TESTING OF VENTILATION SYSTEMS IN FORCED WARM
AIR COMBUSTION HEATED HOUSES

VENTILATION RESEARCH SUPPORT

for

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NOTE: **DISPONIBLE AUSSI EN FRANÇAIS SOUS LE TITRE:**

ESSAIS DE VENTILATION ET DE QUALITÉ DE L'AIR DANS DES MAISONS CHAUFFÉES À L'ÉLECTRICITÉ

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EXECUTIVE SUMMARY

This research project was performed to gather field experience with houses that had ventilation systems that were expected to be able to meet the CSA F326 Residential Mechanical Ventilation Systems Standard.

The study focused on houses that had central forced warm air heating systems along with central ventilation systems. Two of the houses had air to air heat exchangers, and two had central exhaust fans. The four houses were built between 1983 and 1986.

A total of four houses located in Saskatoon were measured for the following quantities: ventilation rates, room air flows, duct leakage, sound levels, fan energy consumption rates and house depressurization levels caused by the operation of the ventilation system.

Three of the four houses had ventilation systems that were found to meet a 0.3 air changes/hour capacity. The fourth house had a measured air change rate of 0.22 ac/h. However, only one of the four houses could meet the minimum ventilation requirement of the CSA F326 standard based on individual room supply requirements. The minimum ventilation supply requirement for the houses varied between 55 and 70 L/s. None of the houses were able to meet the 30 L/s exhaust air flow requirement for the kitchens, and only two of the houses were able to meet the 10 L/s requirement for each of the bathrooms. Using a strict interpretation of the F326 standard, all of the houses would fail the minimum ventilation requirements.

Two of the four houses could meet the ASHRAE Recommended Noise Criterion of NC-30 or less.

In one house, the central exhaust fan had been running for seven years with no maintenance or cleaning (there was no filter on the fan). Approximately 6 mm of dust had accumulated on the fan rotor. After cleaning the fan, the air change rate was found to increase from 39 to 63 L/s, and the noise level of the fan was found to drop from 40.7 to 37 dBA.

Significant air leakage was found to exist in the ductwork in both the warm air distribution system and in the exhaust air system in a number of the houses. One house was found to have 91% leakage in the warm air distribution system (only 9% of the air entered the warm air return grilles, the remainder of the air entered through duct leakage.)

1.0 INTRODUCTION

This research project was developed to assist with the implementation of the CSA F326 Residential Mechanical Ventilation Systems Standard (CSA,1991). The residential minimum ventilation air requirements in the F326 Standard are reproduced in Appendix 5.

To this end, measurements were made on 4 houses in Saskatoon with central forced warm air heating systems that had ventilation systems that were expected to be able to meet the F326 Standard. Included in the measurements were ventilation rates, room air flows, system duct leakage, noise levels, energy consumption rates, and house depressurization levels.

As noise levels from continuously running fans are a concern, laboratory tests of sound pressure levels were made at the Institute for Research in Construction in Ottawa of the characteristics of a Delhi D530 central exhaust ventilation fan, and these results were compared with the values for the identical fan mounted in a residence.

Because of the relatively high electricity consumption associated with continuously running central forced air systems, several higher efficiency electric motors were evaluated.

2.0 METHODOLOGY

2.1 Selection of Houses

Four Saskatoon Houses were chosen for the test work. Two of the houses had central exhaust ventilation systems, and two had air to air heat exchangers. All of the four houses had been built between 1983 and 1986. Two of the houses (A and D) could meet the R-2000 air tightness standard of 1.5 air changes/h at 50 pascals.

The following houses were chosen:

a) House A - Three level split level house built in 1986.

Size: 582 m^3 total interior volume

Type of heating system:

Forced warm air using a natural gas water heater (RHEEM 10.5 kw [36,000 Btu/h] input) with induced draft exhaust fan and continuous pilot. Heat from the water heater is transferred to the warm air using a fan coil connected to the warm air duct system.

Type of ventilation system:

Van Ee 2000 air to air heat exchanger directly coupled to the warm air system. The occupants run the air to air heat exchanger continuously.

Unique features of the house:

This house was the 1989 winner of the Energy Efficient Buildings Association Design Competition Award. The house features RSI 6.3 (R36) Wall insulation, RSI 7.0/8.8 attic/cathedral ceiling insulation, RSI 4.9 basement wall insulation and RSI 1.8 basement floor insulation, and triple glazed windows. The majority of the windows are on the south side.

b) House B - Bi-Level House Built in 1985

Size: 431 m^3 total interior volume

Type of heating system:

Natural gas forced warm air furnace. (Lennox 26.4 kW input, 19.9 kW output) with atmospheric vented chimney.

Type of ventilation system:

Central exhaust fan connected to the bathroom and kitchen. A Delhi D530 fan was used. A 127 mm diameter fresh air duct is connected from outside to the return air plenum on the warm air furnace to provide outside air. The owners have the fan running continuously, except when they are away on vacation.

Unique features of the house:

The house was built with RSI 4.3 walls, RSI 3.5 basement walls, RSI 7.0 ceiling insulation and triple glazed windows. The additional costs for the upgraded insulation were covered by an interest free loan from the Saskatchewan Power Corporation.

c) House C - Split Level House built in 1983

Size: 568 m^3 total interior volume

Type of Heating System:

Natural gas forced warm air heating system ICG unit HGD-100-D 29.3 kW input, 23.4 kW bonnet capacity atmospheric vented chimney with intermittent ignition and a stack damper.

Type of ventilation system:

Central exhaust fan connected to the bathroom and kitchen. Exhaust fan had no identification on it.

Unique features of the home:

The wall system consists of 38 x 140 mm studs with 38 x 64 horizontal strapping and the vapour barrier sandwiched between the strapping and the studs.

d) House D - Bi-Level House Built in 1984

Size: 622 m^3 total interior volume

Type of Heating System:

26.4 kW (90,000 Btu/h) input ICG Model HGD 90 brand natural gas forced warm-air air furnace--19.9 kW output with atmospheric vented chimney.

Type of Ventilation System:

Air-to-air heat exchanger using Fasco 1.0 amp 115 v fans.

Unique features of the home:

The wall system consists of 38 x 140 mm studs with 38 x 64 horizontal strapping and the vapour barrier sandwiched between the strapping and the studs.

2.2 Measurement of Air Flows

Air flows through ductwork were measured using two methods. Air flows inside ducts were measured using a hot wire anemometer traverse in the ductwork. A minimum of 16 points across the cross section were used. Measurement of the air flows near the furnaces were very difficult to make, as the ductwork usually did not have sufficient lengths of straight duct upstream and downstream of the measuring plane.

For smaller air flows, such as those occurring through an exhaust air or supply air grille in a house, a flow grid (averaging pitot tube with manometer) attached to a balancing fan was used.

2.3 Measurement of Power Consumption of the Fans

Measurement of the power consumption of the fans was made using a watt meter (Westinghouse Type CP Portable Meter). In addition, measurements of the voltage and amperage were made, and the power factor calculated. The power factor was calculated using the following formula.

$$\text{Power Factor} = \frac{\text{Watts}}{\text{Volts} * \text{Amps}}$$

2.4 Measurement of the Efficiency of the Fan/Motor Combination in Supplying Air to the Ductwork System.

This efficiency calculation was made using the following formula:

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$= \frac{\text{Air flow} * \text{pressure rise}}{\text{Electrical consumption of fan (watts)}}$$

2.5 Sound Pressure Levels

Sound pressure levels were measured using a Bruel and Kjaer Type 2231 Modular Precision Sound Level meter with an Integrating SLM Module BZ 7110 and Type 1625 1/3-1/1 octave filter set.

The meter was supplied with a calibrated noise source that was used to check the instrument each day of use.

2.6 Whole House Air Tightness Levels

Whole house air tightness levels were measured using a calibrated blower door apparatus using the CAN/CGSB 2-149.10-M85 test procedure.

2.7 Air Change Rates for the Whole House

Whole house air change rates were measured for each house using the tracer gas decay method. A Miran 1B gas analyzer was used to measure the rate of decay of nitrous oxide tracer gas placed in the house.

The procedure was as follows:

a) The house ventilation system was set to maximum.

b) The warm air furnace/distribution system was turned on.

c) Pure nitrous oxide was introduced to the house near the furnace return air grilles. A level of about 200 parts per million was used.

d) The nitrous oxide was allowed to mix for about 20 minutes.

e) Readings were taken of the nitrous oxide levels over another 30 minute interval.

f) A least squares curve fit analysis was done of the time variation in nitrous oxide levels in the house over the 30 minute interval. From this analysis a whole house air change rate was calculated.

2.8 Pressurization Levels Caused by the Ventilation System

Measurements were made of the change in pressure across the envelope of the building caused by the operation of the ventilation system fan. A digital pressure reading instrument, the AIR MP6KS digital manometer, was used to measure the pressures. Readings were taken at several heights in each house.

3.0 RESULTS

Results from the testing are listed according to the various houses.

3.1 Measurement of Air Flows in the Ventilation System

A summary of the results from the 4 houses is as follows:

House	Volume m^3	Type of Ventilation System	Measured Ventilation (outside air) L/s
A	582	A/A Heat Exchanger	79.8
B	397	Central Exhaust	39.3
C	568	Central Exhaust	47.8
D	622	A/A Heat Exchanger	37.1

HOUSE A

A summary of the air flow measurements on the house is presented in Appendix 1. The house was quite tight, measured to be 0.68 air changes per hour at a pressure difference of 50 pascals, easily meeting the R-2000 standard of 1.5 ac/h at 50 Pa.

The central warm air distribution system had a measured air flow of 378 L/s, representing an equivalent air change rate for the whole house of 2.34 air changes/h. The return air flows measured at the return air grilles were very low, amounting to 35.9 L/s; thus, air leakage through the return air flow system amounted to about 91% of the return air flow. The return air ductwork is located at the main floor joist level.

One of the occupants of the house had complained that a pool of cool air tended to lie on the floor in the lower level after the front door was opened during the colder part of the heating season.

As most of the return air flows into the leaky ductwork in the ceiling of the basement, it is not surprising that the return air system does not alleviate stratification in the bottom level of the house. A properly sized and sealed return air duct system could help alleviate this stratification problem. A second problem with the return air system is that there was only one return air grille in the lowest level, and it had a measured flow of only 6.6 L/s.

The house has a south-facing orientation with most of the windows on the south side (9.4 m^2 or 57% of the total window area). Most of the windows are located on the upper level on the south side; thus on sunny days a greater fraction of the solar gains are received by the upper level of the house, where the thermostat for the heating system is located, and as a consequence the lower level tends to be cool during the daylight hours.

The furnace fan system consumed 556 watts in a 1/3 horsepower direct drive fan, or 1.23 watts per L/s of supply air flow. The motor used was a permanent split capacitor 1/3 hp unit. The air to air heat exchanger used 134 watts. The normal operation of the systems was to run the air exchanger continuously and to engage the furnace fan only when heat was required. There was no central air conditioning system in this house.

The air to air heat exchanger provides an outside air flow of 79.8 L/s, which corresponds to an outside air ventilation rate of 0.49 air changes/h.

HOUSE B

A summary of the air flow readings for House B is presented in Appendix 2.

The house had an air tightness level measured at 2.2 air changes per hour at a pressure difference of 50 pascals.

The central warm air distribution system had a measured air flow of 300 L/s representing an equivalent air change rate for the whole house of 2.50 air changes/h. The return air flows measured at the return air grilles were 282 L/s; the return air flow measured at the furnace was 384 L/s; thus air leakage through the return air flow system amounted to about 26.5% of the return air flow.

The furnace fan system consumed 384 watts or 0.8 W/(L/s) of total supply flow.

The occupants of the house have noted that in the winter the basement is at a considerably cooler temperature (3°C to 5°C cooler) than the upstairs. As can be seen from Appendix 2, there are nine supply air ducts upstairs which supply a total of 201 L/s and only four supply air ducts downstairs which supply 99 L/s. Thus, it is not unexpected that the downstairs would be somewhat cooler. In addition, the one return air grille located at the floor level in the downstairs had a measured flow of only 21.1 L/s. Thus, a pool of cool stratified air tends to accumulate on the basement floor. If the occupants wish to raise the temperature downstairs, they will either turn on a forced convection portable electric heater or turn the furnace fan to continuous circulation.

The central exhaust fan had a measured flow of 39.3 L/s. This corresponds to an outside air ventilation rate of 0.33 air changes/h.

HOUSE C

A summary of the air flow readings for House C is presented in Appendix 3.

This house had a measured air tightness level of 2.08 air changes/h at 50 pascals.

The central warm air system had a measured air flow of 501 L/s, representing an equivalent air change of 3.2 air changes per hour. The return air flows measured at the return air grilles were 311 L/s; thus, air leakage through the return air system amounted to 37.9% of the return air flow.

The furnace fan consumed 392 watts on high speed, or 0.78 W/(L/s) of air flow. On low speed, the furnace fan consumed 265 watts, and circulated 347 L/s, or 0.76 W/(L/s) of air flow. The central exhaust fan consumed 105 watts, and provided 47.8 L/s of air flow. This corresponds to an outside air ventilation rate of 0.30 air changes/h.

HOUSE D

A summary of the air flow readings for this house is presented in Appendix 4.

This house had a measured air tightness level of 1.45 air changes/h at a pressure difference of 50 pascals, just meeting the R-2000 standard of 1.5 air changes/h at 50 pascals.

The central warm air furnace had a measured supply flow of 378 L/s, representing an equivalent air change rate for the whole house of 2.19 air changes per hour. The return air flows measured at the grilles were 200 L/s; thus, air leakage through the return air system was 47% of the return air flow.

The furnace fan system consumed 247 watts on high speed, delivering 378 L/s, for a fan consumption of 0.65 W/(L/s).

