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Air Leakage Measurements in a Mobile Home

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Center for Building Technology
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ABSTRACT

Air leakage measurements were made in a mobile home using sulfur hexafluoride (SF_6) as a tracer gas. The home was located in an environmental chamber where it was possible to measure and control the temperature outside the home. The effect on infiltration rate of a number of variables was determined. These included inside-outside temperature difference, simulated wind, installation of storm windows, opening of doors, and operation of the furnace fan. Experiments were also performed in which a fan was sealed to an opening in the house and inside-outside pressure difference measured as the fan blew air into or out of the structure at measured rates.

Key Words: Air infiltration measurement; air leakage measurement; mobile home tightness; sulfur hexafluoride tracer measurement

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1. Introduction

Air leakage is one of the means by which energy is lost by buildings. It is a function of building tightness, weather conditions, and other factors. This report describes some air leakage measurements of a mobile home located in an environmental chamber. The method for determining air leakage employs a sulfur hexafluoride (SF_6) tracer dilution technique.

In addition to tracer dilution measurements of infiltration, pressurization and depressurization measurements were made on the home. Stricker [1] and Tamura [2] describe experiments in which the inside-outside pressure differences of houses were measured when the houses were depressurized with a fan to give a measure of building tightness and to locate leaks. Slight variations of their procedure have been applied to the mobile home.

Mobile homes at present represent the fastest growing segment of the housing market. However, data on the energy utilization of this type of structure is meager. These air leakage measurements are a part of an FEA-sponsored study to evaluate energy utilization in a home built in accordance with ANSI Mobile Home Standard A119.1 (1974). The study was intended to provide a data base for developing energy conservation requirements for inclusion in the mobile home standard. This work was performed to assist the National Fire Protection Association Committee which developed Standard NFPA 501B, which was a prototype for ANSI A119.1. The main part of the study showing energy utilization in the mobile home is presented in a separate report. The present report considers the air leakage aspects of the problem.

2. Experimental Procedures

a. Description of Test House

The test house was a nominal 50 ft x 12 ft (15.2 m x 3.7 m) mobile home with a floor plan as shown in Figure 1. The floor area was 515 ft^2 (48 m^2) and the ceiling height 7 ft (2.1 m), giving a gross inside volume of about 3,600 ft^3 (102 m^3). The mobile home was equipped with storm windows which fitted inside of louvered jalousie-type windows rather than outside where storm windows are normally placed. The combined window area was about 65 ft^2 (6 m^2), or approximately 12 percent of the floor area or 3 1/2 percent of the total floor, ceiling, and wall area. Cabinets and closets represented about 6 1/2 percent of the gross internal volume of the living space. There was also an airspace between the ceiling and roof which is estimated to represent another 5 or 6 percent of this volume.

The home was heated by a gas furnace with a forced warm air distribution system leading to the rooms. The locations of the floor registers are shown in Figure 1. The furnace drew combustion air from a duct leading from the roof and did not communicate directly with the living space.

The home was placed in an environmental chamber of 70,000 ft^3 (1,980 15 m^3) volume, and the inside and outside temperatures were controlled and measured. A number of views of the home are shown in Figures 2, 3, and 4. The skirt around the lower part of the structure was absent during the earlier tracer tests in which infiltration rate as a function of inside-outside temperature difference was measured. Measurements of the effect of operating the furnace fan on infiltration rate were made after the skirt was installed.

b. Infiltration Measurements

An amount of SF_6 tracer gas (usually 1 ml or less) was introduced into the furnace fan and distributed throughout the house. Tracer concentration was measured as a function of time using a gas chromatograph equipped with an electron capture detector, and infiltration rate was estimated from the rate of dilution of the tracer. Samples were introduced into the chromatograph by means of an automated sampling system and measured within a few seconds. The system has been described previously [3].

Replicate samples were collected every 10 minutes through a network of 1/8 in. (0.32 cm) ID tubes of equal length leading from each room (network sampling). Samples were also taken from one of the supply registers (supply sampling). In addition, samples were taken from the environmental chamber immediately outside the house from a point 2 1/2 ft (0.76 m) above ground level and just above the roof level as a check on outside concentration of tracer. This concentration must be small if reentry of tracer into the home is to be neglected.

Infiltration was calculated from tracer concentration measurements by the relationship:

$$\ln \frac{c_i}{c_{io}} = - \frac{v_o}{V} t = - \vartheta t \qquad (1)$$

where

c_i = indoor concentration of tracer at time t, in hours

c_{io} = initial concentration of tracer

v_o = rate at which outside air enters the structure

V = effective inside volume of the structure

ϑ = the infiltration rate, in air changes per hour

If the forces producing air leakage remains constant during the measurement interval, when ln c_i/c_{io} is plotted against time, the relationship calls for a straight line in which the negative slope is proportional to infiltration rate. A simple derivation of equation 1 is given elsewhere [4]. The model assumes complete mixing, and to approach this condition the furnace fan was operated continuously.

c. Fan Experiments

To simulate some of the effects of wind load, eight fans were directed against the rear side of the house from a distance of 5 ft (1.5 m). Four of the fans were 1/4-hp (187 watts output) 1,100-rpm pedestal fans with 27-inch (0.69 m) blades. Four were 1/3-hp (249 watts output) 1,725-rpm smoke ejector fans with 16-in. (0.41 m) blades. Some of the fans are shown in Figure 3.

d. Pressurization-Depressurization Experiments

To pressurize the home the kitchen exhaust fan was removed from its mounting, and a 1 1/2-hp (1.1 KW) centrifugal blower mounted outside was connected to the opening through a 1-ft (0.3 m) ID round flexible duct. To depressurize, the blower was placed inside the house and the process reversed. The delivery rate of the blower was controlled with a damper and measured by determining the pressure drop across a 6-inch (.15 m) calibrated orifice mounted on a short cylindrical duct 1 ft (0.3 m) long and 1 ft in diameter, which was attached to the blower intake. Pressure differences between the inside and outside of the home were measured with a Hook gage to an accuracy of about 0.002 in. W.G.

