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ACT[2] Project Report: Ventilation and Air Tightness Measurement of the Sunset Building

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ACT² *Project Report:* Ventilation and Air Tightness Measurements of the Sunset Building

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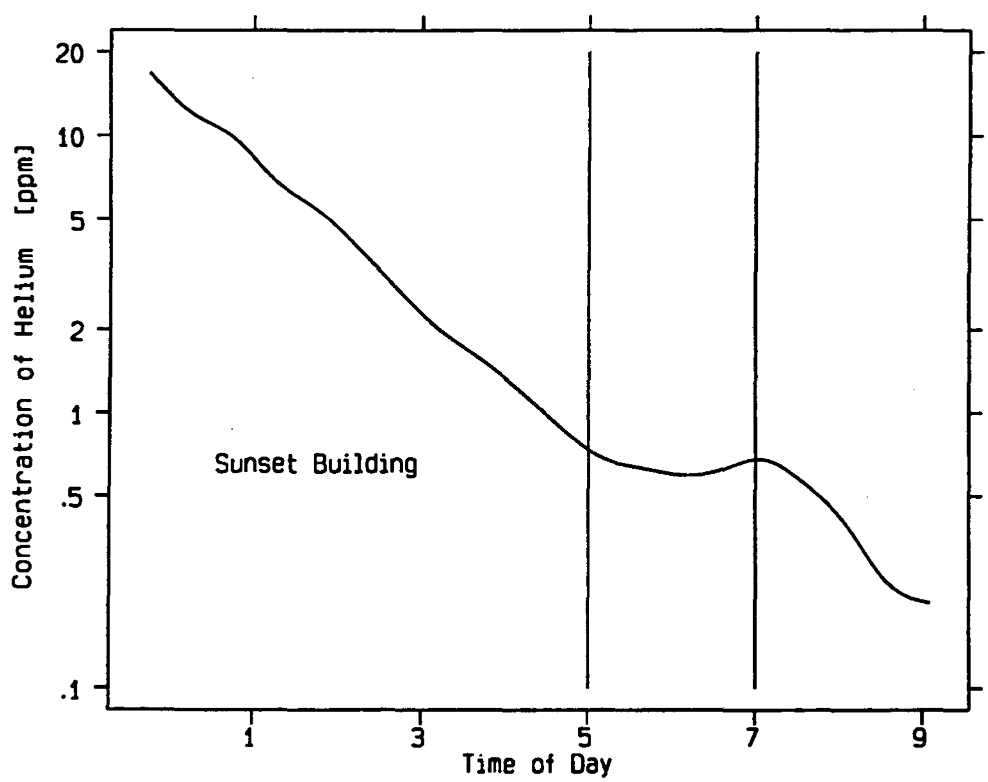

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Executive Summary

This report presents the results of ventilation and air tightness measurements made on the test section of the Sunset Building as part of the ACT^2 project. Real-time measurements were made over a two-week period in July 1991 to determine the building's performance; most of the results derive from intensive measurements made during (unoccupied) weekend periods.

The ventilation rate of the entire building was measured to be about 2 air changes per hour of outdoor air which exceeds ASHRAE Standard 62-1989 design requirements by over a factor of two. Ventilation in all specific locations was found to be adequate, except for conference rooms—some of which were significantly under ventilated. Opportunities exist for energy savings with better control of the ventilation.

Ventilation efficiency was measured for the test section and selected sub-sections as well. In all cases the ventilation efficiency was found to be good. The only improvements possible would require renovating the HVAC system to use displacement ventilation.

The leakage area of the exposed building envelope was measured at 0.5 m^2 plus 0.1m^2 of leakage area estimated (roughly) to other parts of the building. With no mechanical systems operating in the test section, this leakage induced an air infiltration of 0.6 air changes per hour. This air change rate alone would satisfy ASHRAE Standard 62 for the normal occupancy of the building. Opportunities may, therefore, exist for improving the energy efficiency by improving the envelope (and interzonal) tightness in concert with a balanced ventilation system.

In order to account for interzonal and intrazonal interactions, auxiliary information was collected and used to adjust the data. The implications of this data may be important for future interpretation of the building's performance. For example, it was found that the building acts as two well mixed zones with the north and south sides interacting marginally.

More significantly from the perspective of understanding the energy use in the building, it was determined that the test section is highly coupled to other zones of the building through both leakage paths and air handlers. It was also found that the performance of the test section is highly dependent on mechanical systems associated with other zones (See the natural ventilation test for an example of this.) In a typical configuration approximately 25% of air flow comes from this coupling. As the entire building currently runs at a significant overpressure (i.e., about 25 Pa) changes to either the test section's air handlers or leakage paths could have large impacts on the air and energy balance of the test section.

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1.0 Measurement Objectives

The objective of this study is to characterize the envelope and ventilation performance of the test section of the Sunset Building of PG&E's ACT^2 project.

Air leakage measurements, using the air handling systems, are used to quantify the tightness of the exposed envelope of the test section.

Air flow measurements, using tracer gas techniques, are used to quantify the ventilation rates and efficiencies of the test section.

Secondary objectives include characterizing the air flow patterns both within the test space and to adjacent spaces as well as related diagnostics that could affect the energy balance of the building.

1.1 Definition of Ventilation-related Terms

- *Air Change Rate*: The rate (in units of number of zone volumes per hour) at which air is exhausted from the zone to other spaces.
- *Air Flow*: A general term for the flow of air (in m^3/hr). Applied in this report to flow in ducts.
- *Air Flow Patterns*: A qualitative term to describe the distribution of air.
- *Air Leakage*: The flow of air through the building envelope in response to a fixed pressure. (See ASTM E779)
- *Air Tightness*: A qualitative term to describe the resistance of a building envelope to air flow.
- *Effective Leakage Area* (ELA): The equivalent area (m^2) of unit discharge coefficient that would have the same air leakage as the envelope. (See ASTM E779).
- *Infiltration*: The flow of air through the building envelope caused by the action of wind and stack effects.
- *Mean Age of Air*: The time since the average packet of air entered the room. (See Ref 4.)
- *Tracer Gas Test*: A procedure based on ASTM E741 for measuring air flows by tracing the flow using a gas that does not affect those flows.
- *Turn-over Time*: For the purposes of this report, a time approximately equal to the inverse of the *air change rate*. (See Ref. 4 for a more detailed explanation.)
- *Ventilation*: The process of supplying air to a zone, may include mechanical ventilation or natural ventilation (infiltration), may also refer either to total air or to outside air.
- *Ventilation Efficiency*: The ability of the current system to deliver ventilation air relative to a perfectly mixed situation. (See Ref 4.)

2.0 Description of Test Space

We describe here only those features of the test space relevant to our measurements. Figures 2.1 to 2.3 show plan views of the test space and the parts of the rest of the building which interact with the test space. These figures also show the location of the measurement points for the current report, which are listed in Tables 2.1 to 2.4.

There are three air handlers with cooling coils (ACs) serving the test space, one for the north side (AC#4), and two for the south side (AC#1 and AC#5), see Figure 2.3. These units are located on the roof of the building and connect to the first floor by way of a single supply and return duct for each system. There is no physical separation between the areas served by AC#1 and AC#5 (Figure 2.1). These units are equipped with dampers which can control the amount of outside and recirculated air which is supplied to the test space. All three ACs were leaky, with significant amounts of conditioned air leaking to the outside via poorly fitting cover panels. Some of this leakage was due to cabling for monitoring equipment, installed by others, which did not allow complete closure of access panels.

The east entry is designed to be served by the north side air handler (AC#4), while the hallway between the north and south sides is not designed to be served by any space conditioning system. This hallway serves as a fire break and has limited connections between the north and south sides of the test space in the ceiling plenum area. These connections are equipped with fire dampers which, in case of fire, will shut off air flow between the two sides. Return air flows into the area above the dropped ceiling, referred to as the ceiling return plenum, via registers in the dropped ceiling. A single large duct connects the dropped ceiling area with the air handler on the roof. All private offices and conference rooms have at least one supply and return register. The supply ducts of the south side systems are equipped with variable air volume (VAV) dampers which can limit the amount of air flowing in the ducts downstream of the dampers. These are controlled with thermostats but it is not clear which thermostat operates which VAV. It is possible that several thermostats operate together to control one VAV or that one thermostat controls more than one VAV. Also, many of the supply registers are equipped with Thermafuser dampers which can limit the flow through them. They have temperature set points on the units themselves.

Heat is provided to the test space by three separate perimeter gas-fired heating systems. These are 100% recirculating systems, that is they are not designed to bring in outside air. The heating systems, located on the roof, were inspected externally and were found to be very tight.

The total floor area of the test space is 1940 m^2. This zone can be divided into a north side, 740 m^2 and south side, 1200 m^2. The total ceiling height (not the dropped ceiling) is 3.05 meters. This gives a total volume of 5920 m^3 with 2260 m^3 for the north and 3660 m^3 for the south. The actual volumes are less than these values because of interior walls and furniture. For calculations of ventilation rates a volume of 90% of the above volumes are used.

The majority of the measurements described below were made assuming the test space is isolated from the rest of the building. Based on the plans of the building and advice from PG&E staff all known connections between the test space and other parts of the building were sealed. It was anticipated, however, that some connections would be overlooked and their presence could be detected from the field measurements. To the extent possible the results are corrected to characterize the test section as if it were isolated. The ramifications of the coupling to other zones are discussed in later sections.

3.0 Measurements

All of the measurements presented were made from July 12 to July 22, 1991. Five kinds of measurements were made in the course of the experiment: weather, interior temperatures, pressures, register flows, and various tracer gas concentrations and injection rates. Location of the measurement points can be found in Figures 2.1 to 2.3.

- *Weather* measurements were made using a Meteorology Research Institute weather station. Wind speed and direction were measured at a height of about 3 meters above the roof of the south section of the building. Outside temperature was measured using an aspirated thermocouple at ground level on the south side of the test space.
- *Temperatures* inside the building were measured using thermocouples. Twelve locations were monitored including AC return and supply temperatures. The temperatures are known to about 1 degree accuracy.
- *Pressure* differences were measured using Validyne DP103 pressure transducers. Fifteen different locations were monitored including an inside reference, located in the "Smokers" Lunch Room, and an outside reference that is the average of the three outside wall surfaces. The pressure transducers where 70Pa full-scale with an uncertainty of about 1% of reading or 0.2 Pa whichever is greater. The zero offset of the pressure sensors were measured about every ten minutes. All transducers had been calibrated against a water column.
- *Register flows* were measured using an Alnor flow hood to estimate the flow through specific supply and return registers in private offices and conference rooms. These were accurate to about 5% in the flow ranges measured.
- *Tracer* gas concentrations were measured for up to four different gasses using the MultiTracer Multigas System, MTMS.[1] As many as 10 zones were measured during one experment. A total of 21 different locations were used. Tracer gas injection was via a Mass Flow Controller which was calibrated to 1%. The analyzer, mass flow controller combination had been calibrated to an accuracy of about 2% for each gas. The accuracy of the measurement of any air flow, using tracer gas techniques, is usually limited by the assumption that the tracer gas is completely mixed with the air flow of interest. Another assumption, in the decay and step-up techniques, is that the flow is constant over the time period measured. It is rare that any such measurement is better than 5%. We estimate that there is a 10% uncertainty in all the the measurements made at the Sunset building.

Four different tracer gasses were used: Helium, Sulfur Hexafluoride (SF_6), Freon 12 and Freon 13B1. Helium has a background concentration of 5.24 ppm, a convenience which is used to calibrate it; the other gasses have essentially no background. The following chart indicates the typical concentration of each gas for each experiment; the experiments are described in the sectors that follow.

Experiment	*Typical Tracer Gas Concentration [ppm]* Helium	SF_6	Freon 12	Freon 13B1
Air Tightness	400	-	-	-
Natural Ventilation	15	-	-	-
Mechanical Ventilation	10	10	-	-
Vent. Eff., Pulse Injection	-	20	20	20
Vent. Eff., 2 Zone Pulse Injection	-	-	60	60
Vent. Eff., Charge-Up Test	10	10	-	-
Vent. Eff., Decay Test	10	10	-	-
Steady State, 3 Day Test	20	10	-	-
Vent. Eff., 2 Zone Normal Mode	-	-	40	40

3.1 Air-Handler Flows

A standard measurement technique in this experiment was to use a tracer gas to determine the return and outside air flows through each of the air handlers. A representation of one of the air handlers can be found in Figure 3.1. Tracer concentrations were measured at three points: at the entry to the return duct (point A), at the top of the air handler before the introduction of outside air (point B), and in the main supply duct (point C). To determine the flows a tracer gas is injected at a known rate into the air stream just downstream of point A. The flows can then be calculated as follows:

$$Q_{return} = \frac{I}{C_b - C_a} \tag{1.1}$$

$$Q_{supply} = \frac{C_b}{C_c} Q_{return} \tag{1.2}$$

$$Q_{outside} = Q_{supply} - Q_{return} \tag{1.3}$$

where:

Q is the air flow, [m^3/hr]

C is the concentration of tracer gas at point a,b,c [-]

I is the injection of tracer gas [m^3/hr]

The injection rate and tracer gas concentrations are usually known to about 2% accuracy. These errors combined with mixing uncertainties imply that the individual air flows are known to about 10%.

3.2 Air Tightness

In order to measure the air tightness of the envelope the air handlers were used to pressurize the test section to various pressures. The air flow needed to maintain a specific pressure was measured using the method above. By adjusting the outside air dampers it is possible to obtain a range of pressure and flow values. The resulting flow vs. pressure curve characterizes the envelope tightness.

The tightness of the envelope was measured on Saturday July 13. All the interior doors of the test space were open and the exterior doors closed. All the VAV thermostats were set to their minimum settings, which should cause them to fully open. The test space was isolated from the rest of the building by temporarily installing plywood panels in the hallways, two for downstairs at the wall separating the test space from the rest of the building and one at the top of the stairs leading from the east entry to the second floor. No attempt was made to further isolate the test space from the rest of the building.

The effective leakage area (ELA) is used to characterize the tightness of the envelope .[2] Usually a reference pressure of four pascals is used in the definition of ELA. If the average pressure is different than this for the leaks of interest, then a more typical reference pressure can be used. This building was typically pressurized during the day by about 25 Pa. In this report the ELA will be calculated for both reference pressures (4 and 25 Pa).

The pressure measured across the test space envelope to the outside was about 7 Pa with the three ACs off. This value could conceivably be caused by interactions with other zones, an unknown air handler or wind effects. As wind effects would only tend to *de*pressurize the test space, this finding suggests that some air handling equipment, other than the three ACs, is helping to pressurize the test space. Either some other unit is taking air from outside the test space and blowing it into the test space and/or there are large unblocked leaks between the test space and the rest of the building. Evidence will be presented that shows that one or more of the furnaces is the likely source of the air coming from an air handler and, because the furnaces are well sealed at the roof, that this air is most likely coming from the second floor area.

The total flow through the envelope is the sum of the flows from the AC units and these two possible unknown flows and can be expressed as a power law

$$Q_{AC} + Q_{furnace} + Q_{leak} = Q_{total} = K * \Delta P^n \qquad (2)$$

where:
Q_{total} is flow through the envelope
Q_{AC} is the measured flow from outside via the 3 AC units [m^3/hr]
$Q_{furnace}$ is the furnace flow [m^3/hr]
Q_{leak} is the flow through the leak (bidirectional) [m^3/hr]
ΔP is the envelope pressure difference [Pa]
and K and n are coefficients found from regression.

Because the envelope leakage, the leak to other zones and the furnace flow behave differently under pressurization, it is theoretically possible to estimate them independently by assuming that the flow exponent for the leak between the test space and the rest of the building is 0.65 Doing so yields the furnace flow to be 3000 m^3/hr, the leak to the (south)west side of the first floor to be 0.13 m^2, and the envelope ELAs are 0.43 m^2 at a reference pressure of 4 Pa and 0.51 m^2 at a reference pressure of 25 Pa‡. These flows and pressures are shown in Table 3.1. Figure 3 shows the results of the air tightness test.

‡ The 4 Pa reference pressure is typically used for residential buildings. 25 Pa is more typical of pressurized systems (such as ducts or packaged units). As our measurements are in the range of 25 Pa, this value is more precise and more representative.

While the estimate of envelope leakage (at 25 Pa) is rather robust, the individual estimates of the two other air flow paths have uncertainties about the size of their values. Their uncertainties, however, are highly correlated, and so we can say that (at 25 Pa) the two flow paths together contribute about 25% of the total flow.

Air tightness comparisons are usually made by normalizing the leakage area by the floor area. One such measure of tightness is the the Normalized Leakage Area of ASHRAE Standard 119, which for this building is 0.26. For a residential building this would be relatively tight, but little data exists for buildings of this type. The test space is only 1940 m^2 in floor area, but the surface-to-volume ratio is more typical of large commercial buildings (because the test space is only part of the entire building). Thus it is unfortunately more appropriate to compare the envelope leakage with large commercial buildings (for which there is little data) than with residential buildings (for which there is substantial data).

3.3 Ventilation

The ventilation rate, or air change rate, can be measured using a tracer gas either in a transient mode (charge-up or decay) or in steady-state mode. To the extent possible ASTM Standard E741[3] was followed in making these tests, but the complex and multizone character of the experiment required a more customized approach. The error associated with these tests is estimated at about 10% due to incomplete mixing of the tracer gas.

In a transient mode the air change rate (i.e., air changes per hour) is measured. In a steady state mode the actual flow rate of air is measured. If both of these values can be calculated, the effective volume of the space can be estimated from the ratio.

In a transient measurement the concentration data is fit to the appropriate curve and the air change rate given by the regression:

Decay

$$C(t) = C_{initial}\, e^{-At} \qquad (3.1)$$

Charge-up

$$C(t) = C_{final}\left(1 - e^{-At}\right) \qquad (3.2)$$

where:
A is the air change rate $[hr^{-1}]$
C is the concentration of the tracer gas [-]
t is elapsed time [hr]
and $C_{initial}$, C_{final} are from the regression [-].

The steady-state method assumes constant injection of tracer gas until the system is in equilibrium, in which case the air flow is given by the ratio:

Steady-State

$$Q = \frac{I}{C_{steady-state}} \qquad (4)$$

where
Q is the air flow [m^3/hr]
I is the injection rate [m^3/hr]
$C_{steady-state}$ is the steady state tracer gas concentration [-]

Natural Ventilation (Infiltration) Test

As a companion measurement to the air tightness test, a measurement was made on the night of July 12 during which all three air handlers were off and sealed. The building was configured as in the air tightness test: all internal doors were open, and the test space was isolated from the rest of the building by partitions in the hallways. No attempt was made to control the furnaces. The purpose of testing in this configuration is to examine the ventilation that would occur naturally from leakage in the envelope driven by pressures outside the test space. If the test space is truly isolated this result would be the infiltration caused by wind and stack effects; as we shall see, there is an interaction with other mechanical systems and zones.

A tracer gas decay test was made after a tracer gas (helium) had been injected into the test space and allowed to mix. The concentration was allowed to decay overnight.

Figures 3.3 and 3.4 show these data for selected locations in the north and south sections of the test space. It is apparent that something happens at around 5 and 7 AM. An examination of the pressure differences from this time shows a jump at 6 and 7 AM and possibly one at 5 AM (Figure 3.5 and 3.6). The inside - outside pressure difference from midnight to 5 AM averages about -3 Pa. This pressure difference is reasonable for the test space given the prevailing wind speed and direction and temperature differences assuming that there is no mechanical ventilation. The jumps in the pressure difference clearly indicate an influence from a mechanical system.

Temperatures measured during this test also show changes at about 5, 6 and 7 AM (Figures 3.7 and 3.8) in the return air for the south side ACs. It is likely that the night AC#1 return air temperature is approaching the outside air temperature because of leaks in AC#1 on the roof. The sudden increase in temperature of the AC#1 return air at around 5:30 AM could be caused by a change in the air flow direction in the return duct due to operation of some mechanical system (other than AC#1).

The natural infiltration rates measured from midnight to 5 AM averaged 0.49 air changed per hour (ach) for the north side of the test space and 0.58 for the south side. This ventilation rate is higher than might be expected from envelope leakage alone. From our diagnostics (See section 4 and table 4.4.) it appears that much of the rest of the building was being operated at a higher pressure than the test section during these measurements; thus it is possible that a significant fraction of this air exchange is due to air leakage from those areas.

The above two tests, air tightness and natural ventilation, were the only ones made with the interior doors open, all of the following tests were made with the doors closed.

Mechanical Ventilation (Steady-State) Test

On the night of July 13 a constant injection of two different tracer gasses was used to bring the north and south test spaces to a steady-state concentration with the internal doors in their normal (closed) positions. Figures 3.9 and 3.10 show the total ventilation and air flows from outside via the ACs serving the north and south sides of the test space. The change in air flow rate at about 5 to 7 AM is seen again and is echoed in the pressure differentials (Figures 3.11 to 3.15) as before.

The ventilation rate of the north side of the test space during the night (before 5 AM) averaged 3300 m^3/hr (1.6 ach) with 70% or 2300 m^3/hr (1.1 ach) accounted for by outside air from AC#4. The remaining flow is most likely from AC#5 which serves one room on the north side. During the day (after 7 AM) the flows are decreased somewhat to 3200 m^3/hr (1.6 ach) with two thirds or 2100 m^3/hr (1.0 ach) coming from AC#4.

Ventilation of the south side at night is 6500 m^3/hr (2.0 ach) with 92% or 6000 m^3/hr (1.8 ach) coming from the ACs serving the south side. The actual flow via the ACs to the south side may be somewhat less by the amount that is ducted into the one north side room. During the day the flows are increased to 8300 (2.5 ach) total with 90% or 7500 m^3/hr (2.3 ach) coming from the ACs serving the south side. The remaining outside air probably comes from the north side which is at a slightly higher pressure than the south.

A close look at some of the pressure differentials, Figures 3.11 to 3.15, shows the by now expected jumps at 5, 6 and 7 AM as well as one at 7 PM. Also interesting are the data from pressures in the building but not from the test space. These show that the two locations on the west end (first floor) have almost identical pressures whereas the two measurements on the second story have quite different pressures. All pressure measurement locations show jumps at hours 5, 6, 7 AM and 7 PM.

Temperatures in the north and south show little change but the temperatures in the return air do indicate the operation of the heating systems at 6 and 7 AM (Figures 3.16 to 3.18). During at least some parts of the day both heating and cooling of air are happening at the same time. The temperature in Conference Room B during the day is much higher than in other zones.

3.4 Ventilation Efficiency

Ventilation efficiency is the ratio of the turnover time to the age of air in the space of interest. The reader is referenced to the work by Sandberg[4] for more details. Simply put, the ventilation efficiency describes how good the system is at suppling air relative to a perfectly well mixed system. The target value for this kind of building is 100% efficiency. (Under this definition it is possible to get up to 200% efficiency using a displacement system.) The quantities "turn-over time" and "mean age of air" represent respectively, the time necessary to replace the air in the zone (approximately the inverse of the air change rate) and the average length of time air spends in the zone until it is removed.

Ventilation efficiency tests were made both for the north and south sides and for individual offices and conference rooms. Three types of measurements were made, all using tracer gasses to measure the ventilation. The three methods were: pulse injection, decay from steady-state and charge-up to a steady-state.

In the first test, made on Saturday July 13th, a pulse of three different tracer gasses were released, one for each AC. The resulting rise and subsequent fall in the concentration of the tracer gas for each measurement point can be seen in Figures 3.19 to 3.21. Analysis of the data for the entire pulse indicated that the accuracy of the ventilation efficiency indicators was limited by the measurement sampling rate, thus only the decay part of the data is used to calculate ventilation efficiency. Table 3.2 summarizes the results of these measurements. All the zones measured have a ventilation efficiency very close to 100%. This indicates that fresh outside air is almost completely mixed with air that is already in the test space for the case of the VAV boxes being fully opened.

The two tracer gasses used in the south side ACs were found in almost equal concentrations in all the measurement points of the south side. This indicates that there is almost no separation between AC#1 and AC#5, and that there is almost no difference between individual offices and the central open areas.

A second pulse test was done, on Sunday July 14, using just two tracer gasses, one for the north and one into both south side ACs, Figure 3.22. Just the central open areas of the north and south sides were measured. By decreasing the number of zones sampled we increased the sampling frequency of the measurements, but as before, the conditions of near-perfect mixing of the outside air with inside air allow analysis of only the decay part of the pulse. Table 3.3 summarizes these results.

The charge-up method to measure ventilation efficiency can be applied to the initial data of the steady-state test. The data is analyized in both the usual manner and also in the *net* method in which the tracer gas concentration of the supply air is subtracted from the zone of interest. The *gross* method estimates the ventilation efficiency of outdoor air, while the net method estimates the ventilation efficiency of total supply air. Figures 3.23 to 3.25 show the gross and net concentrations and Table 3.4 summarizes the ventilation efficiency results. As can be seen, the ventilation efficiency in both cases in near 100%.

The decay method was used at the end of the overnight steady-state test, Figures 3.26 to 3.27. This time Conference Room B was also measured. This zone had much lower air change rate than the other zones tested, although it still has an efficiency of about 100%. The low ventilation rate is a result of incorrect operation of the Thermafuser, which had set the air flow to its minimum value for this zone. It is possible it was set for heating mode rather than cooling. The ventilation efficiency and net ventilation efficiency for these locations are summarized in Table 3.5. Net concentrations are shown in Figure 3.28 to 3.29.

