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Impact of Heating and Air Conditioning System Operation and Leakage on Ventilation and Intercompartment Transport: Studies in Unoccupied and Occupied Tennessee Valley Homes

T. G. Matthews, D. L. Wilson, C. V. Thompson, K. P. Monar, and C. S. Dudney
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Forced-air heating and air conditioning (HAC) systems caused an average and maximum increase in air infiltration rates of 1.8- and 4.3-fold, respectively, during brief whole-house studies of tracer gas decay in 39 occupied houses. An average increase in air infiltration rate of 0.33 ± 0.37 h^{-1} corresponded to an incremental air leak of 240 m^3/h, based on approximate house volume. More detailed tracer gas decay studies were performed in basement, kitchen and bedroom locations of six homes with low air infiltration rates (i.e., <0.25 h^{-1}). The HAC mixed the indoor air efficiently between measurement sites. HAC operation also caused 1.1- to 3.6-fold increases in air infiltration rates, corresponding to absolute increases of 0.02 to 0.1 h^{-1}. In an unoccupied research house, three-fold increases in average air infiltration rate with HAC operation (i.e., from 0.13 to 0.36 h^{-1}) were reduced to two-fold (i.e., from 0.10 to 0.18 h^{-1}) by sealing the external HAC unit and crawlspace ductwork system. This sealing also resulted in a 30 percent reduction in crawlspace-to-indoor transport rates with the HAC turned on. Blower door tests indicated a <20 percent reduction in house leakage area.

The ventilation and mixing of air in residences strongly influences indoor air quality. Forced-air HAC systems can affect pollutant transport processes and resultant pollution concentrations by large-scale mixing of conditioned indoor air, and introducing air through leaks from outdoors and/or unconditioned locations (e.g., crawlspace or garage) within the residence. Although HAC systems account typically for only a small fraction of house leakage area (e.g., 0.14 in 50 homes[1] and 0.15 in 7 homes[2]), they have been demonstrated to have a significant effect on air infiltration rates.[2–4] Two-fold increases in air infiltration rates were observed in an earlier study of 31 homes in the Tennessee Valley with forced-air HAC operation.[2] The efficient delivery of conditioned air through HAC/ductwork systems is also of concern for energy conservation.[5]

Implications

The operation of residential heating and air conditioning (HAC) systems is shown to markedly enhance gaseous transport between the living area and the basement/crawlspace in 39 occupied houses and an unoccupied research house. The increased flow of air between conditioned and unconditioned space will increase energy costs for residential heating and cooling. In addition, air in basements or crawlspace is frequently enriched in radon, a precursor of radionuclides that are known human carcinogens. Therefore, HAC operation also leads to degeneration of indoor air quality in radon-prone areas. Development of products and/or building codes that result in lower incidence of leaky ductwork will promote energy conservation and public health.

Three studies have been performed to investigate the effect of HAC operation on air infiltration rates and inter-level mixing processes in single-family, detached houses located in the Tennessee Valley. In an unoccupied research house, detailed investigations were conducted of air infiltration rates plus transport between crawlspace and indoor compartments both before and after sealing the HAC/ductwork system (see Figure 1). In six occupied homes, continuous measurements of tracer gas decay were performed for 2 to 7 summer days in basement, kitchen and master bedroom locations with intermittent to continuous HAC operation. In 39 residences, brief comparisons were made of whole-house air infiltration rates when the central air handler was turned on and off.

Experimental Methods

The three-bedroom, unoccupied research house was conventionally constructed according to local building codes. It contained a crawlspace and approximately 110 m^2 floor area on a single indoor level. Transport of tracer gases between the crawlspace and indoor levels was studied by simultaneously injecting Freon 12 into the crawlspace and carbon monoxide (CO) into the indoor living area. Immediately after injection, the tracer gases were mixed for about 2 min on each level. Tracer concentrations were then continuously monitored on both levels for >8 h. Air samples were collected sequentially from four monitoring locations, one in each corner of the house. Considering a clockwise rotation between sampling points, locations 1 and 3 were indoors, and 2 and 4 were in the crawlspace. Tracer gas concentration data were acquired once per minute for 20 min at each monitoring location. Inter-level transport measurements were performed separately with the HAC turned on and off in periods both before and after the sealing of the air leaks in the HAC system.