3. Results

a. Infiltration Rates and Inside-Outside Temperature Differences

Measured infiltration rates and average inside-outside temperature differences are given in Table 1. Most values were between 0.4 and 0.6 air changes per hour with a trend towards increasing infiltration rates with increasing temperature difference. The two methods of sampling (network and supply) gave results which were essentially in agreement, indicating that tracer distribution was nearly uniform. For computational purposes, the data have been fitted to an empirical linear regression equation. For network sampling the relationship was:

$$\mathcal{I} = 0.367 + 0.00560\ (T_i - T_o),\ \sigma = 0.070 \qquad (2)$$

where

T_i = average indoor temperature, °C

T_o = average outdoor temperature, °C

σ = standard deviation of the individual points from the regression line

For supply sampling the relationship was:

$$\vartheta = 0.356 + 0.00612\ (T_i - T_o),\ \sigma = 0.066\ , \qquad (3)$$

or a composite relationship for all the data was:

$$\vartheta = 0.362 + 0.00586\ (T_i - T_o),\ \sigma = 0.080 \qquad (4)$$

The data are also shown graphically in Figures 5 and 6. The random scatter of points may be seen by inspection of the graphs as well as from the standard deviations which are of the order of 0.06 to 0.08 air changes per hour. This represents the combined effect of imperfect mixing and sampling as well as instrumental errors. It is also believed that initial runs often tended to be more divergent than subsequent runs on any given day. This suggests that some marginal reduction in scatter might be obtained by increasing the warm-up time of the instrument and allowing more time for the tracer to distribute itself. The present procedure has been to allow at least an hour for instrument warm-up and 10 to 20 minutes for distribution of tracer throughout the house.

b. Fan Experiments

Infiltration rates obtained with the eight fans operating are given in Table 2 and are presented graphically in Figure 7. For purposes of comparison an average regression line corresponding to equation 4 is drawn in Figure 7. Most of the values with the fans operating were between 0.55 and 0.7 air changes per hour, about 0.1 to 0.3 air changes per hour higher than the average values with no fans operating.

The average air velocity with the fans operating was about 8 mi/hr as measured about 6 inches from the house with a hot-wire anemometer. This was an average of a 46-point scan. It should be pointed out that fans directed against the side of the house do not simulate all of the effects of a natural 8 mi/hr wind. However, the experiment demonstrates that infiltration rates were increased by this air movement.

c. Effect of Storm Windows

Four infiltration measurements were made with the storm windows installed, both with and without the outside fans operating. The results are summarized in Table 3, and they are also included in Figure 7. The effect of storm windows on infiltration rate was quite small.

d. Tracer Measurements With Doors Open

As noted in Tables 1 and 2, there were brief door openings during some of the measurements. This raises the question of how much door opening influences infiltration rate. The problem is also of interest from the point of view of fuel economy. To obtain an approximate estimate of this effect, measurements were made with one or both doors left open. It should be pointed out that a high degree of precision was not obtained under these conditions, because at high infiltration rates the mixing of tracer could not keep pace with the rate of infiltration. However, the assumption was made that the rate of decrease in tracer concentration during the first 3 to 5 minutes of the measurement reflected the true infiltration rate. The rationale for this assumption is that, for a given infiltration rate, plots of concentration vs. time for the cases of perfect mixing and partial mixing nearly coincide in the early stages of the air exchange process [4]. Under this assumption air exchange rates of the order of 2 to 4 air changes per hour were obtained with the front door open. This is roughly 4 to 8 times the normal rate. For a 3,600 ft^3 (102 m^3) house this corresponds to 120 to 240 cfm (0.057 to 0.113 m^3/sec). With both doors left open and with the outside fans operating air exchange rates as high as 2,000 cfm (2.94 m^3/sec) were estimated. Thus, with doors left open air exchange could be a major part of the heating load.

While an open door may have a dominant effect on the infiltration rate, the normal opening and closing of a door in entering and leaving a building may be small. If as a first approximation it is assumed that the observed air leakage rate is a weighted average of the rate during the fraction of time the door is open and the fraction of time it is closed, it may be expressed by the relationship

$$\mathcal{I} = \frac{\mathcal{I}_o t_o + \mathcal{I}_c t_c}{t_o + t_c} , \qquad (5)$$

where

$\mathcal{I}_o$ = infiltration rate during the time, t_o, when the door is open

$\mathcal{I}_c$ = infiltration rate during the time, t_c, when the door is closed

If it is further assumed that the average duration of a door opening is about 4 seconds, this represents about 0.1% of an hour. Thus, in terms of the weighted average assumption the effect of a single door opening would be less than the normal statistical variation of the infiltration measurements. While equation 5 may underestimate the effect of intermittent door openings, empirical evidence supports the view that their effect is usually small.

e. Effect of Furnace Fan on Infiltration Rate

The infiltration rates presented in Figures 5, 6, and 7 were determined with the furnace fan operating continuously in order to eliminate fan cycling as a variable and to achieve good mixing. Comparisons were also made between continuous fan operation and no furnace fan to determine the contribution of the fan to infiltration rate. When the furnace fan was off, mixing was achieved with floor fans placed in the various rooms, and an axial fan with a length of flexible duct, 1 ft (0.3 m) OD, was used to bring air from the rear bedroom to the kitchen-living area. The results of the comparison are presented in Table 4. Since this was primarily a test of the effect of the fan, the furnace was off and inside-outside temperature differences were of the order of 2 or 3 C.

Comparing the average infiltration rate with the furnace fan on and off from the data in Table 4, an estimate of the average contribution of the furnace fan of about 0.3 air changes per hour is obtained. This may slightly overestimate the effect of the furnace fan, because, as noted in the footnote to the table, the measurements were made with the grille off of the furnace compartment allowing the fan to move more air than normally. If the fan-off condition is compared with the results in Figures 5 and 6, an estimate of the order of 0.2 air changes per hour is obtained.

An important path of air leakage when the furnace fan operated was through the airspace between the ceiling and the roof. This airspace opened to the outside through a vent at one end of the mobile home and opened into the furnace fan closet through an annular gap around the chimney. Thus, it provided an almost unobstructed path from outdoors to the furnace fan intake. When SF_6 was introduced into the outside vent, measurable concentrations appeared in the house within seconds. Thus, the infiltration values shown in Figures 5, 6, and 7 represent the additive effect of this fan-induced leakage plus normal leakage through various cracks in the structure which is partly due to the stack effect.

