 ± 18
1710	LR window opened	40 ± 18	291 ± 42	331 ± 46
1725		12 ± 21	321 ± 44	333 ± 48
1740		11 ± 18	310 ± 43	320 ± 47
1755		19 ± 22	304 ± 44	323 ± 50
1810		10 ± 22	299 ± 46	308 ± 51
1825	Door opened	-67 ± 317	374 ± 343	300 ± 42
1840		-62 ± 973	396 ± 1098	317 ± 44
1855		91 ± 356	210 ± 452	317 ± 45
1910		18 ± 246	291 ± 318	303 ± 44
1925		423 ± 761	-83 ± 827	324 ± 46
1940	Door ajar and	9 ± 27	169 ± 34	177 ± 44
1955	windows closed	12 ± 22	163 ± 32	175 ± 38

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*Door was between zones 2 and 3; window opened at 1710 was in living room.
+Test apartment rate was the addition of zones 2 and 3 infiltration rates except when the door was opened, which required separate zone reduction calculation.

results in Table 3 listed for each 15-minute measurement period. Note that in the living room/kitchen zone, before the window was opened, the infiltration rate was about 130 ± 16 m^3/h. After the window was opened, the rate immediately jumped up 300 to 320 ± 44 m^3/h, with a standard deviation of still less than ±15%.

However, after the door was opened and the two zones became intermixed, the infiltration rates in this zone (zone 3) as well as the bedroom/bathroom zone (zone 2) were calculated with a high degree of uncertainty, with standard deviations of ±100% and more, which means the values are meaningless. Averaging methods in the MTMS and CTGG procedures tend to mask the flow variations.

When the two zones are calculated as a single zone, shown as Figure 3, i.e., the whole test apartment, for the five 15-min periods with the door open, the infiltration rates are quite constant at 300 to 320 m^3/h and in perfect agreement with the rates in the five previous periods (see Table 3). Note that the standard deviations for the combined test apartment results are now less than ±15% and they are therefore meaningful. The total infiltration into the test apartment determined by the three methods, is shown in Figure 3. Before the window was opened at 17:10, all three gave results of about 80 to 130 m^3/h. With the window open, the PFT-BATS and MTMS tracked each other quite well, with the former about 10% higher than the latter. And when the window was closed both systems returned to about the same level, 160 to 180 m^3/h. The CCTG results seemed to be about 2/3 of the PFT-BATS results, both before and after the window was opened.

Measured Infiltration into Zone 3 (Bedroom/Bath Basement Apartment)

Similar to the zone 2 data, zone 3, as illustrated in Figure 4, indicates good agreement of the three air infiltration measurements through hour 18:25 (their values were in the 20 m/s range). After that point, with the door opened, the PFT-BATS measurements become very scattered because of the previous mentioned interzone mixing problem. After initial close agreement during hours 14 through 18, CCTG measurements indicate a slightly decreasing trend in air infiltration, while MTMS points out a slightly increasing air infiltration rate beyond 17:10. Again, this appears to be due to a problem of zones influencing each other not a problem with a measurement method -- two zones become one and especially for the PFT-BATS, a separate calculation such as illustrated in Figure 3, should be performed to avoid the flow fluctuations.

Measured Infiltration into Zone 1 (Apartment 1B)

The air infiltration rate for zone 1, which is the two-story apartment, is illustrated in Figure 5. The measurement systems indicated that this zone is isolated from the others. The air infiltration, as characterized by all three systems, consists of two peaks at approximately hours 16 and 19. However, the level of infiltration is different for each measurement system with MTMS exhibiting the highest values, PFT the middle, and CCTG the lowest range of infiltration values.

Measured Infiltration in Zone 4 (Basement Storage)

Measured air infiltration in the basement storage area is shown in Figure 6. The trend for all measurement systems is a generally rising infiltration rate over time, gaining almost 200 m^3/h from hours 16 to 19. The general level of the CCTG airflow predictions is noticeably less than those using PFT-BATS or MTMS.

Interzone Flows

As shown in Figure 7, values of the airflow rates between zones 2 and 3 are near zero prior to the window opening at 17:10; and the window opening shows little effect based upon hour 18 readings. In contrast, the opening of the door between the zones at 18:25 does result in an immediate increase in air exchange between the zones. The two methods of measurement predict similar air exchange between the zones at the low exchange levels in the plot on the left. However, there is a greater difference at the high airflow levels which follow the door opening with unrealistic values recorded, (see plots on the right where 3500 m^3/h using PFT and 1000 m^3/h using MTMs are shown). Closing both door and window at 19:40 drops the interzone flowrates back to near the zero reading.

Tables of Airflow

Looking at the Tables, the following observations are made. When the MTMS was free of restarting incidents and flowrates were less than 100 m^3/h, values of air infiltration matched the CCTG values closely ($\pm$ 10%, $\pm$5% and $\pm$ 1% of mean flowrate). When higher flowrates prevailed (following the window opening), the CCTG readings were observed to fall below the MTMS and PFT-BATS values (although the PFT-BATS values were fluctuating due to the interzone mixing previously discussed).