Measurements of the flows into individual rooms are summarized in Table 3.6. The minimum ventilation rates, as set by ASHRAE Standard 62-1989, for these zones are also listed in Table 3.6. These assume a an occupancy rate of $7/100\text{m}^2$ for an office and $50/100\text{m}^2$ for conference rooms. In both cases the required ventilation is 36 m^3/hr/person of outside air. The measured flow rates include about 30% outside air and 70% recirculated air.

The test space as a whole would require 5040 m^3/hr (0.95 ach) for 140 people, this is easily exceeded by the 9600 m^3/hr (1.8 ach) measured from the ACs. These measurements show that with the VAV dampers full open, the outdoor air supplied is over twice that required by the standard, for the entire building. As will be shown in table 4.3, the ventilation in the building in the as used condition (i.e., no partitions, VAV thermostats in normal position) does not vary much from our test conditions and so this result is generalizable.

Local ventilation measurements were made at selected points to see if offices and conference rooms were properly ventilated. For all of the individual offices tested there was at least an adequate supply; the conferences rooms, however, are underventilated for design occupancy. Conference Room B would be underventilated for even a single person.

4.0 Diagnostics

The experimental design for this project assumed that the test space could be treated as a single, well-mixed zone that was isolated from the rest of the building. As a check on this assumption additional sensors for temperature, pressure, and tracer gas were distributed both within the test zone and in adjacent zones. Analysis of this extra data quickly revealed that the assumptions were wrong and that the data would need to be corrected. In the sections that follow the inferences made from these diagnostics are summarized.

4.1 Intrazonal Diagnostics

Although the test space was treated as a single well mixed zone for the air tightness and natural ventilation tests, an examination of the tracer gas concentrations from the natural ventilation test shows that there was distinct difference between the north and south sides (Figures 3.3 and 3.4). The initial concentrations of the tracer gas on the south side is almost twice that of the north. Both sides decay at different rates until they reach the same concentration at about 5 AM. A volume weighted total air change rate of 0.61 ach can be given to the total test space. It is not possible, from the data of this test, to say with certainity that the north and south sections are actually at different rates. However all the other ventilation measurements made are consistent with there being a real difference.

The various pressure differences which were measured show that the single zone assumption is good for the air tightness test (which had all the interior doors open).

Results from the first pulse injection test, with the interior doors closed and one tracer gas for each AC, can be used to show the amount of interaction between the three AC systems. The results indicate that, as expected, the two south side systems are well-coupled. There is, however, good separation between the north side and the south side of the building; for practical purposes there is little mixing between these two zones.

This is confirmed in the steady-state test which treated the space as a two-zone system. The ratio of the concentration of the north side gas in the south vs the north is 0.06. The ratio of the concentration of the south side gas in the north vs the south is 0.12. This is not a complete analysis of flows between the two sides of the test space but is a good indication that at most 10% of the outside air entering one side has actually gotten there via the other side.

Pressures measurements echo the conclusions of the tracer study, showing about a 1.6 Pa difference in the pressures between the north and south zones whereas the pressures to outside were about 26 Pa (i.e., about 6%).

4.2 Interzonal Diagnostics

As a precaution against interzonal coupling, pressure and tracer gas measurements were made in areas of the building adjacent to the test space. These pressure and tracer gas measurement indicate that the test zone was not completely isolated.

Pressure measurements in all zones show a jump in the pressure at 5, 6 and 7 AM and at 7 PM (Figures 3.5 to 3.6 and 3.11 to 3.15). Clearly these jumps are caused by air handling equipment, but it is not clear why all the zones exhibit the jump. If, say, the AC serving the second floor on the north side comes on at 6 AM why does the pressure on the west end of the first floor increase as well. It may be that the two zones are well connected or it may be that the AC serving the first floor also comes on at 6 AM.

Tracer gas concentrations were measured in parts of the building adjacent to the test space at the end of the steady-state test; Table 4.1. These cannot be used to quantitative estimate the flows between zones. Rather they qualitatively indicate some relative flow rates. The low concentrations of the two tracer gasses in the first floor spaces on the west side of the test space indicate that there is little flow from the test space to these zones relative to the amount of outside air these spaces receive. Contrasting this situation is the adjoining second story spaces which have large amounts of tracer gas. Indeed it is estimated that for the air entering the north second floor zone, as much as two thirds of the air came from the north side of the test section and one third from the south side. While this seems an unlikely result it could be true for weekend days (which is when these tests were done).

The pressures also show that the second story is operating at a lower pressure than the test section. This is consistent with the flows paths indicated by the tracer gas concentrations.

The pressures from the zones adjacent to the test space during the air tightness test also changed as we changed the flow into the test space. These pressures indicate that the effective leakage areas calculated from the air tightness test are too large. It is estimated that as much as 25 % of the apparent leakage may be to the adjacent zones, assuming that their leakage is similar to the test space.

In the analysis of the air tightness test it was suggested that one or more of the furnaces was also blowing air into the test space from outside the test zone. Because of the high concentrations of tracer gas found in the second floor, and the relatively low pressures in the second floor, it appears likely that the source of that air was from the second floor. If the returns of one or more of the furnaces are connected from the test space to a second floor return then the pressure jumps and concentrations could be explained.

The pulse and steady-state tests were repeated during normal working hours to further test the isolation of the test space from the rest of the building. The building was in its normal configuration: the doors to the hallway were closed, most of the doors to offices and conference rooms were open, there are no partitions in the hallway and the VAV thermostats were set to their mid points.

The results from this pulse test are shown in Figure 4.1 and 4.2 and summarized in Table 4.2. There is no significant change in the ventilation efficiency or in the ventilation rates.

The steady-state test was made for a three day period starting on a Thursday afternoon. The results of these measurements can be seen in Figures 4.3 to 4.7. The step changes in pressure and ventilation rate at 5, 6, and 7 AM and at 7 PM are seen as before. Assuming that the anomaly around 2 PM Saturday is due to an open door, probably for cleaning, there seems to be no difference between weekday and weekend operation. The total ventilation rate for the south side increases somewhat when the hallways are not sealed during the day but the ventilation rate actually decreases some during the night, Table A.3. It is expected that the biggest changes should be to the south side because there were no temporary partitions directly to the north side of the test space.

The most significant changes in the pressures are for the zones that include one of the temporary partitions, Table 4.4. It is apparent that there is little difference between the hallways sealed and the normal operating configuration during the day. The change in ventilation rates noted above could easily be due to the flow just in the hallways. The decrease in ventilation rate during the night is consistent with the decrease in pressures seen in most zones.

It appears that the assumption of the test space being isolated from the rest of the building breaks down in two respects. The effective leakage area is smaller than what is measured directly and the air flows to the second floor come, in large part, from the test space rather than outside. The air change rate and ventilation efficiency are largely uneffected by the the incomplete separation of the test space from the rest of the building.

4.3 Flow Paths

Figure 4.8 shows the presumed air flows during the day at the end of the steady-state test with the test space isolated. Knowledge of the existing leaks, as well as the pressure and tracer gas concentration data were used to create this figure.

One of the more interesting flows is the one from the north side ceiling return into the east entry. The entry was designed to be serviced by the north side AC and furnace, thus the return register should have flow from the entry to the north side ceiling plenum, but this is not the case. Because the second floor is at a much lower pressure than the any of the test section, we infer that it draws up air from the entry, but no such flow path was obvious at our inspection of the entry.

Also shown is the assumed flow from the second floor to the first by way of the furnaces. It is not known exactly which of the second floor zones or which of the first floor zones are involved, but is shown as connecting the North sides.

5.0 Conclusion

The air tightness measurements give an effective leakage area, at 25 Pa, of 0.64 m^2, of which an estimated 20% is to other parts of the building, leaving an effective leakage area of 0.51 m^2 to outside. The specific leakage area is 2.6 cm^2/m^2, comparable to values typically seen in residential construction. However, the test space has a very low exterior surface area compared to its floor area.

The average ventilation rate of 2.1 ach is more than enough to satisfy normal fresh air requirements, although some individual zones e.g., Conference Room B, within the test space may be inadequately ventilated.

The measurement of air tightness and natural ventilation rate assume that the test space can be treated as a single well-mixed zone. While this appears a good assumption for the air tightness test, it is evident that the two zones do not naturally exchange air between them to a large extent.

All of the tests assume that the test space is isolated from the rest of the building with respect to air flows. This is not the case and is potentially a very bad assumption. The impacts of this assumption on the ventilation rates is small but the effect on the effective leakage area is large, causing an estimated 20% error in the measured values for which we corrected.

Often leaks in the supply duct systems are not important in buildings of this kind because the leaks are all inside the building. In this building, air leaking out of the supply ducts generally enters the ceiling return area, where these ducts are located. In fact the ceiling return area was found to be cooler than the occupied space even though most of the lighting was vented to this area. Air conditioning system performance could be improved if only the occupied spaces are conditioned.

5.1 Predictions of Ventilation Rates and Energy Use

Predictions of ventilation rates of the test space based on the measurements presented in this report should be made with caution. Any changes in the building configuration could make large changes in the ventilation rates, for example it was common to find exterior doors open. This will lower the inside/outside pressure difference and increase the ventilation rate.

An example calculation of air flow rates into the test space for the conditions found at the end (day) of the (hallways sealed) steady-state test follows. From the data one finds an average pressure in the test space of about 26 Pa, Figure 3.11. Using the leakage curve, Figure 3.2, one calculates a total flow into the test space of about 12200 m^3/hr. Of this some 3000 m^3/hr are from the furnace whose air is presumed to be from the second floor. It was shown that at least two thirds of the air entering the second floor actually came from the test space, so only about 1000 m^3/hr of the furnace air is air from outside. This reduces the fresh air ventilation rate to about 10200 m^3/hr. The ventilation rate measured with the tracer gasses is 11500 m^3/hr, in reasonable agreement.

If the test space is retrofited with a new "balanced" air handling system then several changes in the air flow patterns will happen. If the test space is also isolated from the rest of the building then a "balanced" system would not pressurize the test space. In this case weather induced pressure differences would act on the test space envelope and cause infiltration in addition to the ventilation supplied by the air handling system. The infiltrating air will sometimes increase and sometimes decrease the load on the air conditioning system. However, if the test space remains connected to the rest of the building then the test space will be pressurized by the adjacent zones of the building and conditioned air will flow into the test space. This would reduce the load on the air conditioning system serving the test space and increase the load on the air conditioning systems serving the rest of the building.

We anticipate that any new ventilation system, which is not based on pressurized ventilation, will significantly alter the existing air flow paths. It is likely that the ventilation from the new system will have an increased interaction with both the outside and the adjacent parts of the building, and a corresponding increase in the effect on the space conditioning loads.

5.2 Lessons for ACT^2

In conventional HVAC systems, which incorporate the thermal distribution system and the ventilation system together, it is difficult to achieve an energy-efficient optimum, especially one which includes adequate comfort and ventilation. The systems tested in the Sunset building were poorly controlled and were supplying far more air than was necessary to meet ASHRAE Standard 62.

Based on our measurements of the Sunset Building, large opportunities exist for improving the energy efficiency of the ventilation and thermal distribution system in this kind of commercial building. In such a retrofit the control of outdoor air intake should be improved with such features as enthalpy controlled economizers* (or evaporative cooling) and demand controlled ventilation (e.g., based on CO_2 sensing). For new construction or in-depth renovation the separation of the ventilation system from the thermal distribution system (e.g., by using hydronic heating and cooling) should also be considered.

Multizone systems are both hard to control and hard to measure when the zones interact appreciably as they did in the Sunset building. The measurement was made especially difficult because only a part of the building was the subject of measurement. The high level of communication between different zones of the building suggests that an understanding of the air flow patterns in other buildings will also require a multizone measurement approach.

Since the energy and air balance of the Sunset building is critically dependent on the internal pressures, it may not be possible to evaluate the planned retrofits without a similar set of measurements post-retrofit. Although envelope leakage is not currently an important part of the energy balance of the building, it may become so, if the retrofits are successful and reduce the building overpressure. Under such a situation, however, large air flows from the other areas of the building should be expected—which is likely to reduce the actual energy demand in the test section.

* The economizer controls on the units tested in the Sunset Building were non-functional and the amount of outside air was uncontrolled. Anecdotally, it appears that few such economizers are well controlled in commercial buildings, suggesting a topic for further study.

The measurements at the Sunset building suggest a few recommendations for future monitoring of ACT^2 sites. It would be substantially easier to measure whole building performance, than only a part of the building. It is, therefore, recommended that future monitoring be done only on whole buildings. To a lesser extent the presense of multiple packaged units increases the level of effort necessary to monitor the building. Since these units partially interact, it is necessary to measure all the effects simultaneously; central systems would require somewhat less effort to monitor. Finally, since pressure imbalances can be a key factor in the ventilation performance, it is important to identify all air handlers in the system, even those that are not expected to affect the ventilation.

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2. ASTM (1987) "Standard Test Method for Determining Air Leakage Rate by Fan Pressurization," *ASTM E779-87*, American Society for Testing and Materials.

3. ASTM (1990) "Standard Test Method for Determining Air Leakage Rate by Tracer Dilution," *ASTM E741-83*, American Society for Testing and Materials.

4. M. Sandberg, M. Sjoberg, The use of moments for assessing air quality in ventilated rooms, *Buildings and Environment* 18, No. 4, 181-195 (1983).

LIST OF TABLES

LIST OF FIGURES

Sensor Locations

Table 2.1: Pressures

Identification	Description of Location
P1	* South and West of the Test Section on the First Floor
P2	* North and West of the Test Section on the First Floor
P3	* Second Floor North
P4	* Second Floor South
P5	South, in center of open office space
P6	North, in center of open office space
P7	Conference Room B
P8	AC#1 Ceiling Return Area
P9	AC#5 Ceiling Return Area
P10	AC#4 Ceiling Return Area
P11	Ceiling Return Area Over Conference Room B
P12	Hallway between the North and South
P13	East Entry
P14	* Outside Reference, The Physical Average of the three Outside Walls
P15	Inside Reference, The "Smokers" Lunch Room

* These locations are outside the test space.

Table 2.2: Temperatures

Identifier	Description of Location
T1	* Outside, On the South Side
T2	South, Center of the open office space
T3	North, Center of the open office space
T4	AC#1 Return Air, in Duct
T5	AC#4 Return Air, in Duct
T6	Ceiling Return Area over Conference Room B
T7	AC#5 Return Air, in Duct
T8	AC#1 Supply Plenum Air, just after cooling coils
T9	AC#5 Supply Plenum Air, just after cooling coils
T10	AC#3 Supply Plenum Air, just after cooling coils
T11	Hallway between the North and South
T12	"Smokers" Lunch Room

Table 2.3: Tracer Gas Sample Points	
Identifier	Description of Location
S1	* Outside, On the South Side
S2	AC#1 Ceiling Return Air, at entrance to duct to roof
S3	* AC#1 Return Plenum Air, just before the fan on the roof
S4	AC#1 Supply Air, in Supply duct
S5	AC#5 Ceiling Return Air
S6	* AC#5 Return Plenum Air
S7	AC#5 Supply Air
S8	AC#4 Ceiling Return Air
S9	* AC#4 Return Plenum Air
S10	AC#4 Supply Air
S11	South, Center of open office area
S12	North, Center of open office area
S13	South Side Office
S14	North Side Office
S15	Conference Room A
S16	Conference Room B
S17	* South and West of the Test Space on the First Floor
S18	* North and West of the Test Space on the First Floor
S19	* South Side of the Second Floor
S20	* North Side of the Second Floor
S21	East Entry
* These locations are outside the Test Space.	

Table 2.4: Tracer Gas Injection Locations	
Identifier	Description of Location
I1	AC#1 Return Air, Downstream of the Return Air Sample Location
I2	AC#5 Return Air, Downstream of the Return Air Sample Location
I3	AC#4 Return Air, Downstream of the Return Air Sample Location

Table 3.1: Air Tightness Test Flows and Pressures

Pressure [Pa]	Q_{AC} [m^3/hr]	West-Inside [Pa]	Q_{Leak} [m^3/hr]	$Q_{Furnace}$ [m^3/hr]	Q_{total}
11.5	3710	2.8	1010	3000	7720
11.5	3740	2.8	1010	3000	7750
19.1	5790	0.7	500	3000	9290
19.1	5740	0.7	500	3000	9240
28.3	11700	-1.8	-820	3000	13900
28.3	9900	-1.8	-820	3000	12100
30.8	11900	-2.5	-960	3000	13900
30.8	10700	-2.5	-960	3000	12800
32.2	11300	-2.9	-1040	3000	13300
32.2	13000	-2.9	-1040	3000	14900

Table 3.2: Ventilation and Efficiency from Pulse Injection

Location	Air Change Rate [ach]	Turnover Time [hours]	Mean Age of Air [hours]	Ventilation Efficiency [%]
North Zone	1.90	0.53	0.53	99
North Office	1.64	0.57	0.57	101
Conf. Rm. A	1.99	0.52	0.52	99
AC#4 Return A	1.96	0.53	0.54	99
AC#4 Return B	1.87	0.54	0.55	99
South Zone	3.16	0.35	0.37	94
South Office	2.60	0.38	0.38	99
AC#1 Return	3.21	0.36	0.38	95
AC#5 Return	2.63	0.38	0.38	99

Table 3.3: Ventilation and Efficiency from Two Zone Pulse Test

Location	Air Change Rate [ach]	Turnover Time [hours]	Mean Age of Air [hours]	Ventilation Efficiency [%]
North	2.10	0.50	0.51	97
South	2.56	0.40	0.40	100

Table 3.4: Gross and Net Ventilation and Efficiency for Charge-Up Test				
Location	Air Change Rate [ach]	Turnover Time [hours]	Mean Age of Air [hours]	Ventilation Efficiency [%]
Gross Method				
AC#4 Return	2.03	0.51	0.51	100
AC#4 Supply	1.94	0.56	0.57	99
AC#1 Return	2.06	0.52	0.52	99
AC#1 Supply	1.77	0.63	0.64	99
AC#5 Return	1.80	0.55	0.55	100
AC#5 Supply	1.83	0.54	0.54	99
Net Method				
AC#4 Return	3.04	0.32	0.32	98
AC#1 Return	2.81	0.37	0.38	97
AC#5 Return	1.63	0.56	0.56	101

Table 3.5: Gross and Net Ventilation and Efficiency for Decay Test				
Location	Air Change Rate [ach]	Turnover Time [hours]	Mean Age of Air [hours]	Ventilation Efficiency [%]
Gross Method				
North Zone	1.91	0.57	0.59	96
North Office	1.81	0.56	0.57	99
Conf. Rm. A	2.04	0.51	0.52	100
AC#4 Supply	1.91	0.58	0.60	97
South Zone	2.57	0.40	0.43	95
South Office	1.97	0.47	0.48	100
Conf. Rm. B	0.75	1.11	1.11	101
AC#1 Supply	2.55	0.44	0.48	92
AC#5 Supply	2.31	0.52	0.59	89
Net Method				
North Zone	1.90	0.54	0.57	93
North Office	1.68	0.54	0.52	103
Conference Rm. A	2.29	0.40	0.36	112
South Zone	2.60	0.37	0.37	99
South Office	1.83	0.46	0.43	106
Conference Rm. B	0.95	0.95	0.93	101

Table 3.6: Air Flows to Individual Rooms

Location	Volume [m^3]	Return Flow [m^3/hr]	Total Supply Flow [m^3/hr]	Outdoor Air Flow [m^3/hr]	ASHRAE Req. Flow [m^3/hr]
North Office	29	130	140	42	36
Conference Rm. A	130	540	870	260	1044
South Office	34	90	110	33	36
Conference Rm. B	46	20	40	12	396
TOTAL	*5328*	*22000*	*31600*	*9600*	*5040*

Table 4.1: Tracer Gas Concentrations at end of Steady-State Test

Location	Gas 1 [ppm]	Gas 2 [ppm]
North	1.1	8.8
South	7.4	0.5
Zones out of Test Space		
North 2nd Floor	2.9	7.2
South 2nd Floor	0.9	4.5
North West End of 1st Floor	0.6	1.9
South West End of 1st Floor	0.2	0.1

Table 4.2: Ventilation and Efficiency With Hallways NOT Sealed from the Pulse Injection Test

Location	Air Change Rate [ach]	1/ach	Turnover Time [hours]	Mean Age of Air [hours]	Ventilation Efficiency [%]
North	1.89	0.53	0.53	0.53	99
South	2.65	0.38	0.39	0.40	98

Table 4.3: Change in Ventilation Rates with Hallways NOT sealed Flows in m^3/hr

	Day			Night		
	Sealed	Open	Open-Sealed	Sealed	Open	Sealed-Open
North	3210	3250	40	3320	3280	-40
South	8330	9390	1060	6530	6030	-500

Table 4.4: Pressure Changes Due to Isolating the Test Space

Pressures are referenced to the Outside [Pa]

	Day			Night		
Location	Sealed	Open	Sealed-Open	Sealed	Open	Sealed-Open
North	27.6	24.7	2.9	10.0	6.1	3.9
AC#4 Return	26.9	24.3	2.6	9.1	5.7	3.4
East Entry	24.0	22.8	1.2	7.1	1.1	6.0
South	25.0	23.1	1.9	6.5	1.3	5.2
Conference Rm. B	24.3	22.5	1.8	5.9	1.3	4.6
AC#1 Return	23.8	22.6	1.2	5.6	1.2	4.4
AC#5 Return	23.9	22.8	1.1	5.7	1.2	4.5
Conf. Rm B Plenum	24.1	23.2	0.9	6.0	1.1	4.9
Hallway	24.3	22.9	1.4	6.1	0.8	5.3
Northwest 1st Floor	26.9	23.2	3.7	-1.4	0.8	-2.2
Southwest 1st Floor	26.6	22.9	3.7	-1.6	1.1	-2.2
Second Floor North	18.6	22.5	-3.9	5.0	2.7	2.3
Second Floor South	12.7	13.0	-0.3	3.8	2.5	1.3