Another suspected source of air leakage was through the joints in the furnace ducts under the house. During infiltration measurements, air samples from under the house were monitored regularly for SF_6. None was found. This suggests that furnace ducts plus the sheeting under the house which protects them from direct exposure to the outside, were not a major source of air leakage. It also suggests that the predominant direction of air movement through the structure was upward even at the small inside-outside temperature difference of 2 to 3 C.

f. Tracer Estimate of Effective Indoor Volume

In addition to use of SF_6 to measure air infiltration, the tracer gas was also used to estimate the effective inside volume of the home. The gross inside volume of 3,600 ft^3 (102 m^3) noted previously was based on floor area and ceiling height. It did not consider the volume occupied by furniture, cabinets, or any poorly accessible volumes. However, by introducing a measured amount of SF_6 and distributing it throughout the house, it is possible to estimate the effective internal volume of the house from the average initial tracer concentration. Four repetitions of this procedure on different days, using both network and supply sampling, resulted in an estimate of 3.1×10^3 ft^3 (88 m^3) as the effective internal volume of the house. The standard deviation of the measurement was slightly less than 0.3×10^3 ft^3 (9 m^3).

g. Pressurization-Depressurization Experiments

The results of pressurization and depressurization experiments are shown in Table 5 and presented in log-log plots in Figures 8 and 9. Figure 8 also shows the effect of installing storm windows. There is evidence of some increase in flow resistance at higher flow rates due to the storm windows, but the effect is small and not consistent over the entire range. This would tend to support the observation based on tracer measurements that the installation of storm windows produced little if any reduction in air leakage. It is to be noted in Table 5 that when flow rates were expressed in air changes per hour, these values were much higher than those plotted in Figures 5 and 6. An air change rate of 0.5 air changes per hour, if achieved by depressurizing the building, would correspond to an extrapolated inside-outside pressure difference of the order of 0.004 in. W.G. (1 N/m^2).

The effects of pressurization and depressurization are compared in Figure 9. It may be seen that small differences exist. The pressurization experiment showed that one of the leakage paths was around the perimeter of the structure where the base trim meets the external aluminum wall covering. When the fan was blowing into the building, air leakage could be felt all around the lower portion of the wall.

Stricker [1] and Tamura [2] have described fan depressurization of homes for measuring building tightness. This technique shows promise as a possible means of quality control of factory-built homes. As a matter of technique, it was also observed that pressurization may have some advantage over depressurization in that steady-state conditions were reached more rapidly when air was forced into the home. On the other hand, depressurization may be more suitable to apply in an occupied home, because it is less intrusive to the occupants.

4. Summary

Air infiltration measurements of a mobile home were made in an environmental chamber under controlled temperature conditions. When wind velocity was negligible, it was found that infiltration, $\mathcal{I}$, could be approximated by the relationship:

$$\mathcal{I} = 0.362 + 0.00586\,(T_i - T_o), \quad \sigma = 0.069$$

where T_i and T_o are inside and outside temperatures, respectively, and σ is the standard deviation.

When fans were directed against the house, the approximation was:

$$\mathcal{I} = 0.579 + 0.00298\ (T_i - T_o),\ \sigma = 0.080$$

The foregoing estimates were made with the furnace fan in continuous operation. In separate experiments it was estimated that furnace fan operation contributed about 0.2 air changes per hour on the average. An important leakage path was an annular gap around the chimney which linked the ventilated airspace above the ceiling to the furnace fan intake.

Installation of storm windows did not have an appreciable effect on air infiltration rate as determined by tracer measurement.

Pressurization-depressurization experiments were made in which the pressure difference between the inside and outside was measured with a Hook gage while air was forced into or out of the house with a fan. This test also showed that the effect of storm windows was small. When air was forced into the house, noticeable leakage was observed all around the perimeter of the structure where the base trim meets the external aluminum wall covering. Pressurization-depressurization measurements may have value for quality control of factory-built housing.

5. Metrication

English and metric units have been used in this report. For purposes of interconversion, some appropriate factors are given:

feet (ft) x 0.3048 = meters (m)

square feet (ft^2) x 0.09294 = square meters (m^2)

cubic feet (ft^3) x 0.02832 = cubic meters (m^3)

miles per hour (mi/hr) x 26.82 = meters per minute (m/min)

inches of water (in. W.G.) x 249.1 = Newtons per square meter (N/m^3)

6. Acknowledgment

This work is part of a work effort sponsored by FEA to provide base data for developing energy conservation requirements for mobile homes.

The authors are indebted to Mr. DeWitt R. Showalter for his valuable assistance in setting up some of the apparatus used in the measurements.

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[3] Hunt, C. M., and Treado, S. J., "A Prototype Semi-Automated System for Measuring Air Infiltration in Buildings Using Sulfur Hexafluoride as a Tracer", National Bureau of Standards Tech. Note 898, (March 1976).

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Table 1 Infiltration Rate of Mobile Home Under Conditions of Negligible Wind Velocity

Average $T_i - T_o$ °C		Run	Infiltration Rate Air Changes Per Hour Network Sampling	Supply Sampling
4.1	October 16	1	0.40	0.40
4.5	October 4	1	.52	.50
5.5	October 16	2	.38[a]	.38[a]
5.6	October 4	2	.34	.30
19.7	September 20	1	.44	.44
21.8	October 10	1	.49	.52
22.5	October 10	2	.39	.42
30.0	September 24	1	.49	.49
30.0	September 24	2	.59	.60
34.4	September 25	1	.57	-
39.0	September 27	1	.70	.70
39.5	September 24	4	.53	.53

[a] Brief door openings during these measurements.

Table 2 Infiltration Rate of Mobile Home With External Fans Simulating Wind Load

Average $T_i - T_o$ °C		Run	Infiltration Rate Air Changes Per Hour Network Sampling	Supply Sampling
4.5	October 15	1	0.65[a]	0.61[a]
5.1	October 15	2	.56	.54
21.5	October 9	1	.82	.75
21.9	October 9	4	.56	.56
22.4	October 9	3	.58	.60
22.7	October 9	2	.65[a]	.65[a]

[a] Brief door openings during these measurements.