The air to air heat exchanger consumed 138 watts delivering 37.1 L/s. This flow rate corresponds to an outside air exchange rate of 0.22 air changes/h.

3.2 Measured Power Consumption of the Fan/Duct Systems

The measured efficiency of the fan/duct system was quite low for the systems tested.

The theoretical power required to drive a fan system may be expressed as:

$$\text{Power} = \text{air flow} * \text{pressure rise}$$

where compatible units are watts, m^3/s and pascals.

For House A, the theoretical power required for the air flow was 69.1 watts (based on an air flow of 452 L/s and a pressure rise across the fan of 153 pascals), and the measured consumption was 556 watts, for an efficiency of 12.4%.

A table listing the measured power consumption for the warm air distribution systems is presented below:

Table 1

Measured Power Consumption of the Furnace Fan/Motor Combinations

House	Air Flow (L/s)	External Static Pressure (Pa)	Power (W)	W (L/s)
A	452	50	556	1.23
B	480	59	384	0.80
C	501	50	392	0.78
D	378	24	247	0.65

House A has a much higher power consumption per unit air flow (1.23 W/(L/s) than the other houses. The main reason for this is that House A has a fan-coil heating system with a high air pressure drop internal to the unit because of the presence of a three-row finned coil. The measured pressure drop across the three row coil was 80 pascals. The other three houses have conventional natural gas furnaces with relatively small pressure drops across the heat exchangers.

3.3 Sound Pressure Levels

Measurements were made of the sound pressure levels associated with the ventilation equipment in the houses. The sound meter used was a Bruel and Kjaer Model with a 1/3 octave band capability able to read over the frequency range from 50 to 10000 hz.

The measurements were made in the bathroom closest to the room where the ventilation equipment was located. The ventilating equipment was operated at maximum speed throughout all the tests. Sound pressure levels were measured at three locations in each bathroom, and the readings were averaged at each frequency band. A time-averaged reading lasting 30 seconds was taken at each frequency band. The sound meter was mounted on a tripod 1.5 metres above the floor level, and the three locations were 1.0 metres apart.

The CAN/CSA-C260-M90 Standard "Rating the Performance of Residential Mechanical Ventilating Equipment" (CSA, 1990) was used as a guide to making the sound power level readings. As the standard was developed for use in the laboratory, it was not possible to duplicate the laboratory test conditions. For instance, the standard requires that the sound power levels be determined in a reverberation chamber with a volume greater than

200 m^3. The readings were taken in the bathrooms of the houses, which have volumes of the order of 20 m^3. A second major difference between the laboratory and the house is the presence of background sound in the house. In Figure 2, the background sound level measured in House B with no appliances or fans operating is presented. A background noise level of 23.1 dBA was measured.

The dBA readings were calculated using the formulas presented in the CSA standard mentioned above.

According to ASHRAE (ASHRAE, 1989), the A-weighted sound pressure level has the advantage of identifying the desirable sound level as a single-valued number that correlates well with human judgment of relative loudness. However, the A-weighted sound pressure level has the disadvantage of not correlating well with the relative noisiness or the subjective quality of the sound. The A-weighted level comparison is best used with noises that sound alike but differ in level. It should not be used to compare sounds with distinctly different spectral characteristics; i.e., two sounds at the same dB level, but with different spectral content, may be judged differently by the listener for an acceptable background sound. One of these noises might be completely acceptable, while the other could be objectionable because its spectrum shape was rumbly, hissy, or tonal in character.

Table 2

Summary of House Sound Level Readings
House Ventilation System On
Warm Air Furnace Fans Off

House	Type of Ventilation System	dBA Reading	Location of Sound Reading	Meets ASHRAE Noise Criteria (NC-30)?
A	Air to air heat exchanger	42.3	Lower bathroom	No
B	Central exhaust fan	40.7	Main floor bathroom	No
C	Central exhaust fan	33.1	Lower bathroom	Yes
D	Air to air heat exchanger	28.9	Main floor bathroom	Yes

Graphs comparing the sound pressure levels measured in the four houses with the ASHRAE Noise Criterion of 25 to 30 (ASHRAE,1989) are presented in Figures 3, 4, 5, and 6. The ASHRAE Noise Criteria curves define the limits that the octave band spectrum of a noise source must not exceed to achieve a level of occupant acceptance.

As can be seen from the graphs for Houses A and B (Figures 3 and 4), the Noise Criterion of 30 is exceeded at the lower frequencies for these two houses. In the ASHRAE Handbook, it is pointed out that fans will generally radiate sound in the octave band center frequency range from about 50 to 600 hz.

In House A, the air-to-air heat exchanger was rigidly mounted to a stud wall. As a consequence, there was no isolation of the unit from the structure of the house. An improved installation would have the air-to-air heat exchanger mounted on flexible straps from the floor joists. Flexible ductwork was used to attach the air exchanger to the ductwork for the house.

In House B, the central exhaust fan was rigidly mounted to the underside of the floor joists. As with House A, low frequency vibrations from the fan were directly transmitted to the structure of the house. In House B, rigid connections were made between the fan and the metal ductwork, again allowing low frequency sound to be transmitted. An improved installation would have flexible straps used to hang the fan, along with flexible duct connectors.

In House B, the Delhi D530 fan that was used had been installed in 1985, and had been running continuously for seven years. The fan had no filtration system on it, and over the years about 6 mm of dust had accumulated on the squirrel cage rotor of the unit. A photograph of the fan with the accumulated dust is shown in Figure 7. The dust was unevenly distributed on the rotor, and caused an imbalance which added to the low frequency sound generation. As will be seen in a later part of this report, a new Delhi fan, when installed in the same location, was able to meet the ASHRAE Noise Criterion of NC-30.

3.4 Laboratory Tests With the Delhi D530 Fan

A laboratory test (Quirt, 1992) for sound levels from the Delhi D530 exhaust fan was performed at the Institute for Research in Construction at the National Research Council using the CAN/CSA-C260-M90 protocol. Details of the test procedure are presented in the report by Quirt.

A graph comparing the laboratory tests with the ASHRAE Noise Criterion of 25 to 30 is presented in Figure 8. Two comparisons are presented: one with the fan mounted directly to the floor joists, and the other with the fan mounted on flexible straps to the floor joists.

As can be seen from Figure 8, the use of a flexible mount for the fan lowered the noise level, particularly at the lower frequencies. The sound reading dropped from 58.4 dBA to 55.0 dBA when the flexible mount was used.

3.5 Comparison of the Laboratory Tests With the In-House Tests at House B

The identical Delhi fan was returned to Saskatoon, and mounted in House B. The fan was rigidly attached to the floor joists as shown in Figure 9. The comparative readings are presented in Figure 10 for the laboratory tests. The laboratory tests were done to the CSA C260 standard. The sound levels reported are sound power levels, which are different than sound pressure levels. In the ASHRAE Handbook of Fundamentals (ASHRAE, 1989), there is a formula that can be used to relate sound pressure levels to sound power levels in normal rooms. The equation is as follows:

$$L_p = L_w - 5 \log V - 3 \log f - 10 \log r + 12 \text{ dB} \qquad (1.)$$

where

L_p = room sound pressure level at the chosen reference point, dB re 20 micropascals

L_w = source sound power level, dB re 10^{-12} W

V = room volume, m^3

f = octave band centre frequency, Hz

r = distance from source to observation point, m

In the bathroom where measurements were made in House B, the room volume was 10.1 m^3, and the distance from the source (exhaust air duct grille) to the observation point was 1.2 metres. The fan was located 4.4 metres from the grille.

The results of the two tests were as follows:

Table 3

Delhi Fan With Rigid Mounting
Sound Pressure Level (dBA)

Laboratory Value (Converted Using Equation 1.)	House B
56.2	37.0

As can be seen from Table 3 and Figure 10, there was a considerable difference in the Sound readings between the laboratory and House B. In the laboratory, the sound readings were taken at approximately the same elevation as the fan; in the house, the sound levels were measured in the bathroom, which is one floor above the fan. A sketch of the relative position of the fan and the bathroom in House B is presented in Figure 11. In the house, there are two 90 degree bends in the duct connecting the grille in the bathroom to the fan. These bends would tend to attenuate the sound. In addition, the bathroom is approximately 2 metres horizontal distance from the fan.

The field test was then repeated using a flexible mounting for the fan. The flexible mounting detail is shown in Figure 12. The comparative results are shown in Table 4 and Figure 13.

Table 4

Delhi Fan With Flexible Mounting
Sound Pressure Level (dBA)

Laboratory Value (Converted Using Equation 1.)	House B
55.2	41.4

As can be seen by comparing Tables 3 and 4, the flexible mounting for the Delhi Fan was found to increase the sound level in the house, while in the Laboratory the flexible mount was found to decrease the sound level. The explanation for the increased sound level with the flexible mount in the house is as follows. A relatively long, unsupported, galvanized steel duct is attached to the outlet of the Delhi fan in the house. When the fan was mounted on flexible straps, the steel duct was free to move, and the fan caused the steel duct to vibrate. An improved installation would have had the ducts connected to the fan with flexible connectors, and the steel duct independently supported.

3.6 Comparison With a Lower Noise, Higher Efficiency Fan

For comparison purposes, a lower noise fan was also tested for sound output. The fan was an engineering sample from the Penn Ventilator Company. The unit has a permanent split capacitor FASCO motor (U90B1), and a stationary bell-mouth inlet to the 140 mm diameter, 51 mm wide stamped steel squirrel cage rotor.

A comparison of the two fans when mounted in House B is presented in Table 5, with the Delhi fan flow reduced by use of a damper.

Table 5

Comparison of Penn Ventilator Fan With Delhi D530 Fan (New)

	Penn	Delhi
Power Consumption (W)	26.4	66.1
Sound Pressure Level (dBA)	26.4	37.0
Air Flow (L/s)	39.4	39.3

A graph comparing the flow characteristics of the two fans is presented in Figure 14. The Delhi D530 fan has considerably higher air flow capacity than the Penn unit. However, the smaller Penn Fan provided enough air supply to meet the CSA Standard.

The sound pressure level for the Penn Fan compared with the background sound level is presented in Figure 15. The sound pressure level of the Penn Fan is 10.6 dBA lower than the Delhi unit. As was mentioned earlier, the background sound level in the house was 23.1 dBA, and thus the Penn Fan was only 3.3 dBA higher than background. According to the ASHRAE Handbook, a change in sound pressure level of 3 dB is just noticeable. The technologist taking the readings on the Penn Fan noted that he had to double check to ensure that the fan was running, as it was so quiet. A difference of 5 dB is needed for the change in loudness to be clearly noticeable.

3.7 Measurement of the Change in House Differential Pressure Caused By Operation of the Ventilation System

The differential pressure across the walls of the house was measured with the ventilation system off and with the ventilation system on. Measurements were made with a digital manometer with a resolution of 0.1 pascals. The differential readings were taken at three different elevations in the house(at the tops and bottoms of openable windows and doors).

The results of the measurements were as follows:

Table 6

Change in House Differential Pressure Caused By Operation of the Ventilation System

House	Change in Differential Pressure (Pa)
A	+.1
B	+.8
C	+.6
D	-.6

3.8 Tracer Gas Tests of Whole House Air Change Rate

Measurements of the whole house air change rates were performed using nitrous oxide as a tracer gas. The ventilation systems were placed on maximum speed for the tests. The results of the tests are presented in Table 7. Weather conditions were very windy during the tests; as a consequence, the whole house air change rates were considerably higher using the tracer gas than were measured using the flow apparatus in the ventilation system.

Table 7

Measured Whole House Ventilation Rates

House	ac/h	Wind Speed (km/h)	Outside Temperature (°C)
A	1.14	24	15
* B	0.74	17	12
C	0.92	28	16
D	0.76	33	25

* When this test was done on house B, the original Delhi D530 fan had been cleaned. The measured air flow rate of the fan was 62.9 L/s. (Cleaning had increased the flow rate from 39 L/s)

3.9 Comparison of the Measured Kitchen and Bathroom Exhaust Flows With the CSA F326 Recommended Flows

In the CSA F326 Standard, a continuous exhaust flow of 30 L/s is recommended for the kitchen, and 10 L/s for each bathroom. In Table 8, measured exhaust flows for each of the four houses are presented.

Table 8

Measured Exhaust Air Flows
L/s

Recommended Minimum Air Flow		Measured Room Flows			
		House A	House B	House C	House D
Kitchen	30	17.0	13.5	14.7	--
Bathroom 1	10	17.8	8.5	10.9	4.3
Bathroom 2	10	16.7	--	11.7	4.3
Bathroom 3	10	19.7	--	10.0	13.6

As can be seen from the table, none of the houses were able to meet the 30 L/s recommendation for the kitchen flow. The measured bathroom flows were able to meet the standard of 10 L/s in Houses A and C, but Houses B and D were unable to meet the 10 L/s value.

3.10 Comparison of the Measured Ventilation Rates with CSA F326 Specified Values

The CSA F326 standard specifies minimum ventilation air requirements. The values are presented in Appendix 5. For each of the four houses in the study, a calculation was made of the minimum ventilation requirement using Appendix 5,and these values are compared with the measured values in Table 9.

Table 9

Comparison of CSA F326 Minimum Ventilation Requirement with Measured Values

House	CSA F326 Minimum Ventilation Requirement L/s	Measured Ventilation Rate L/s	Meets CSA F326 Ventilation Requirement?
A	70	79.8	Yes
B	55	39.3	No
C	65	47.8	No
D	60	37.0	No

3.11 Energy Efficient Electric Motors for Forced Air Furnaces

The warm air distribution fan used in these houses had electric power consumption values ranging between 253 and 556 watts. Assuming that a furnace warm air distribution fan was running continuously, and that the average power consumption was 400 watts at a total cost of 7 cents per kWh, the annual running cost for the fan would be $245.