In Table 5, which tabulates the data for the occupied apartment and the storage room, again at higher flowrates CCTG would appear to be reading low. In zone 4, hours 17-19, PFT-BATS and MTMS agreement was good.

In Table 6 in the periods when the MTMS was working properly there was good agreement with CCTG ($\pm$ 1-2%, hours 13 and 17). PFT-BATS would appear to be the high reading in hour 17 (+30%). The last two hours again point to CCTG reading below those of the other two systems for the higher flowrates.

Table 7 provides further information on interzone flows including zones 2 and 4 as well as 2 and 3 describe in Figure 7. Except for the question of two zones becoming one (* data), general agreement between MTMS and PFT-BATS is good.

Table 8 describes the period following the three system tests where in this case a six-day comparison took place between CCTG and PFT-CATS measurement systems. At the higher flowrates the CCTG measurements averaged

Table 5

Comparison of Hourly Average
Infiltration Rate: Zones 1 & 4

Infiltration Rate (m^3/h)

Hour	Zone 1 CCTG	Zone 1 MTMS	Zone 1 PFT	Zone 4 CCTG	Zone 4 MTMS	Zone 4 PFT
13	356	598	-	64	193	-
14	262	758+	-	53	207+	-
15	390	585+	-	14	194+	-
16	386	902+	602	137	237+	233
17	230	367	318	205	328	343
18	380	528	625	233	303	349
19	196	571	389	208	375	379

+ - see Table 4.

Table 6

Comparison of Hourly Average
Infiltration Rate: Combined Test Apartment

Infiltration Rate (m^3/h)

Hour	CCTG	MTMS	PFT
13	89	92	-
14	81	100+	-
15	86	121+	-
16	92	141+	148
17	225	227	297
18	192	273	323
19	175	278	271

+ - see Table 4.

Table 7

Comparison of Hourly Average
Interzone Rates: Between Zones 2 & 3 and 2 & 4

	Flow Rate (m^3/h)							
	Zone 2 to 3		Zone 3 to 2		Zone 2 to 4		Zone 4 to 2	
Hour	MTMS	PFT-BAT	MTMS	PFT-BATS	MTMS	PFT-BATS	MTMS	PFT-
13	131	-	91	-	7	-	26	-
14+	94	-	22	-	0.0	-	56	-
15+	69	-	39	-	0.1	-	61	-
16+	3	3.6	29	39	7	13	33	0.3
17	30	45	88	120	28	46	0.5	0.0
18*	274	2254	349	2134	55	82	1.0	0.9
19*	930	2458	1060	2088	46	-10	0.5	-0.1

* - Door between Zones 2 and 3 open during part of these periods.
\+ - see Table 4.

Table 8

Comparison of 6-day, 4 Zone
Measurements: CCTG and PFT

	PFT			CCTG		
ZONE	AVG INF(m^3/h)	STD Error(m^3/h)	%	AVG INF(M^3/h)	NORM STD DEV	% DIF
1) APT 1B	236	29	(12)	193	0.30	20
2) BED/BATH	9.5	2.8	(30)	12.4	0.50	-26
3) KITCHEN	135	15	(11)	112	0.23	19
4) STORAGE	262	29	(11)	201	0.28	26

CONCLUSIONS

Aside from the fact that cross comparisons of airflow measurement systems in a field test situation does not provide an absolute standard for comparison, the advantages are that "real effects" are constantly taking place which force each measurement system to make constant, and hopefully consistent adjustments. The test period points out just how much the opening of a window or door can influence air infiltration and the air movement between zones of the building. All three systems were shown to respond quickly to such changes.

Varying complexities of the tracer gas systems allow similar measurements to be made with various compromises. The perfluorocarbon tracer, PFT, systems allow elimination of plastic tubing to each measurement zone since PFT sources and samplers can be readily placed in each space. However, if such BATS or CATS sampling is employed the airflow measurements must await subsequent laboratory analysis. If immediate readings are desired, a real-time PFT analyzer can be utilized, but then a single plastic tube to each zone is necessary for sampling. The variety of individual PFT tracer gases allow interzone measurements to be made at the same time air infiltration is being determined.

Where one desires primarily air infiltration data in many rooms or zones of the building, the constant concentration tracer gas, CCTG, system offers a means of analyzing 10 (or even more) zones. Sampling and injection tubes are required for each zone. Air infiltration readings are immediately available and are updated with each survey. To perform CCTG interzone measurements the system operation becomes more complex, since it is based on depriving zones of tracer gas and observing tracer gas concentration variations in that zone and surrounding zones(9).

The multiple tracer mass spectrometer, MTMS, system provides immediate measurements of air infiltration and interzone flow, in up to five zones. Again, two tubes to each zone are required, and because of detection requirements, higher tracer gas concentrations are necessary. Although it is the most complex of the three systems tested, the measurement unit can still be readily transported to the test site.

The importance of the data analysis technique that is chosen was demonstrated with the PFT analysis of zones 2 and 3, when the door was opened between the zones. The very evident data scatter was not a reflection of the measurement technique but rather pointed out that the proper interpretation of data for that case required a single zone analysis once the zones were actively communicating with each other. The characteristic pattern of the data is indicative of when the separate zone assumption should be altered.