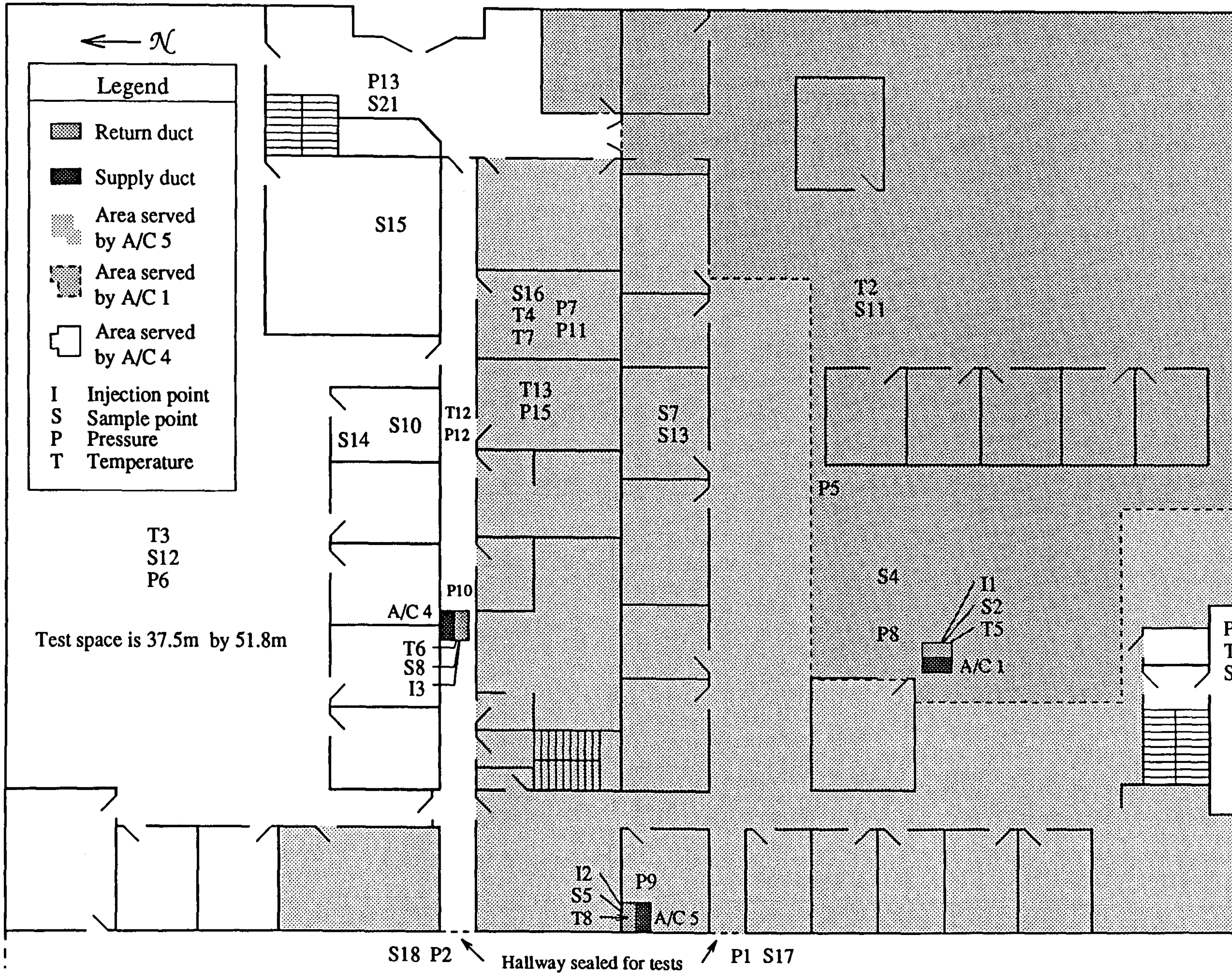

Figure 2.1 First Floor Plan View, with Sensor Locations

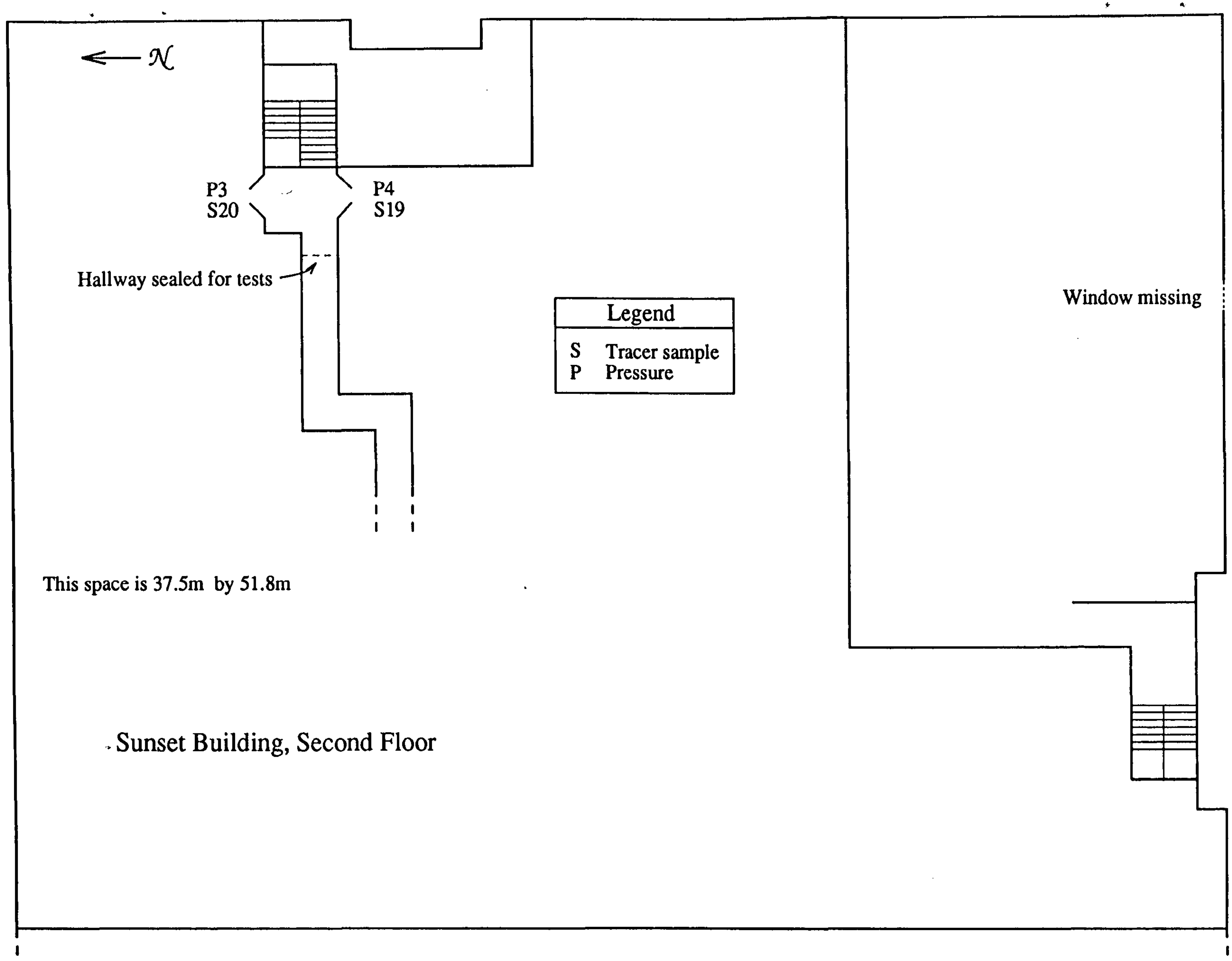

Figure 2.2 Second Floor Plan View, with Sensor Locations

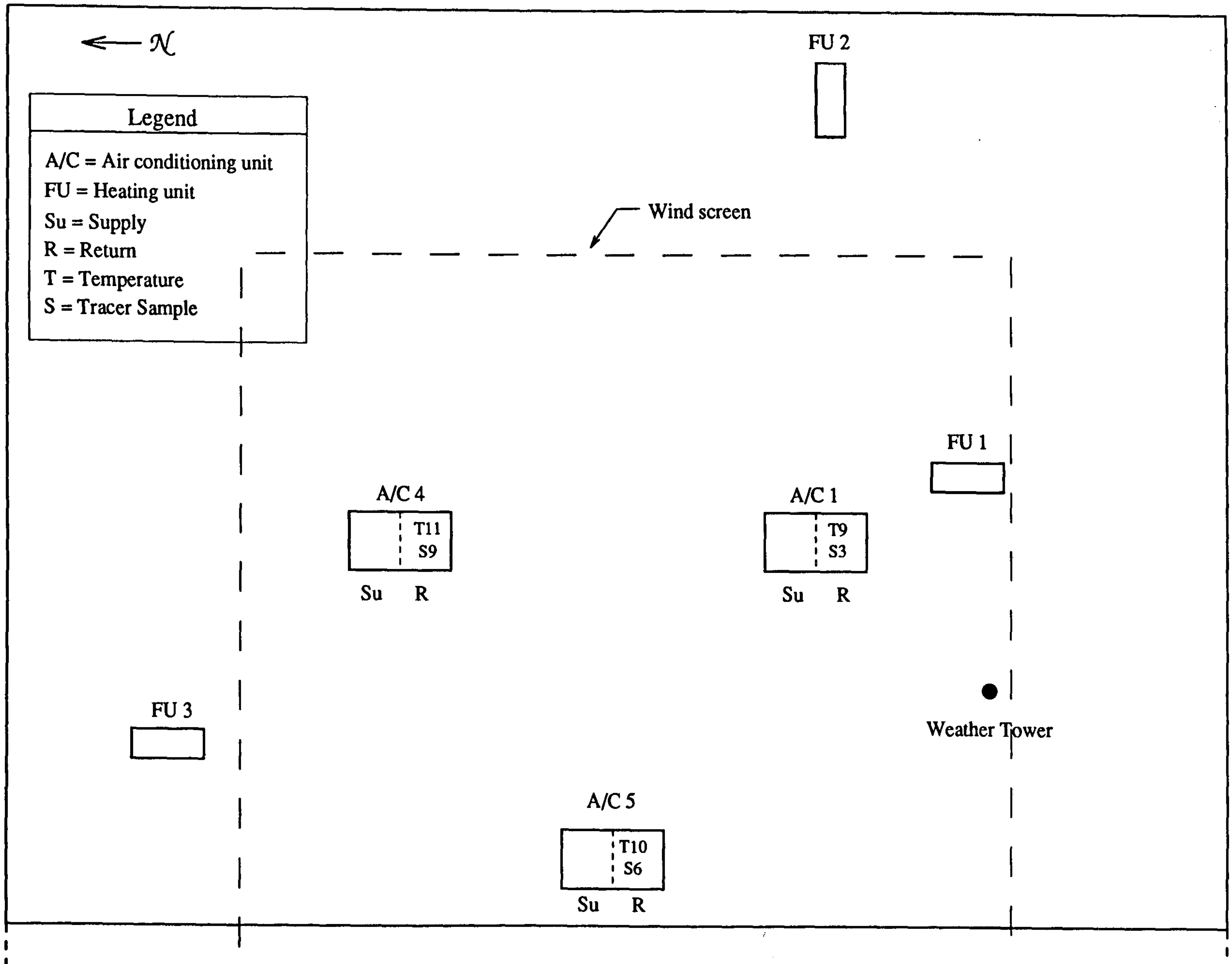

Figure 2.3 Roof Plan View, with Sensor Locations

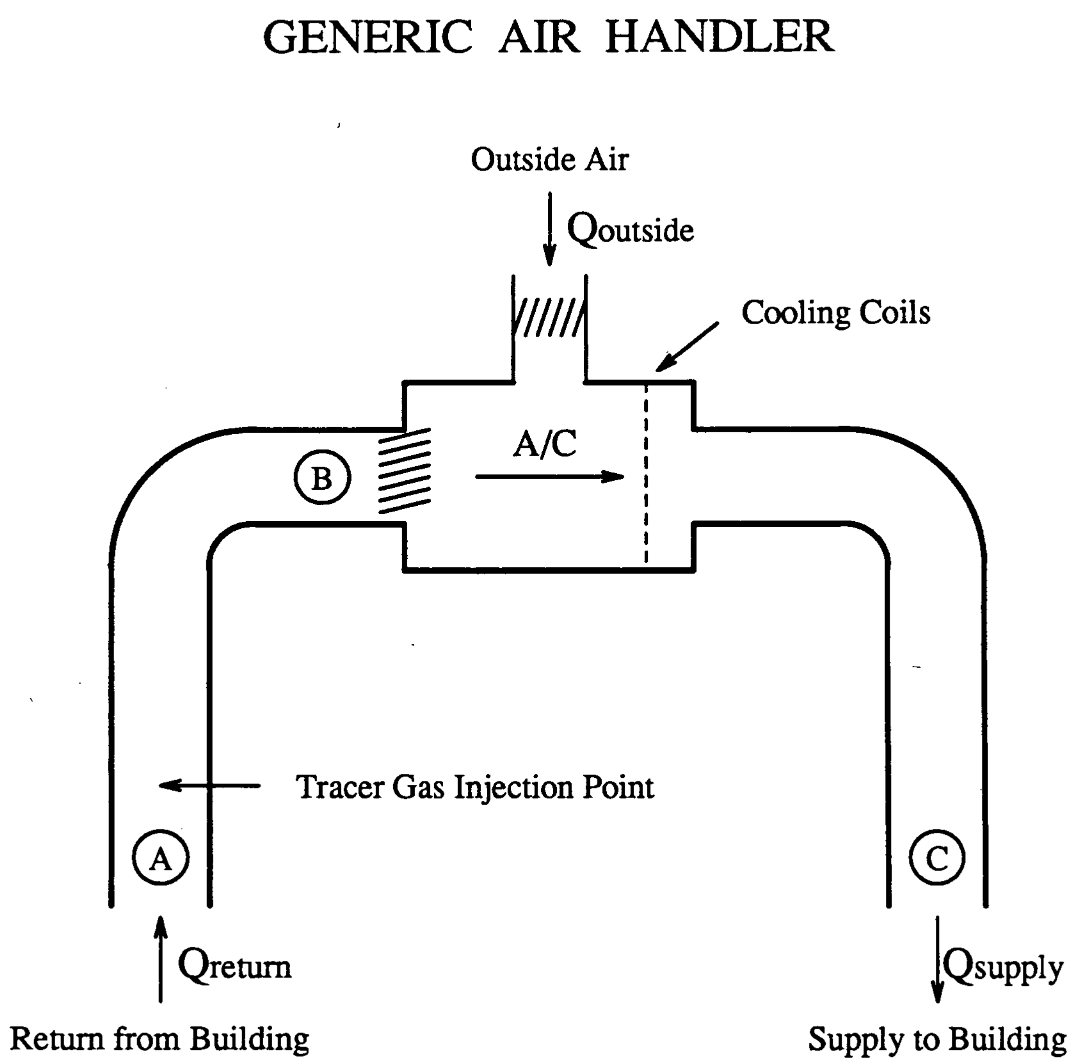

Figure 3.1 Generic Air Handler
Showing Measured Flows and Tracer Gas Sample and Injection Points

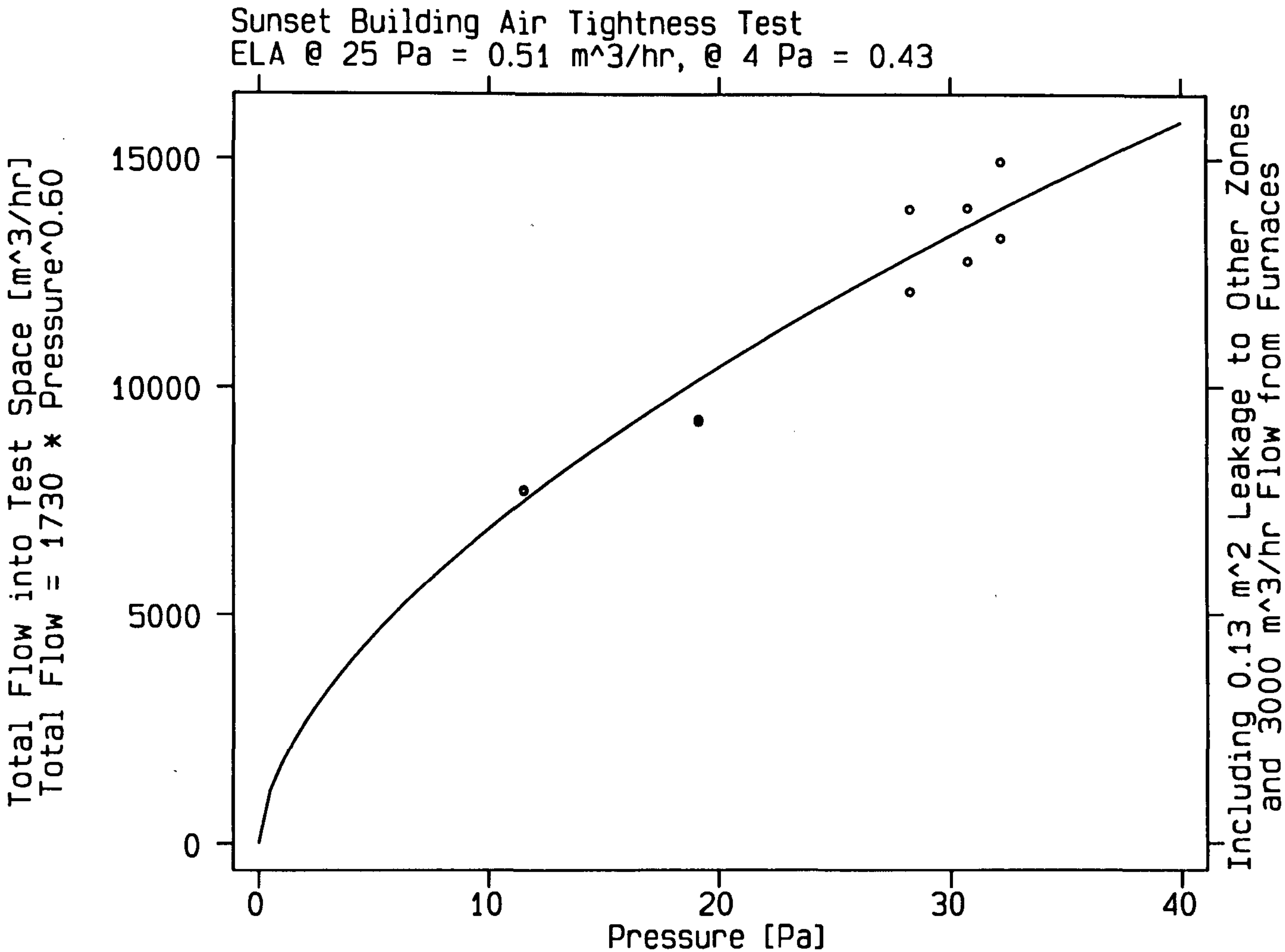

Figure 3.2 Air Tightness Test
Flow Points are Adjusted for Leakage to Adjacent Zones and Assumed Furnace Flows