Table 3 Infiltration Rate of a Mobile Home With Storm Windows Installed

Average $T_i - T_o$ °C		Run	Infiltration Rate Air Changes Per Hour Network Sampling	Supply Sampling
22.7	October 24	1	0.66[a]	0.67[a]
23.1	October 24	2	.63[a]	.63[a]
38.3	September 27	2	.64[b]	.64[b]
38.8	September 27	3	.57[b]	.52[b]

[a] Outside fans on, storm windows and doors sealed.

[b] Outside fans off, storm windows and doors not sealed.

Table 4 Effect of Furnace Fan Operation on Infiltration Rate

	Infiltration Rate Air Changes Per Hour	
	Furnace Fan On[a]	Furnace Fan Off
	-	0.19
	0.64	.19
	.46	.17
	.47	.24
	.59	.13
	.48	-
	.40	.19
average	0.51	0.19
	σ = 0.09	σ = 0.04

[a] The grille over the fan compartment was removed to make wiring changes and was off during these measurements. This allowed the fan to move more air than normally.

Table 5 Flow Rate as a Function of Inside-Outside Pressure Differences for Mobile Home

	Flow Rate (cfm)	Inside-Outside Pressure Difference (in. W.G.)	$\mathcal{I}$ Air Changes Per Hour[a]
Inside Pressure Negative, Storm Windows In	380	0.054	7.4
	445	.075	8.6
	530	.091	10.3
	620	.117	12.0
	650[b]	.115	12.6
	840[b]	.175	16.3
Inside Pressure Negative, Windows Out	310	0.050	6.0
	480	.090	9.3
	560	.087	10.8
	622	.097	12.0
	635[b]	.102	12.3
	830[b]	.148	16.1
Inside Pressure Positive, Storm Windows In	180	0.025	3.5
	388	.061	7.5
	582	.099	11.3
	600[b]	.104	11.6
	800[b]	.142	15.5

[a] $\mathcal{I} = \frac{\text{cfm} \times 60}{3{,}100}$; 3,100 ft^3 (88 m^3) is an estimate of the "effective" indoor volume of the mobile home based on tracer dilution measurements.

[b] These flow rates measured with 7-inch (17.8 cm) orifice plate. All others measured with 6-inch (15.2 cm) orifice plate.