Looking at the five hour test data it is clear that the CCTG air exchange measurements were never higher than the PFT-BATS or MTMS. This observation does not prove these measurements were incorrect, however, subsequent testing of the CCTG and MTMS systems in a Princeton radon test house pointed to tracer contamination from MTMS as the source for reduced readings on the CCTG. Although the tracer gases are different, at 1000 times the consentration levels of the SF_6, the freons were found to alter the SF_6 peak readings.

PFT results would appear to be compromised by high interzonal flows especially when it is rapidly changing. The response time using the PFT-BATS approach, however, was very rapid due to the 15-minute sampling, where the MTMS analysis used a half-hour time constant and a weighted measurement algorithm (using a degree of influence of past measurements).

The entire range of instrumentation choices, subjected to a series of tests from rapidly changing air infiltration conditions during the "test period," interzone testing, and multiday average airflow measurements should be viewed as an introduction to the research and building monitoring communities of just what air exchange measurement tools are currently available. These measurement techniques were shown to be capable of meeting challenges in both interzone and multizone situations with rapidly changing airflows.

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Figure 1. The array of airflow measurement systems in the living room of the basement test apartment. From left to right are the Multi-tracer Mass Spectrometer, MTMS; the Constant Concentration Tracer Gas, CCTG; and the "real time" version of the Perfluorocarbon Tracer, PFT. Two other versions of the PFT Systems are not shown.

Figure 2. Three airflow measurement systems evaluating the air infiltration into zone 3, kitchen and living room. Airflow changes have been introduced at several time intervals.

Figure 3. Three airflow measurement systems evaluating the air infiltration into the test apartment which comprised zones 2 and 3.

Figure 4. Three airflow measurement systems evaluating air infiltration in zone 2. Evidence of incorrect zone assumptions is shown in the PFT readings.

Figure 5. Three airflow measurement systems evaluating air infiltration in the occupied apartment (zone 1). CCTG airflow readings are the lowest of the three.

Figure 6. Three airflow measurement systems evaluating zone 4, the storage room. Again, CCTG readings are noticeably less than MTMS and PFT-BATS.

Figure 7. Interzone flows between zones 2 and 3 (bedroom/bath and living room/kitchen) evaluated by MTMS and PFT-BATS.