The basic experimental design of the inter-level transport experiments is illustrated in a 21-h segment of data in Figure 2. At time zero, Freon 12 was injected inside the crawlspace and CO was injected upstairs. HAC operation resulted in uniform exponential decays in Freon 12 concentration at two monitoring locations in the crawlspace and in CO concentration at two indoor locations. The rapid rise of CO in the crawl-

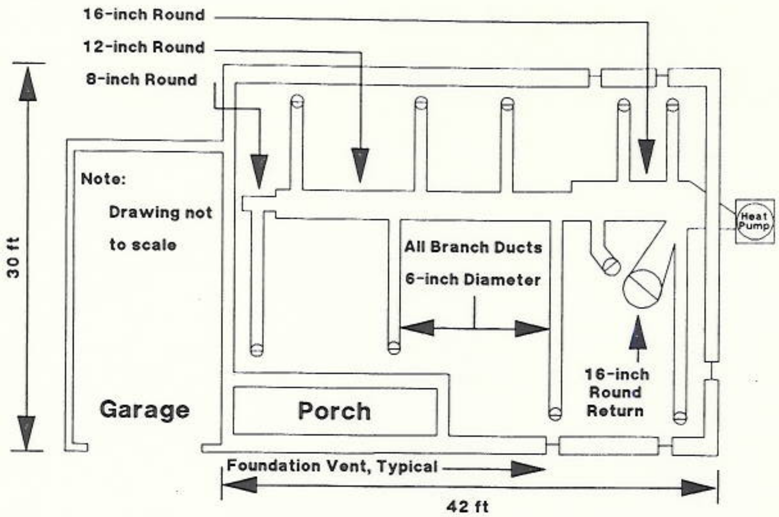

Figure 1. Crawlspace supply and return ductwork at the unoccupied research house.

tion and mixing of Freon 12 was made whenever levels dropped below a response of 5 percent full scale on the spectrometer. This experimental design is illustrated in a 22-h segment of data in Figure 3 for House 917. Tracer gas injections and mixing occurred at hours 37 and 46 at all three monitoring locations, followed by fairly uniform decay in tracer gas concentrations.

The experimental design and homeowner controlled use of the HAC system strongly influenced the analysis of the tracer gas decay data. The resolution interval for all air infiltration calculations in the six house studies was 100 min. (Since 20-minute measurements were sequentially performed at three indoor and one outdoor (i.e., blank) sites, sequential data acquisition intervals at a single site spanned

space and of freon indoors indicated HAC enhanced transport between indoor and crawlspace locations.

Air leaks in the HAC system were thoroughly investigated in both the outdoor heat pump unit and the supply and return ductwork systems located in the crawlspace. The house (and to a lesser degree the HAC system) were depressurized with a blower door to observe smoke entering any leaky HAC joints. Principal leaks were found in (1) joints perpendicular to the main supply plenum; (2) joints to interior and exterior "boxes" for the supply and return air located near the heat pump; and (3) in the air exchanger inside of the outdoor heat pump unit. Sealants (i.e., duct tape and clay) were installed in a temporary fashion such that the house could be returned to its original condition at the end of the study.

Blower door measurements of whole-house leakage area were performed both before and after the sealing of the air leaks in the HAC system. The impact of the HAC system on the measured leakage areas was evaluated by temporarily plugging and taping the ductwork vents from indoors. For all blower door measurements, interior doors were opened, exterior doors and windows were closed, and bathroom and kitchen exhaust fans were sealed.

Continuous monitoring of air infiltration was performed in six occupied residences as part of a multicomponent, instrumented study of indoor air quality.[6] Freon 12 was automatically injected into multiple upstairs and basement locations and mixed briefly by automated operation of several 0.5 m fans (i.e., >300 m^3/min air flow). The decay in tracer gas concentration was then monitored with an infrared spectrometer for sequential 20 min intervals at single locations in the basement, kitchen, and master bedroom. Reinjec-