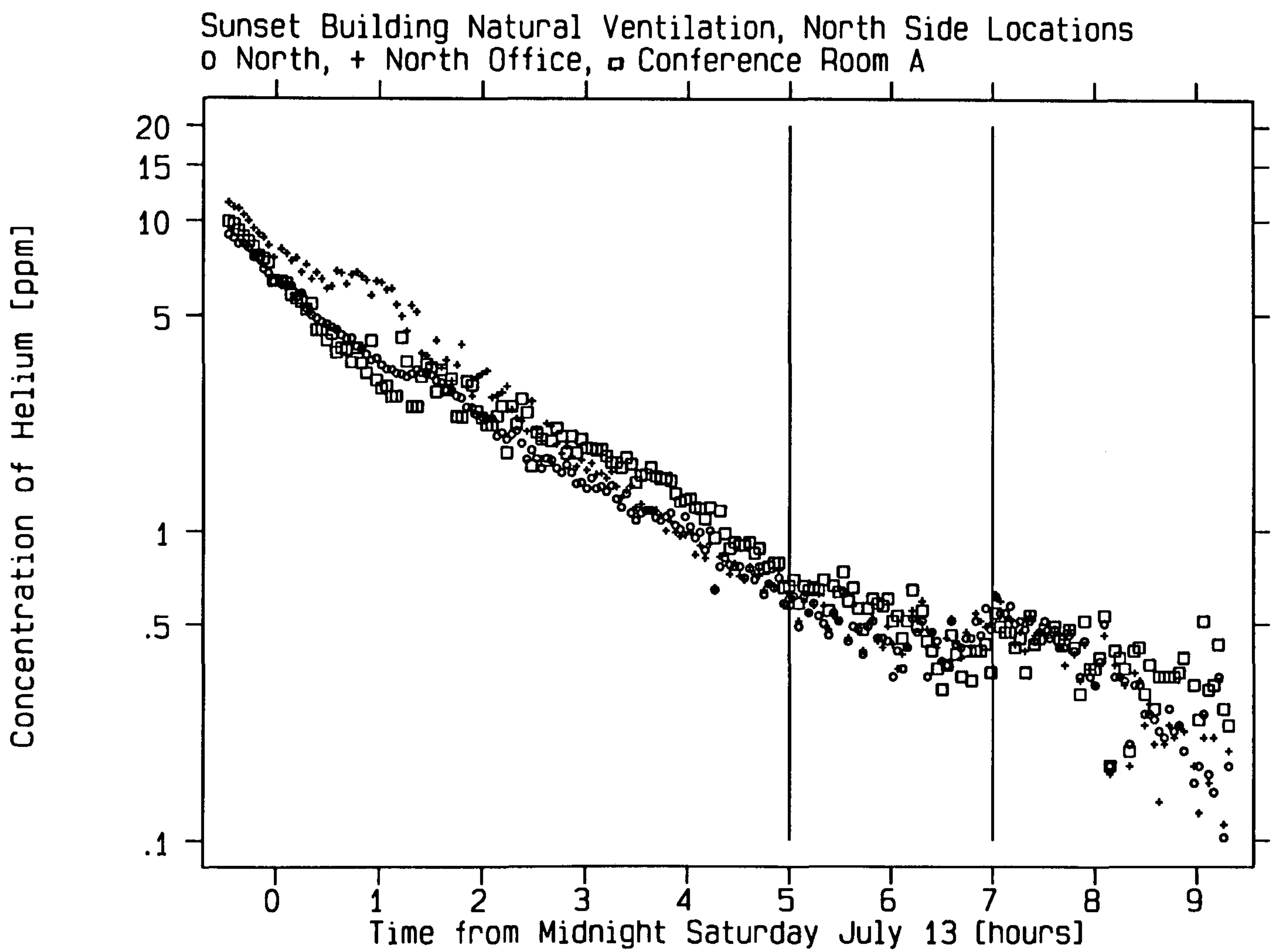

Figure 3.3 Natural Ventilation, Tracer Gas Concentrations of the North Side

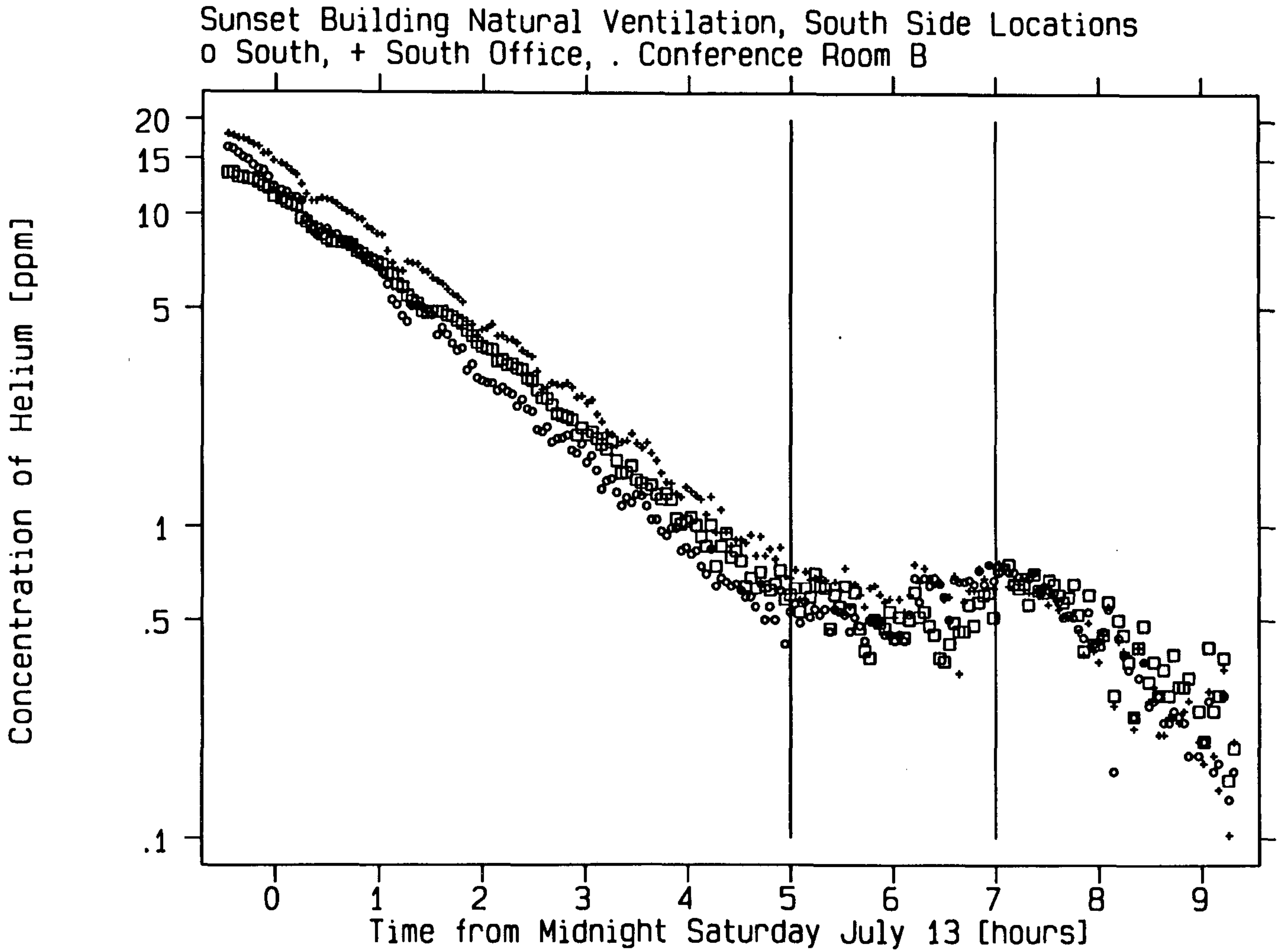

Figure 3.4 Natural Ventilation, Tracer Gas Concentrations of the South Side

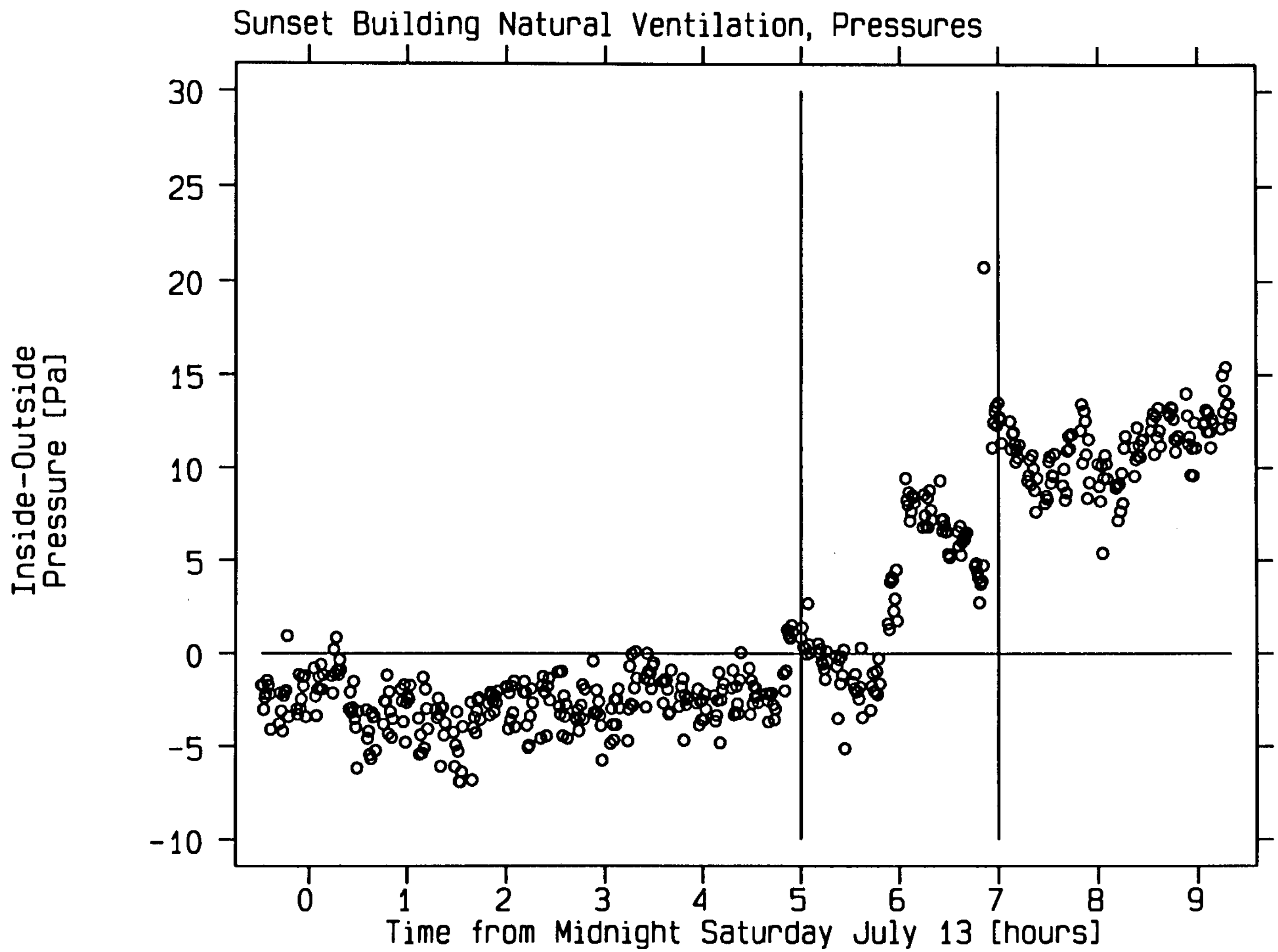

Figure 3.5 Natural Ventilation, Inside - Outside Reference Pressure

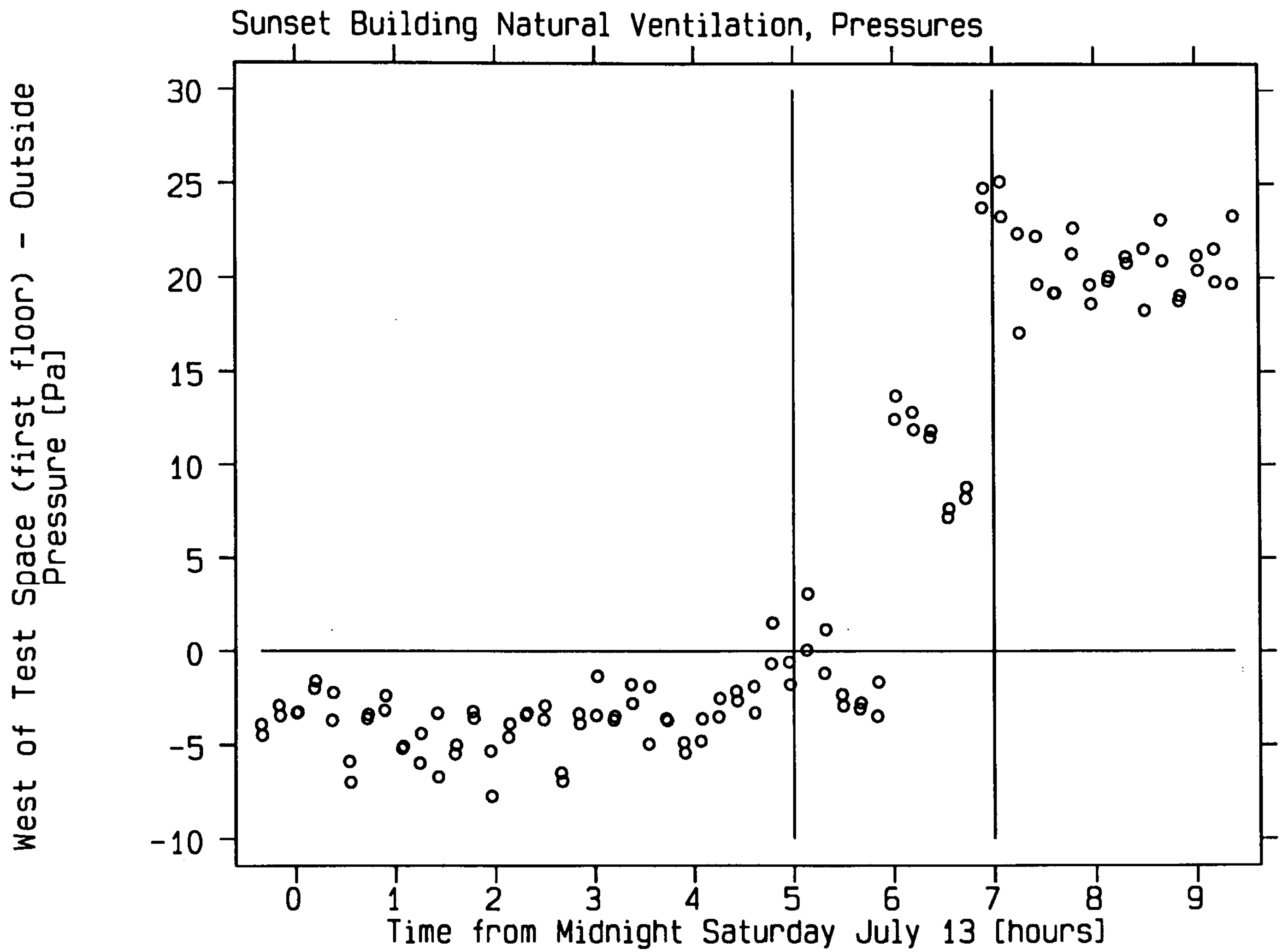

Figure 3.6 Natural Ventilation, North and West First Floor - Outside Pressure. Pressure Measurement Location is West of the Test Space on the First Floor

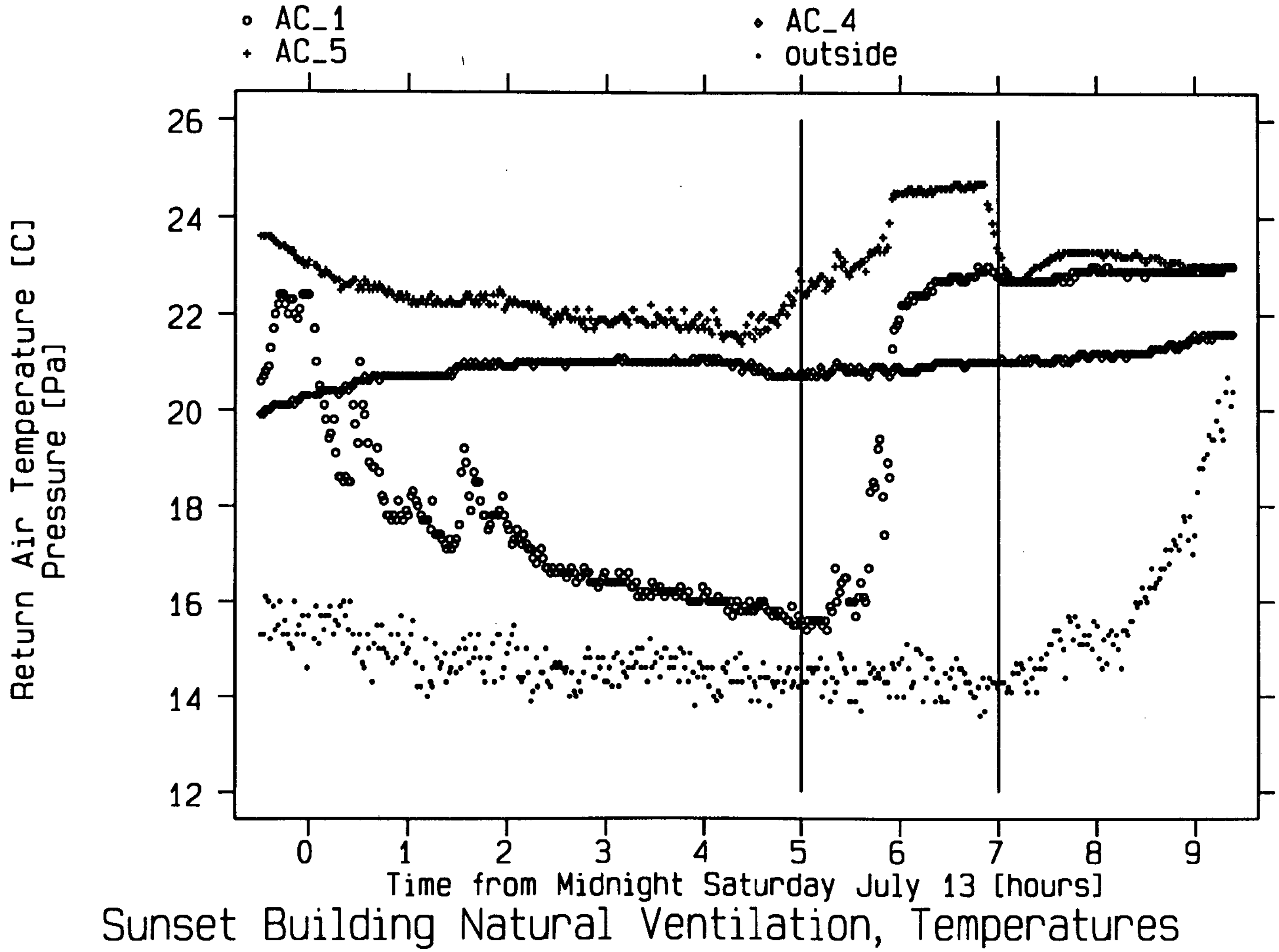

Figure 3.7 Natural Ventilation, Return Air Temperatures

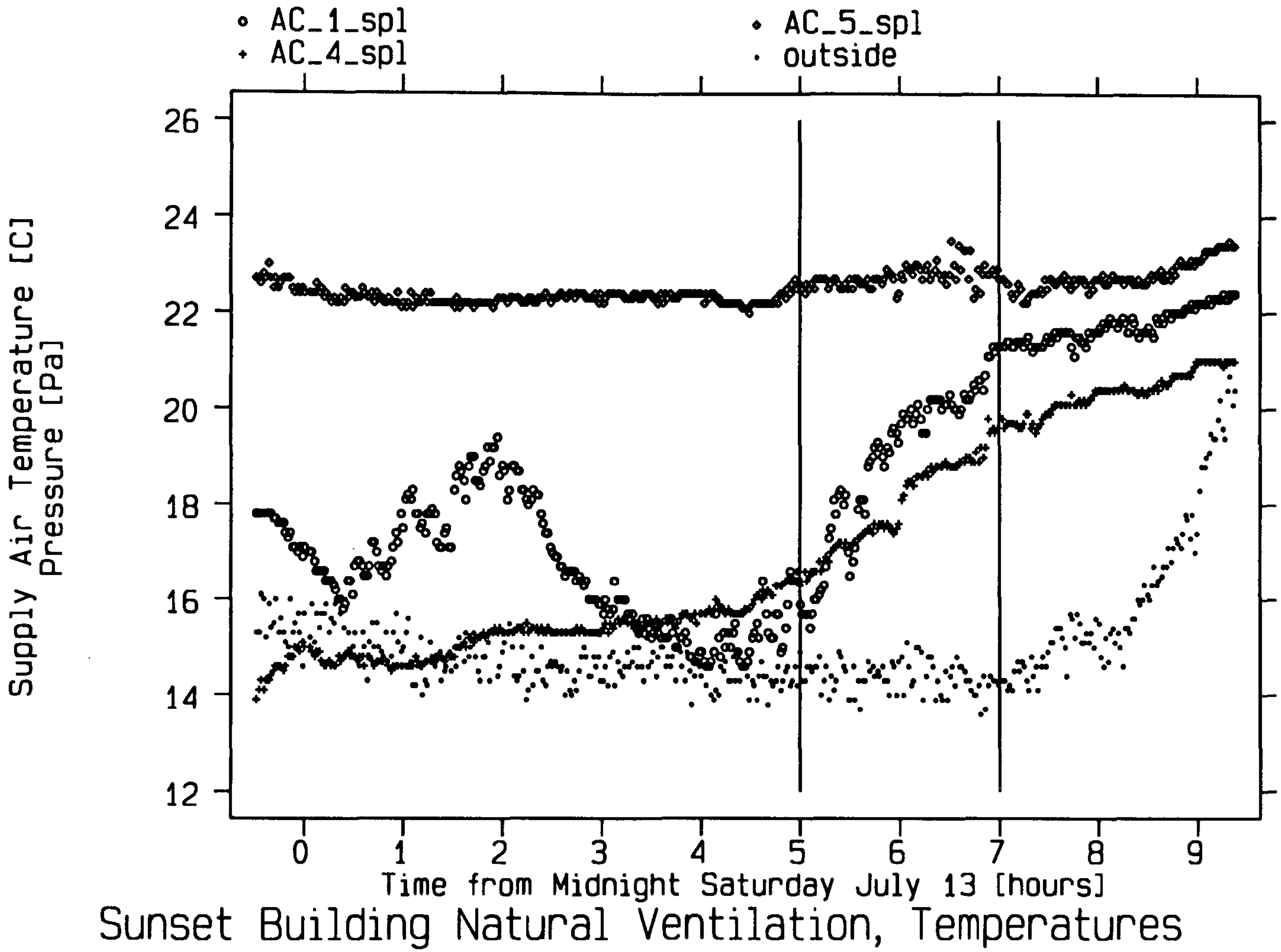

Figure 3.8 Natural Ventilation, Supply Air Temperatures
Temperatures Measured Just Downstream of the Cooling Coils