FIGURE 1

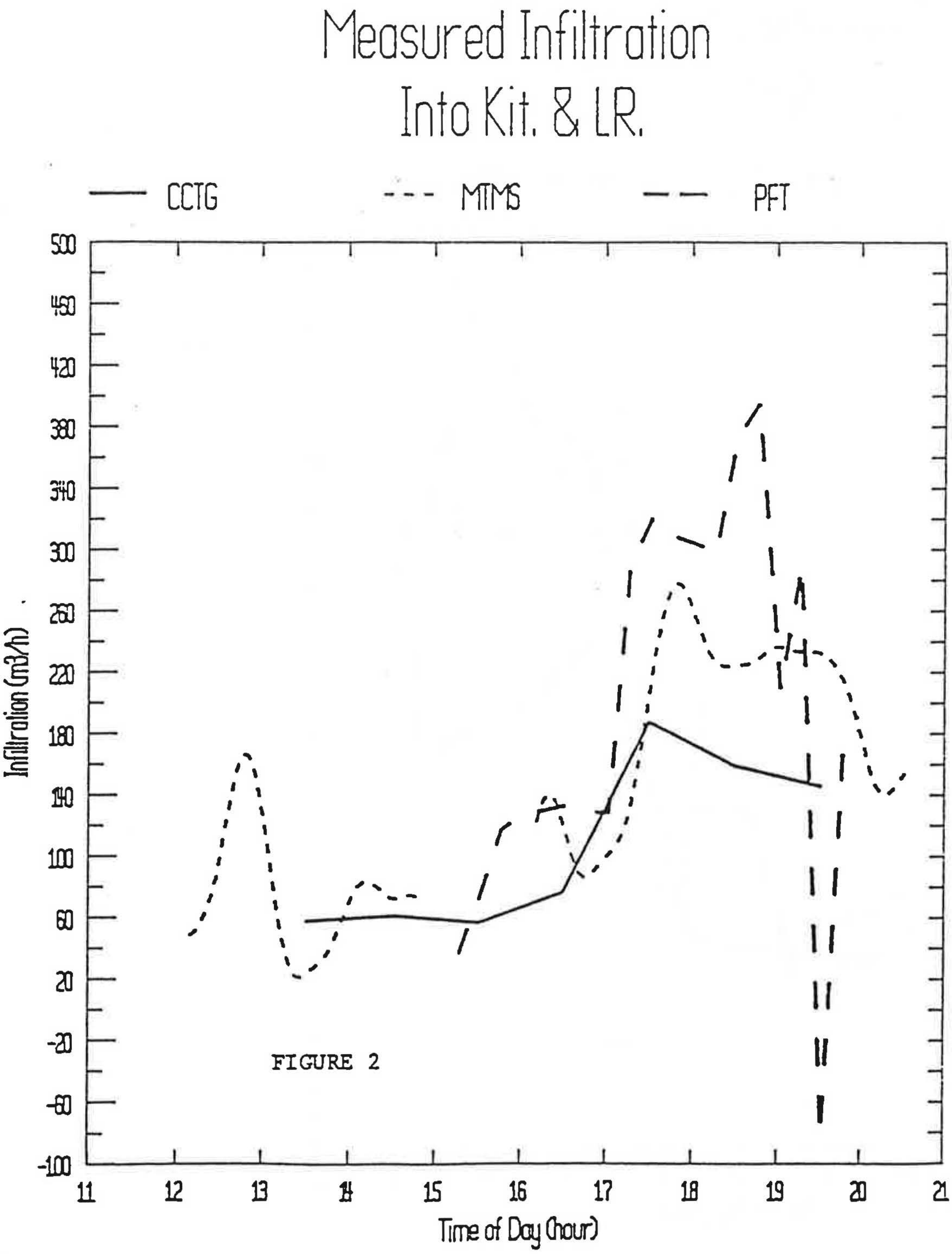
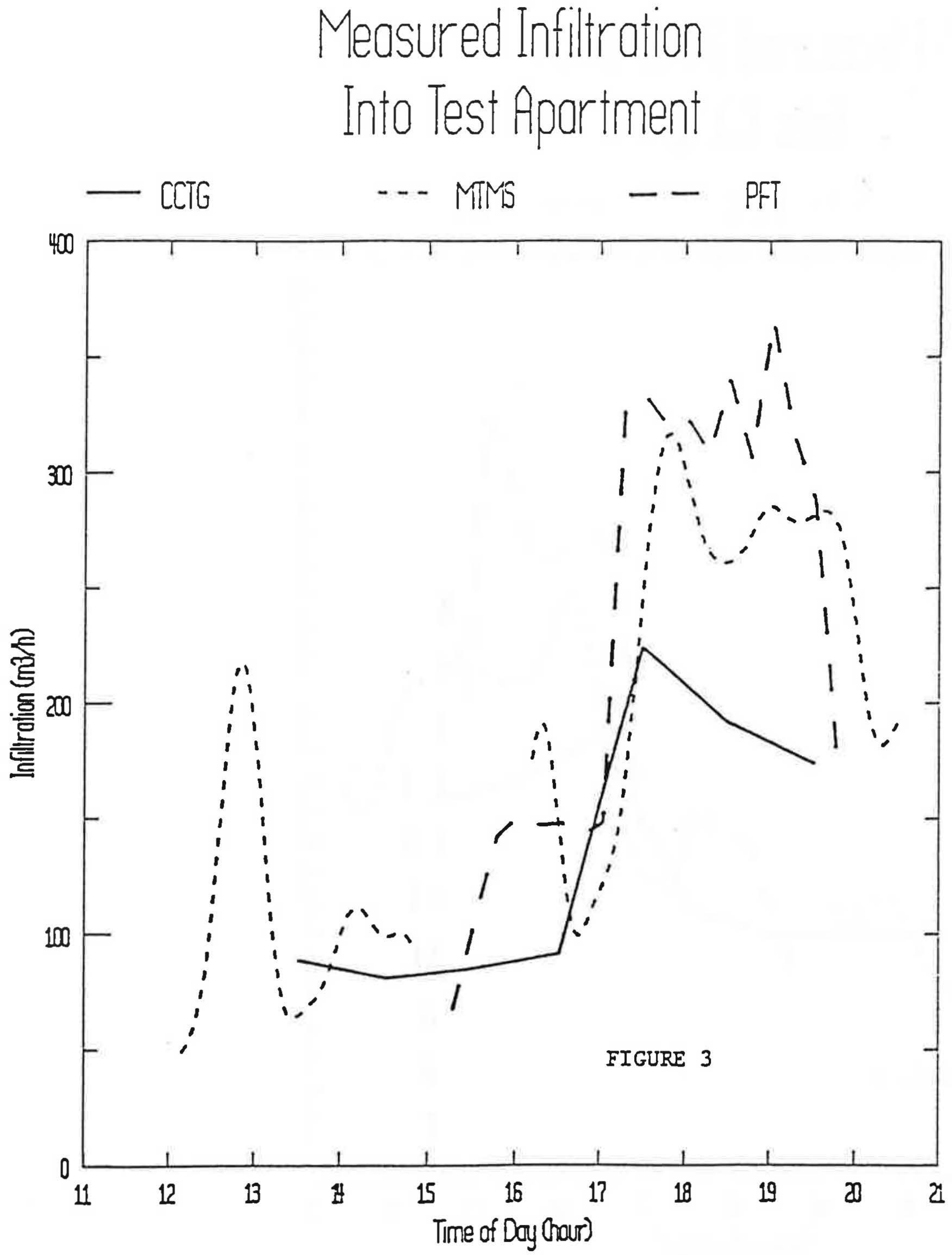