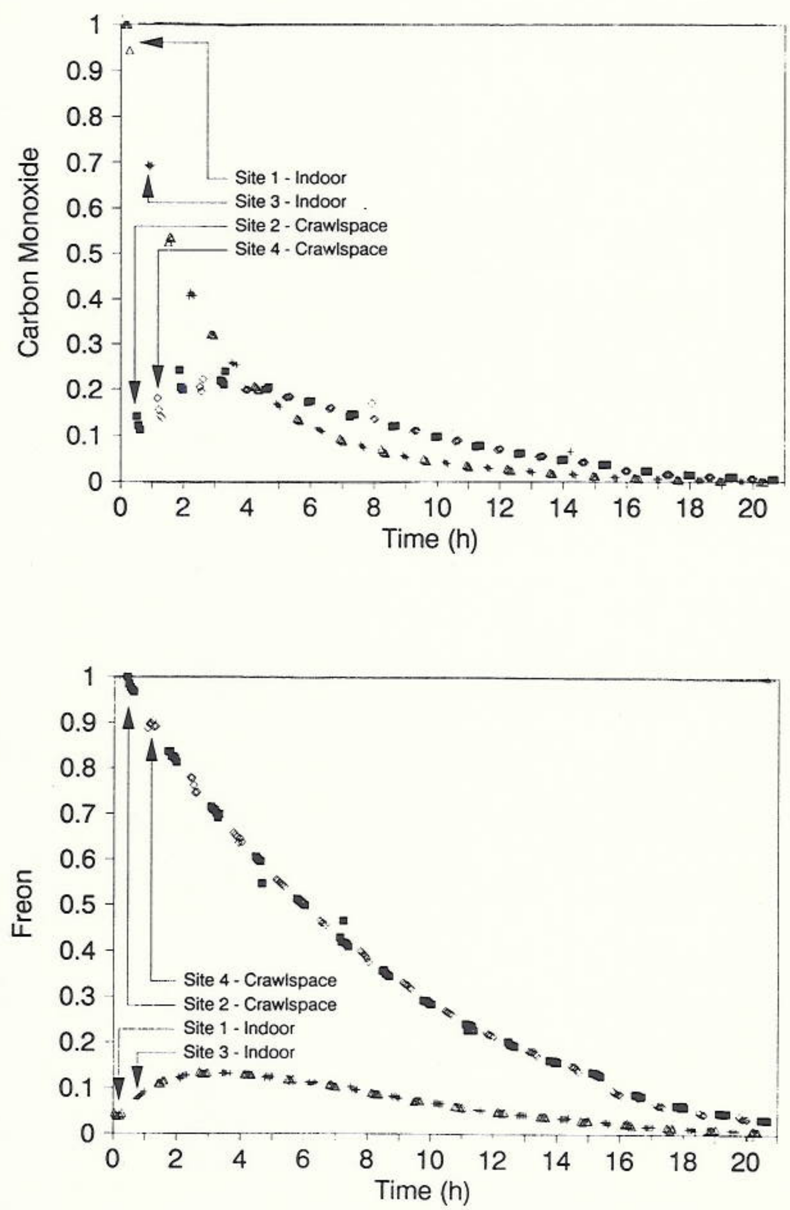

Figure 2. Intercompartment mixing data taken prior to sealing of the ductwork with the HAC turned on. Freon and CO were injected simultaneously and briefly mixed inside the crawlspace and upstairs living area, respectively. Freon and CO data are normalized to unity.