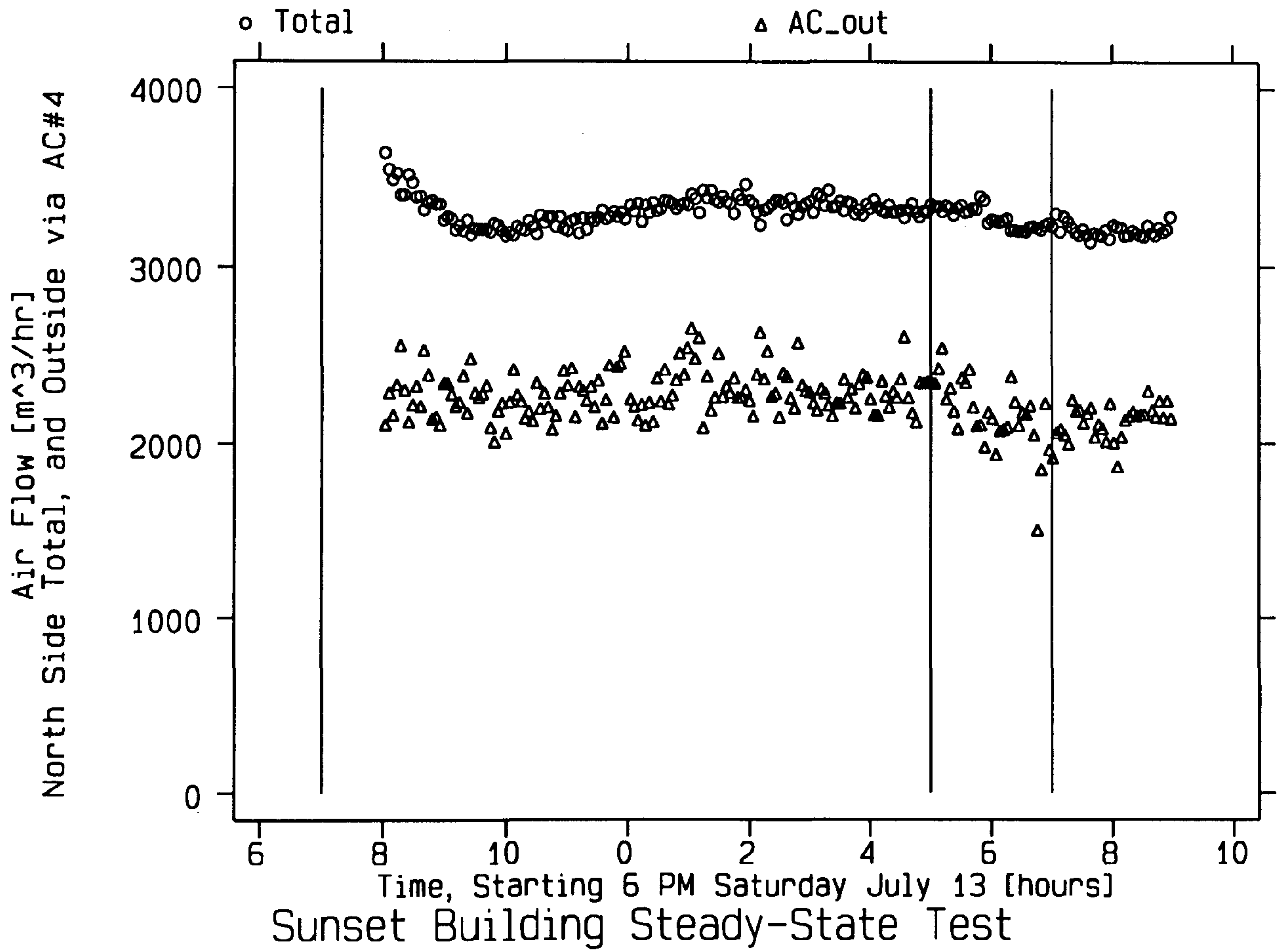

Figure 3.9 Steady-State Ventilation of the North Side

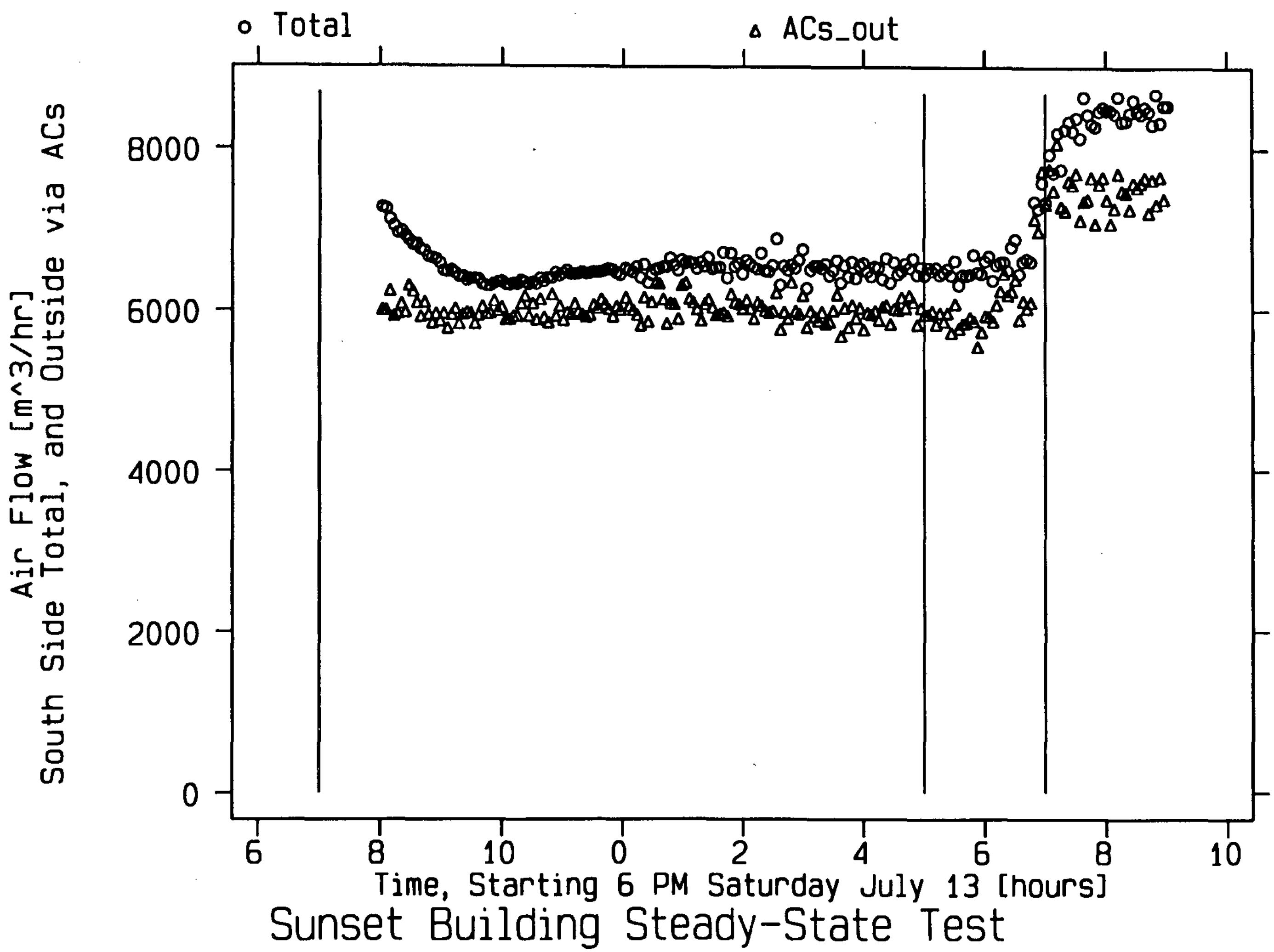

Figure 3.10 Steady-State Ventilation of the South Side

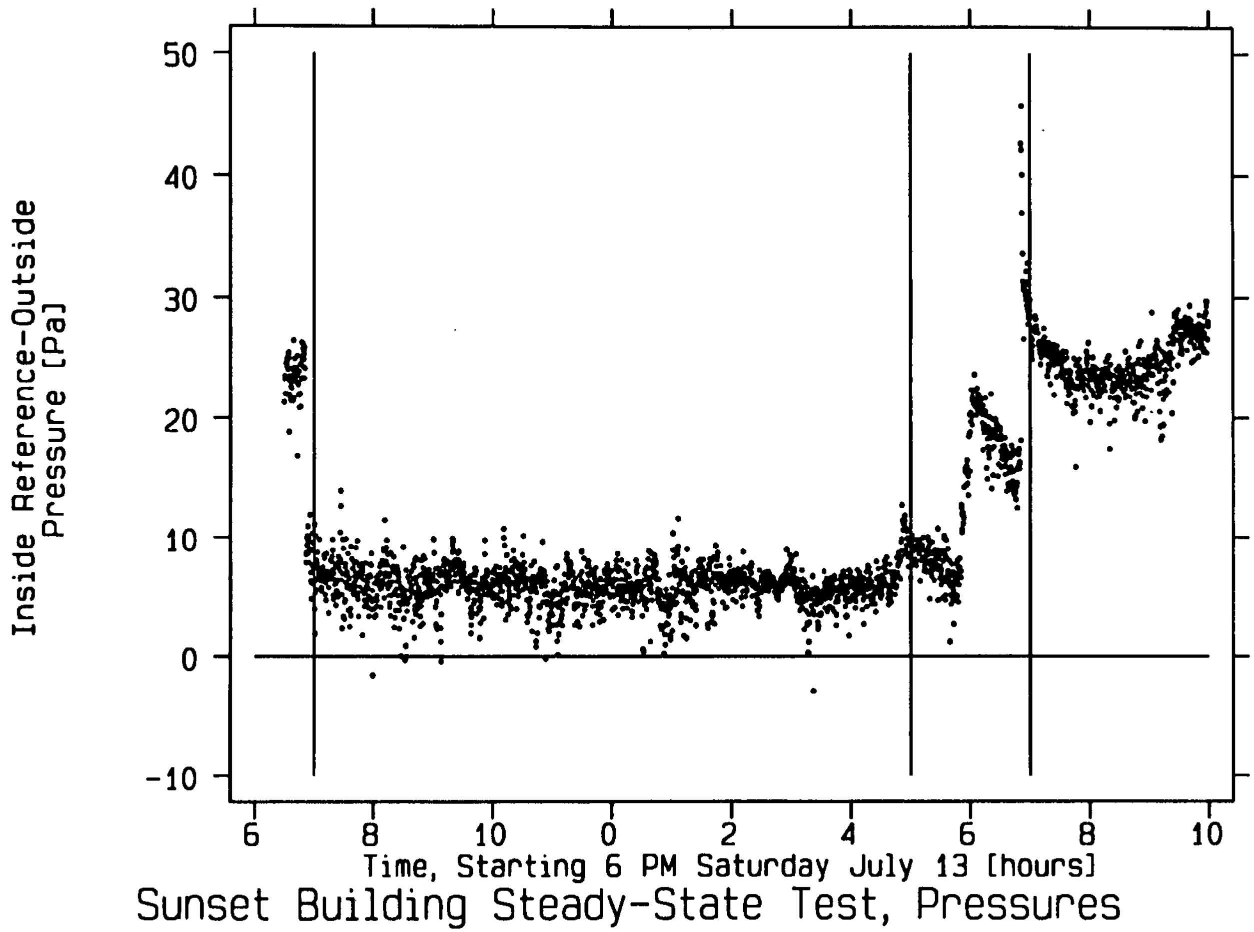

Figure 3.11 Steady-State Inside - Outside Reference Pressure

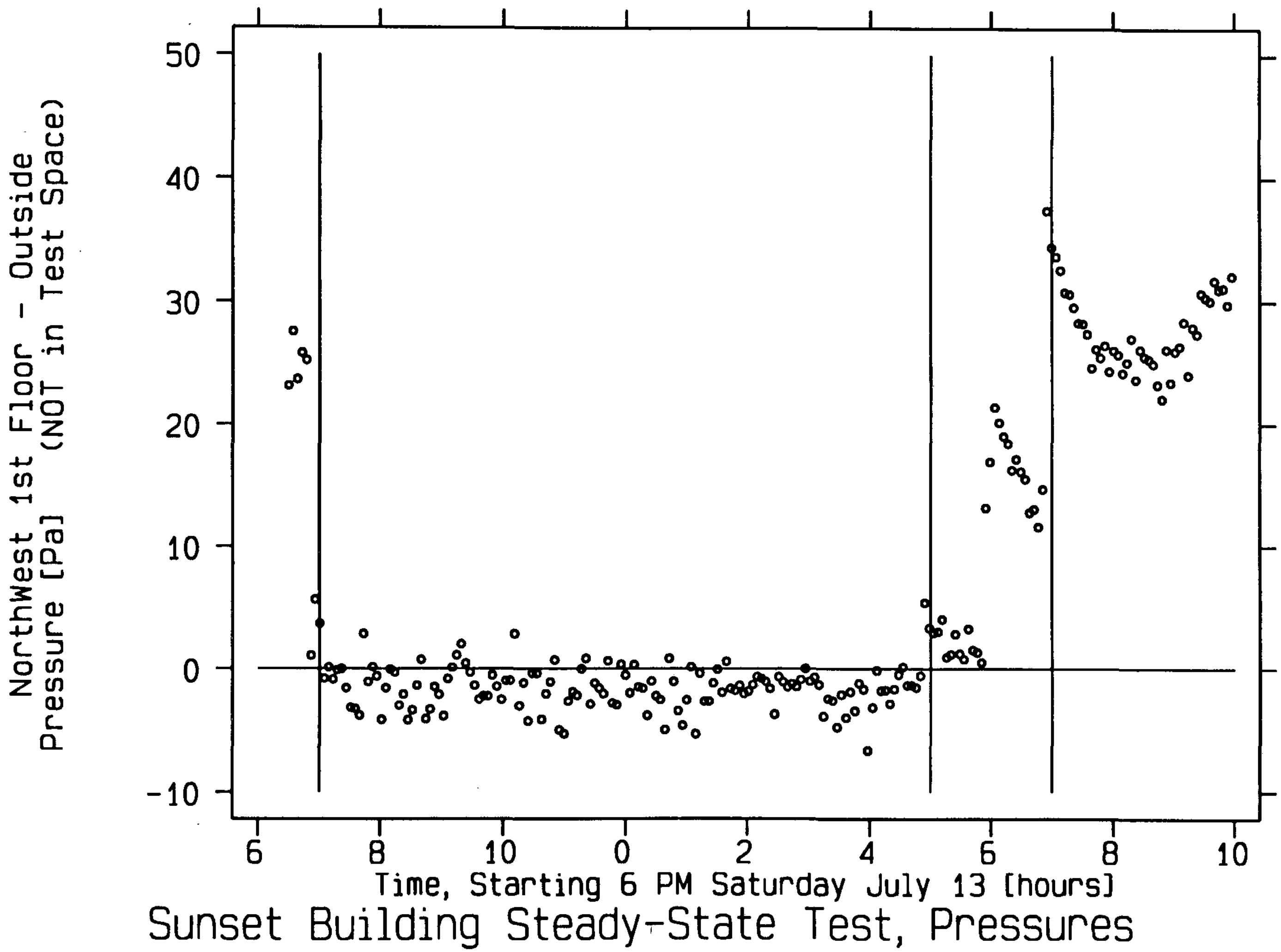

Figure 3.12 Steady-State North and West First Floor - Outside Pressure
Pressure Measurement Location is West of the Test Space on the First Floor

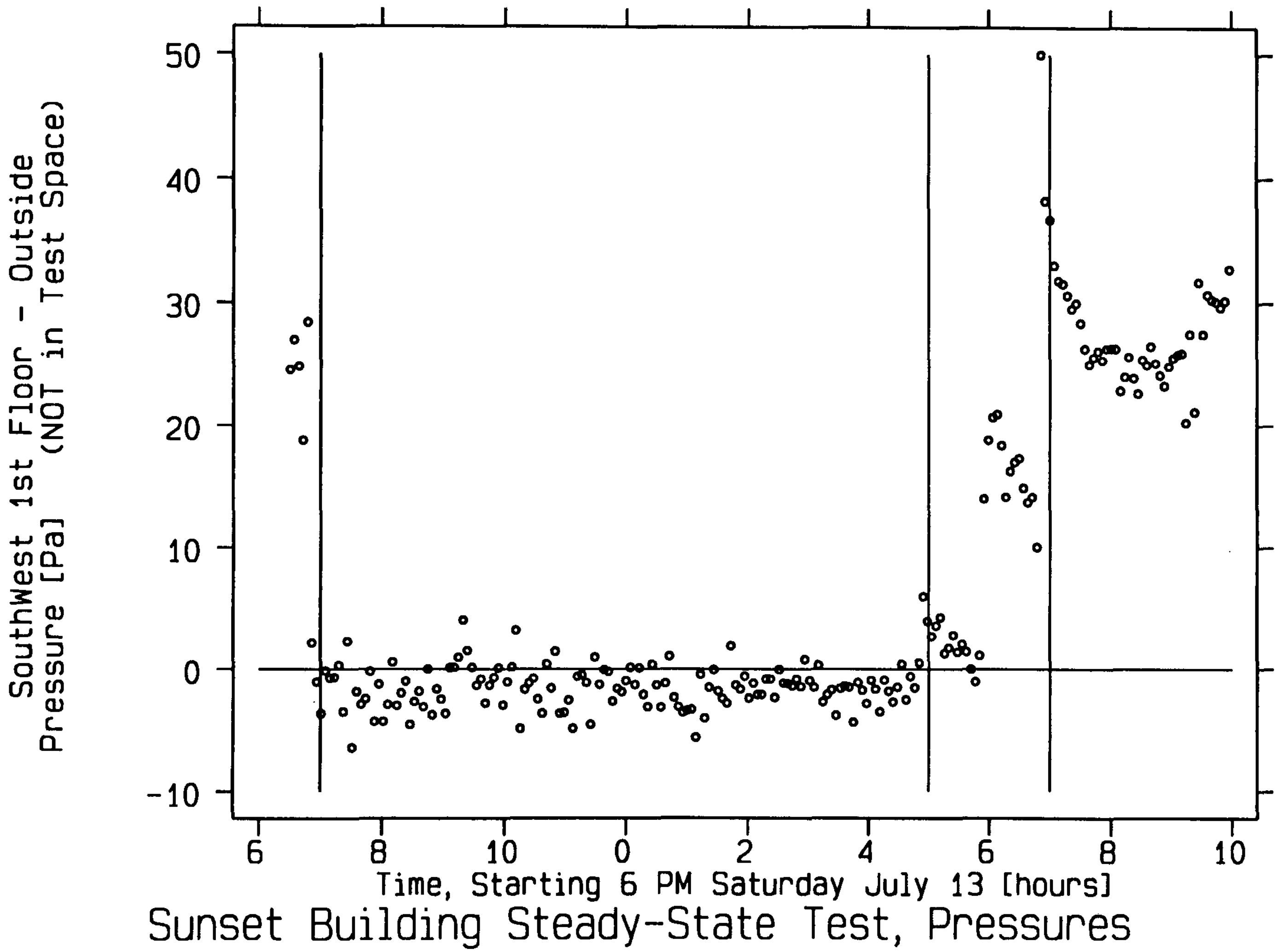

Figure 3.13 Steady-State South and West First Floor - Outside Pressure
Pressure Measurement Location is West of the Test Space on the First Floor

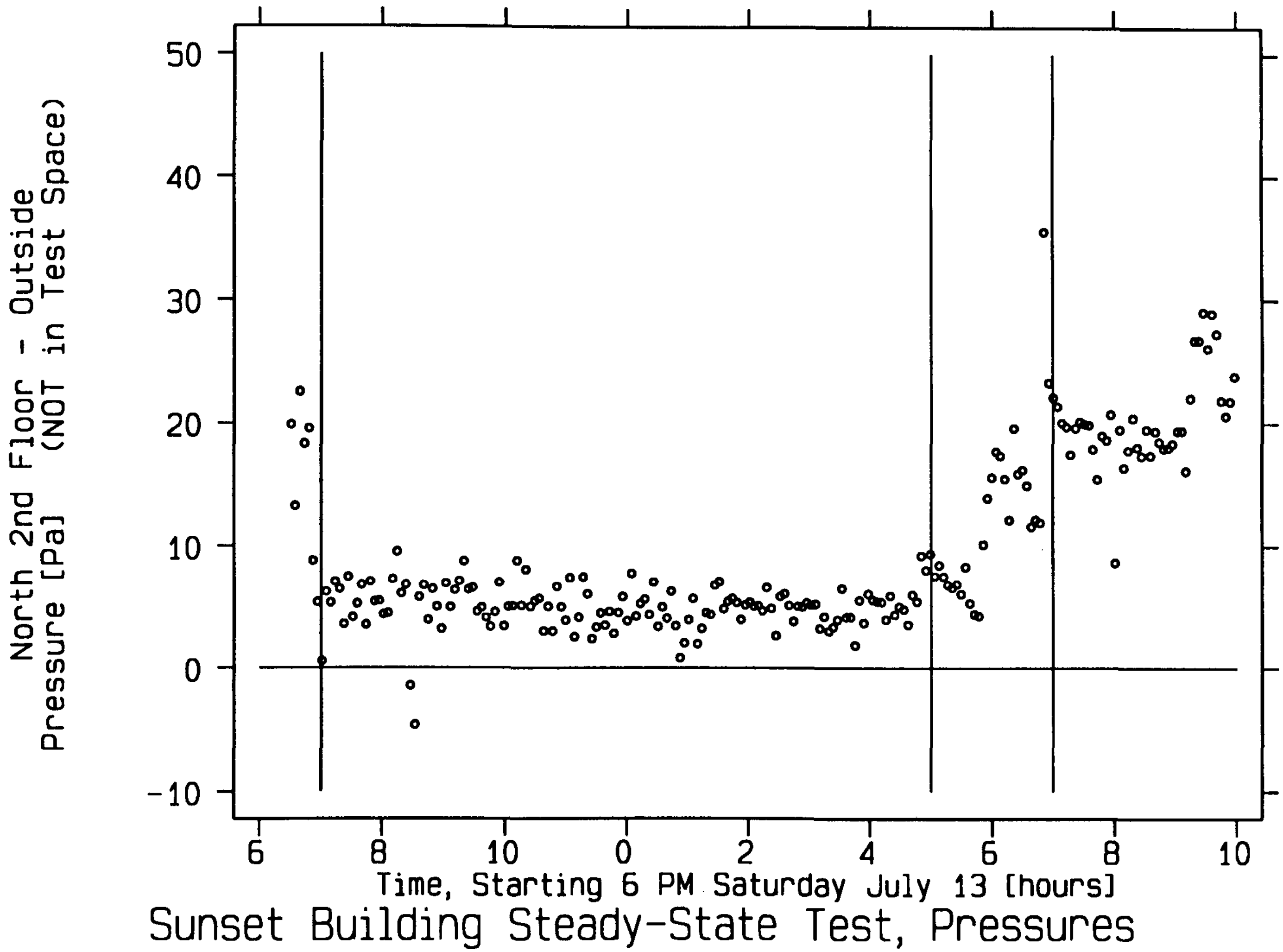

Figure 3.14 Steady-State North Second Floor - Outside Pressure
Pressure Measurement Location is West of the Test Space on the Second Floor

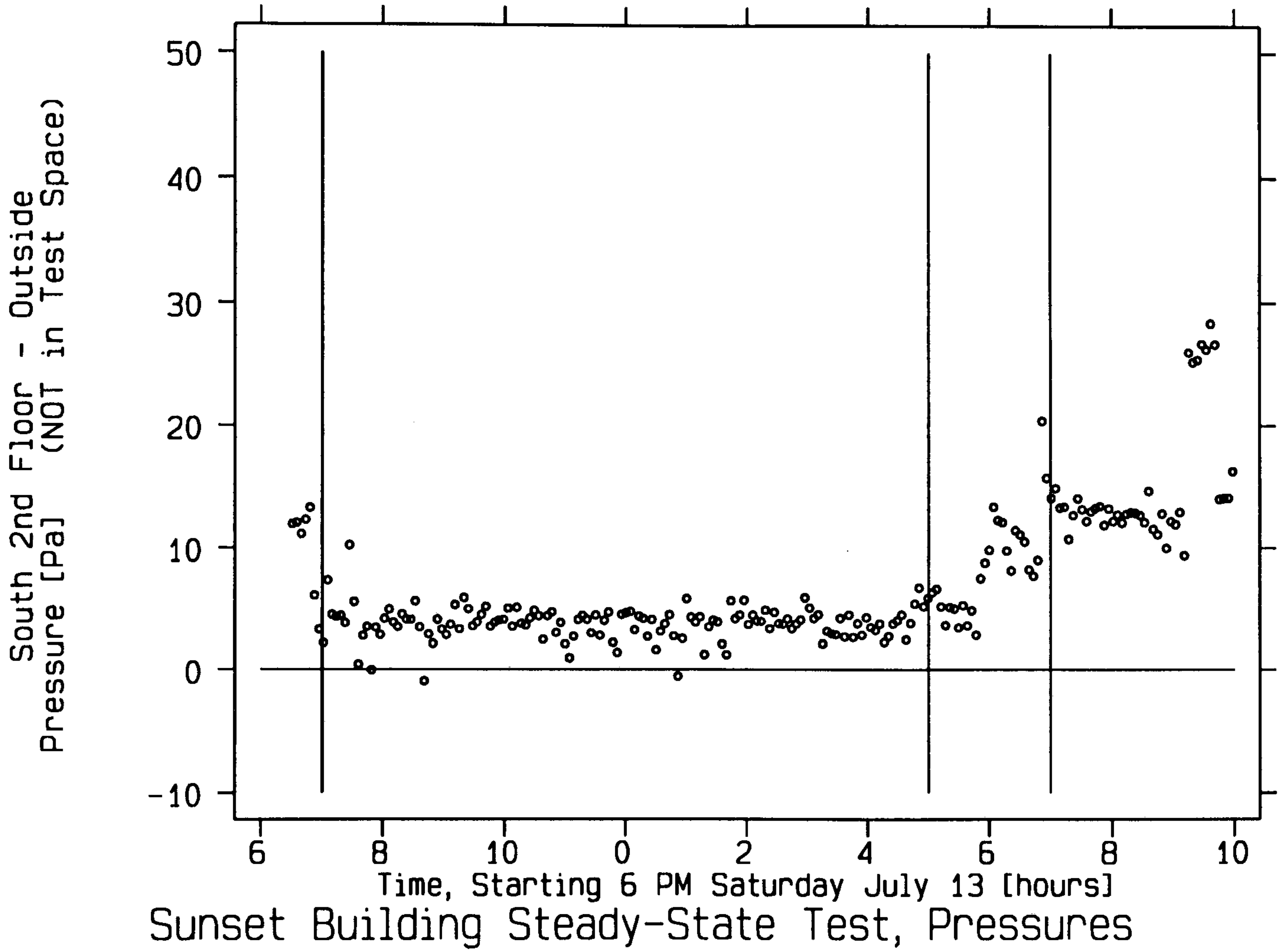

Figure 3.15 Steady-State South Second Floor - Outside Pressure
Pressure Measurement Location is West of the Test Space on the Second Floor

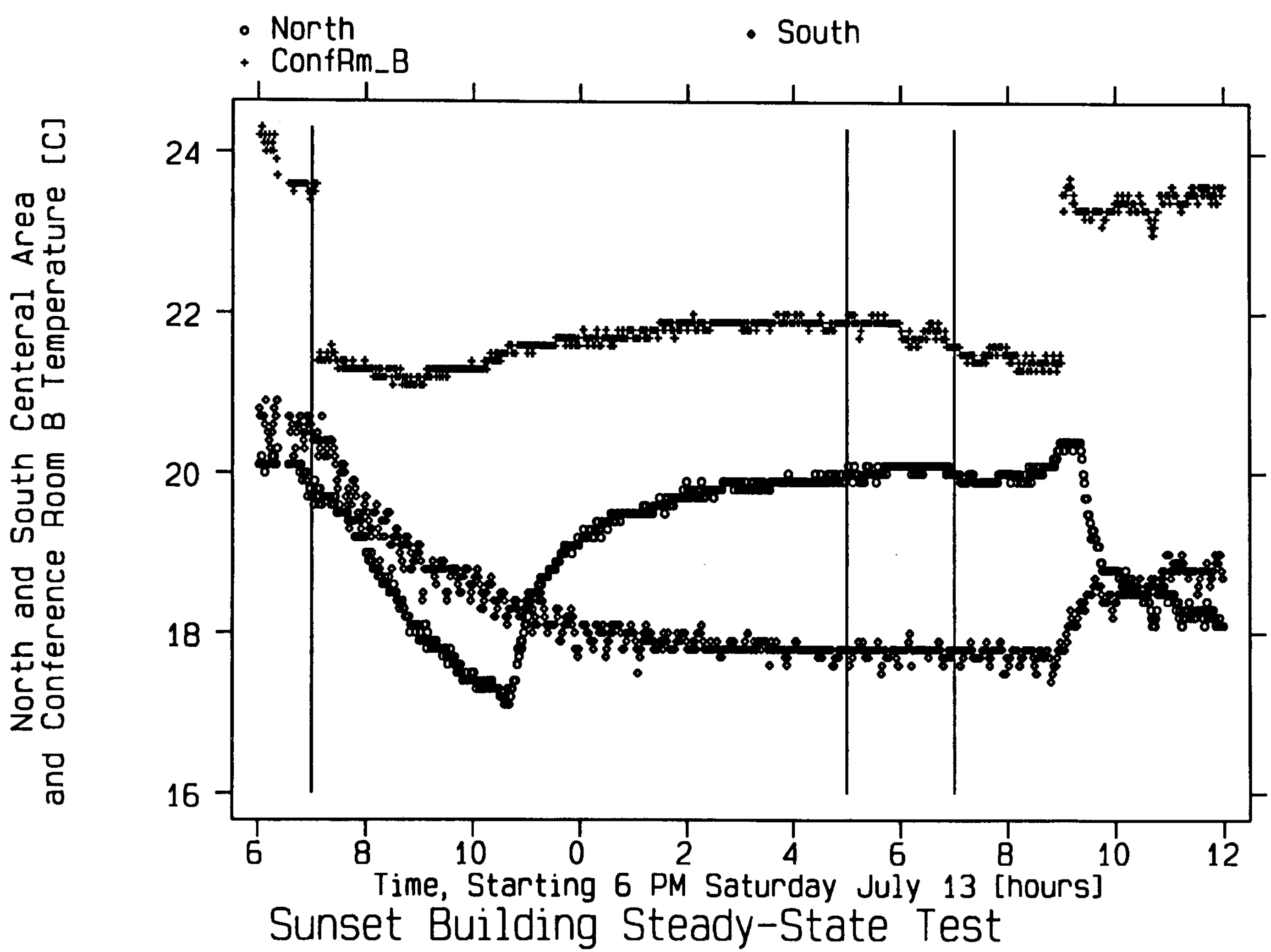

Figure 3.16 Steady-State Temperatures of the North, South and Conference Room B

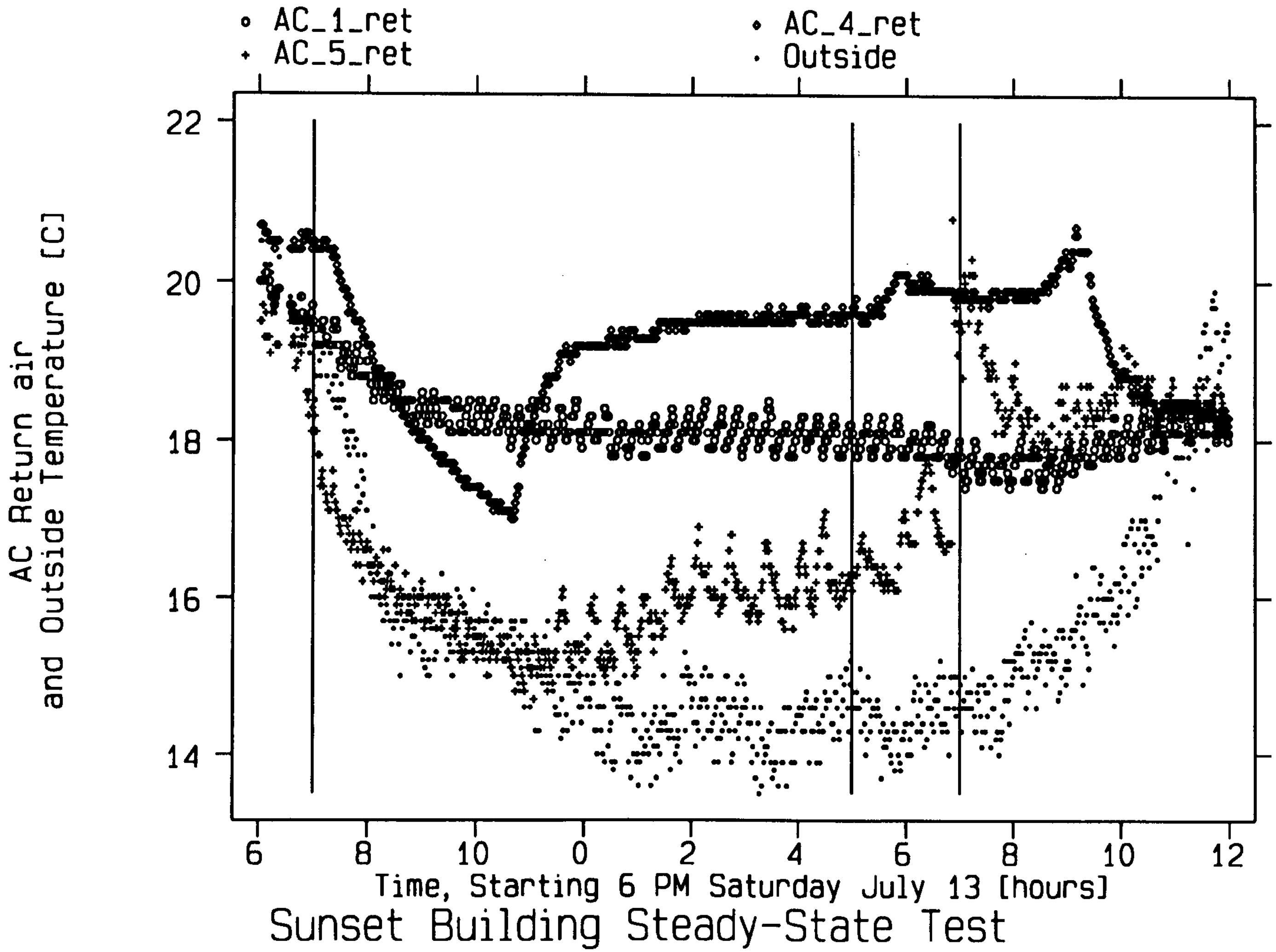

Figure 3.17 Steady-State Return Air Temperatures

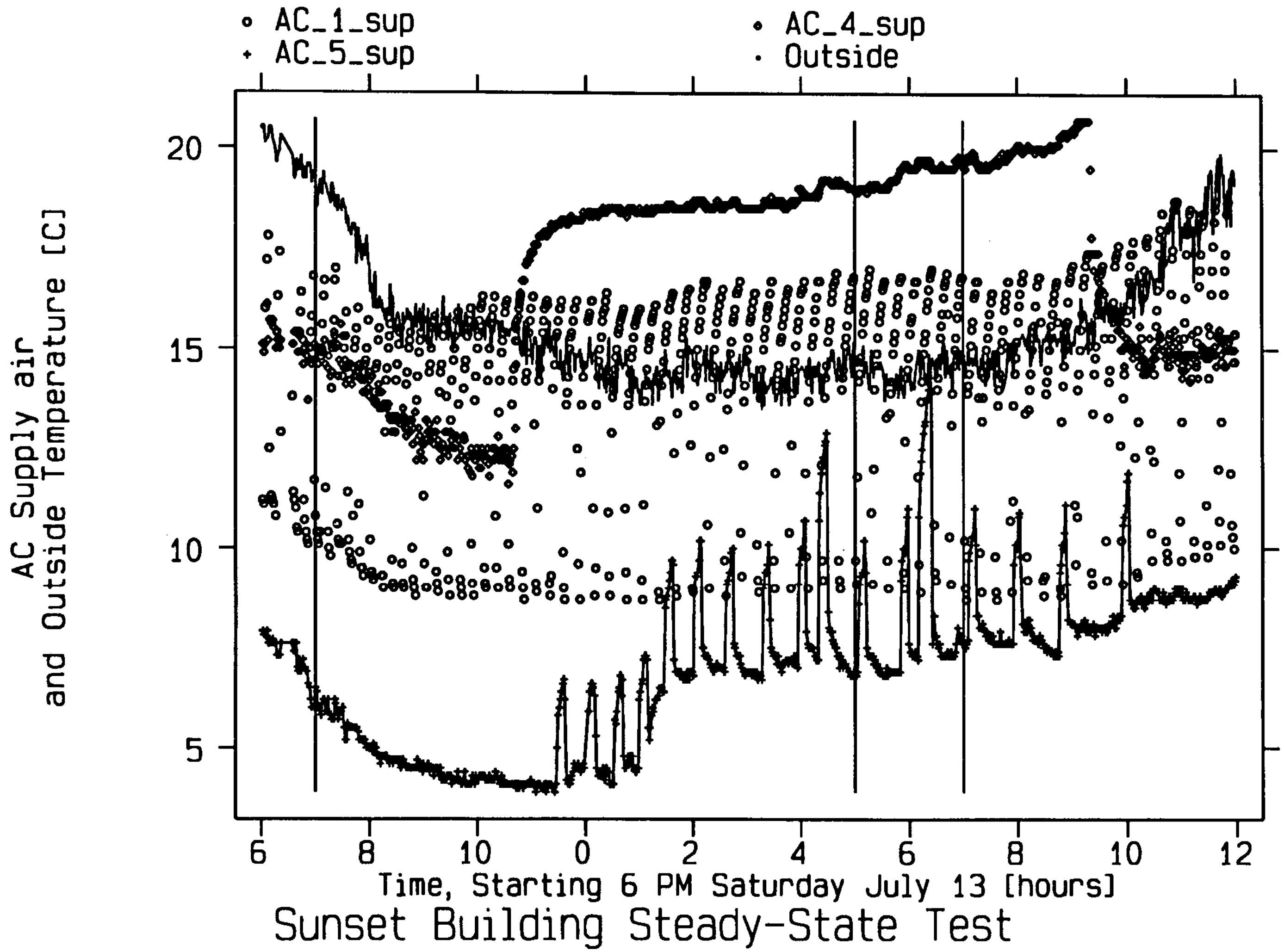

Figure 3.18 Steady-State Supply Air Temperatures
Temperatures Measured Just Downstream of the Cooling Coils