This is a relatively high cost, given that many homes in Saskatchewan have natural gas bills of only $600 per year.

A product search was undertaken as part of this project to locate very efficient electric motors in the 1/4 horsepower range. Using the Thomas Register (Thomas Publishing, 1991), a list of ten manufacturers were contacted. Manufacturers were asked to supply information on their electronically commutated permanent magnet DC motors, as these motors have been recognized as being among the most efficient in the fractional horsepower range.

The results of this product search were not very satisfactory, as the suppliers of these potentially more efficient motors were unable to supply a motor. Many of the companies contacted only build such motors on demand, some of the companies supply motors only in large quantities to other manufacturers such as furnace and heat pump suppliers, and the remaining companies supplied motors that were not very efficient.

However, one company, General Electric, produces electronically commutated (ECM) DC permanent magnet motors and supplies to a number of furnace manufacturers. According to a recent article (Energy Design Update, May 1992), these motors are now featured in several high efficiency Carrier, Heil, and Lennox natural gas furnaces that have variable speed operation. While the maximum efficiency of the GE ECM motors is not outstanding (approximately 68%), the efficiency remains high over a wide speed range. The accompanying graph (Figure 1) (Energy Design Update, May 1992) illustrates the efficiency of the ECM motor compared with a conventional motor over a range of speeds.

According to the article, at low speeds the Lennox, Carrier and Heil variable speed furnaces consume about 60, 80, and 100 watts respectively.

With the most efficient Lennox unit running at 60 watts consumption, the annual cost of running the furnace fan would be $37 at 7 cents per kWh. (This electricity cost does not include the cost of running the fan when it is in the high speed mode, as would be the case when the natural gas burners are on. The length of time the fan was in the high speed mode would depend on the furnace size, the heat loss rate of the house, the climate zone, use of set-back thermostats and other factors.)

This type of fan motor appears to be most attractive for ventilation purposes, as it would allow continuous fan circulation at a lower speed with only a modest electrical power usage.

As these ECM motors are not sold directly to end users at the present time, an alternative that could be considered for a retrofit application would be the use of a high efficiency AC motor. For this project, a 70.5% efficient 1/4 hp electric motor was purchased for $175 from Leeson Electric Motors. Specifications for the motor are as follows:

Motor Type:	Industrial/Residential Belted Fan Motor Open Drip Proof
Frame Size:	J48
Volts:	115
Amps @ 115v:	2.8
Wattage:	265
Power Factor:	0.82
Features:	Automatic thermal reset Resilient "cradle" base for quieter operation. Permanently lubricated, double shielded ball bearings. Dynamically balanced rotor for smooth operation

Price including taxes: $175 Canadian

4.0 DISCUSSION

4.1 Air Change Rates

A list of the measured air flows from the ventilation systems is shown in Table 10.

Table 10

Measured Air Flows of Ventilation Systems

House	Equivalent Air Change Rate (ac/h)
A	0.49
B	0.36
C	0.30
D	0.22

As can be seen from the above table, only three of the four houses could provide more than 0.3 ac/h. House D was able to provide only 0.22 ac/h. In Table 9, the measured CSA F326 ventilation rate was shown to be able to met only for House A. In the CSA standard, the houses must meet a minimum ventilation air capacity that is the greater of either the sum of the individual room requirements or 0.3 ac/h. In general, the systems had been providing satisfactory ventilation to the houses, and the occupants were satisfied with their performance.

4.2 Leakage in the Duct Systems

The warm air distribution systems in the houses tended to be quite leaky, particularly on the return air side. A summary table listing the duct leakage in the systems is presented in Table 11.

Table 11

Measured Air Leakage in the Warm Air Systems

House	Leakage in Return Air System (%)
A	91
B	27
C	38
D	47

The most popular method of providing a return air path at the ceiling level in the basement was to nail a flat sheet of galvanized steel along the bottom of two parallel floor joists. This detail results in a large amount of air leakage, as the resultant duct is not sealed at the joint between the galvanized steel and the bottom of the joists.

This duct leakage causes the return air grilles to be relatively ineffective, and also can cause stratification of air to occur at the floor levels in the houses. For those houses relying on return air to provide adequate mixing, a more carefully designed return air duct system is required.

4.3 Electrical Consumption of Warm Air Furnaces and Ventilation Systems

The measured electrical consumption of the Warm Air Furnaces and Ventilation Systems in the houses is presented in Table 12.

Table 12

Measured Electrical Power of Furnaces and Ventilators: High Speed Settings (watts)

House	Warm Air System	Ventilation System
A	556	134 (HRV)
B	384	66 (Fan)
* C	392	105 (Fan)
** D	247	138 (HRV)

* This house had a two speed furnace (1725/1140 rpm). On low speed the furnace power consumption was 185 watts.

** This house also had a two speed furnace. On low speed the furnace power consumption was 187 watts.

As was mentioned earlier, the efficiency of the warm air furnace fan systems was quite low.

These low efficiency values were discussed with an expert in fan systems at the Saskatchewan Research Council, Dr. T. Kaminski. He attributes the low efficiency to several factors. Generally the fans used in domestic warm air furnaces have forward curved squirrel cage rotors that are made out of stamped steel. No attempt is made to provide air-foil shapes on the blades. Much higher fan efficiencies are possible if backward curved, airfoil design fans are used. In general, existing furnace fans also run at a much higher blade speed than is optimum from an energy efficiency standpoint. The electric motors that are commonly used are usually either shaded pole or permanent split capacitor types, with the shaped pole motors generally less than 40% efficient, and the permanent split capacitor motors generally less than 65% efficient.

Dr. Kaminski suggested that fan system efficiencies as high as 50% were possible with present fan and motor technologies. For a furnace delivering 400 L/s of air against a 60 pascal static pressure difference, a 50% efficient system (70% efficient fan with a 70% efficient motor) could supply that amount of air against that pressure drop using only 48 watts of electricity. Yet another improvement in the systems would be to use larger ductwork with corresponding lower pressure drops. (It is useful to recall that the now-obsolete gravity warm air furnaces used no fan at all to distribute warm air. The main disadvantages of the gravity furnaces was the large size of ductwork required, and the relatively low efficiency of the furnaces.) The cost of improvements to fans and ductwork to substantially improve their efficiency was not studied in this report. As more houses begin to use mechanical ventilation systems, the operating cost of the fans is likely to become an issue.

4.4 Efficient Electrical Motors

Several relatively high efficiency electrical motors in the fractional horsepower range were identified. The Leeson 1/4 hp motor has a rated efficiency of 70.5%. The General Electric Electronically Commutated Motors (Direct Current, permanent magnet) have maximum efficiencies in the 68% range. Another advantage of this type of DC motor is that the efficiency remains high over a large range of speeds, unlike many ac motors.

4.5 Sound Pressure Levels

Two of the four houses tested were able to meet the ASHRAE Noise Criterion of NC-30. The other two houses exceeded the NC-30 Criterion because of low frequency sound transmitted from the rigid mounting of the ventilation equipment. Greater care in installation of the fan systems to isolate the fans would likely have allowed the other two houses to have met the NC-30 criterion.

The sound levels measured with the Delhi D530 fan in the laboratory did not agree well with the sound levels measured in House B. The main reason for the difference was likely the greater separation between the fan and measuring apparatus in the house, along with the fact that in the house the fan and the measuring apparatus were on different floors.

4.6 Effect of Dirt Buildup on the Delhi Fan

In House B, the original Delhi D530 fan was installed without any filter. As a consequence, the fan accumulated about 6 mm of dust on the squirrel cage rotor over the seven years it had been operating. Because of the dust buildup, the fan air flow had decreased from 62.9 L/s to 39 L/s. A plot of the sound pressure levels for the original fan with the dust buildup compared with the new Delhi fan is presented in Figure 16. The original Delhi fan has considerably higher sound pressure levels at the lower frequencies because of the dirt buildup. The change in the noise level was quite noticeable when the fan was cleaned and re-installed.

For central exhaust fans of this type, it would be desirable to have an easily removable filter upstream of the fan that could be used to reduce dust buildup on the fan. In addition, it would be desirable to have the fan installed in such a way that it could be easily accessed for cleaning of the rotor and scroll.

Dust accumulation was also present on the slotted grilles in the bathroom and kitchen of the house. The homeowners would wash them off periodically, as the dust buildup became unsightly. Different types of grille could be used that would not accumulate as much dust over time.

4.7 Test of a Low Electricity Consumption, Low Noise Fan

A Penn Ventilator fan was successfully demonstrated in House B. The unit was able to deliver 39.4 L/s of air with a power consumption of 26.4 watts and a measured sound pressure level of 26.4 dBA. The fan noise was barely noticeable, as the background sound level in the house was 23.1 dBA. A plot of the sound pressure level for this fan is presented in Figure 14.

This fan has a lower air moving capacity compared with the Delhi D530, but the fan would be suitable for modest sized homes. Assuming that the fan installed in a house could deliver 40 L/s, the fan could provide at least 0.3 air changes per hour in houses with interior volumes up to 480 m^3.

4.8 Change in House Differential Pressures Caused By Operation of the Ventilation System

The changes in the house differential pressure caused by operation of the ventilation system were all less than 1 pascal. The two houses that had unbalanced exhaust fans would be expected to have higher changes; however, these two houses also were considerably more leaky than the two houses that had balanced air to air heat exchangers.

4.9 Comparison of the Measured Kitchen and Bathroom Exhaust Flows With the CSA F326 Recommended Flows

None of the houses were able to meet the 30 L/s continuous kitchen flow rate recommended in the CSA F326 Standard. The measured bathroom flows were able to meet the standard of 10 L/s in Houses A and C, but Houses B and D were unable to meet the 10 L/s value.

In House A, flexible, ribbed plastic flexible pipe was used to connect the kitchen and bathroom exhaust grilles to the air to air heat exchanger. Air leakage was quite small in these lines, as the individual grille flows were 71 L/s, and the exhaust air flow was 78 L/s. Thus, only 7 L/s of air leakage occurred in the ductwork.

However, in House B, galvanized ductwork without any sealing was used to connect the bathroom and kitchen grilles to the central exhaust fan. The sum of the bathroom and kitchen grille flows was 22 L/s, and yet the exhaust flow measured at the fan was 39 L/s. Thus for this house the duct leakage amounted to about 44% of the air flow on the exhaust system. Normally no sealing is used on residential galvanized ductwork; in the case of exhaust systems this can make it very difficult for the ductwork to provide adequate exhaust capability.

4.10 Comparison of the Measured Ventilation Rates with CSA F326 Specified Values

Only one of the four houses (House A) was able to meet the CSA F326 specified flow values. After cleaning of the fan, House B was able to meet the CSA standard, as the flow increased from 39 to 63 L/s. Three of the four houses were able to provide 0.3 ac/h. At the time that the houses were constructed, the CSA standard had not been issued.

5.0 CONCLUSIONS

It is difficult to generalize results taken from a sample of four homes; however, it is evident that a number of problems are likely to exist with many ventilation systems in Canadian homes with forced air systems, based on the measurements taken in this study.

1. Duct leakage can be a major problem with ventilation systems. Although adequate flows are present at the fans, adequate room distribution is unlikely to occur unless sealed ducts are used. Standard galvanized ductwork installed without sealing is likely to cause problems. Return air systems in warm air furnace heating using joist spaces were also seen to be a problem.

2. Noise levels from fans can be a problem. Rigid mounting techniques along with inflexible connections to rigid ductwork are likely to cause noise problems, particularly at the low frequencies.

3. Accumulation of dust on fan rotors, particularly continuously running fans, is likely to be a problem both in terms of reducing air flow and in increasing noise levels from the fans. Filtration systems and methods of easy access to the fans for cleaning should be incorporated.

4. The electrical power consumption of warm air furnace fans can be significant. The 1/4 and 1/3 horsepower motors used in this study had measured power consumption values ranging between 253 and 556 watts.