Measured Infiltration
Into Kit. & LR.
CCTG
MTMS
PFT
Infiltration (m3/h)
Time of Day (hour)
500
460
420
380
340
300
260
220
180
140
100
60
20
-20
-60
-100
11
12
13
14
15
16
17
18
19
20
21

FIGURE 2



Measured Infiltration
Into Test Apartment
CCTG
MTMS
PFT
400
300
200
100
0
Infiltration (m3/h)
11
12
13
14
15
16
17
18
19
20
21
Time of Day (hour)
FIGURE 3

Measured Infiltration Into Bed & Bath

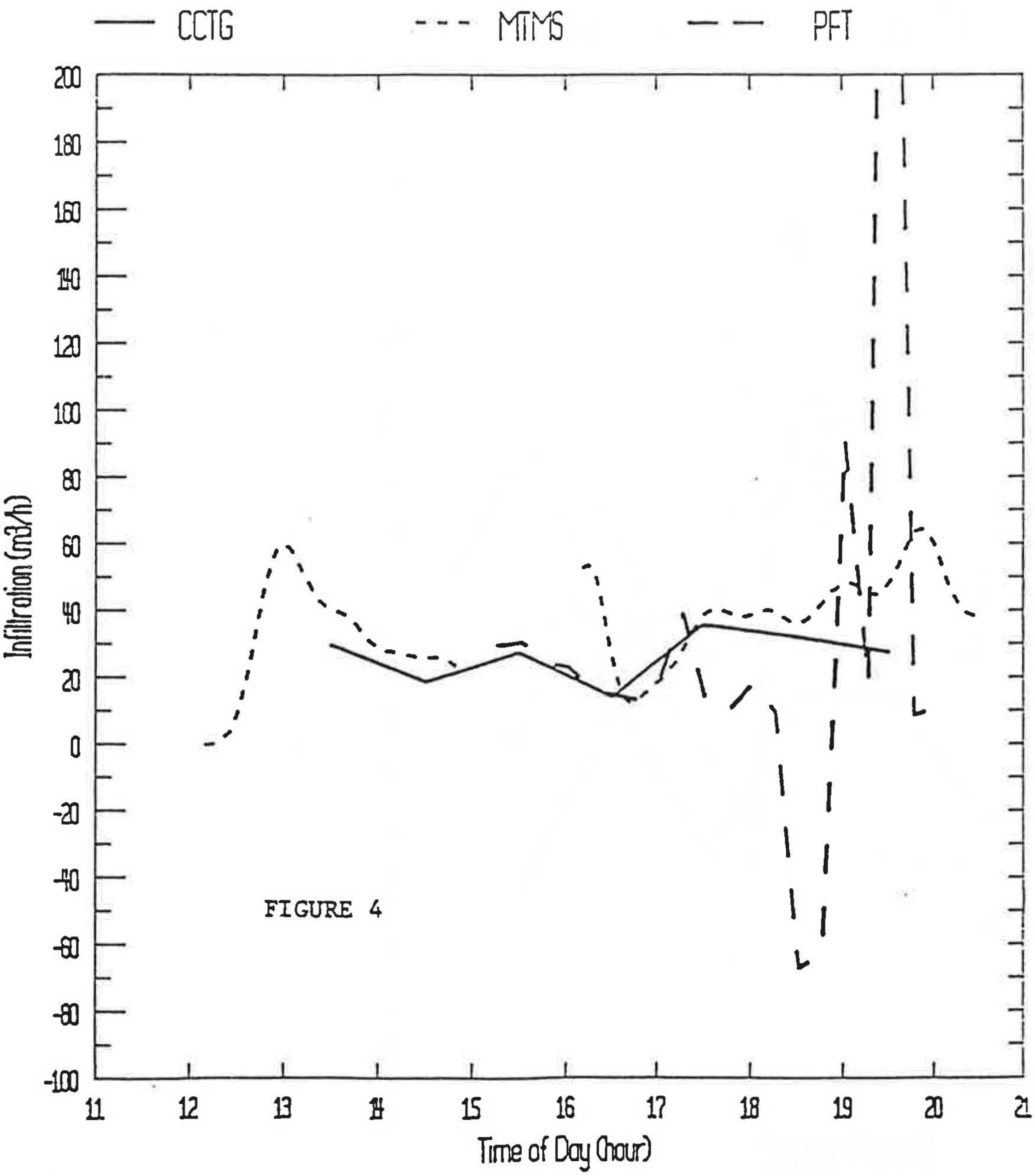


FIGURE 4

Measured Infiltration Into Apartment 1B

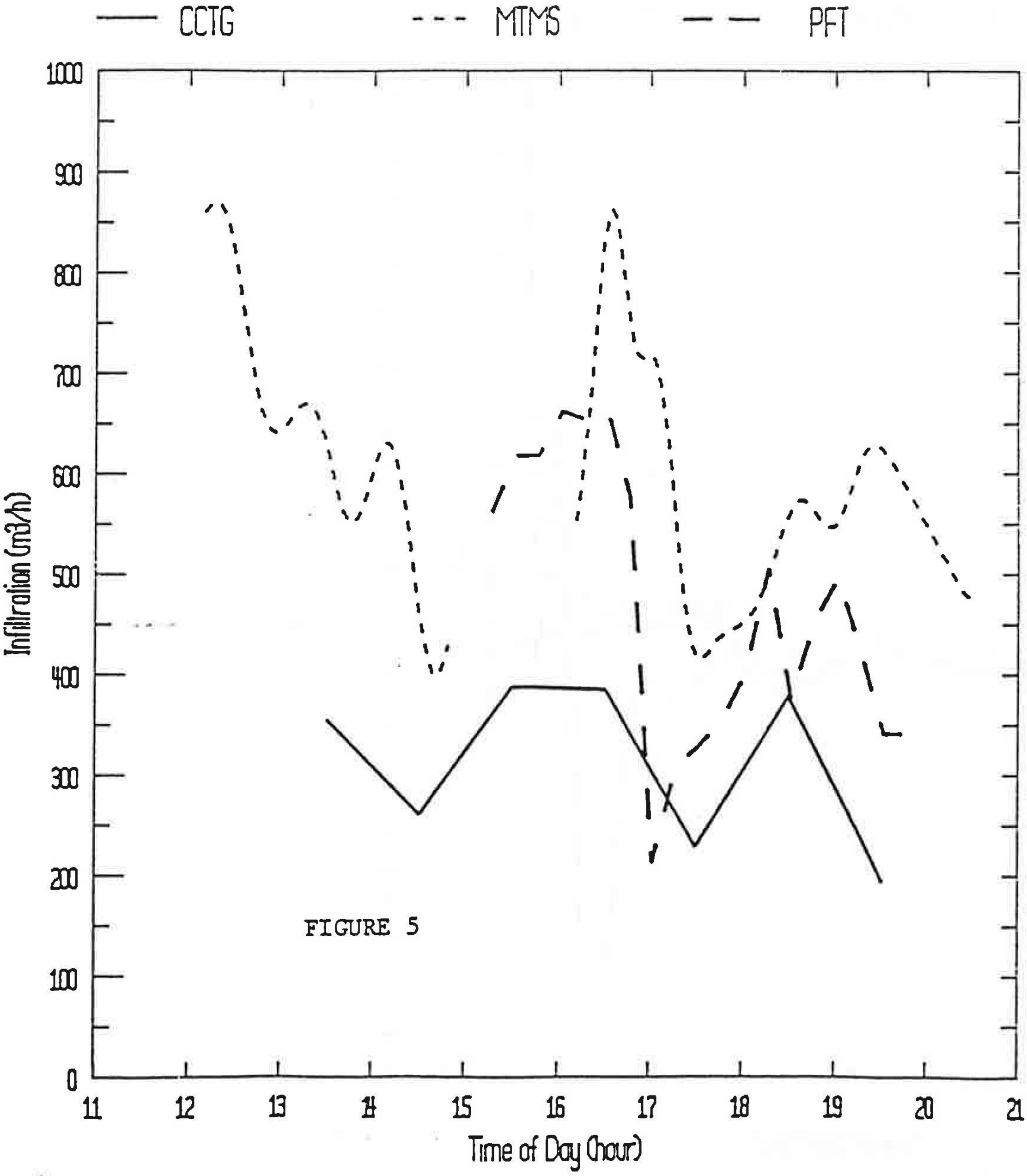
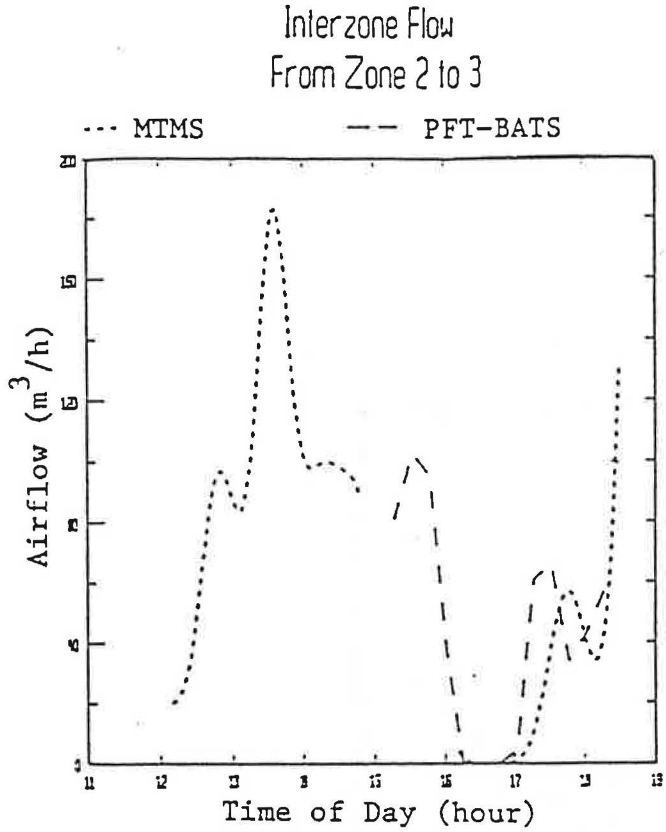
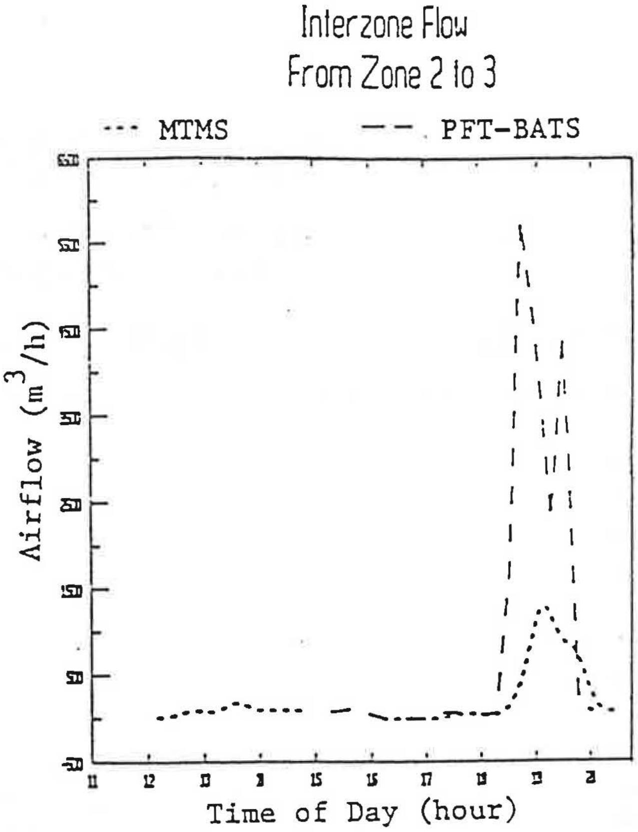