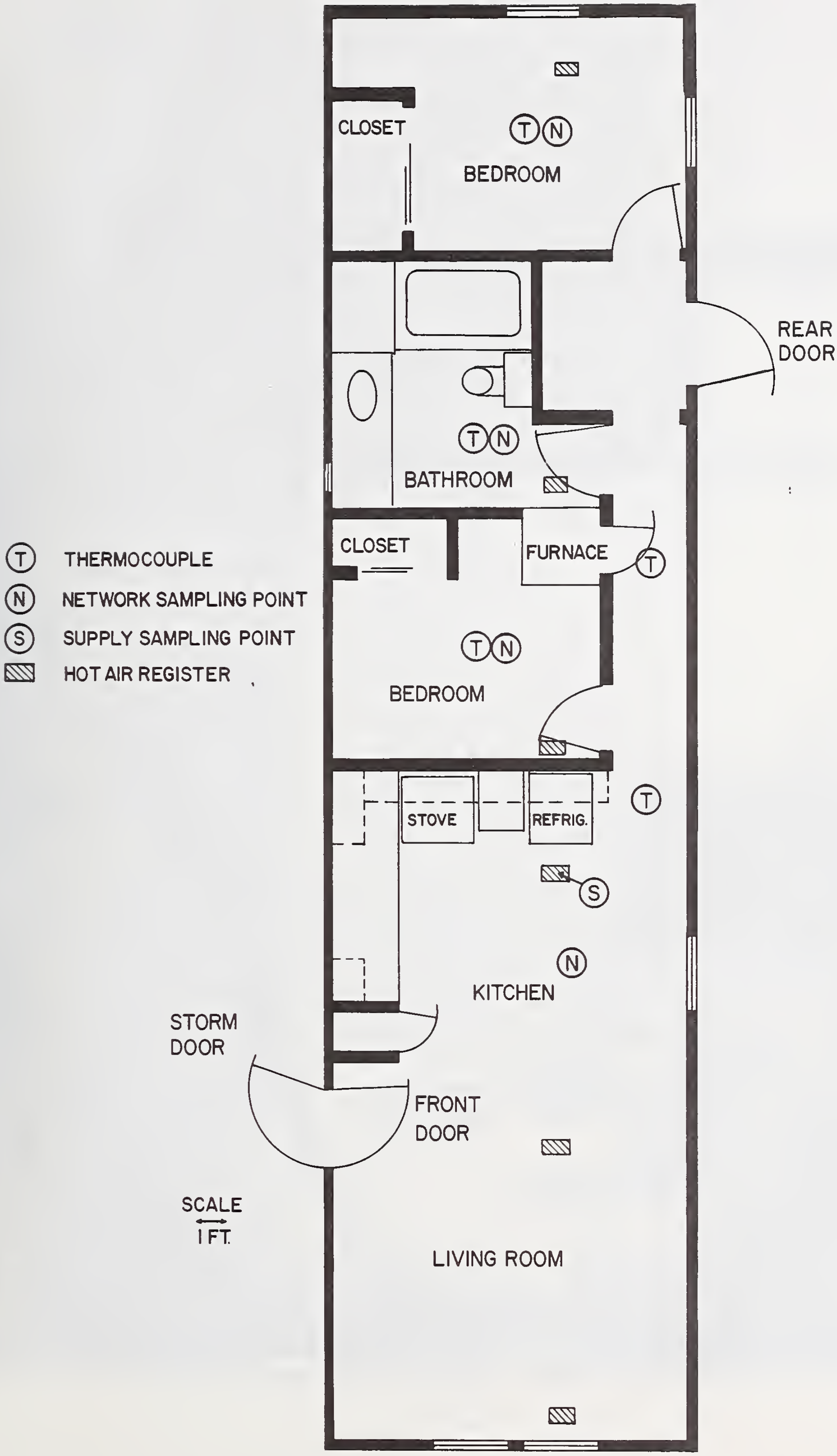

Figure 1 Floor Plan of Mobile Home

Figure 2 Front View of Mobile Home

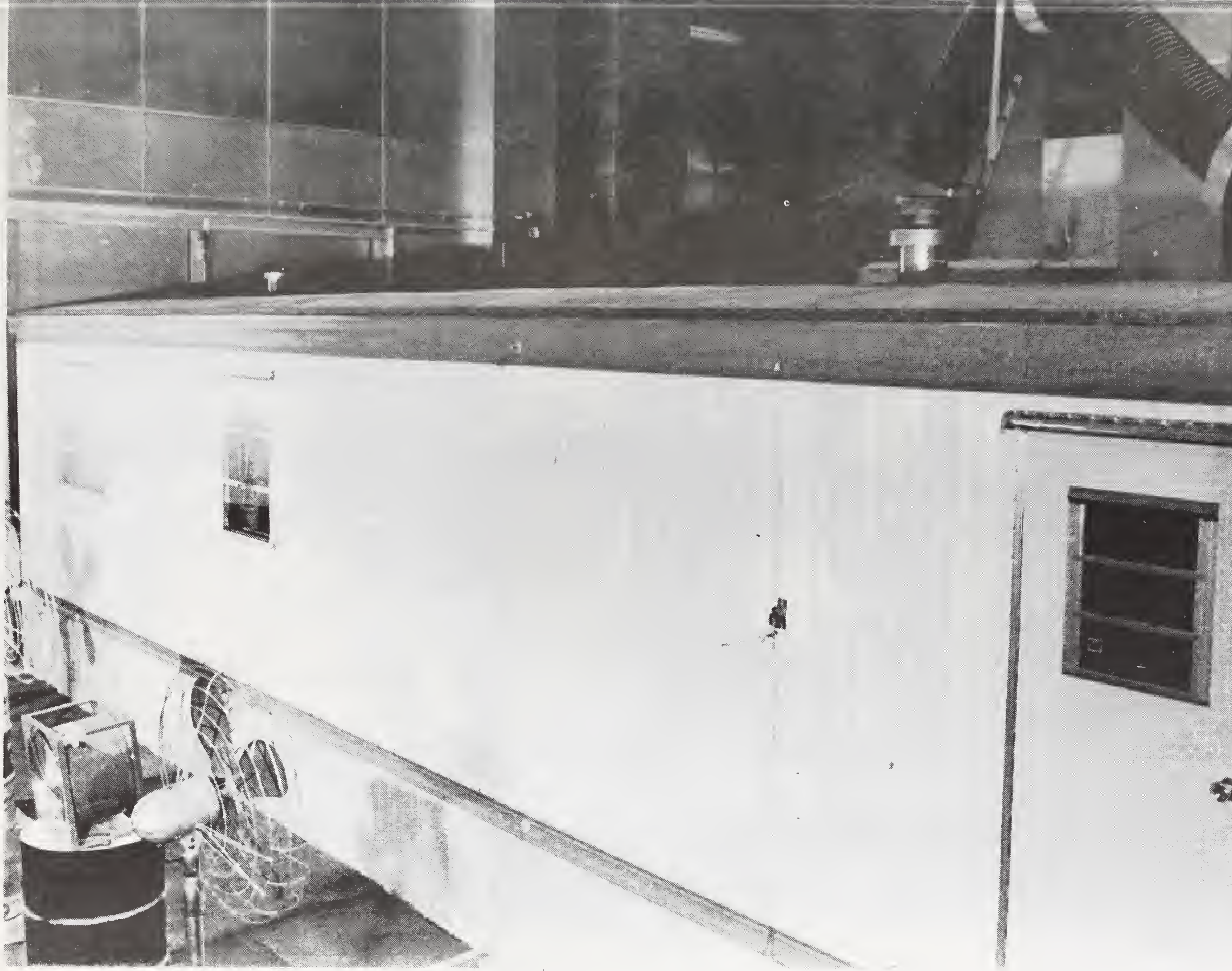

Figure 3 Rear View of Mobile Home

Figure 4 SF_6 Tracer Apparatus in Living Room of Mobile Home