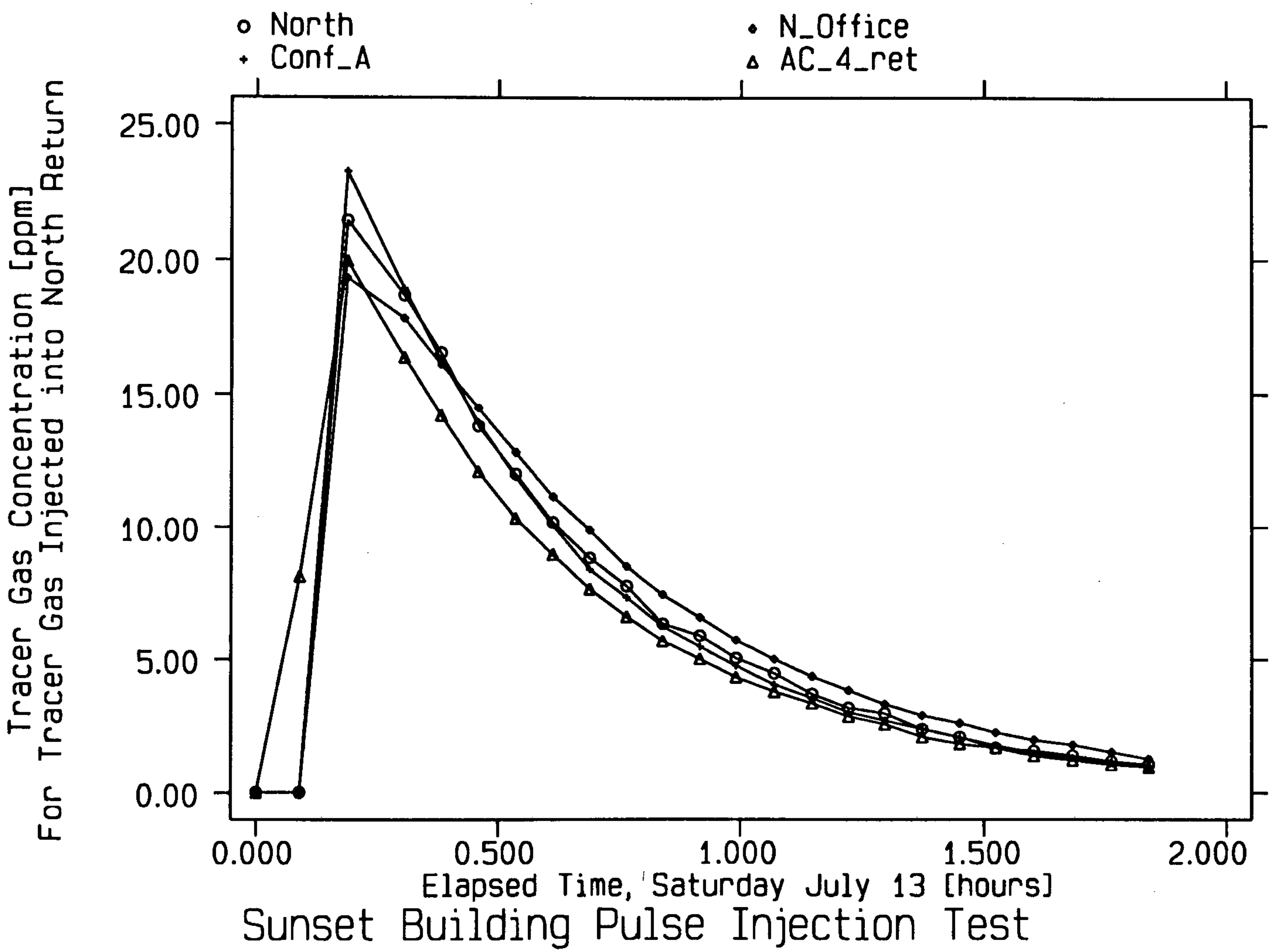

Figure 3.19 Pulse Injection, Tracer Gas Concentrations via AC#4 (North)

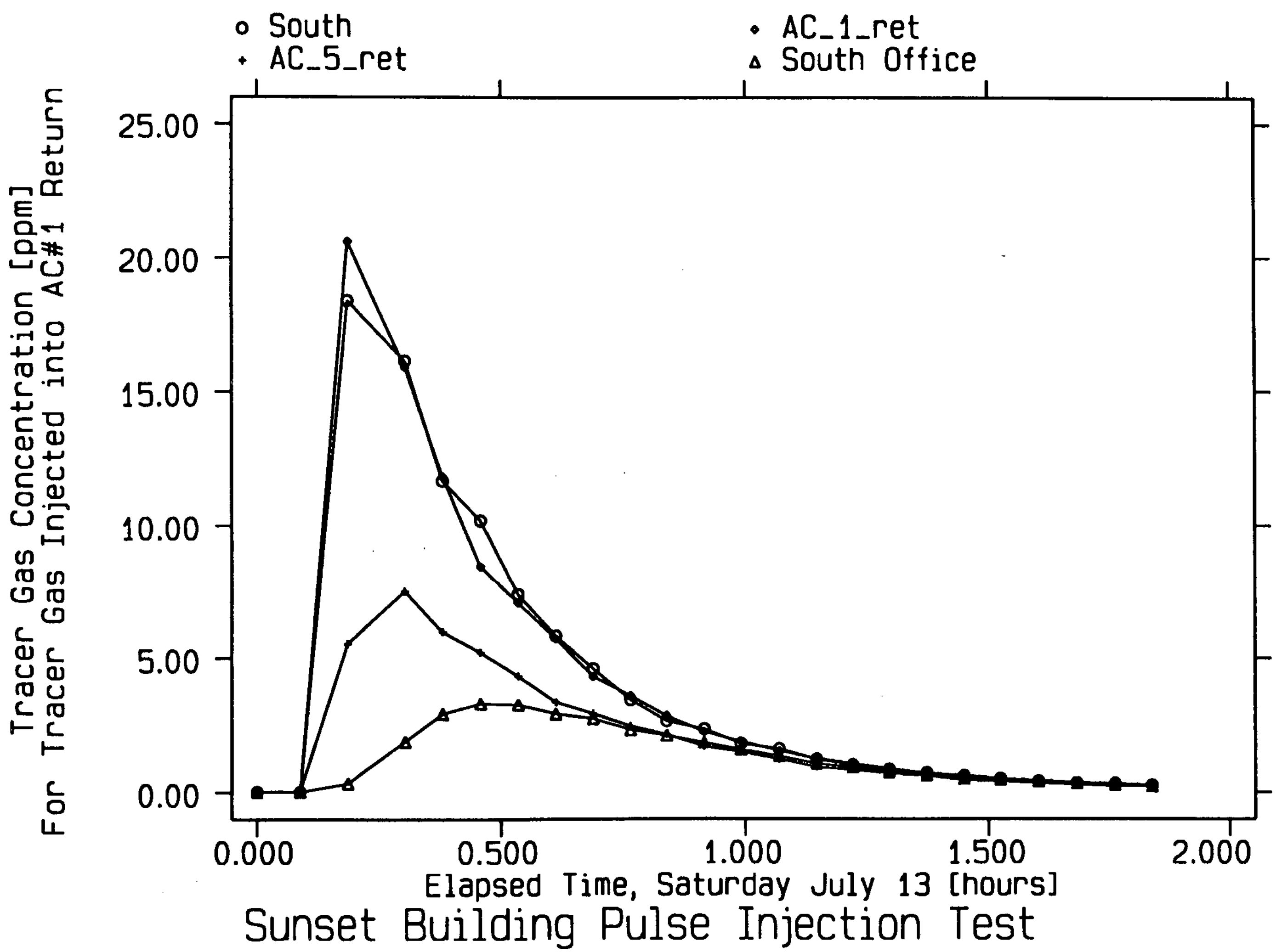

Figure 3.20 Pulse Injection, Tracer Gas Concentrations via AC#1 (South)

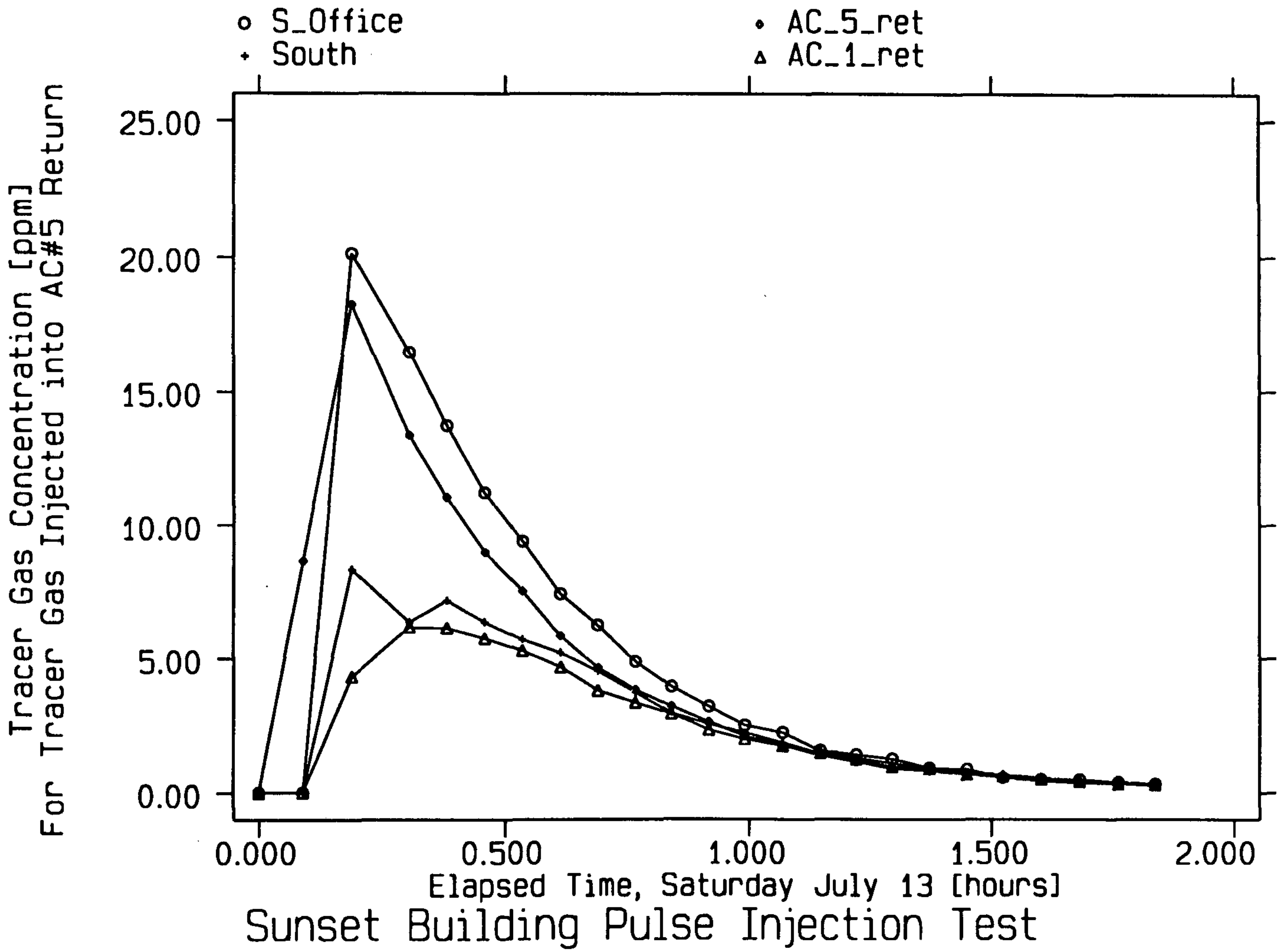

Figure 3.21 Pulse Injection, Tracer Gas Concentrations via AC#5 (South)

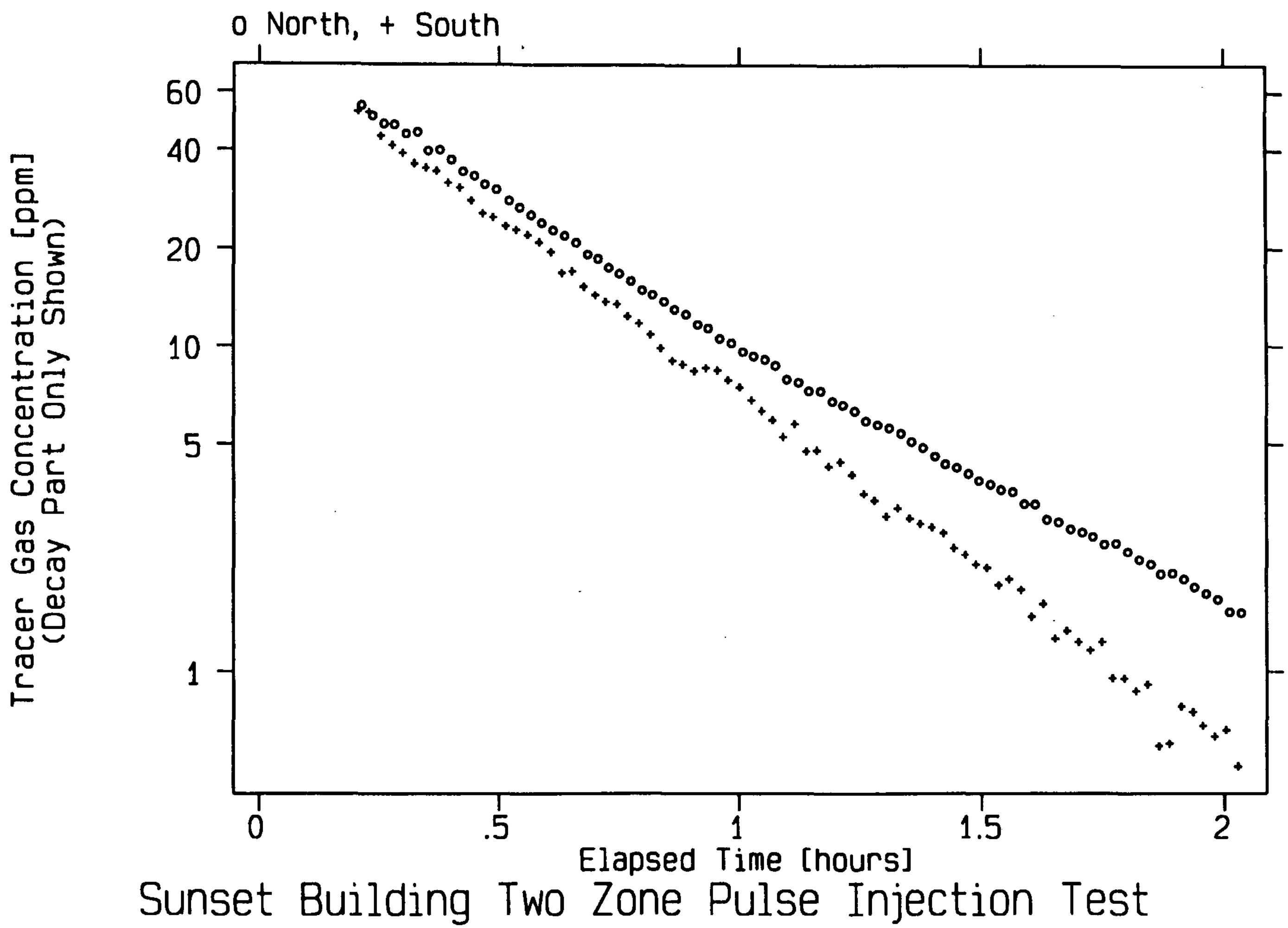

Figure 3.22 Two Zone Pulse Injection Tracer Gas Concentrations

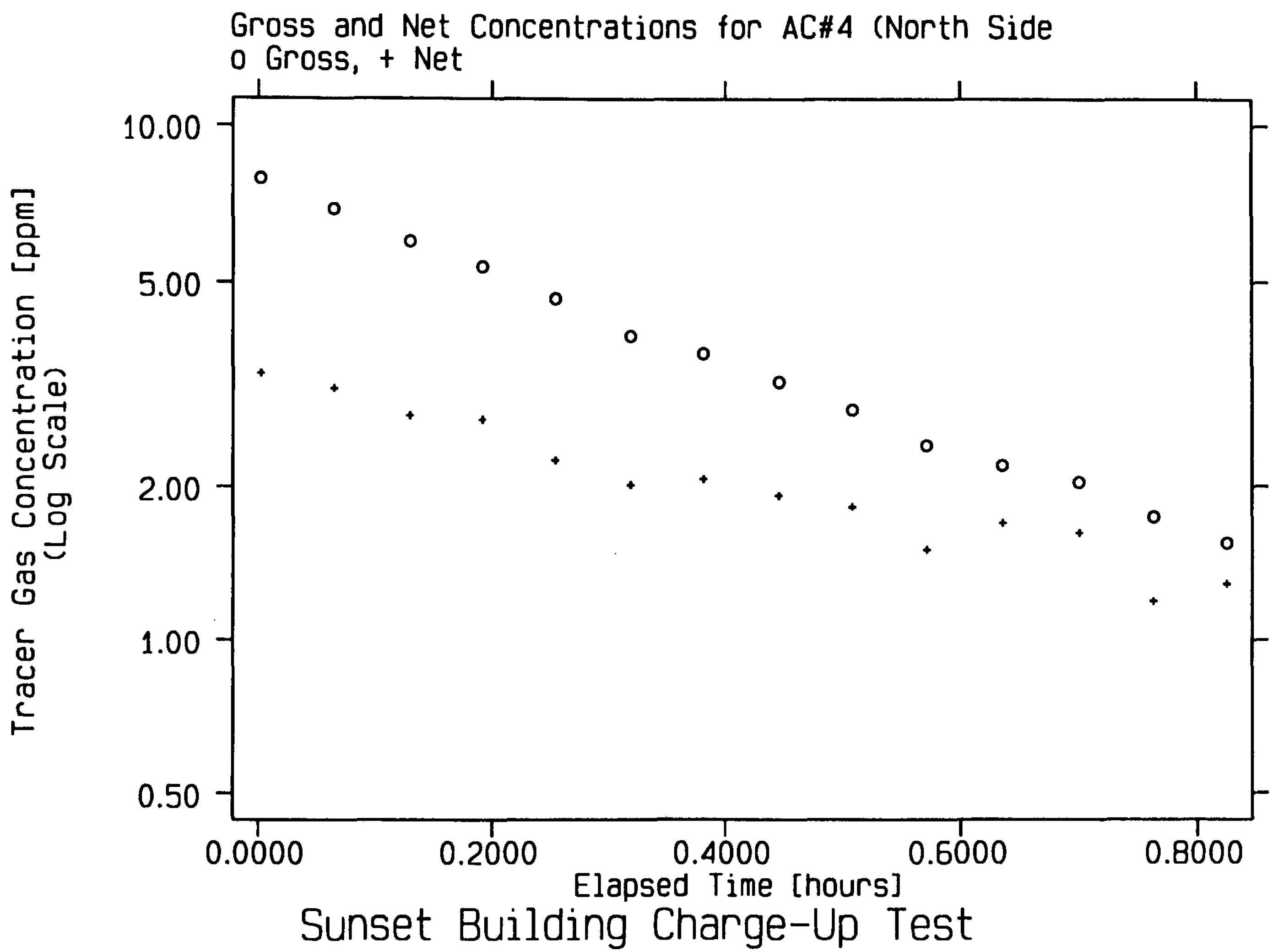

Figure 3.23 Charge-Up Gross and Net Tracer Gas Concentrations for AC#4 (North)

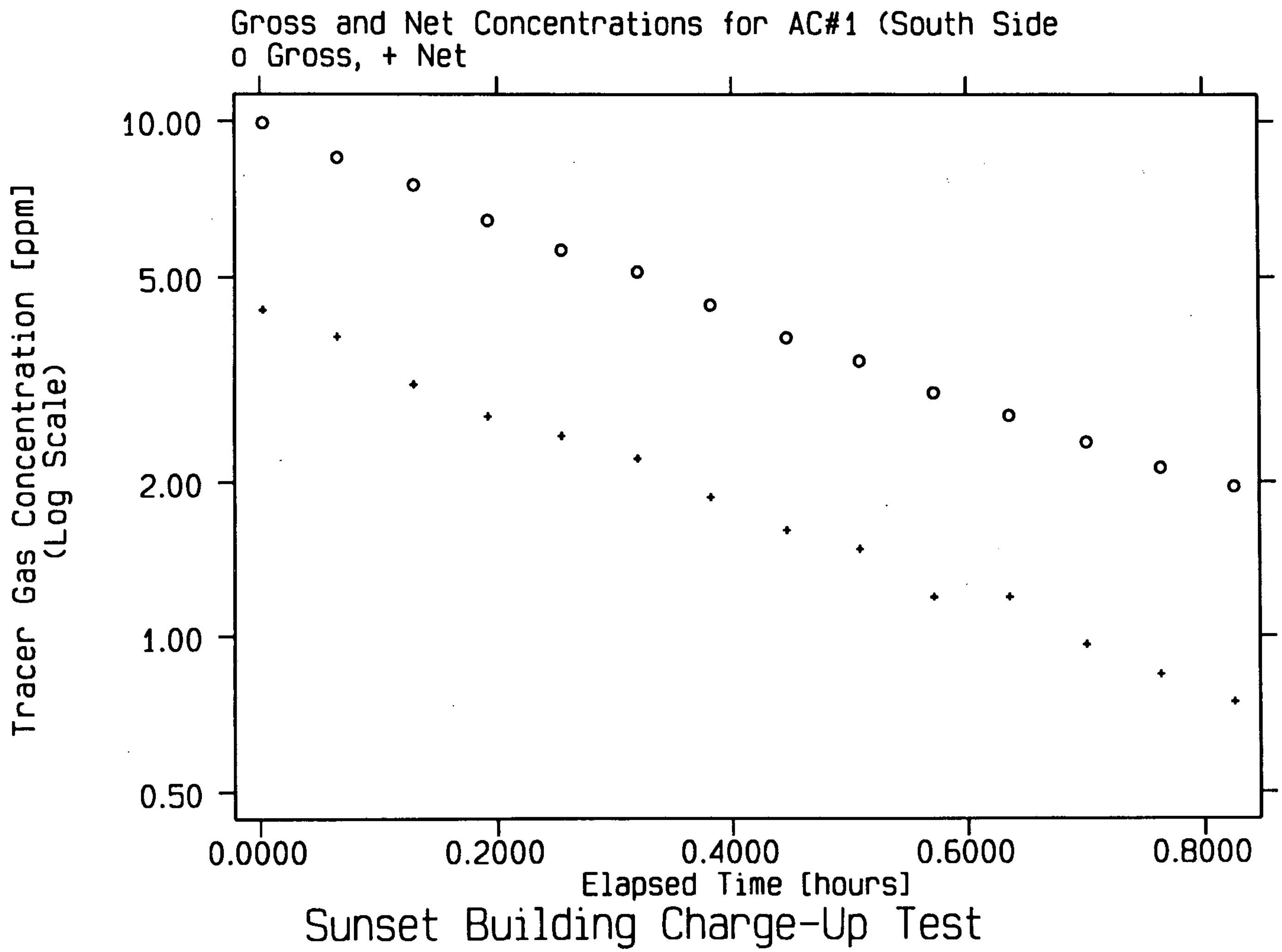

Figure 3.24 Charge-Up Gross and Net Tracer Gas Concentrations for AC#1 (South)