FIGURE 5

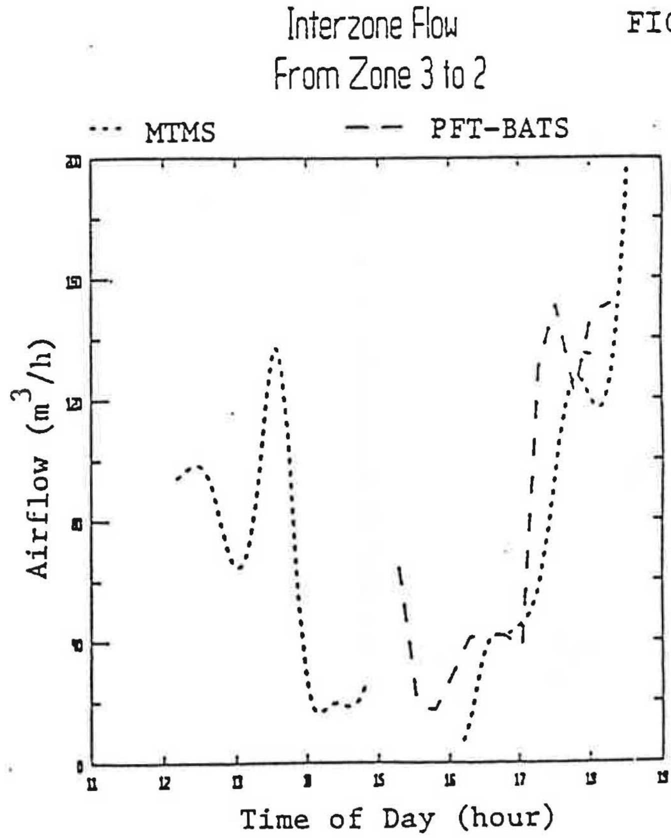


Interzone Flow
From Zone 2 to 3
MTMS
PFT-BATS
Airflow (m3/h)
Time of Day (hour)

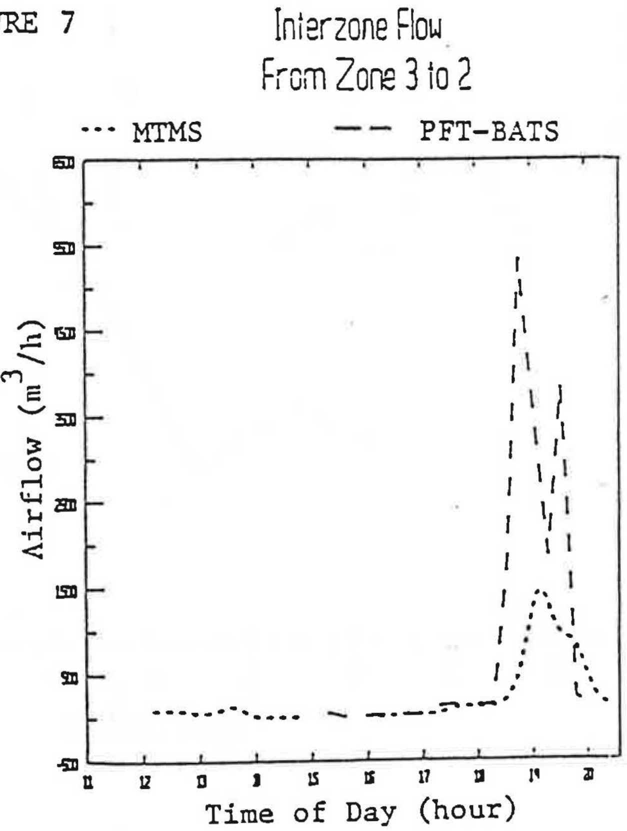


Interzone Flow
From Zone 2 to 3
MTMS
PFT-BATS
Airflow (m3/h)
Time of Day (hour)