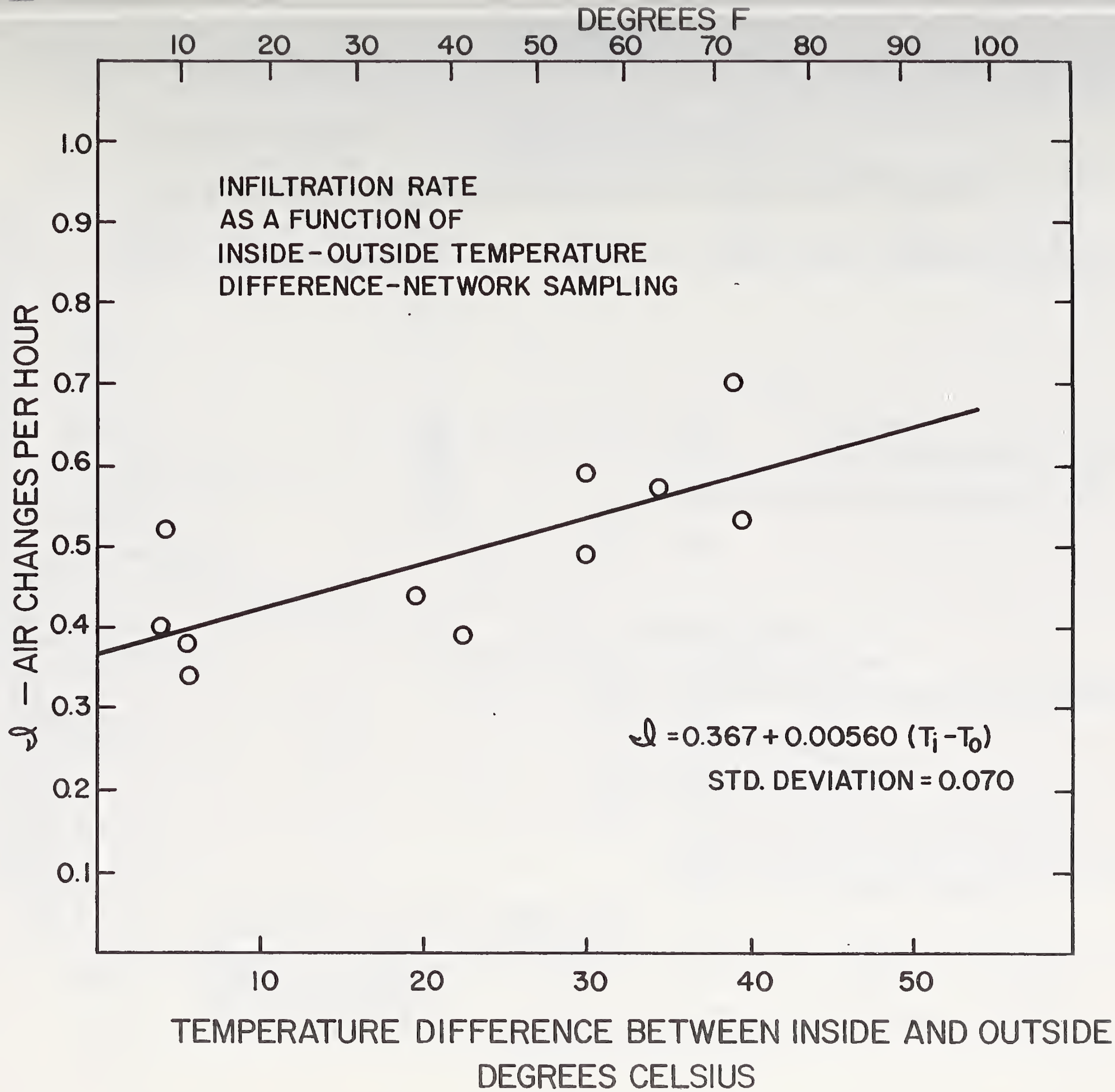

Figure 5 Infiltration Rate as a Function of Inside-Outside Temperature Difference - Network Sampling

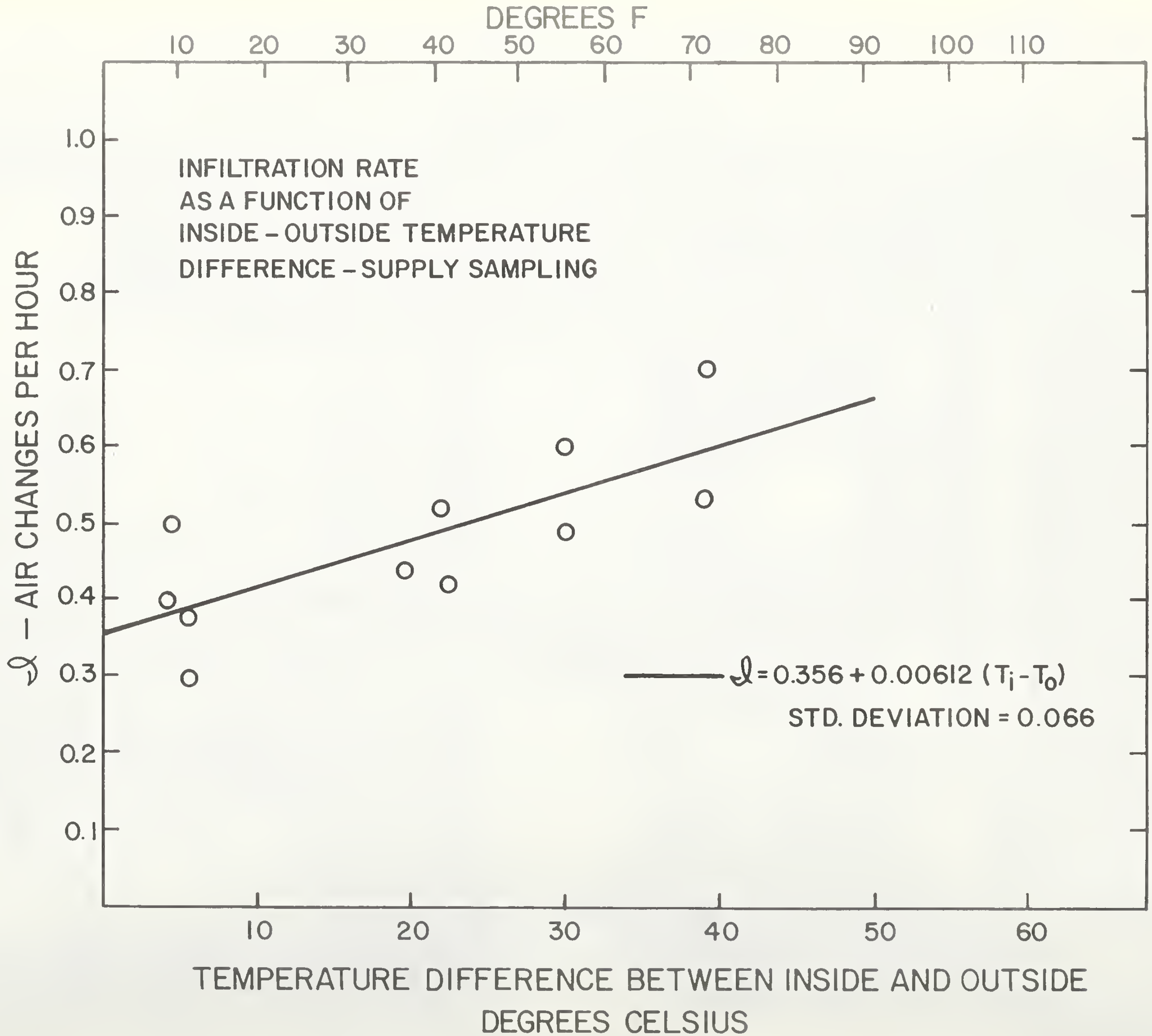

Figure 6 Infiltration Rate as a Function of Inside-Outside Temperature Difference - Supply Sampling