6.0 LIST OF REFERENCES

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APPENDIX 1

AIR FLOW AND ELECTRICAL ENERGY MEASUREMENTS FOR HOUSE A

AIR FLOW AND ELECTRICAL ENERGY MEASUREMENTS FOR HOUSE A

		MEASURED AIR FLOWS (L/s)		
		SUPPLY	**RETURN**	**EXHAUST**
MAIN FLOOR	Front Entry	17.1	0.0	
	Living Room 1	18.1		
	Living Room 2	18.4		
	Dining Room 1	25.9		
	Dining Room 2	29.3		
	Kitchen			17.0
	Laundry/bathroom	24.1		17.8
	Master Bedroom Bathroom	24.3		16.7
	Bedroom A	25.4		
	Master Bedroom 1	23.5	12.9	
	Hallway		12.9	
BASEMENT	Bedroom B	21.5		
	Bedroom C	21.3		
	Hall		3.5	
	Recreation Room 1	30.2		
	Recreation Room 2	39.6		
	Recreation Room 3	38.0		
	Bathroom	21.3		19.7
	Storage under living room		6.6	
TOTAL		377.7	35.9	71.2

Total Return Air near Furnace (L/s)	450.0
Total Supply Air near Furnace (L/s)	Could not be measured
Water Heater/boiler Natural Gas Input Capacity (Btu/h) Rheem PV40-36M	36000.0
Rated recovery efficiency (%)	74.0
Electrical power consumption of circulation fan (Watts)	556.4
Power factor of motor	0.80
Amperage draw (amps)	5.9
Line Voltage (v)	117.5
Pressure Rise Across Furnace (Pa) (External Static Pressure)	50.0
Pressure Difference between Supply and Room	24.0
Pressure Difference between Return air and Room	-26.0
Heat Recovery Ventilator Power (2 Fans) Watts	134.1
Power factor of HRV	0.95
Amperage draw (amps)	1.2
Line Voltage (volts)	118.0
Heat Recovery Ventilator Supply Flow (L/s)	79.8
Heat Recovery Ventilator Exhaust Flow (L/s)	77.8

APPENDIX 2

AIR FLOW AND ELECTRICAL POWER MEASUREMENTS FOR HOUSE B

AIR FLOW AND ELECTRICAL POWER MEASUREMENTS FOR HOUSE B

		MEASURED AIR FLOWS L/s		
		Supply	Return	Exhaust
MAIN FLOOR	Front Entry	18.4		
	Living Room 1	21.8	127.8	
	Living Room 2	28.3		
	Dining Room 1	16.4		
	Kitchen	16.4		13.5
	Bathroom	27.3		8.5
	Bedroom A	20.7		
	Master Bedroom 1	23.3		
	Master Bedroom 2	28.3		
	Hallway		132.9	
BASEMENT	Bedroom B	36.7		
	Bedroom C	16.5		
	Hall	19.0		
	Recreation Room	26.4	21.1	
TOTAL		299.5	281.8	22.0

Total Return Air near Furnace (L/s)	383.6
Total Supply Air near Furnace (L/s)	480.0
Furnace Natural Gas Input Capacity (Btu/h)	90000.0
Output Capacity (Btu/h)	68400.0
Electrical power consumption of circulation fan (watts)	383.5
Power factor of motor	0.85
Amperage draw (amps)	3.8
Line Voltage (v)	119.8
Pressure Rise Across Furnace (Pa) (External Static Pressure)	59.0
Pressure Difference between Supply and Room (Pa)	20.0
Pressure Difference between Return air and Room (Pa)	-39.0
Central Exhaust Fan Flow (L/s)	39.3
Electrical power consumption of exhaust fan (watts)	66.1
Power factor of motor	0.4
Amperage draw (amps)	1.3
Line voltage (v)	118.2
Pressure Rise Across Exhaust Fan (Pa)	59.0
Pressure Difference between fan inlet and room (Pa)	-43.0
Pressure Difference between fan outlet and room (Pa)	16.0
Outside air duct inflow (L/s)	48.9

APPENDIX 3

AIR FLOW AND ELECTRICAL POWER MEASUREMENTS FOR HOUSE C

AIR FLOW AND ELECTRICAL POWER MEASUREMENTS FOR HOUSE C

			MEASURED AIR FLOWS L/s		
			Supply	High Speed Return	Exhaust
UPPER LEVEL 1	1		22.7	38.0	
	2		18.3	21.1	
	3		18.8	21.5	
	4	Bathroom	15.6		11.7
	5	Master Bathroom	17.3		10.9
LEVEL 2	1		30.5	48.6	
	2		14.1		
	3	Kitchen	31.3		14.7
	4		13.1		
	5		26.7		
	6		21.5		
LEVEL 3	1		32.4		
	2		21.7		
	3		22.3		
	4		12.4		
	5	Bathroom	20.9		10.0
LEVEL 4 (Basement)	1		16.8	57.0	
	2		28.9		
	3		24.6	124.6	
TOTAL			409.9	310.8	47.3

Total Return Air near Furnace (L/s)	446.0
Total Supply Air near Furnace (L/s)	501.0
Furnace Natural Gas Input Capacity (Btu/h)	
Output Capacity (Btu/h)	
Electrical power consumption of circulation fan (watts)	392.0
Power factor of motor	0.59
Amperage draw (amps)	5.7
Line Voltage (v)	118.5
Pressure Rise Across Furnace (Pa) (External Static Pressure)	52.0
Pressure Difference between Supply and Room (Pa)	30.0
Pressure Difference between Return air and Room (Pa)	-22.0
Central Exhaust Fan Flow (L/s) (Single speed)	47.8
Electrical power consumption of exhaust fan (watts)	105.0
Power factor of motor	0.52
Amperage draw (amps)	1.7
Line voltage (v)	120.7
Pressure Rise Across Exhaust Fan (Pa)	118
Pressure Difference between fan inlet and room (Pa)	-26
Pressure Difference between fan outlet and room (Pa)	92
Outside air duct inflow (L/s)	4.6

APPENDIX 4

AIR FLOW AND ELECTRICAL POWER MEASUREMENTS FOR HOUSE D

AIR FLOW AND ELECTRICAL POWER MEASUREMENTS FOR HOUSE D

			MEASURED AIR FLOWS L/s		
			Supply	Return	Exhaust
MAIN FLOOR	1	Living Room	13.5	14.9	
	2	Living Room	11.3		
	3	Living Room	11.7		
	4	Rear Entry	11.3		
	5	Kitchen	14.1	21.9	
	6	Kitchen	15.6		
	7	Kitchen	14.7		
	8	Bathroom	15.6		4.3
	9	S. Bedroom	14.4	23.1	
	10	S. Bedroom	15.9	22.9	
	11	Master Bedroom	12.4	24.1	4.3
	12	Master Bedroom	12.4		
	13	Master Bedroom Closet	4.3		
	14	Master Bedroom Bathroom	13.4		
		Hallway		93.3	
FRONT ENTRY	1		9.5		
BASEMENT	1	Recreation Room	14.4		
	2	Recreation Room	10.9		
	3	Recreation Room	15.6		
	4	Recreation room	18.3		
	5	Bedroom	15.6		
	6	Bedroom	15.6		
	7	Laundry	13.1		
	8	Bathroom			13.6
TOTAL			293.6	200.2	22.2

Total Return Air near Furnace (L/s)	313
Total Supply Air near Furnace (L/s)	377
Furnace Natural Gas Input Capacity (Btu/h)	90,000
Output Capacity (Btu/h)	68,000
Electrical power consumption of circulation fan (W)	247
Power factor of motor	0.39
Amperage draw (amps)	5.45
Line Voltage (v)	119.2
Pressure Rise Across Furnace (Pa) (External Static Pressure)	24.0
Pressure Difference between Supply and Room (Pa)	6.0
Pressure Difference between Return air and Room (Pa)	-18.0
Air to Air heat exchanger Flow (L/s)	
Supply air to house	37.1
Exhaust air from house	31.6
Electrical power consumption of HRV (watts)	133.2
Power factor of motor	0.60
Amperage draw (amps)	1.85
Line voltage (v)	119.2

APPENDIX 5

VENTILATION AIR REQUIREMENTS
CAN/CSA-F326-M91 STANDARD

5. Ventilation Air Requirements

5.1 Minimum Ventilation Capacity for Dwelling Units

5.1.1

The ventilation system shall be designed so that it
(a) can operate on a continuous basis, except as permitted by Clause 5.1.2; and
(b) has a minimum ventilation air capacity that is the greater of
  (i) the sum of the individual room requirements as defined in Column 1 of Table 1; or
  (ii) 0.3 air changes per hour (ac/h), based on the conditioned volume of the dwelling unit.

Table 1
Minimum Ventilation Air Requirements
(See Clauses 5.1.1(b)(i), 5.2.1, 5.2.2, 5.2.3, and 5.4.)

	Column 1	Column 2*	Column 3*
Space classification	Minimum ventilation capacity, L/†	Intermittent exhaust, L/s†	Continuous exhaust, L/s†
Category A			
Master bedroom‡	10	—	—
Basement§	10	—	—
Single bedrooms	5	—	—
Living room**	5	—	—
Dining room**	5	—	—
Family room	5	—	—
Recreation room	5	—	—
Other habitable rooms††	5	—	—
Category B			
Kitchen**	5	50‡‡	30
Bathroom	5	25	10
Laundry	5	—	—
Utility room	5	—	—

**Either intermittent or continuous exhaust is required (see Clause 5.3).*
†Based on an air temperature of 20°C.
‡Master bedroom is the bedroom most likely to be occupied by two adults.
§Where a basement incorporates rooms of the types designated in this Table the ventilation requirements for each room shall be as specified above. Basement areas used for other purposes that exceed 2/3 of the total basement area shall have a minimum ventilation requirement of 10 L/s; those that are less than 2/3 of the total area shall have a minimum requirement of 5 L/s. This Standard does not require ventilation of mechanical service and storage rooms.
***Ventilation requirements for any combined living room, dining room, and kitchen shall be determined as if they were individual rooms.*
††Other habitable rooms not listed shall have a minimum ventilation requirement of 5 L/s. This does not include spaces intended solely for access, egress, or storage, such as vestibules, halls, landings, storage rooms, service closets, and furnace rooms.
‡‡This minimum rate assumes the use of a hood consistant with Clause 8.13.5. If a higher rate is required by Clause 8.13.5, it shall apply. With other exhaust configurations such as ceiling, wall, and range-top fans, higher rates of flow may be required; see manufacturer's literature.

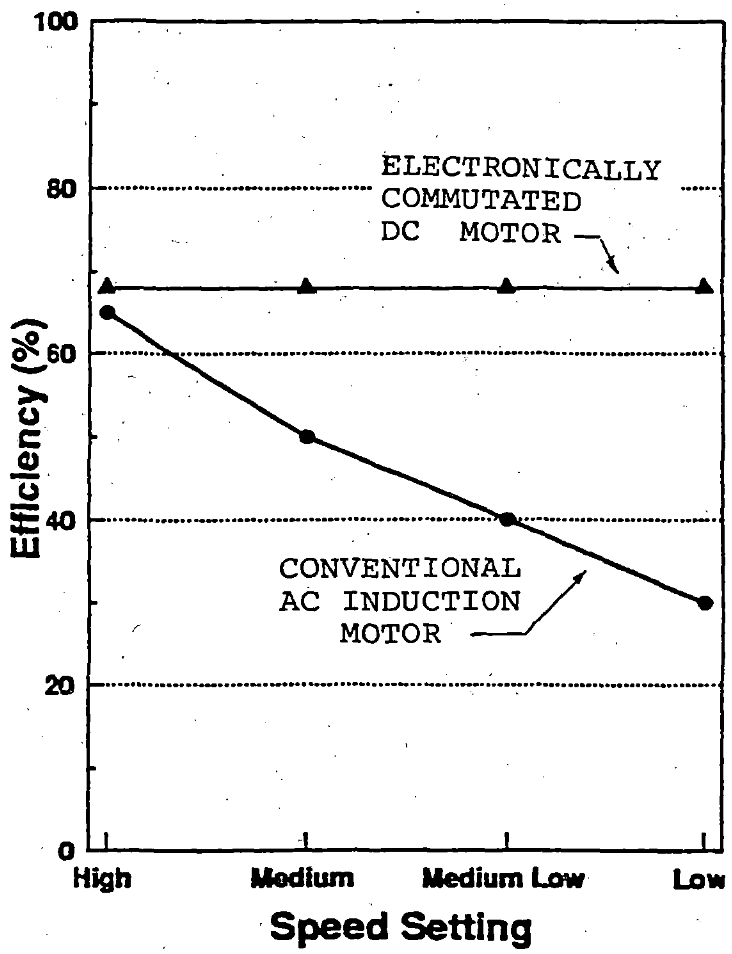


Figure 1. Comparison of the efficiency of a variable speed electronically commutated DC motor with that of a conventional AC induction motor over a wide range of speed settings