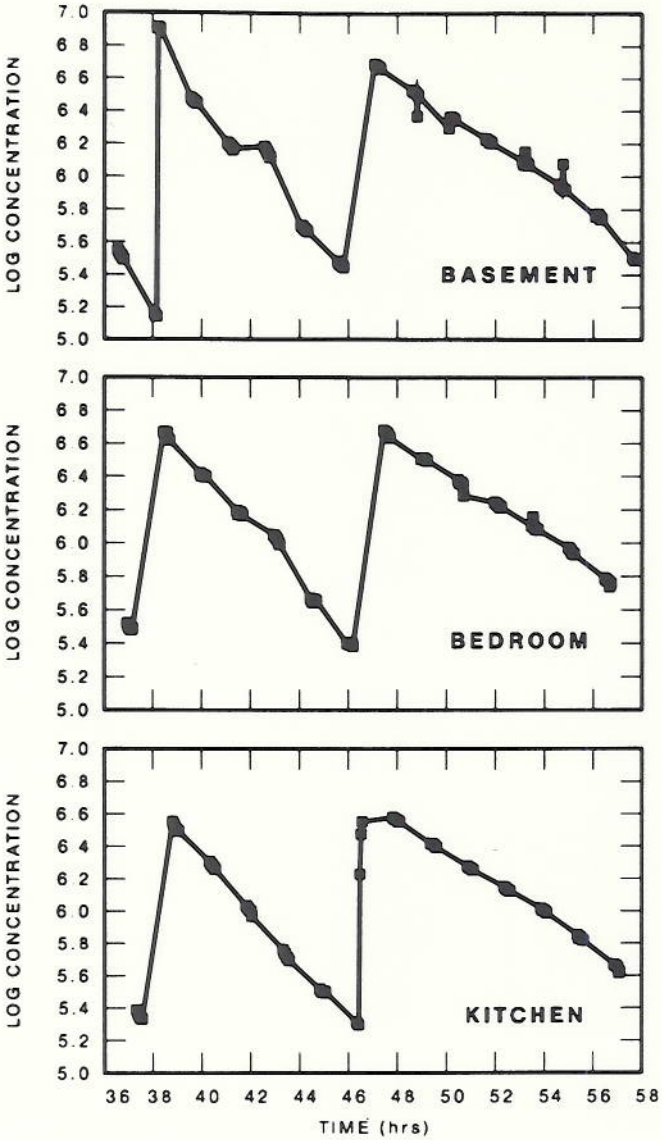

Figure 3. Tracer gas concentration records (i.e., log μvolts) at three locations inside House 917 during 22 hours spanning two days in August, 1985.

100 min). HAC operation was monitored with a temperature probe in the exhaust of a HAC supply duct. In Houses 922 and 942, the central air handler was operated continuously. In House 905 HAC on- and off-conditions could not be distinguished because of probe failure. For these houses, all available data was used to determine the average air infiltration rates at individual sites. In Houses 936, 958, and 917, HAC operation was intermittent and the HAC on- and off-periods were accurately recorded. For these houses a subset of data was used to isolate those 100-minute periods for each measurement site when the HAC was continuously on or off.

Air infiltration measurements in 39 occupied houses were performed by monitoring tracer gas decay for 30-min intervals with the HAC sequentially turned on and off. Initially, Freon 12 was injected into all conditioned compartments on upstairs, downstairs and basement floors (when available) and thoroughly mixed for about 5 to 10 min with seven 0.5 m fans (i.e., >300 m^3/min air flow) and the central air handler. The 0.5 m fans were left on during the entire decay experiment to minimize the impact of room-to-room variation in air infiltration rates. The decline in freon concentration was continuously monitored in a central upstairs location. Unless otherwise specified, all tracer gas decay rates were calculated assuming a one-compartment, single exponential decay model.

Results and Discussion

Consistent with published results,[1,2] the HAC/ductwork system of the unoccupied research house contributed only slightly to the house leakage area measured in blower door tests (Table I). Under pressurized test conditions (i.e., + 10 to 60 Pa), the approximate 20-percent contribution to house leakage area observed with "leaky" ductwork decreased to near zero levels with sealed ductwork. Interestingly, depressurized testing yielded higher leakage areas overall, but no significant change between "leaky" and "sealed" ductwork conditions.

Air infiltration rates into the crawlspace and indoor compartments of the research house were strongly affected by HAC operation (see Table II). With a "leaky" HAC system, average air infiltration rates increased about threefold from 0.05 to 0.15 h^{-1} upstairs and from 0.13 to 0.36 h^{-1} in the crawlspace. After sealing, the HAC caused a somewhat smaller twofold increase in average air infiltration rate indoors (i.e., 0.10 to 0.18 h^{-1}), but threefold increases (i.e., 0.05 to 0.17 h^{-1}) persisted to the crawlspace. To minimize the impact of weather-induced fluctuation in air infiltration rate on the HAC on/off comparison, the HAC on- and off-experiments were conducted on alternating days (see Table II). Fluctuations in air infiltration rates between measurement sites at opposite corners of the house were small and unimportant in the HAC on/off comparison.

Simple, two-compartment, mass-balance models are used to examine the convective transport rate of Freon 12 from crawlspace-to-indoor locations and CO from indoor-to- crawlspace locations. The models assume uniform mixing in the crawlspace and indoor compartments, zero outdoor concentrations, and zero indoor and crawlspace concentrations prior to tracer gas injection.

Freon 12 was injected and mixed inside of the crawlspace. The Freon 12 concentration indoors (i.e., [FR]in) was modeled as the integral with time of freon transport indoors minus the integral of freon transport from indoors (in) to the crawlspace (cs) and outdoors (out). Gaseous transport was expressed as the product of an effective air volume [i.e., EV (m^3)] transported from one compartment to another times the freon concentration in the initial (i.e., source) compartment.