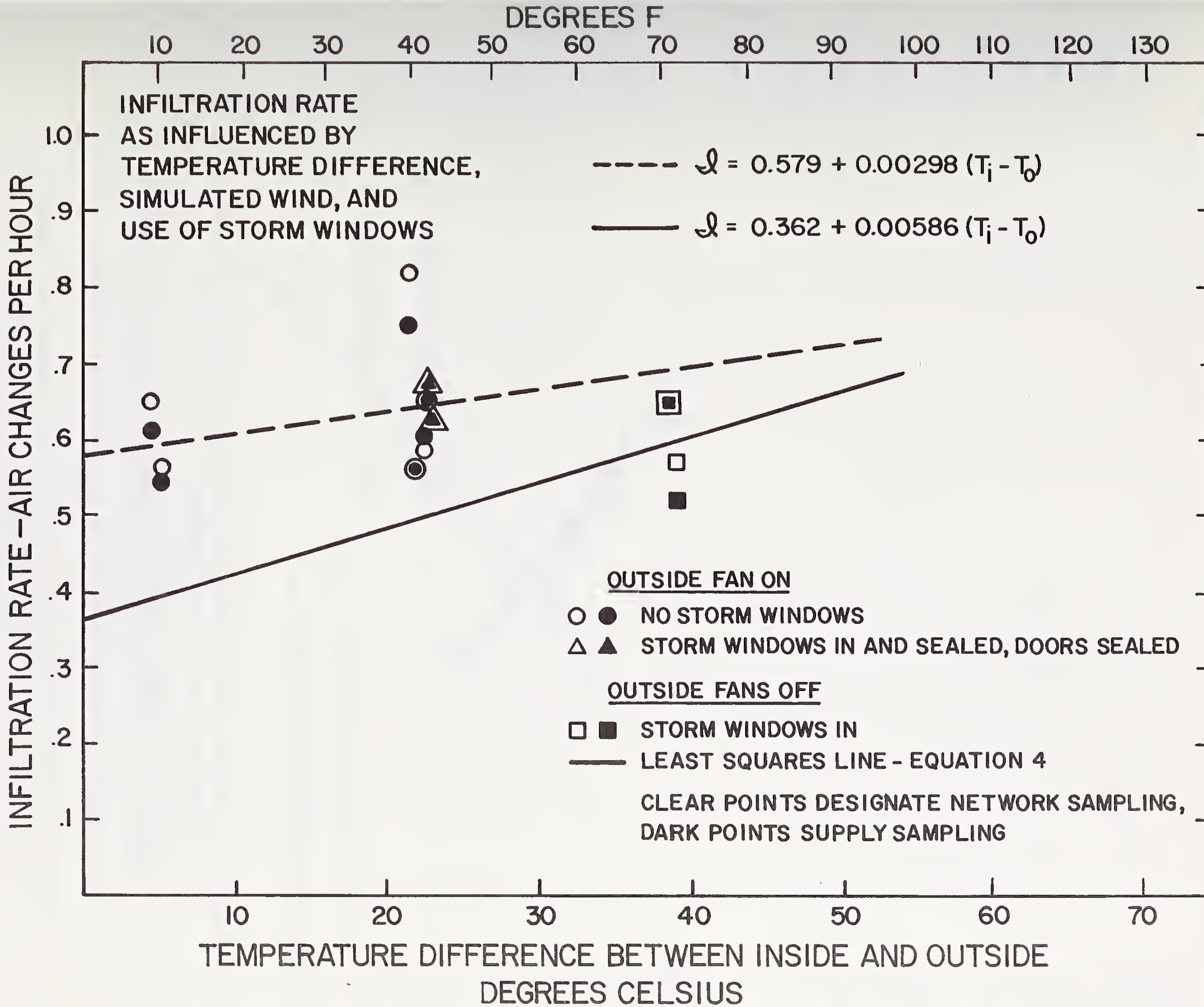

Figure 7 Infiltration Rate as Influenced by Temperature Difference, Simulated Wind, and Use of Storm Windows