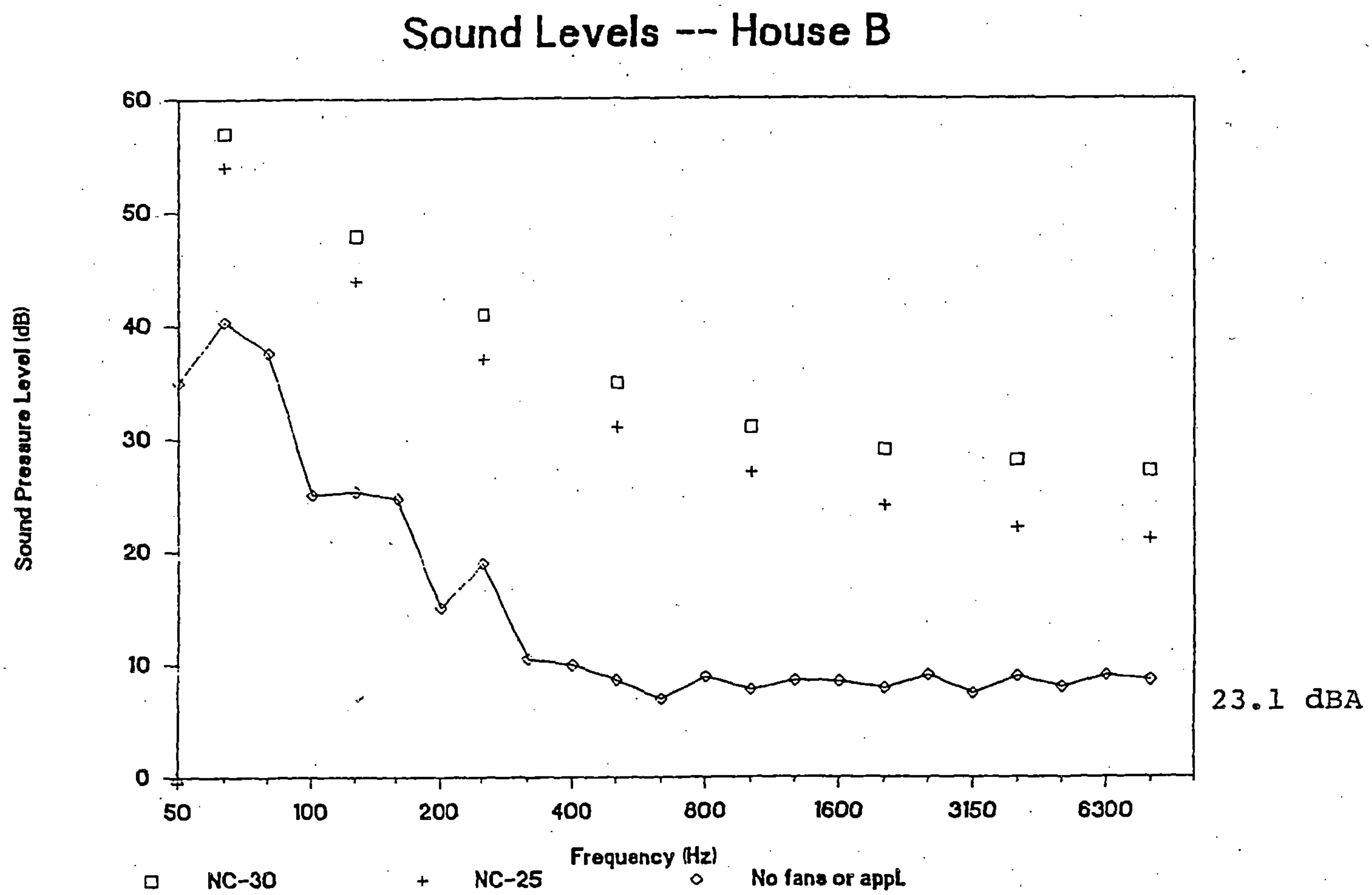


Figure 2. Background sound level in House B with no fans or appliances operating

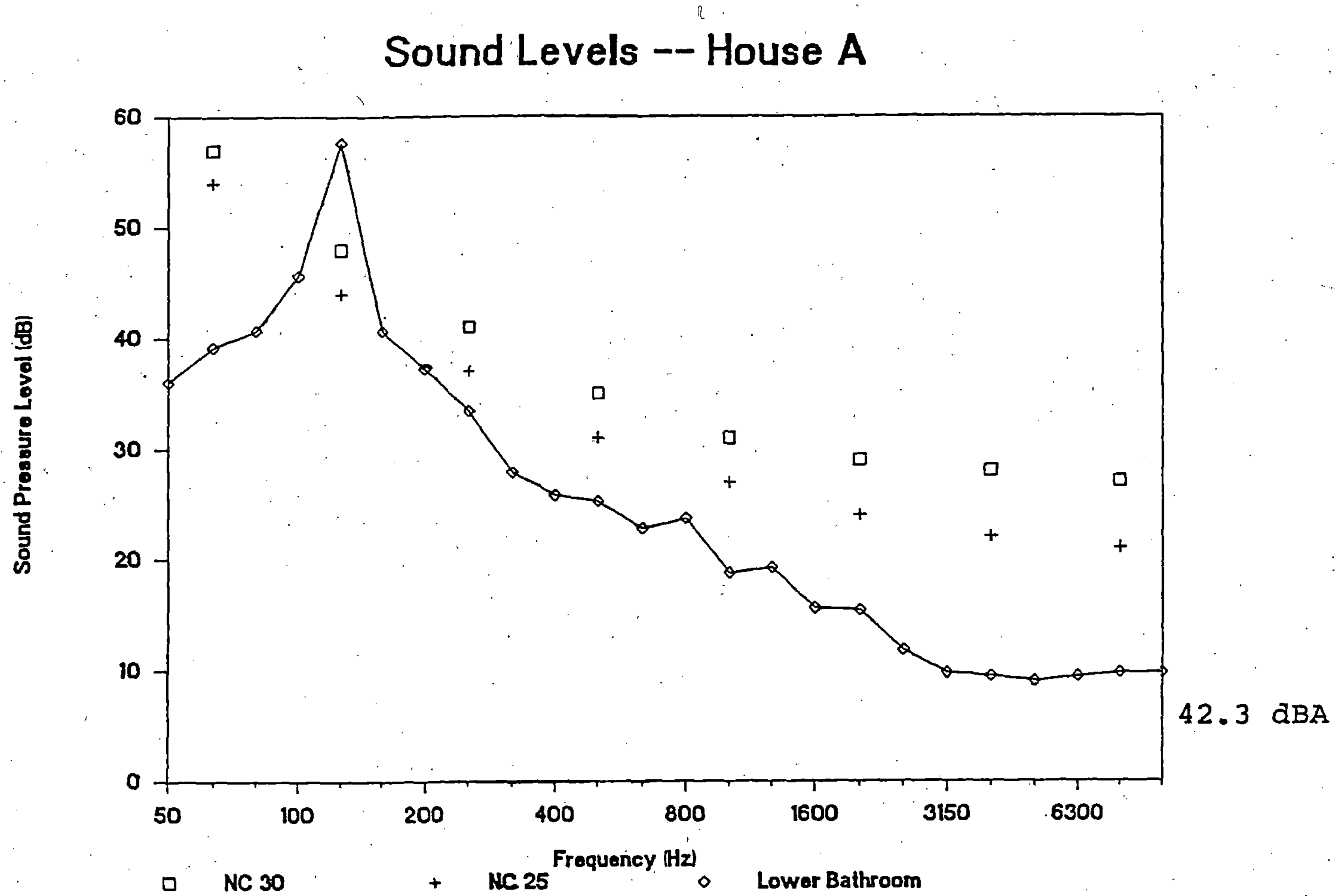


Figure 3. Measured sound pressure levels in House A

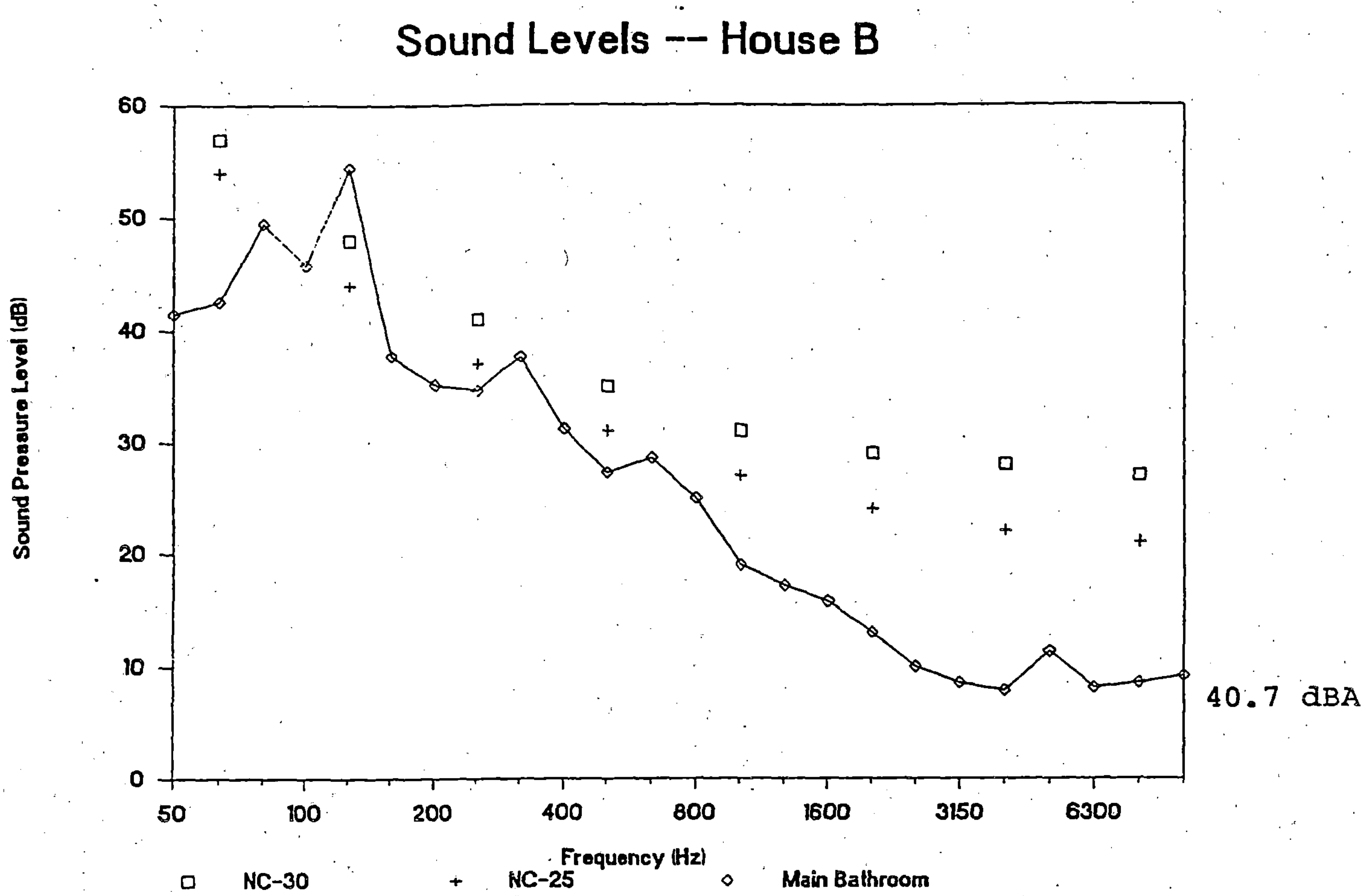
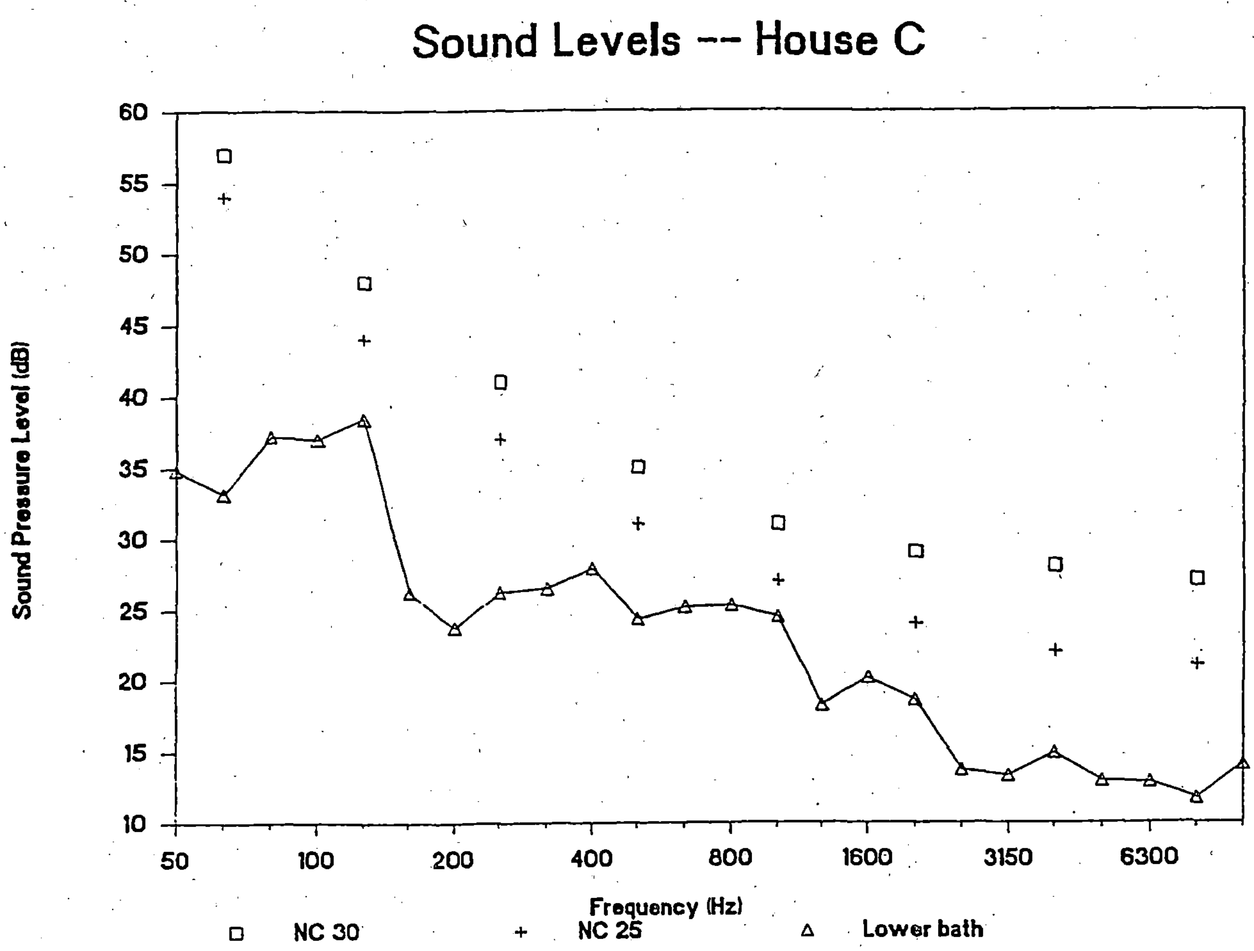


Figure 4. Measured sound pressure levels in House B.



33.1 dF

Figure 5. Measured sound pressure levels in House C.