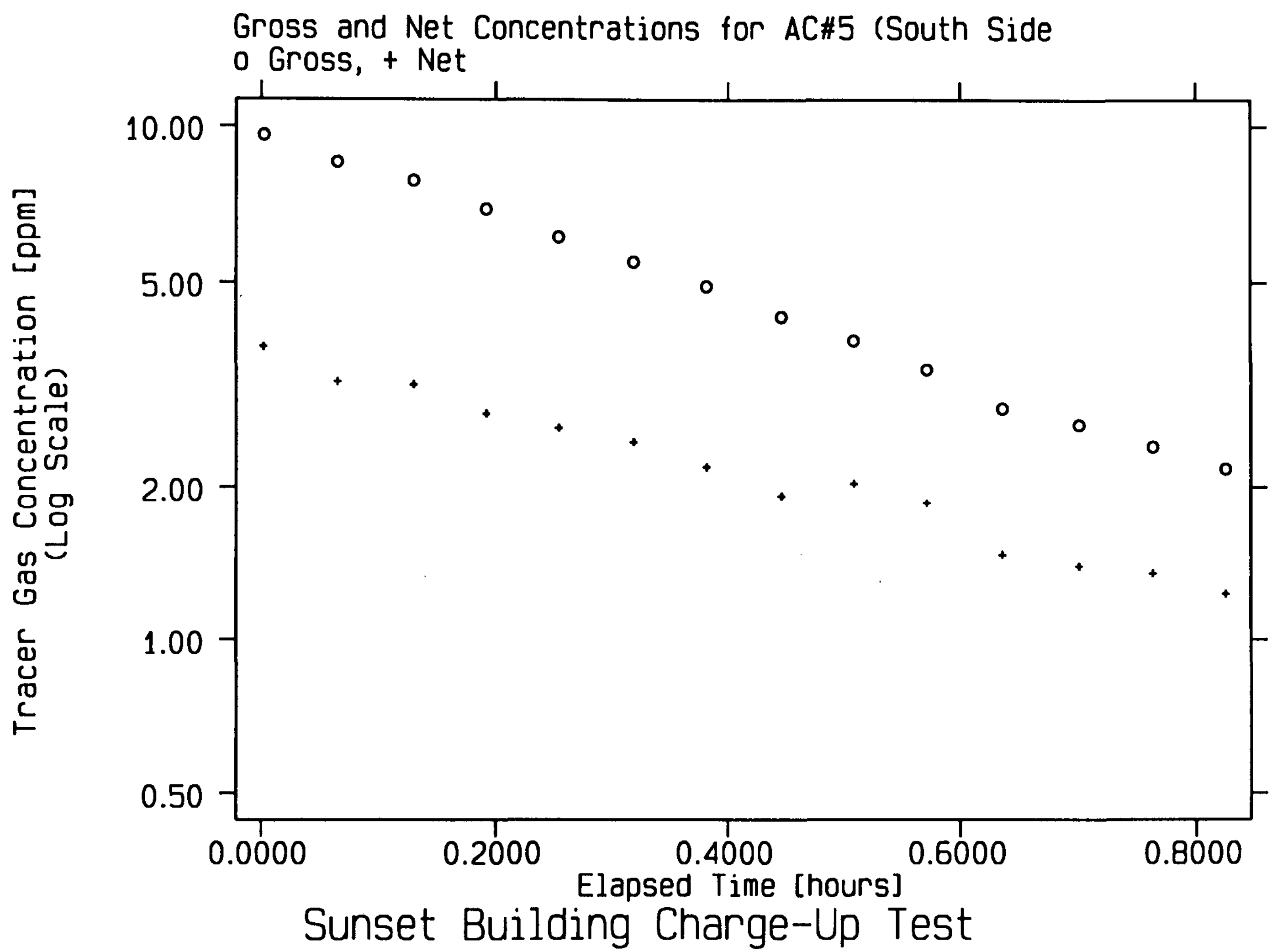

Figure 3.25 Charge-Up Gross and Net Tracer Gas Concentrations for AC#5 (South)