Table I. Results of blower door leakage tests in the unoccupied research house.

HAC system	Indoor duct openings	Uncalibrated leakage area (m^2) Pressurized	Depressurized
Leaky	Open[a]	0.31	0.37
Leaky	Closed[a,b]	0.26	0.35
Sealed	Open[a]	0.26	0.38
Sealed	Closed[b]	0.26	0.36

[a] All exterior windows and doors closed and exhaust fans sealed.
[b] Ductwork vents solidly plugged and taped.

Table II. Summary of air infiltration rates (h-1)[a] into crawlspace and indoor levels as a function of HAC operation and sealing.

HAC	Date	Crawlspace Site 1	Crawlspace Site 3	Indoor Site 2	Indoor Site 4
A. "Leaky" HAC system					
Off	10/18a	0.078	0.092	0.104	0.135
Off	10/18b	0.041	0.042	0.129	0.145
Off	10/20	0.032	0.039	0.120	0.115
Ave ± S.D.		0.05 ± 0.02		0.13 ± 0.02	
On	10/17	0.118	0.116	0.335	0.385
On	10/19a	0.198	0.194	0.366	0.368
On	10/19b	0.126	0.126	0.343	0.385
Ave ± S.D.		0.15 ± 0.04		0.36 ± 0.02	
B. "Sealed" HAC System					
Off	11/14a	0.053	0.067	0.099	0.094
Off	11/16	0.049	0.047	0.106	0.114
Off	11/18a	0.061	0.083	0.083	—
Off	11/18b	0.037	0.040	0.092	0.101
Ave ± S.D.		0.05 ± 0.02		0.10 ± 0.01	
On	11/14b	0.110	0.114	0.178	0.385
On	11/15	0.192	0.208	0.176	0.368
On	11/17	0.137	0.140	0.194	0.385
On	11/19	0.243	0.236	0.165	0.174
Ave ± S.D.		0.17 ± 0.05		0.18 ± 0.02	

[a] Each air infiltration rate is the modeled result of a >8 h experiment.
Note: Standard errors for the linear regression analyses were generally <3 percent.

$$[FR]_{in} = \int \{EV_{cs\rightarrow in}*[FR]_{cs} - (EV_{in\rightarrow out} + EV_{in\rightarrow cs})*[FR]_{in}\}dt/VOL_{in} \quad (1)$$

CO was injected and mixed indoors. The CO concentration inside the crawlspace (i.e., $[CO]_{cs}$) is modeled as the integral with time of CO transport into the crawlspace minus the integral of CO transport from the crawlspace to indoors and outdoors.

$$[CO]_{cs} = \int \{EV_{in\rightarrow cs}*[CO]_{in} - (EV_{cs\rightarrow out} + EV_{cs\rightarrow in})*[CO]_{cs}\}dt/VOL_{cs} \quad (2)$$

Crawlspace-to-indoor ($EV_{cs\rightarrow in}$) and indoor-to-crawlspace ($EV_{in\rightarrow cs}$) volumetric transport coefficients are determined from Equations 1 and 2, respectively. The results (Table III) show interesting affects of HAC operation, the sealing of the HAC system, and potential complicating factors. Additional variables minimally include (1) the effect of seasonal changes in environmental conditions such as temperature and windspeed between "leaky" and "sealed" time periods (i.e., 10/88 vs. 11/88, respectively); and (2) gaseous transport between the crawlspace and indoors through cracks in the floor, which were not sealed as part of the HAC studies.

Crawlspace-to-indoor transport: Moderate (i.e., 30 percent) reductions in crawlspace-to-indoor transport are observed after sealing of the HAC system (Table III). HAC_{on} transport rates decrease from 33 ± 1 to 24 ± 3 m^3/h under "leaky" and "sealed" conditions, respectively. The corresponding change in HAC_{off} transport rates from 11 ± 1 to 8 ± 3 m^3/h was considered too small to distinguish.