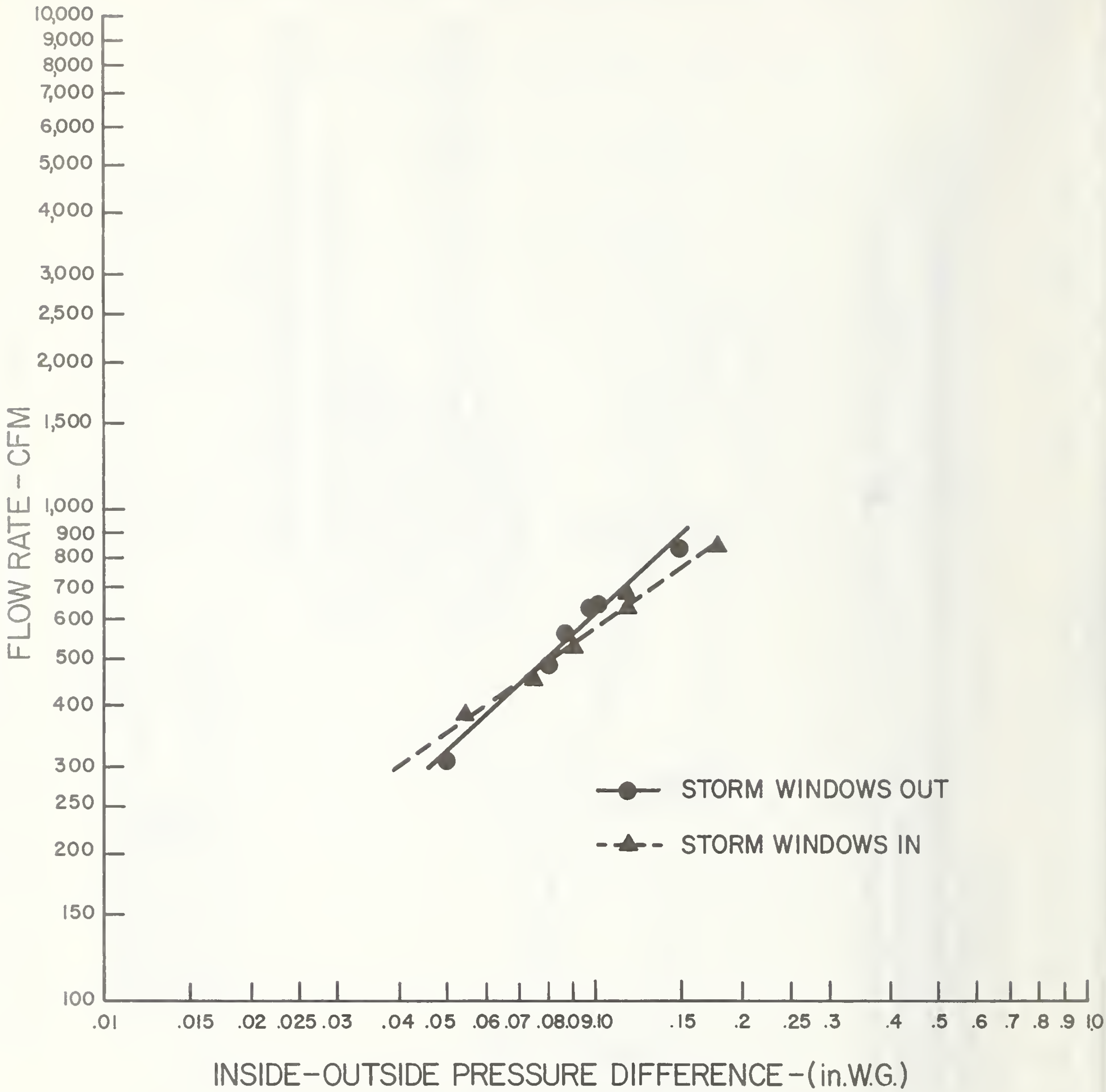

Figure 8 Effect of Storm Windows on Mechanically Induced Air Leakage - Pressure in Mobile Home Negative

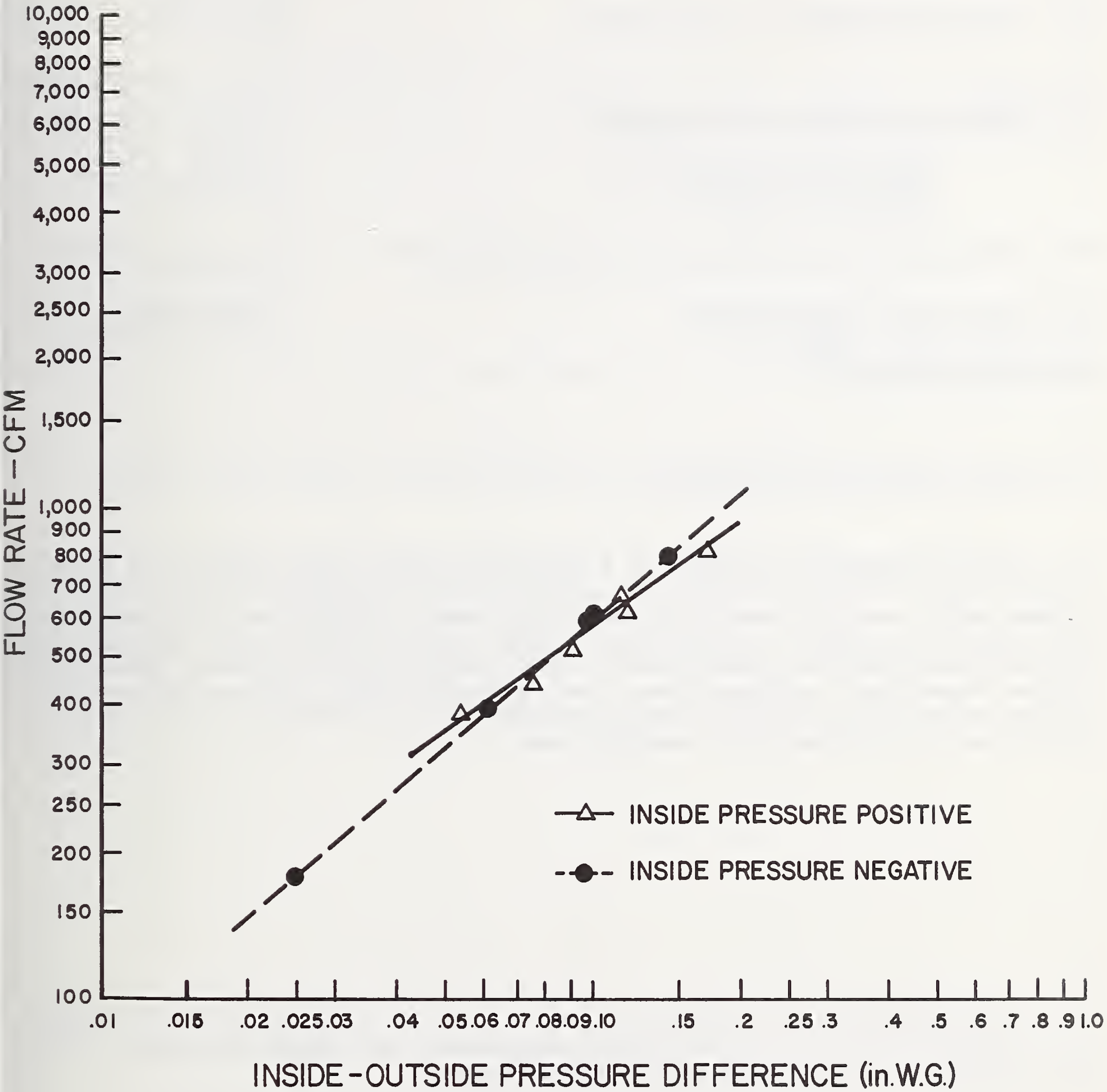

Figure 9 Comparison of Air Leakage Induced by Positive or Negative Pressurization of Mobile Home

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Air leakage measurements were made in a mobile home using sulfur hexafluoride (SF_6) as a tracer gas. The home was located in an environmental chamber where it was possible to measure and control the temperature outside the home. The effect on infiltration rate of a number of variables was determined. These included inside-outside temperature difference, simulated wind, installation of storm windows, opening of doors, and operation of the furnace fan. Experiments were also performed in which a fan was sealed to an opening in the house and inside-outside pressure difference measured as the fan blew air into or out of the structure at measured rates.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Air infiltration measurement; air leakage measurement; mobile home tightness; sulfur hexafluoride tracer measurement

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