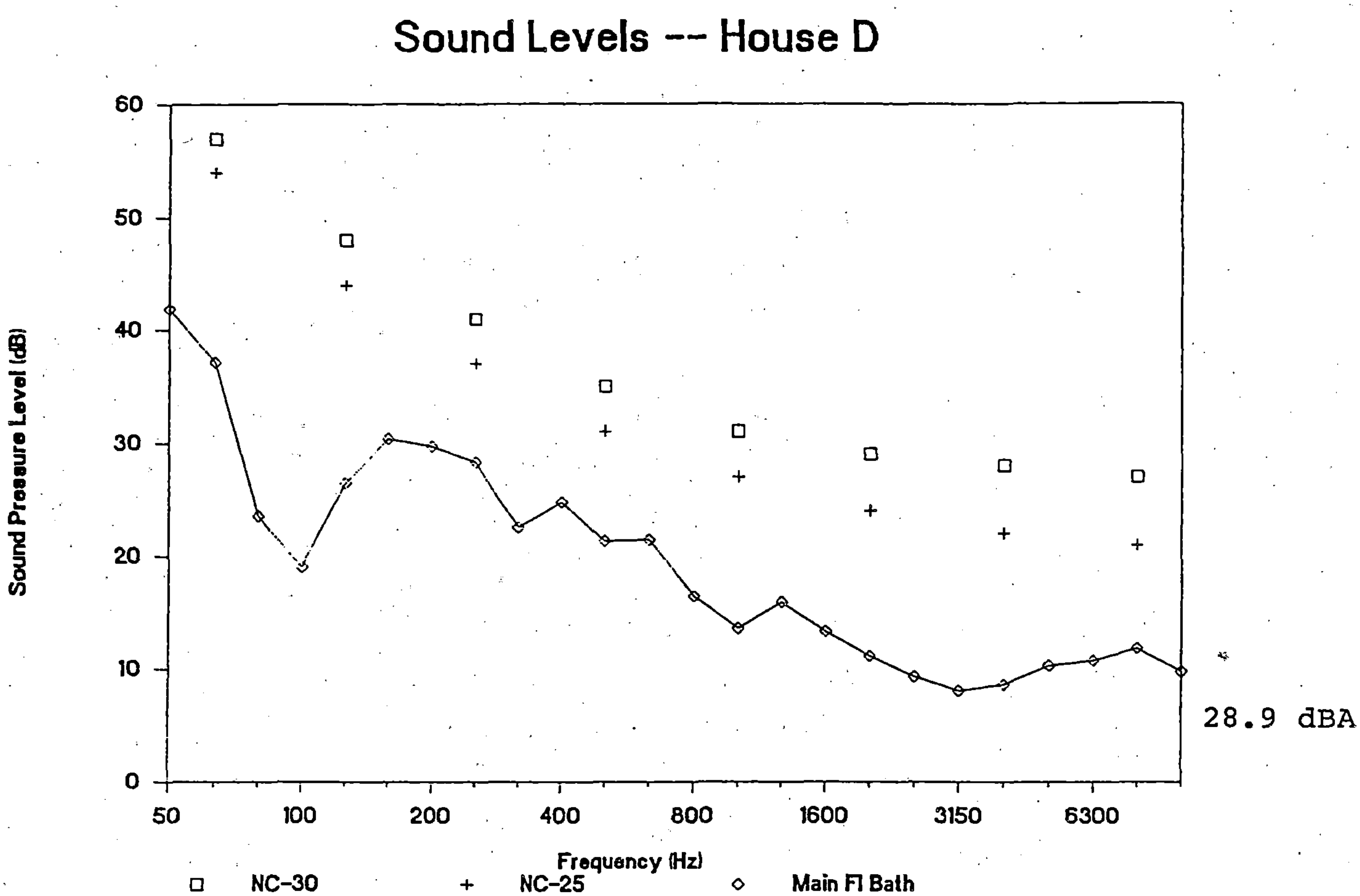


Figure 6. Measured sound pressure levels in House D.

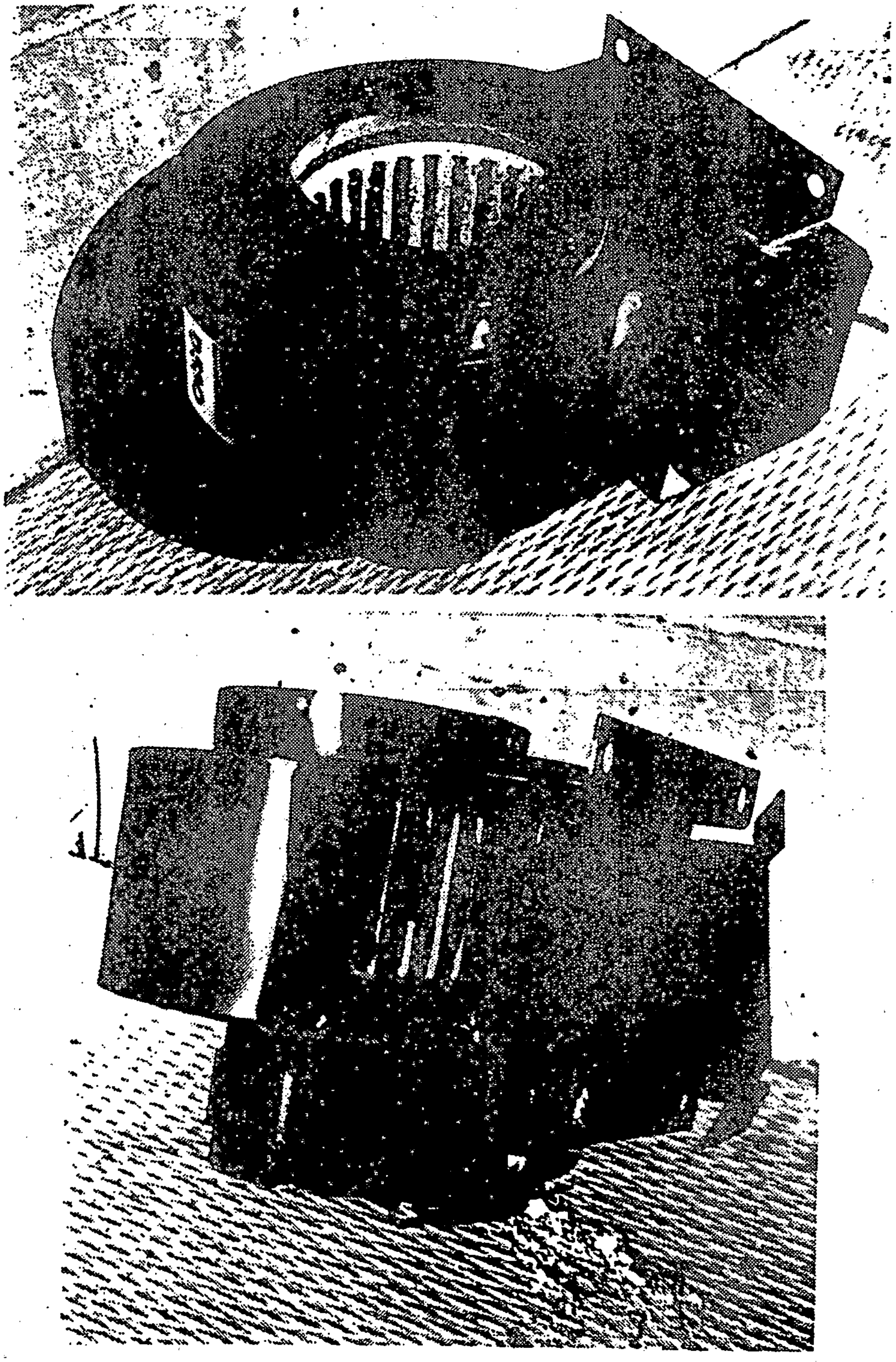


Figure 7. Dust accumulation on fan rotor after 7 years of continuous operation with no filter.

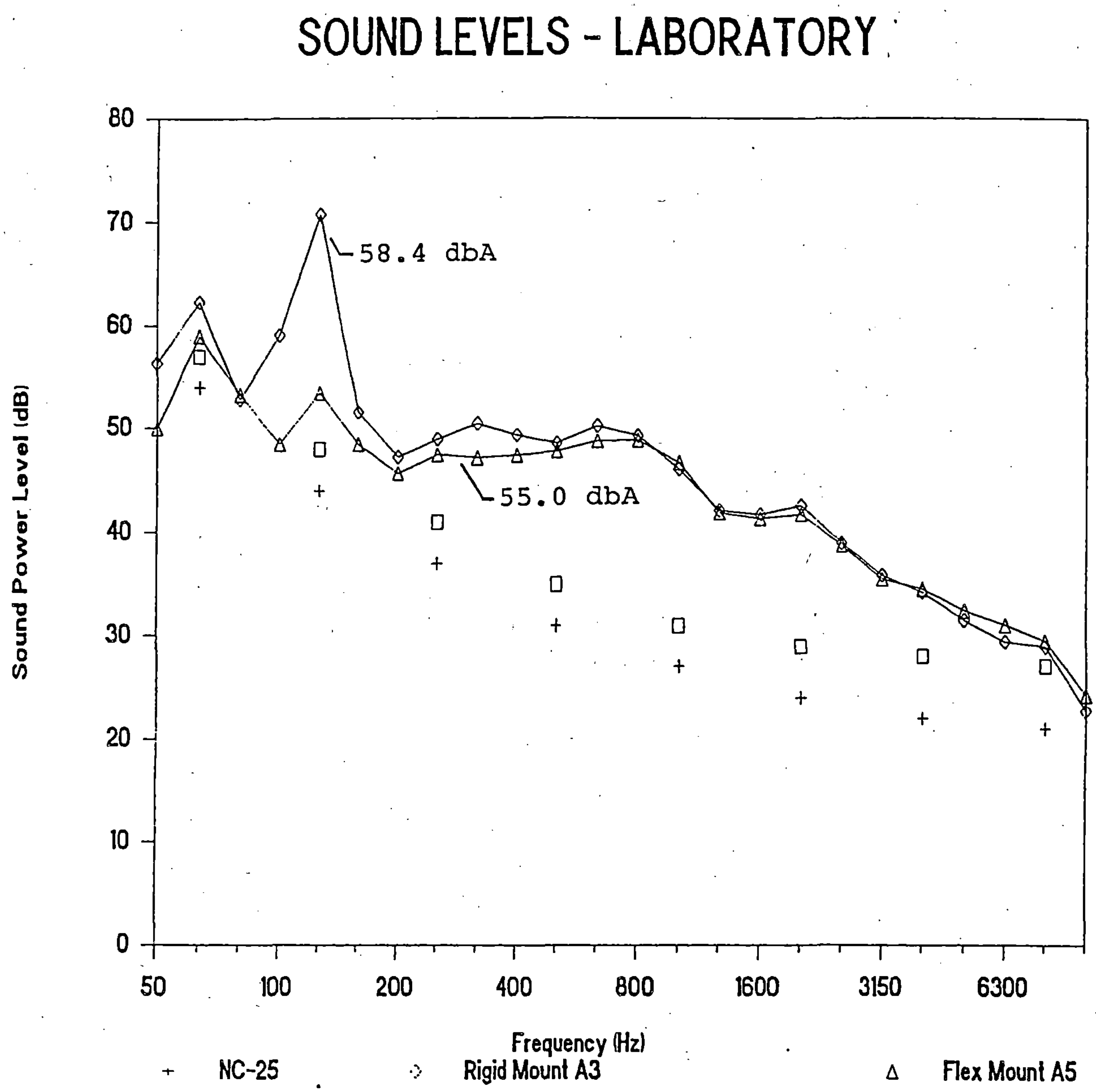


Figure 8. Measured sound power levels in the laboratory using the Delhi D530 fan and two different mounting systems