Indoor-to-crawlspace transport: In contrast to the crawlspace-to-indoor transport data, the indoor-to-crawlspace transport rates remained basically unchanged during HAC_{on} periods before and after sealing. In addition, indoor-to-crawlspace transport was highly variable during HAC_{off} periods (e.g., 27 ± 22 m^3/h), perhaps due to weather (e.g., wind) or stack effects. Thus, HAC/ductwork sealing in the research house appeared to reduce crawlspace to indoor transport modestly during HAC operation, but had uncertain impact on indoor-to-crawlspace transport. Reductions in crawlspace-to-indoor transport would be beneficial for considerations of indoor air quality and energy conservation. The transport into the home of unconditioned (e.g., cold) air and in particular, soil gas (e.g., radon and water vapor) could be reduced.

Table III. Two-compartment modeling of crawlspace-indoor transport rates (m^3/h).[a]

Duct-work	HAC	Crawlspace to indoor	Indoor to crawlspace
leaky	on	33 ± 1	26 ± 3
leaky	off	11 ± 1	27 ± 22
sealed	on	24 ± 3	27 ± 5
sealed	off	8 ± 3	2 ± 0.4

[a] Uncertainties represent the standard deviation in multiple replicate experiments.

The tracer gas decay rates measured in 2 to 7-day studies of six occupied homes indicated quite low air infiltration rates. The average decay rates ranged from 0.08 h^{-1} with the HAC off in the master bedroom of House 936 to 0.29 h^{-1} with the HAC on in the kitchen of House 958 (Table IV). Operation of the HAC (i.e., central air conditioner) handles resulted generally in moderately enhanced decay rates, and uniform decay rates between measurement sites. With the exception of the basement in House 917, 1.1- to 3.5-fold enhancements in average decay rate were observed with HAC operation. However, the absolute increases in decay rate were small, ranging from 0.02 to 0.1 h^{-1}. House 917 was a new home with comparatively well-sealed ductwork that drew and exhausted air from upstairs compartments only. Thus, HAC operation was expected to have comparatively little effect on the infiltration rate of this home.

Intersite variation in tracer gas decay rates decreased three-fold to five-fold with HAC operation in Houses 936, 958, and 917, in which HAC on and off conditions could be accurately compared. The coefficient of variation declined from 40 percent to 10 percent in 936, 27 percent to 9 percent in 958 and 26 percent to 5 percent in 917. In houses where the HAC air handler operated continuously (i.e., 922 and 942), site-to-site variations were <5 percent in the basement of House 922 where occupants left a window open for much of the study. Thus, HAC operation in these study homes caused efficient mixing, but generally small increases in air infiltration rates.

The studies of 39 occupied, Tennessee Valley houses yielded average air infiltration rates of 0.90 ± 0.54 h^{-1} and 0.56 ± 0.37 h^{-1} under HAC on and off conditions, respectively. The 60 percent increase in air infiltration rate was reasonably consistent with an earlier study of East Tennessee homes[2] in which HAC operation caused approximate two-fold increases in air infiltration rates.[2] The absolute increase in air infiltration rate with HAC operation averaged 0.33 ± 0.37 h^{-1} in the current study. Accounting for conditioned house volume, this corresponded to an air flow of approximately 240 ± 390 m^3/h. Examining the ratio of air infiltration rates under HAC_{on}/HAC_{off} conditions, maximum, average, and minimum rates of 4.3, 1.8 ± 0.9, and 0.8 were observed. The larger 2- to 4.5-fold increases were typically observed in houses that had low air infiltration rates (i.e., <0.5 h^{-1}) with the HAC

Table IV. Average air infiltration rates (h^{-1}) in six occupied houses.

House	HAC	Basement	Kitchen	Master bedroom	Site to site variation (CV)
922	on	0.27[b]	0.19	0.18	24%[a]
942	on	0.14	0.14	0.14	1%
905	on & off	0.19	0.17	0.14	14%
936	on	0.13	0.16	0.15	10%
	off	0.04	0.09	0.08	40%
	on/off ratio	3.6	1.8	2.0	
958	on	0.28	0.29	0.24	9%
	off	0.25	0.19	0.15	27%
	on/off ratio	1.1	1.5	1.6	
917	on	0.20	0.20	0.18	5%
	off	0.27	0.18	0.14	26%
	on/off ratio	0.7	1.1	1.3	

[a] A basement window was open during much of the study enhancing variation in site to site air infiltration rates.
[b] Temperature probe malfunctioned confusing the time-dependent assignment of HAC operation.

turned off (Figure 4). Although confirmatory leakage areas are not available, these houses were probably the tighter homes in the study. In contrast, 90 percent of the houses with residual air infiltration rates of >0.5 h^{-1} had HAC_{on}/HAC_{off} ratios ranging from 0.8 to 2.0.