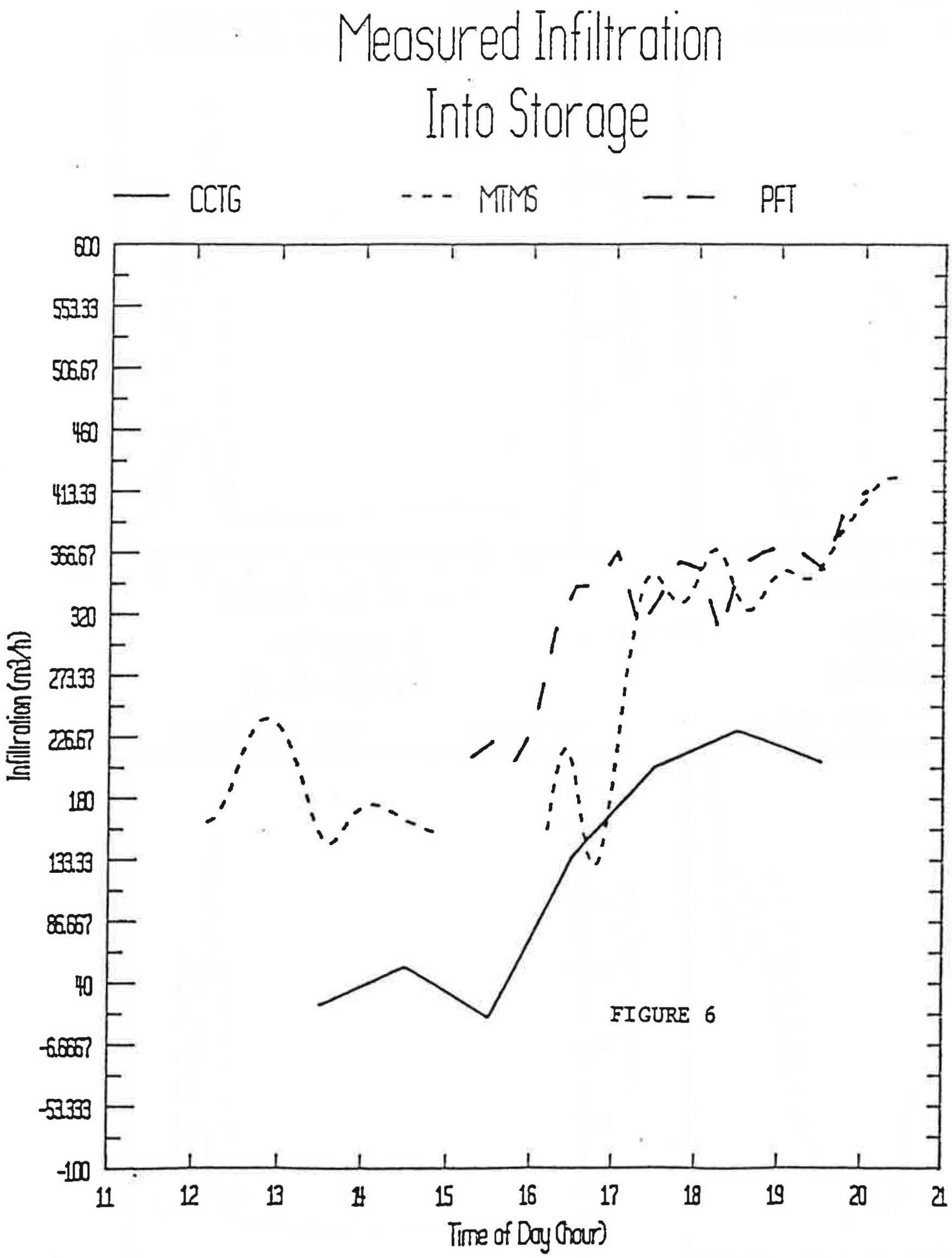
FIGURE 7



Interzone Flow
From Zone 3 to 2
MTMS
PFT-BATS
Airflow (m3/h)
Time of Day (hour)



Interzone Flow
From Zone 3 to 2
MTMS
PFT-BATS
Airflow (m3/h)
Time of Day (hour)



Measured Infiltration
Into Storage
CCTG
MTMS
PFT
600
553.33
506.67
460
413.33
366.67
320
273.33
226.67
180
133.33
86.667
40
-6.6667
-53.333
-100
Infiltration (m3/h)
11
12
13
14
15
16
17
18
19
20
21
Time of Day (hour)

FIGURE 6