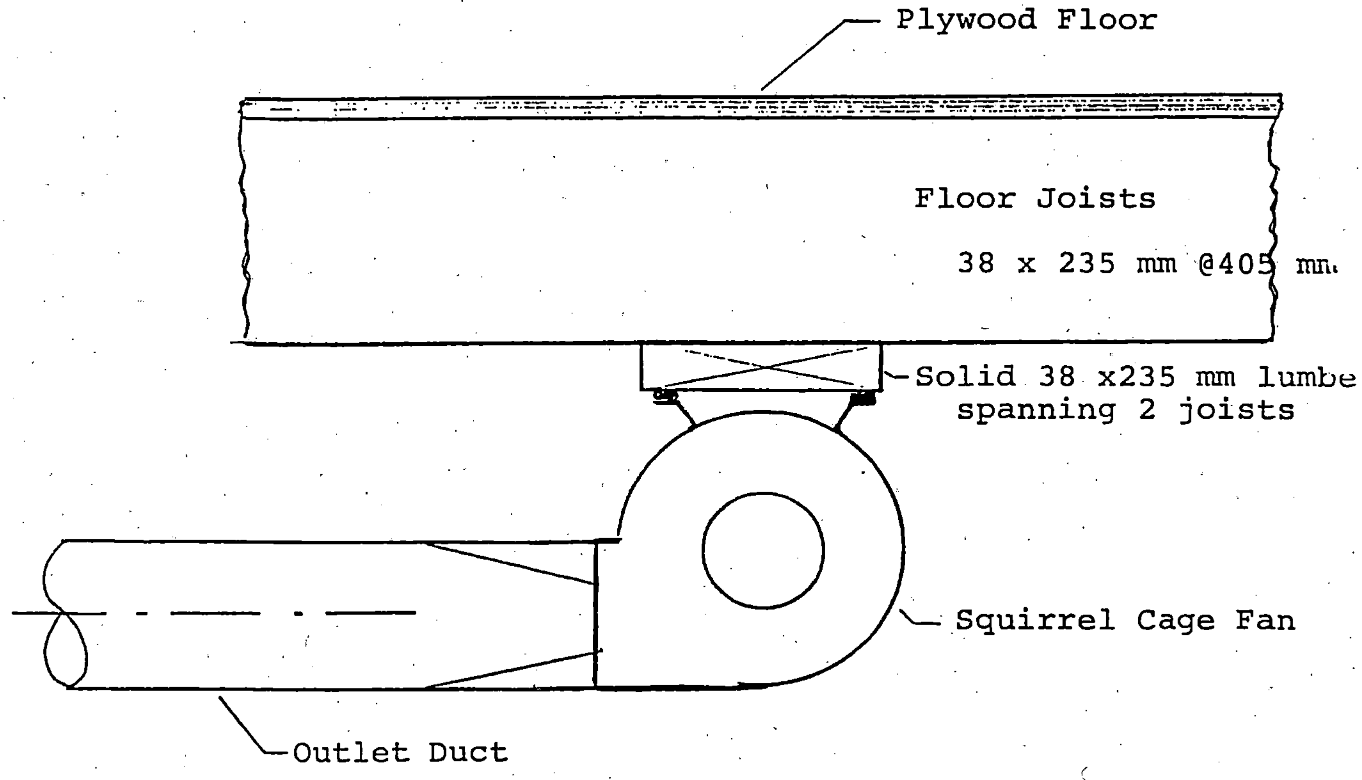


Figure 9. Rigid attachment of Fan to Floor Joists

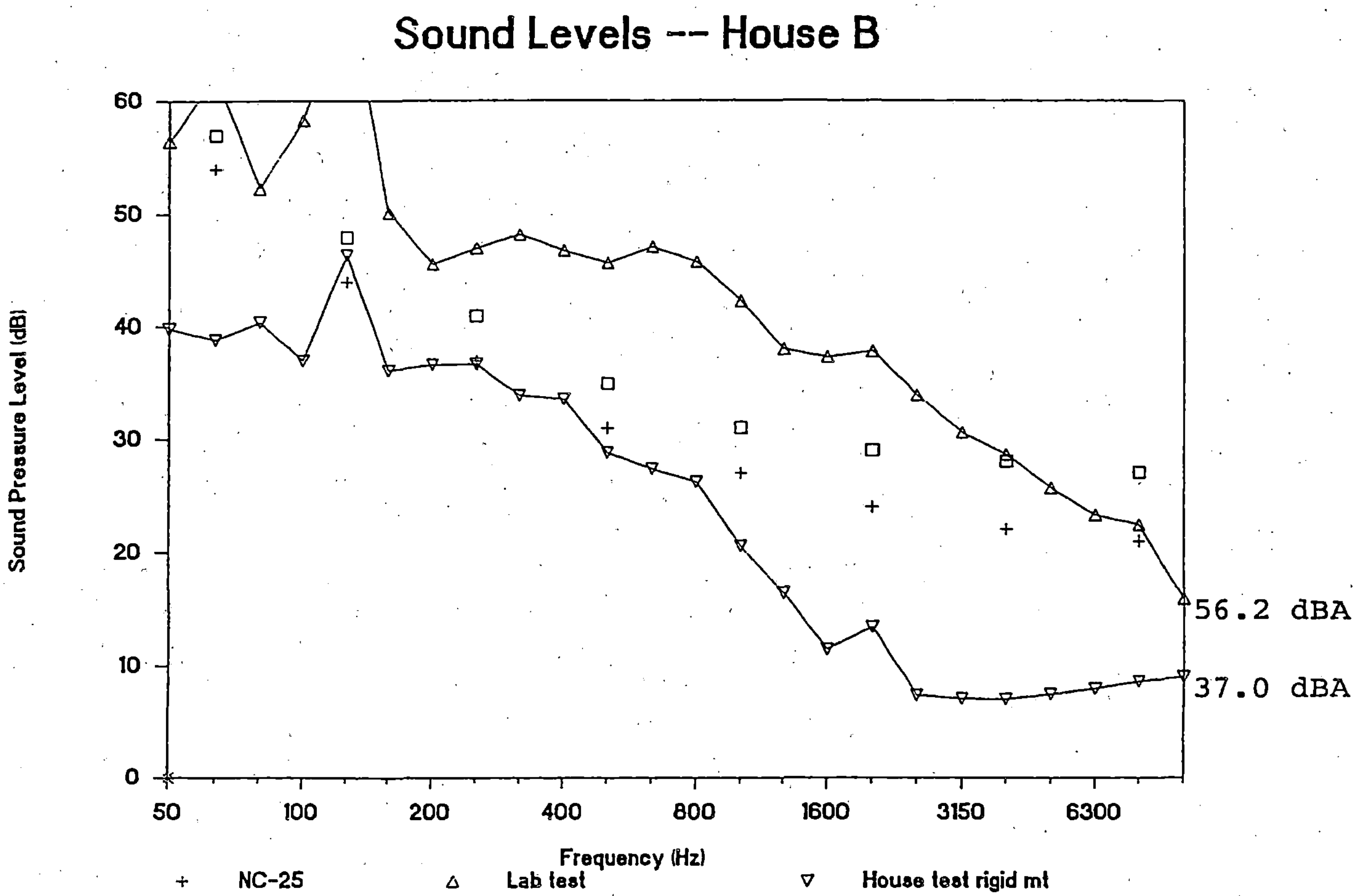


Figure 10. Comparison of the sound pressure levels measured in House B using the Delhi Fan against the sound power levels measured in the lab. (Sound power levels were converted to sound pressure levels using formula 1.)

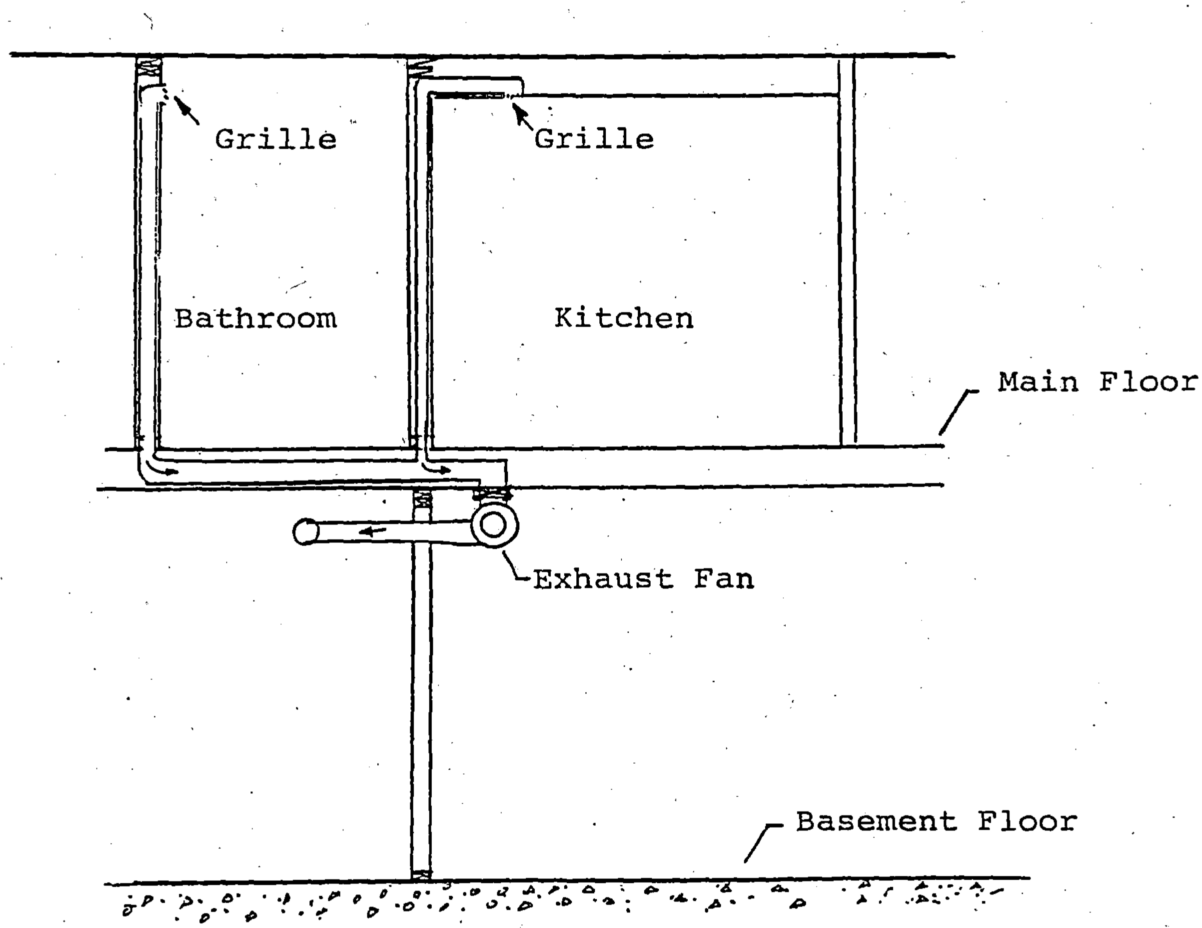


Figure 11. Location of Exhaust Fan relative to Bathroom in House B.