Conclusions

HAC operation resulted in excellent mixing of tracer gases between basement, kitchen and master bedroom locations in five of six occupied houses. Coefficients of variation were consistently <10 percent for site-to-site variation in air infiltration rate with the HAC turned on in comparison to 25 to 40 percent with the HAC turned off. In 39 occupied houses, the air infiltration rate increased on average 0.33 ± 0.37 h^{-1} with HAC operation. The increases were proportionately larger for those homes with low air infiltration rates under HAC_{off} conditions. The ratio of air infiltration rates under HAC_{on}/HAC_{off} conditions averaged 2.1 and 1.4 for houses with air infiltration rates of <0.5 h^{-1} and >0.5 h^{-1}, respectively, with the HAC turned off. Sealing the HAC (i.e., exterior heat pump and air distribution system) of a house with a crawlspace reduced the impact of HAC operation on both the rate of air infiltration indoors and crawlspace to indoor transport. After HAC sealing, the average air infiltration rate increased from 0.10 to 0.18 with HAC operation in comparison to increases from 0.13 to 0.36 h^{-1} before sealing. Crawlspace to indoor transport with the HAC turned on declined from 33 to 24 m^3/h with HAC sealing. Potential improvements in energy conservation and reduced pollutant (e.g., radon) transport from crawlspace to upstairs compartments should be investigated.

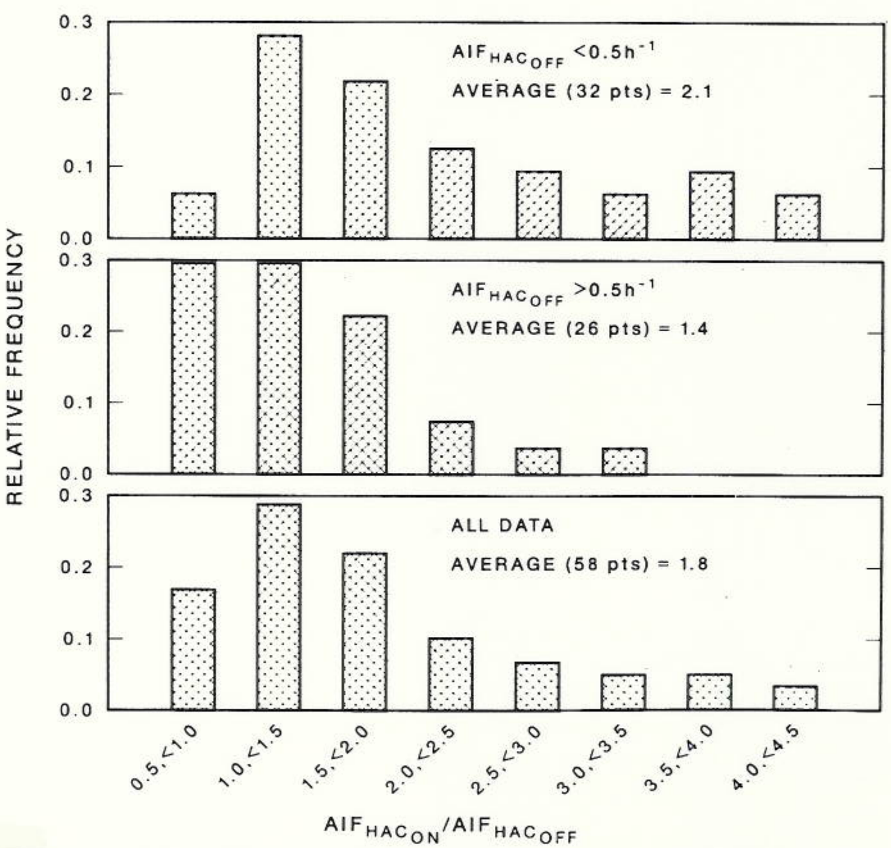

Figure 4. Distribution of air infiltration ratios for HAC on/off conditions in 39 occupied homes.

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The authors are with the Measurement Systems Research Group, Health and Safety Research Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831-6113. Address correspondence to Charles S. Dudney at the above address.

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