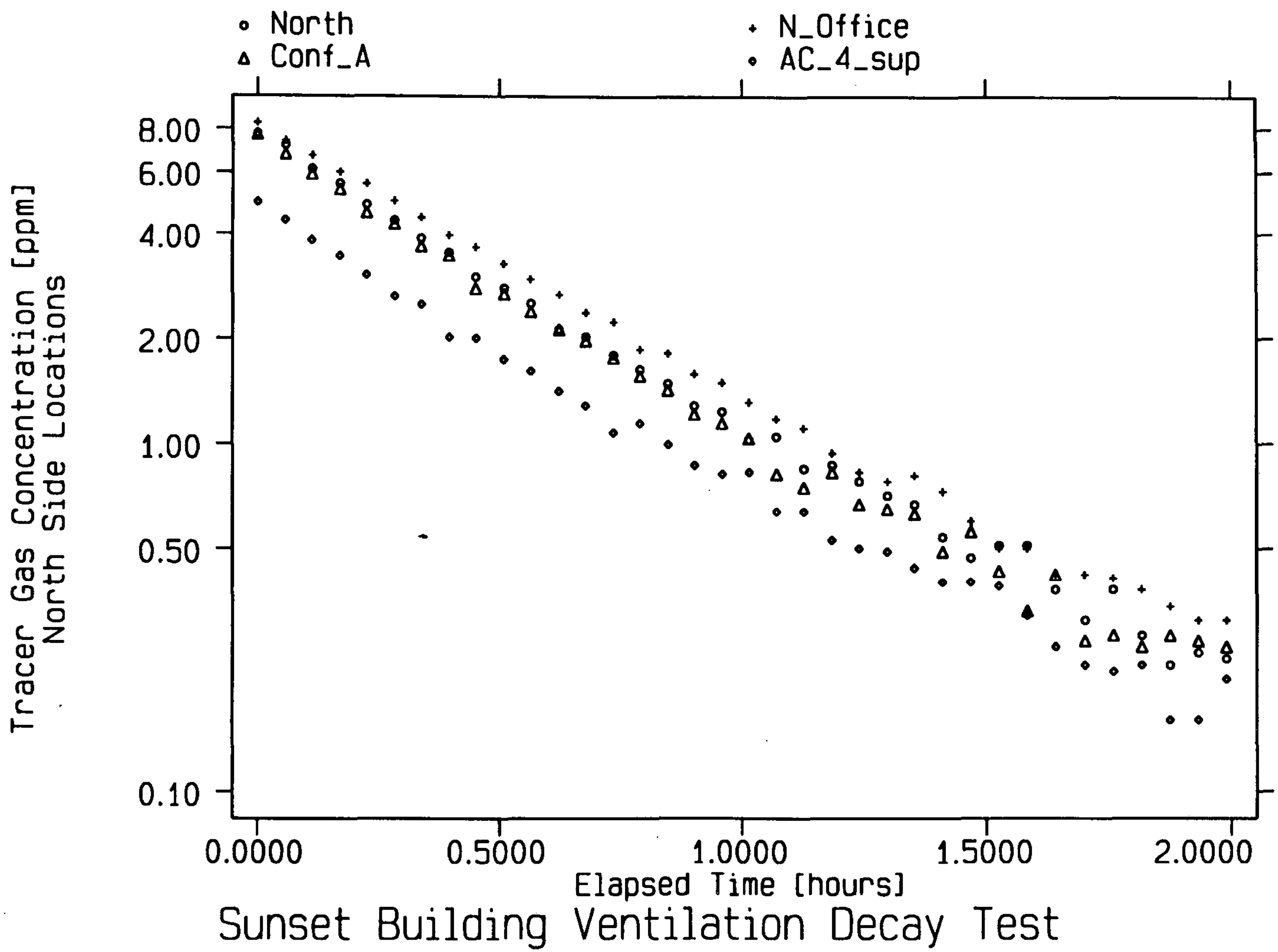

Figure 3.26 Decay Gross Tracer Gas Concentrations for the North Side

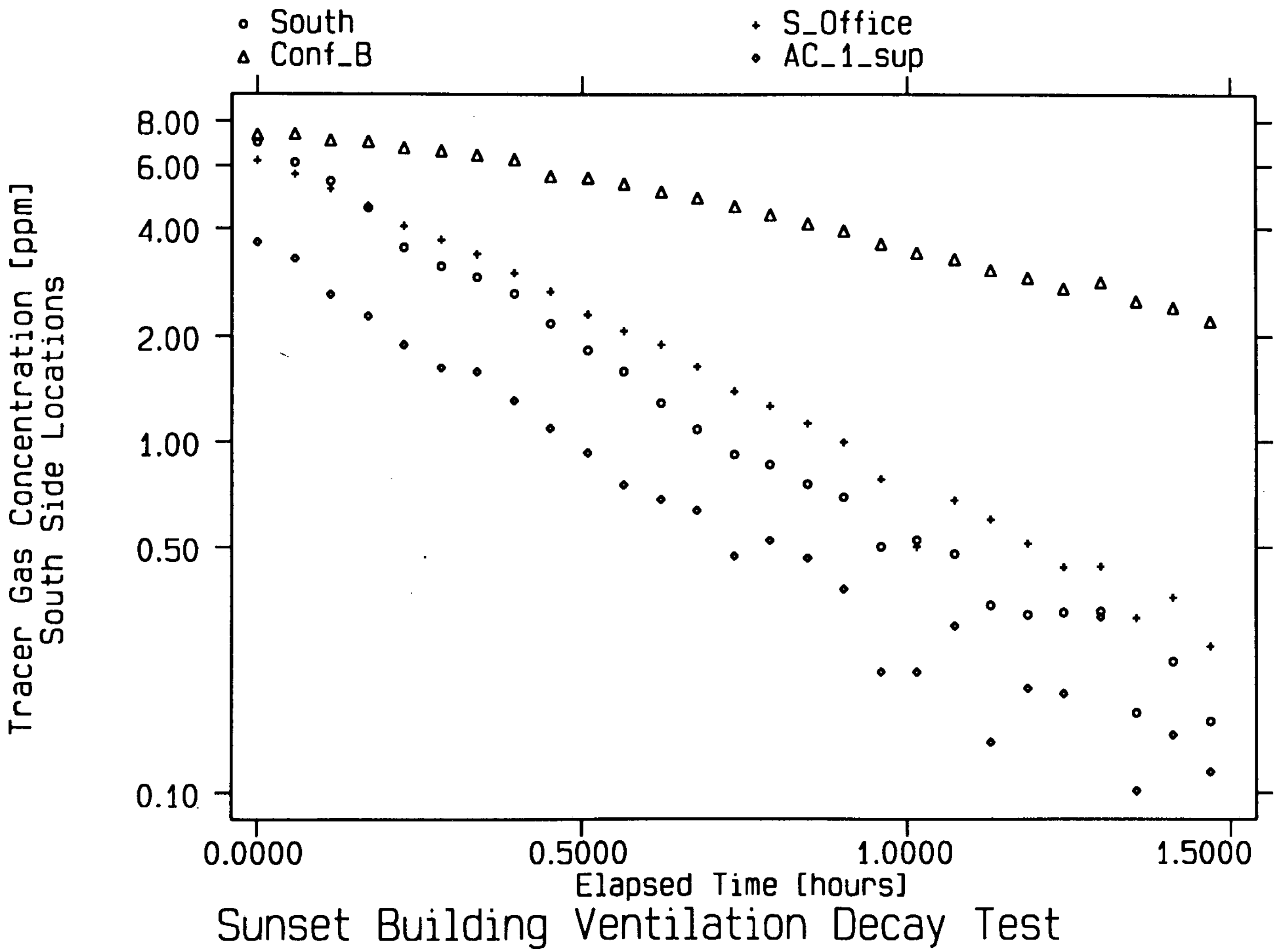

Figure 3.27 Decay Gross Tracer Gas Concentrations for the South Side

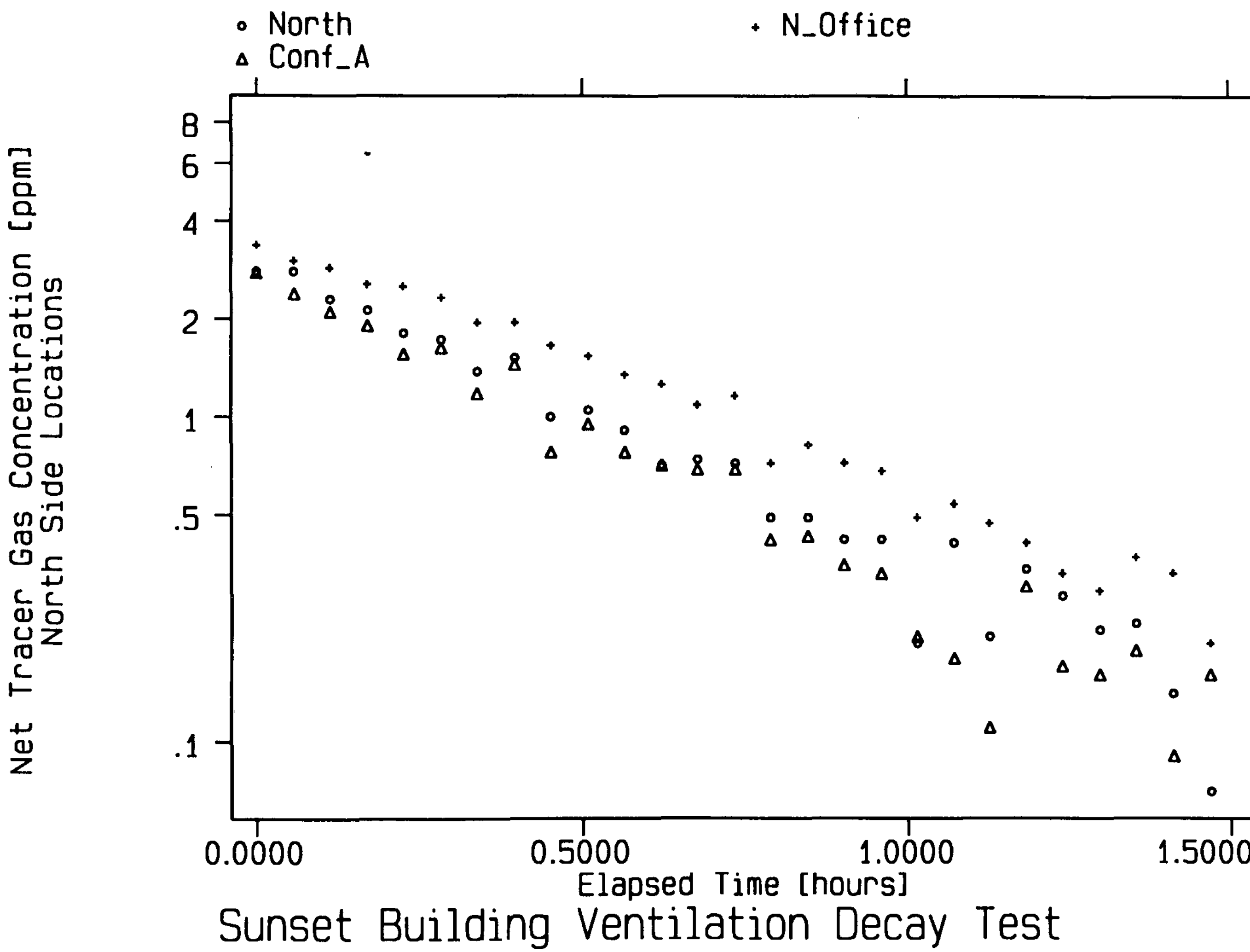

Figure 3.28 Decay Net Tracer Gas Concentrations for the North Side

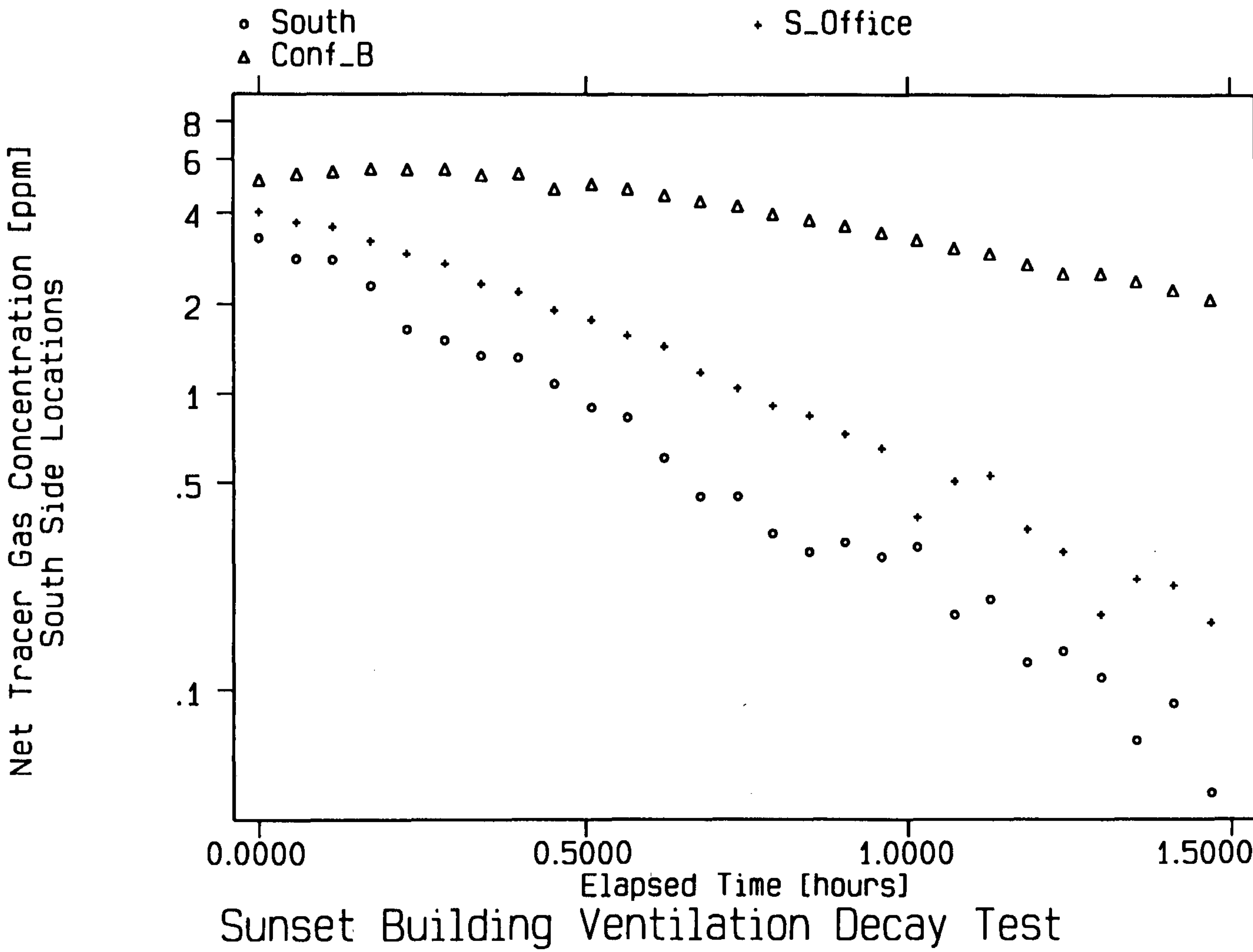

Figure 3.29 Decay Net Tracer Gas Concentrations for the South Side

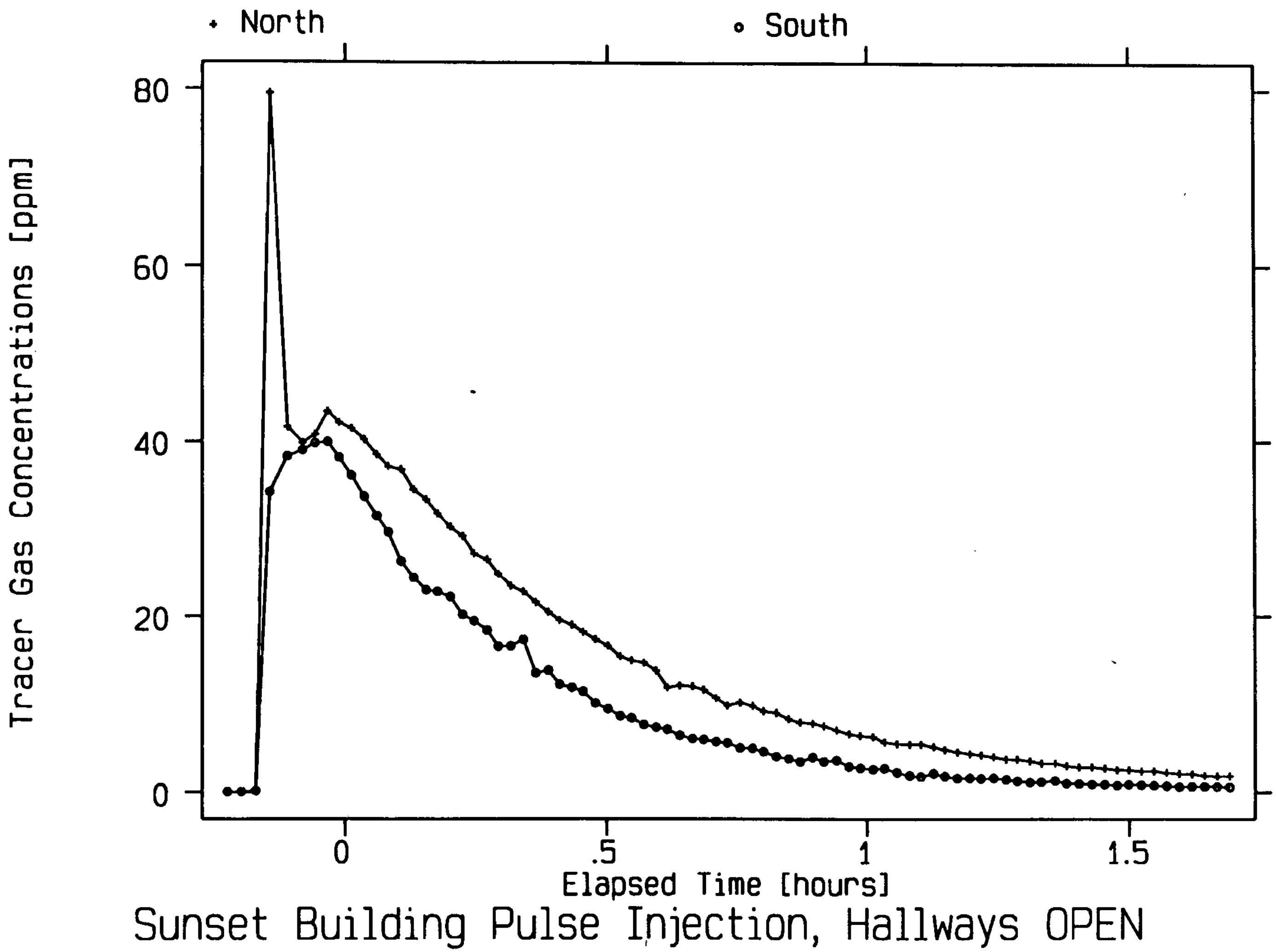

Figure 4.1 Two Zone Pulse Test, Tracer Gas Concentrations

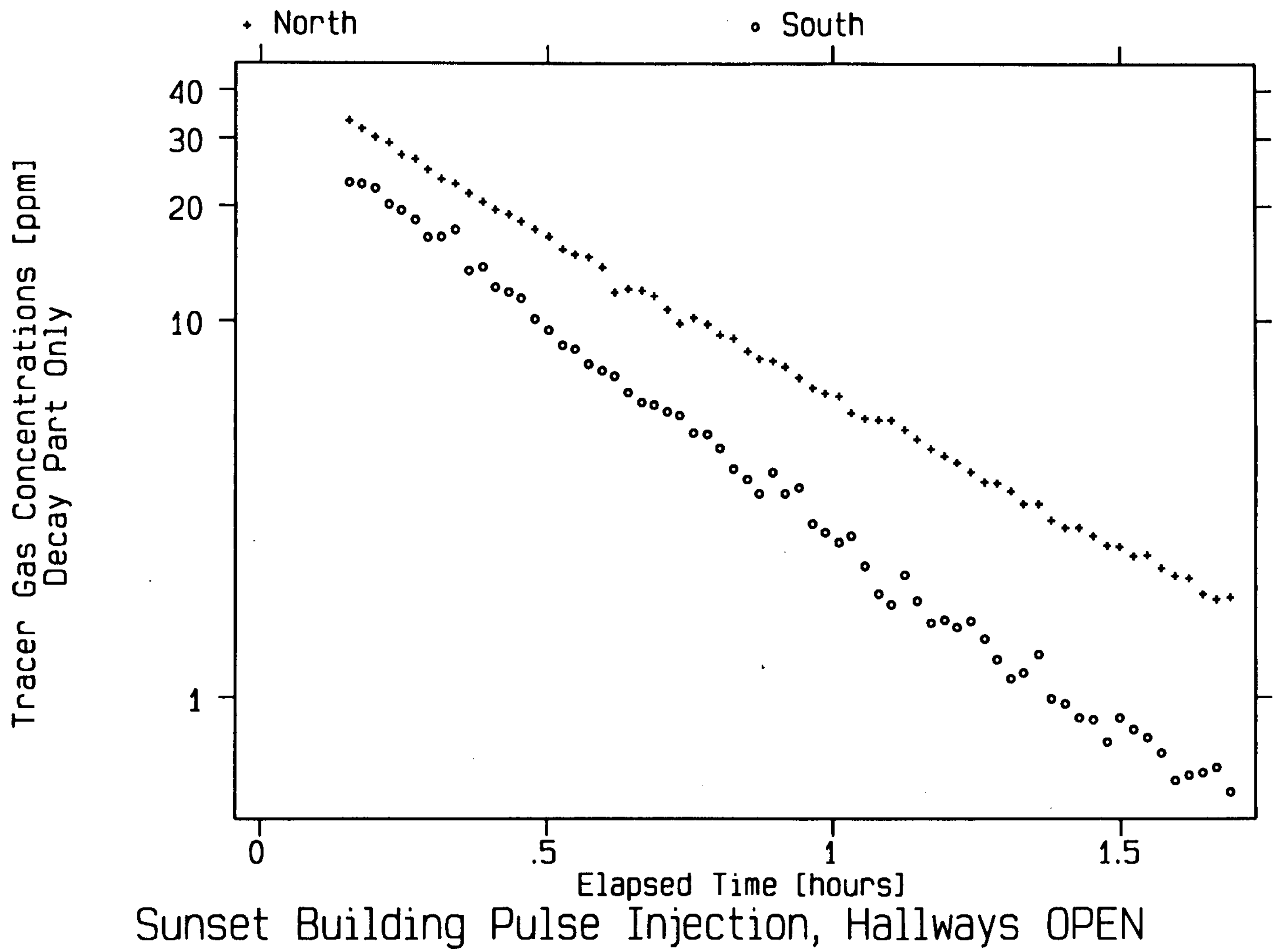

Figure 4.2 Two Zone Pulse Test, Decay Part Only, Tracer Gas Concentrations

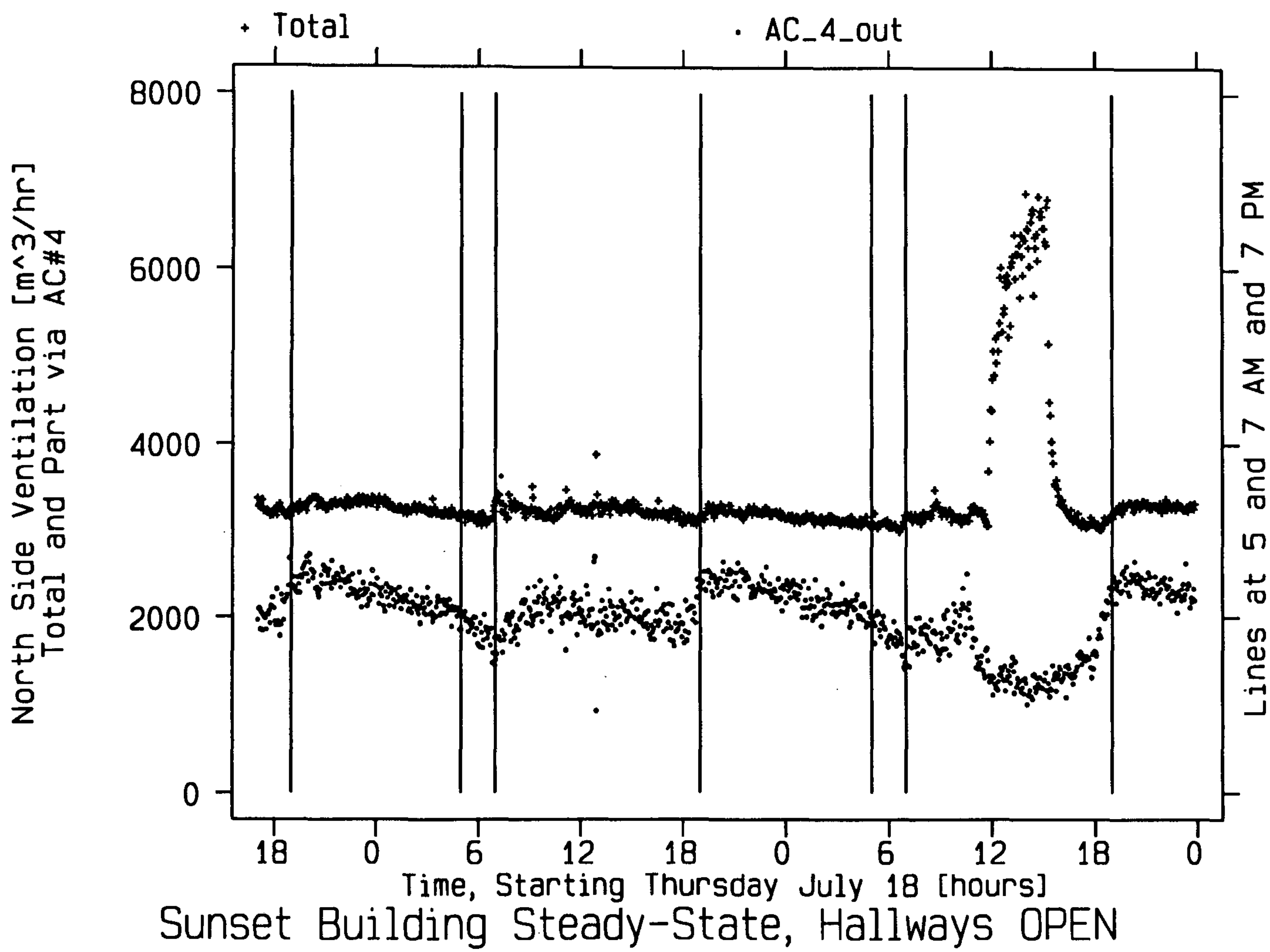

Figure 4.3 Steady-State North Side Ventilation

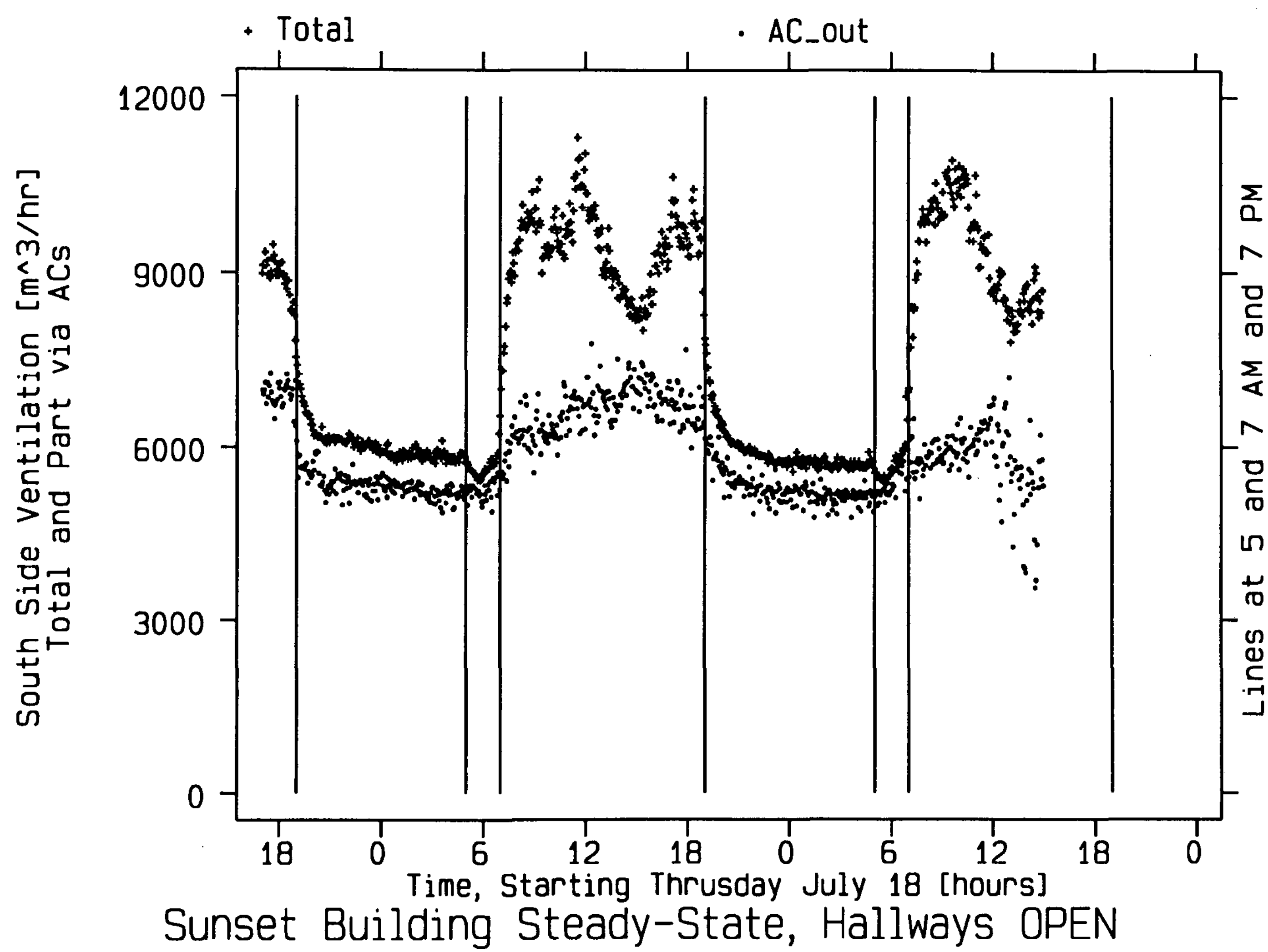

Figure 4.4 Steady-State South Side Ventilation

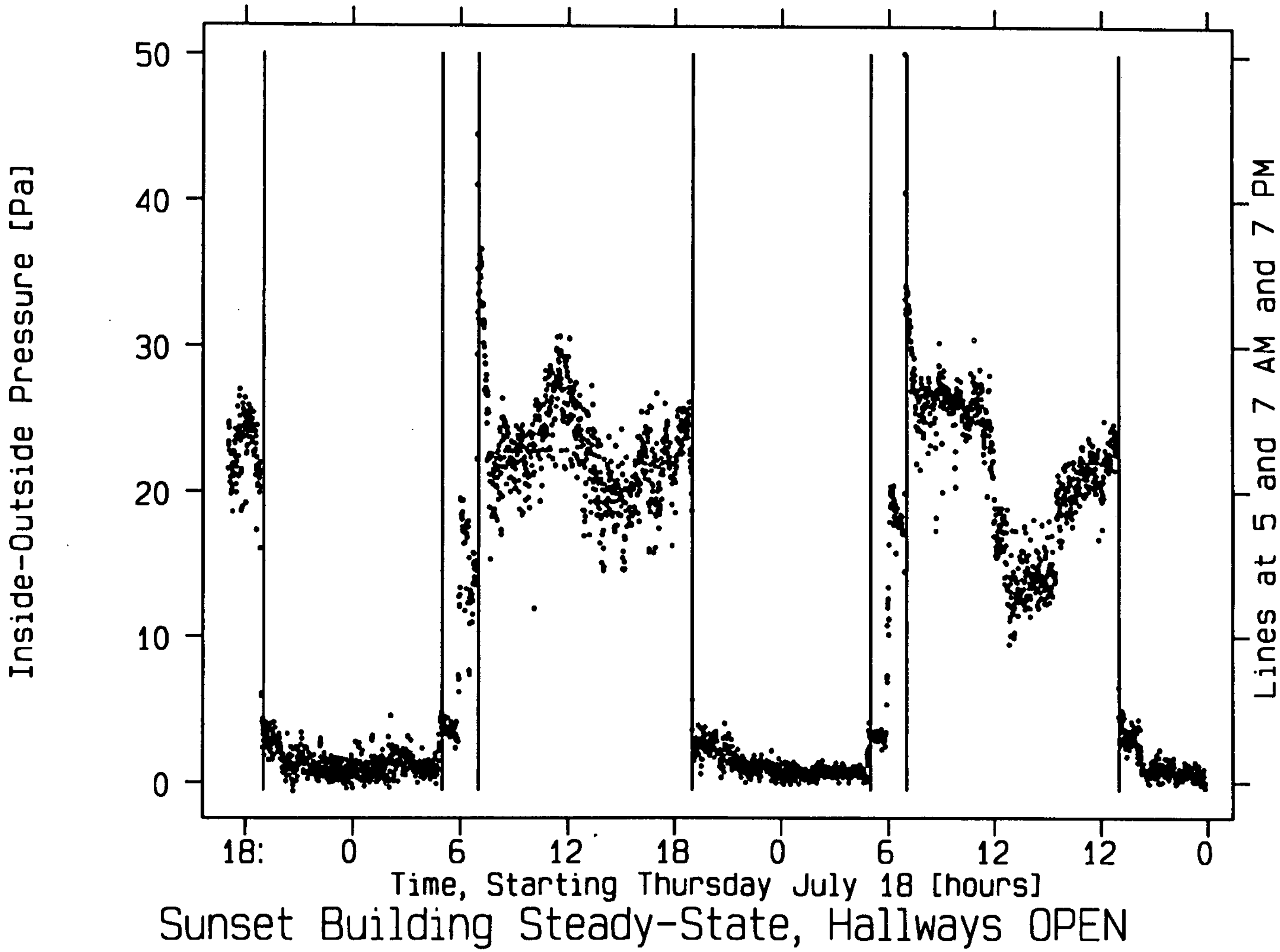

Figure 4.5 Steady-State Inside - Outside Reference Pressures

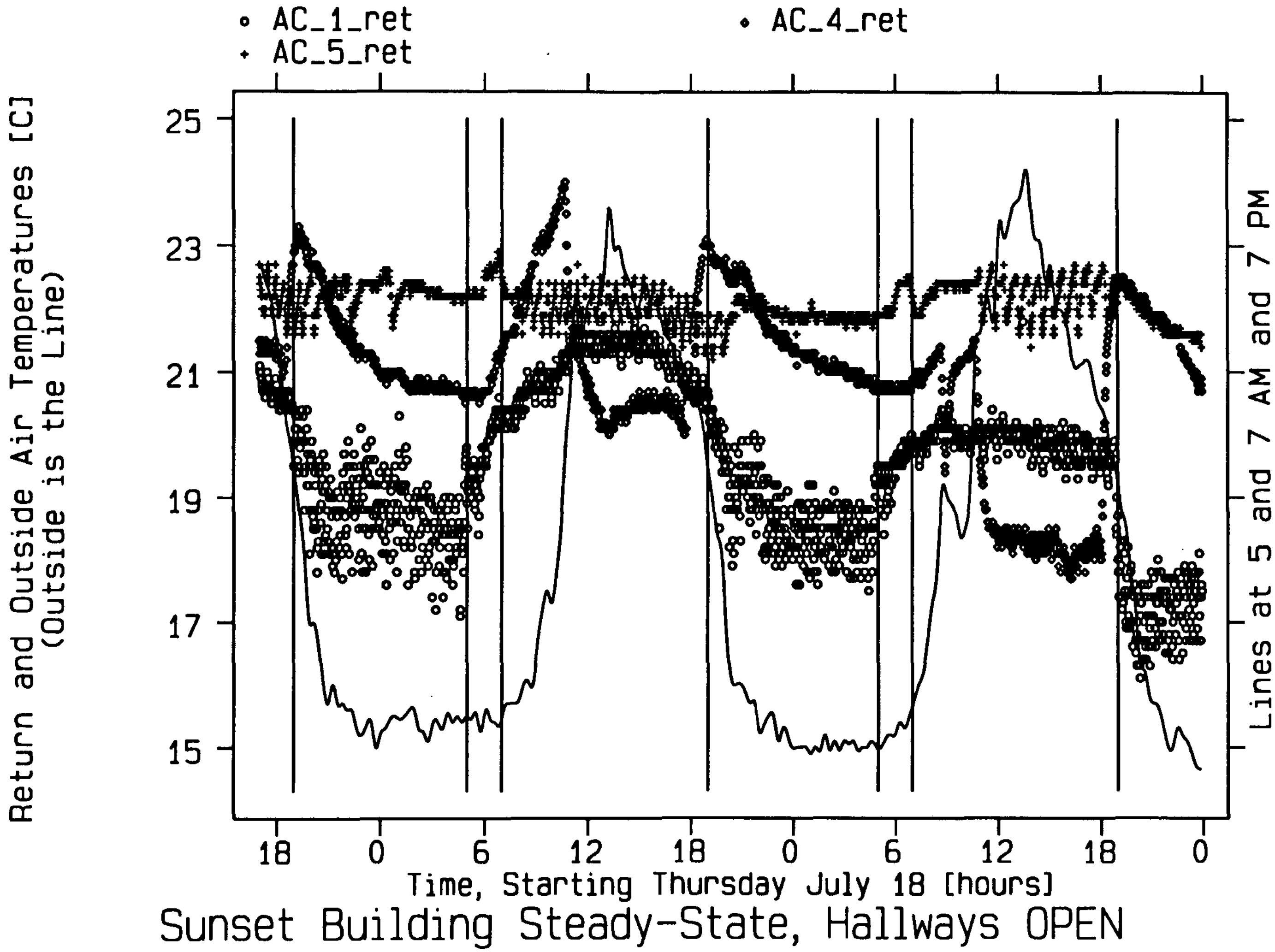

Figure 4.6 Steady-State Return Air Temperatures

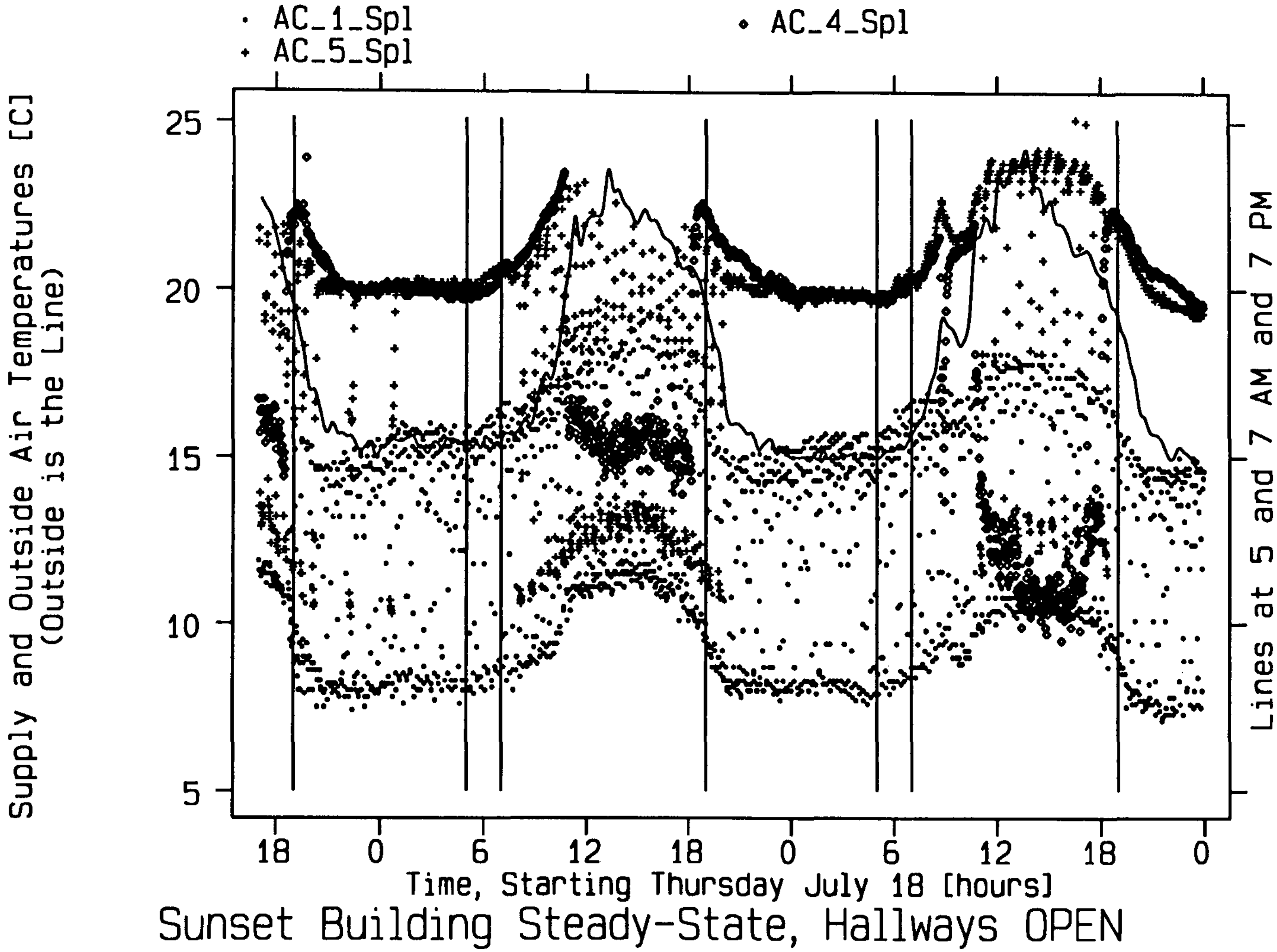

Figure 4.7 Steady-State Supply Air Temperatures
Temperatures Measured Just Downstream of the Cooling Coils

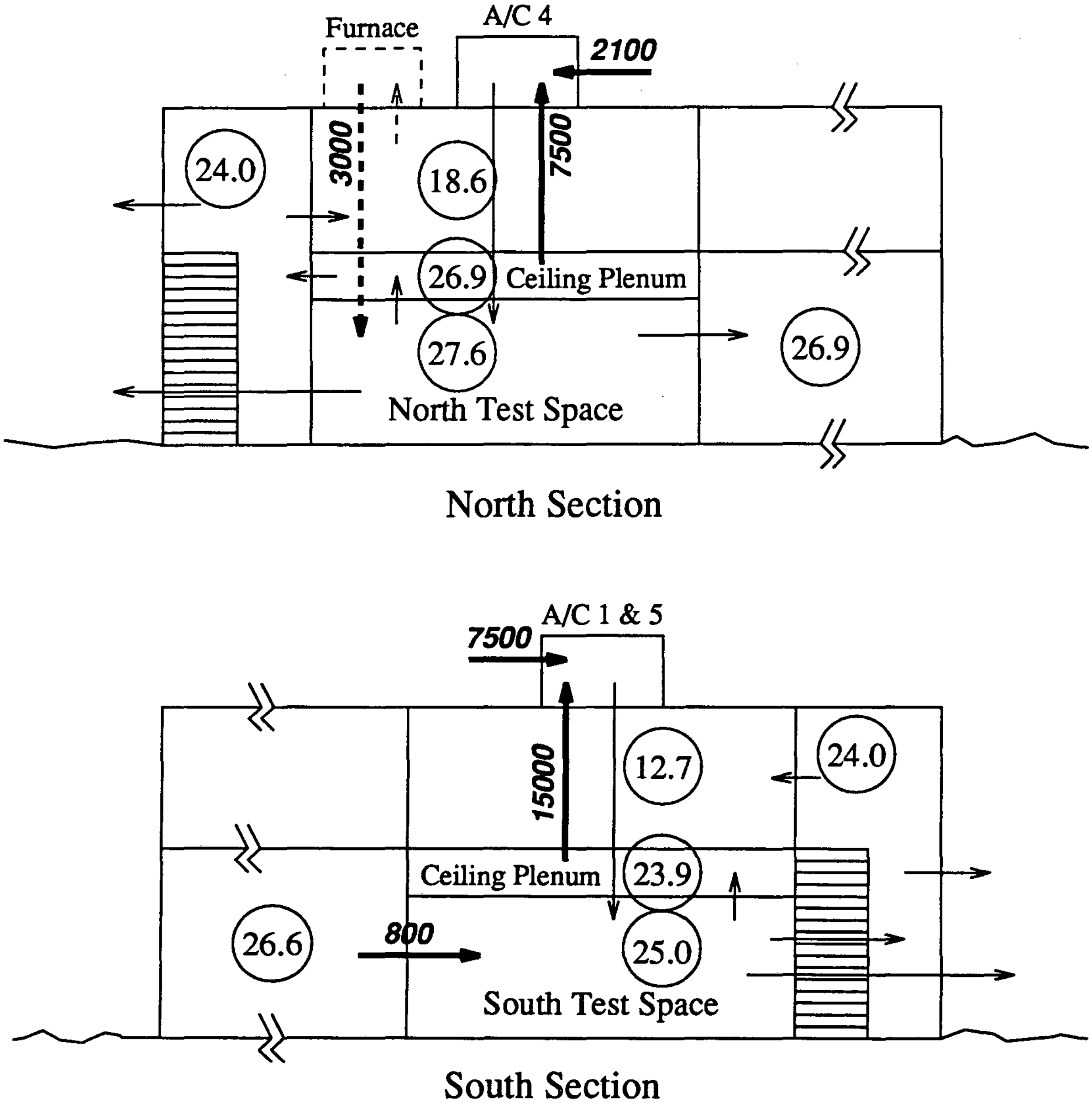

Figure 4.8 Typical inside air flow paths and pressures in the hallways-sealed configuration. Pressures, circled, are in Pascals. Flows, ***italicized,*** are in m^3/h. The dashed values show the inferred furnace flows.

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