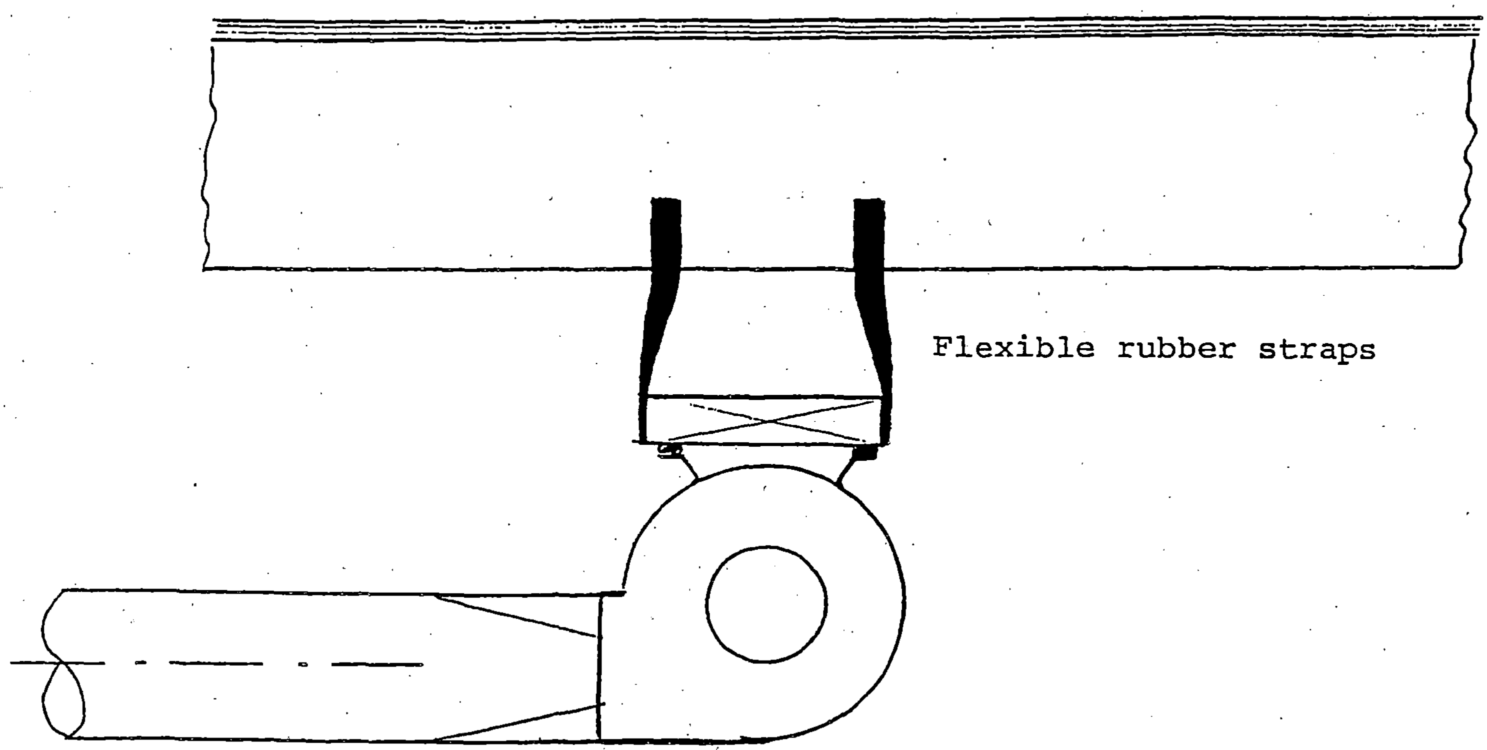


Figure 12 Flexible attachment of Fan to Floor Joists

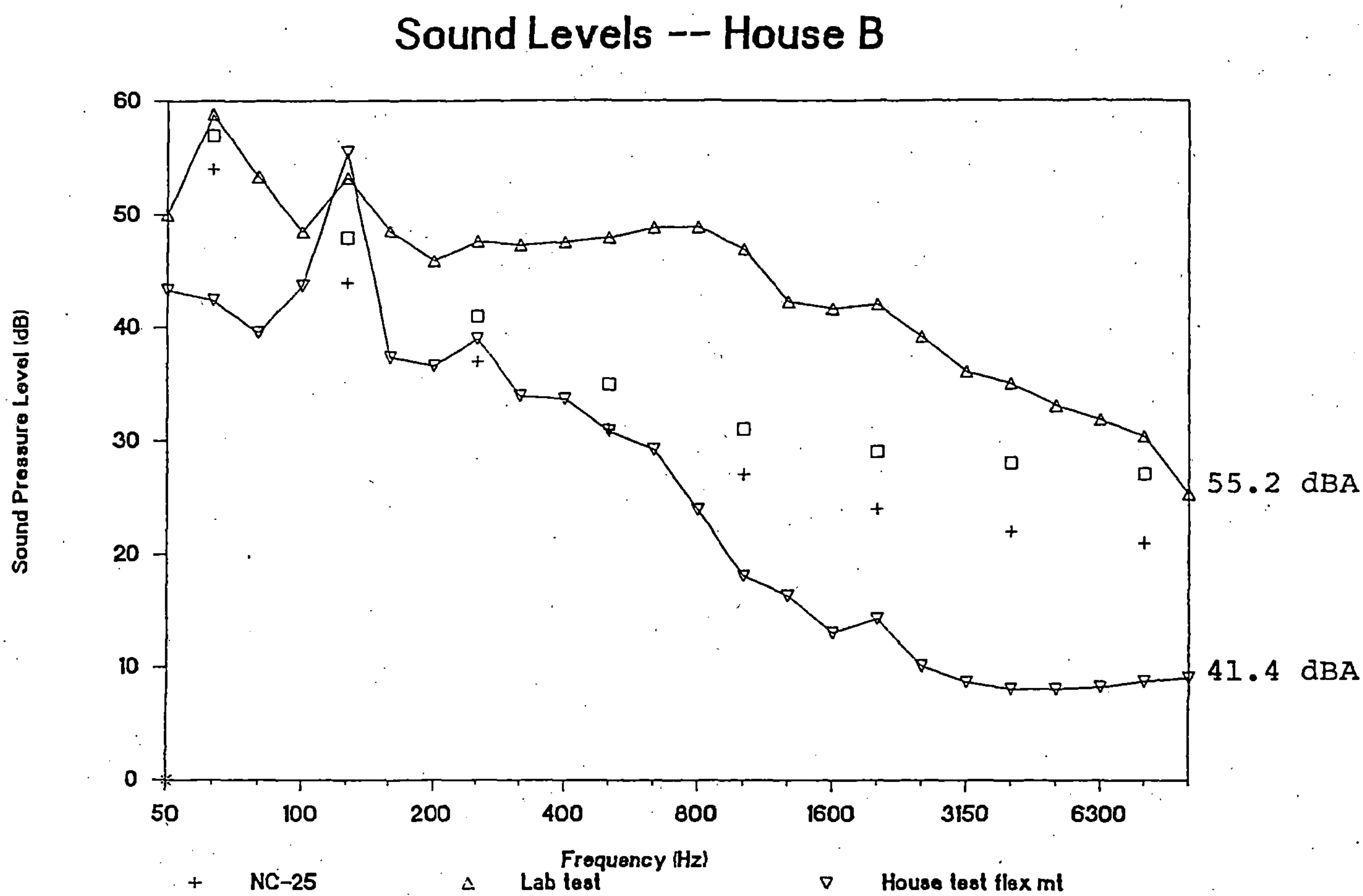


Figure 13. Comparison of the sound pressure levels measured in House B using the Delhi Fan against the sound power levels measured in the lab. (Sound power levels were converted to sound pressure levels using formula 1.)

Flexible mounting of fan.

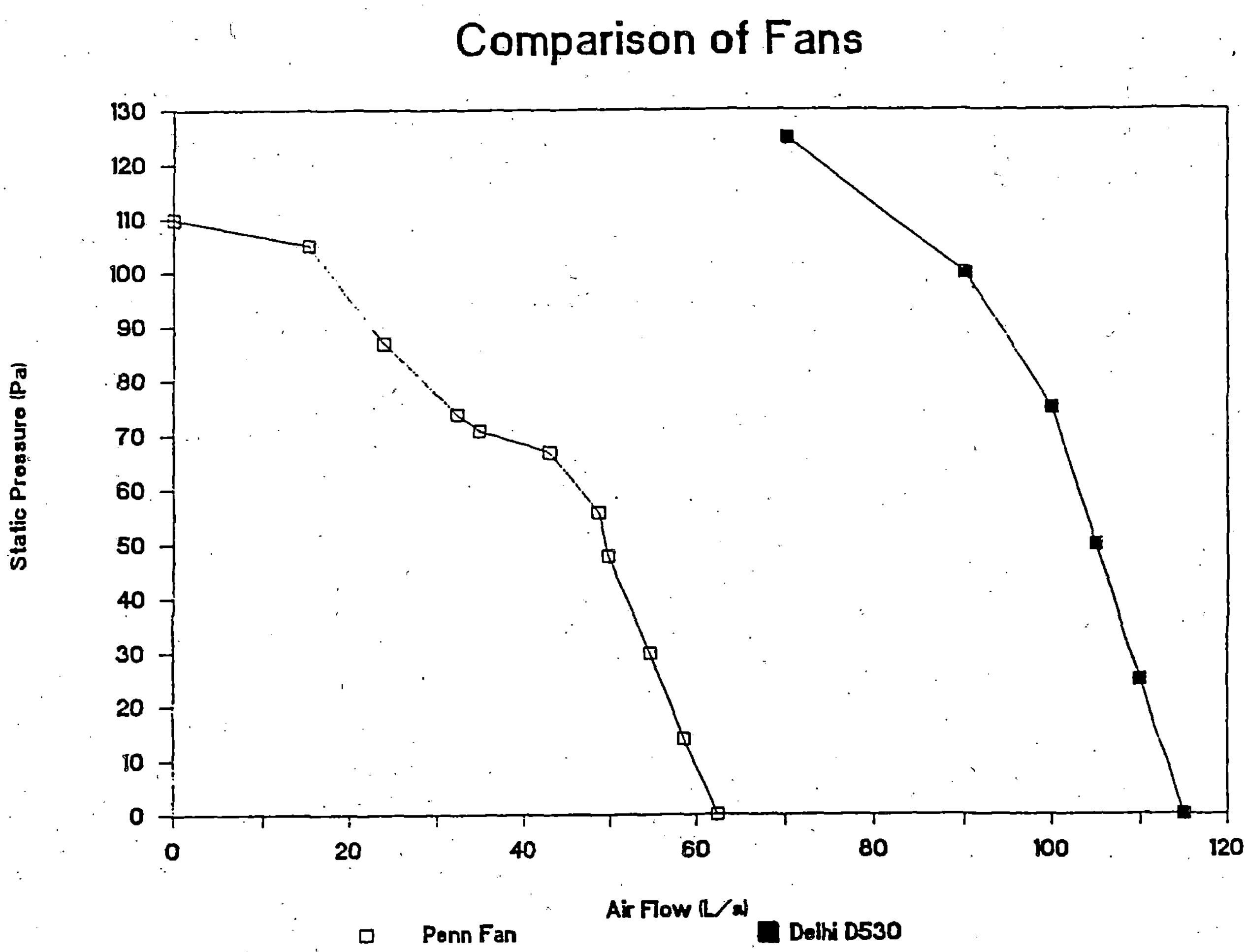


Figure 14. Comparison of Penn and Delhi D530 Fans

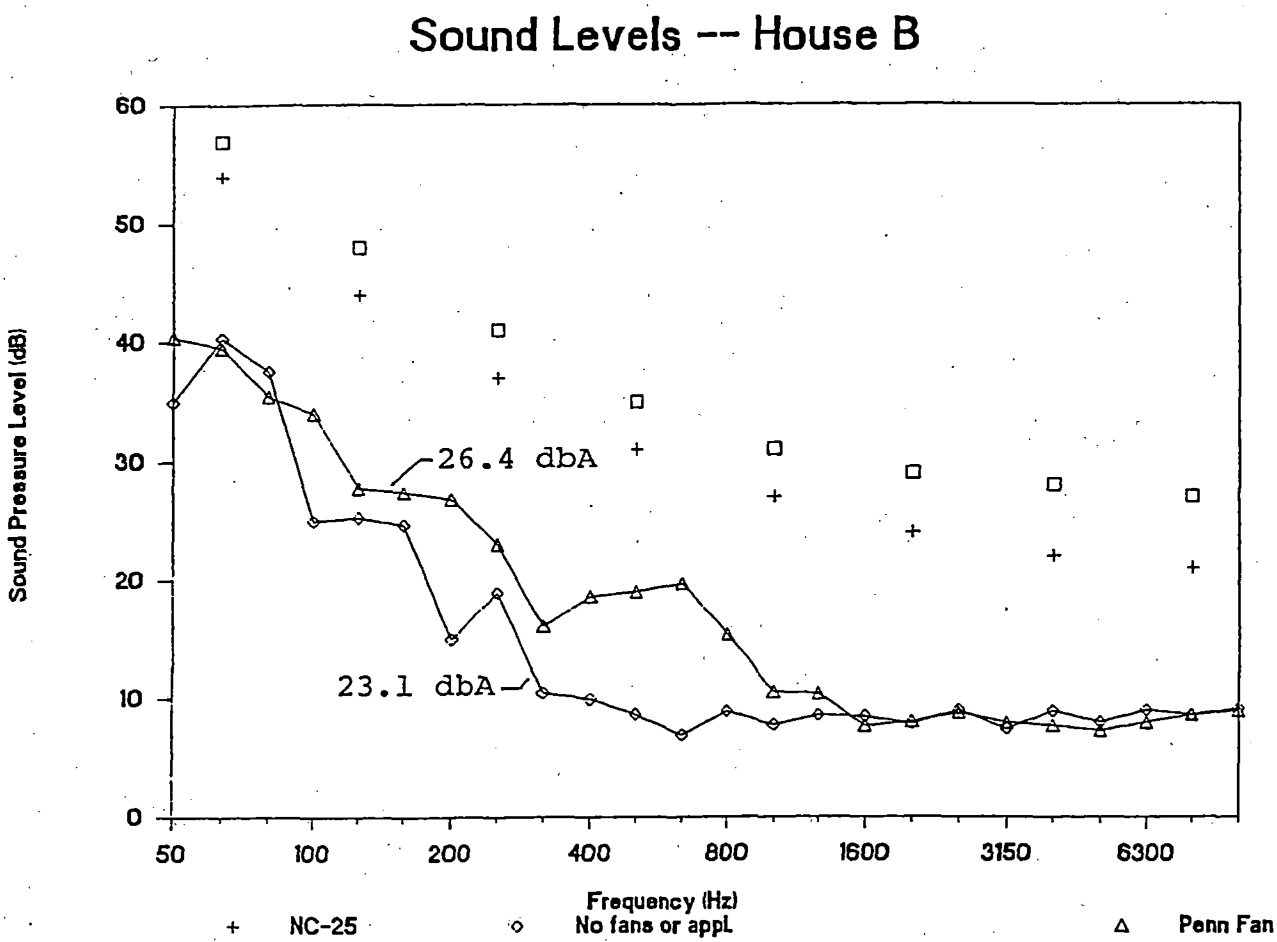


Figure 15. Measured sound pressure levels in House B using the Penn Fan compared with pressure levels using no fans or appliances.

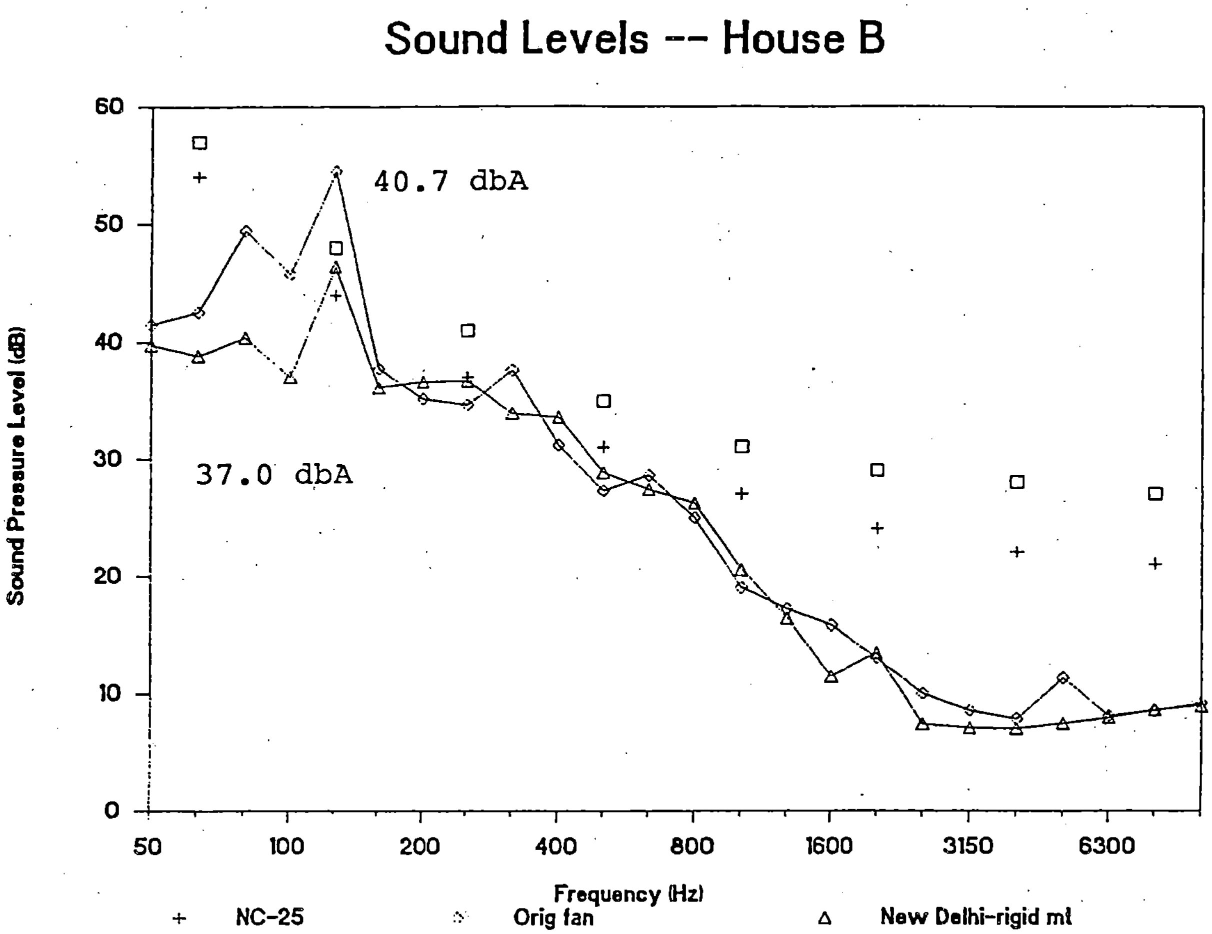


Figure 16. Comparison of the sound pressure levels from the original Delhi fan (with 7 years of dust accumulation) with the new Delhi fan.