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The Possible Role of Indoor Radon Reduction Systems in Back-Drafting Residential Combustion Appliances

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Abstract A computational sensitivity analysis was conducted to identify the conditions under which residential active soil depressurization (ASD) systems for indoor radon reduction might most likely exacerbate or create back-drafting of natural-draft combustion appliances. Parameters varied included: house size; normalized leakage area; exhaust rate of exhaust appliances other than the ASD system; and the amount of house air exhausted by the ASD system. Even with a reasonably conservative set of assumptions, it is predicted that ASD systems should *not* exacerbate or create back- drafting in most of the U.S. housing stock. Only at normalized leakage areas lower than 3 to 4 cm^2 (@ 4 Pa) per m^2 of floor area should ASD contribute to back-drafting, even in small houses at high ASD exhaust rates (compared to a mean of over 10 cm^2/m^2 determined from data on over 12,000 U.S. houses). But on the other hand, even with a more forgiving set of assumptions, it is predicted that ASD systems *could* contribute to back-drafting in some fraction of the housing stock – houses tighter than about 1 to 2 cm^2/m^2 – even in large houses at minimal ASD exhaust rates. It is not possible to use parameters such as house size or ASD system flow rate to estimate reliably the risk that an ASD system might contribute to back-drafting in a given house. Spillage/back-draft testing would be needed for essentially all installations.

Key words Radon; Mitigation; Active soil depressurization; Back-drafting; Spillage; Residential combustion appliances; House depressurization.

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Introduction

Active soil depressurization (ASD) systems for indoor radon reduction utilize a fan to draw radon-containing soil gas from around the foundation of a building – e.g., from the fill underlying a concrete floor slab – and exhausting this soil gas outdoors (Henschel, 1993). Typically, 20% to 80% of the gas exhausted by the ASD fan is indoor air that has been drawn down into the depressurized sub-slab region through slab openings and has then been drawn into the system's suction piping. The ASD system thus has the effect of a continuous building exhaust fan.

If sufficient house air is exhausted by the system and if the building shell is sufficiently tight, the house depressurization induced by the system exhaust might be sufficient to exacerbate or create spillage of combustion products from any natural-draft combustion appliances in the building. Spillage could potentially expose occupants to hazardous levels of carbon monoxide, if the spillage continued for an extended period and if the products of combustion contained high concentrations of carbon monoxide. Consequently, current standards governing the installation of residential ASD systems specify that post-mitigation spillage/back-drafting tests must be conducted when natural-draft appliances are present (EPA, 1993).

This article describes a computational sensitivity analysis, to predict the conditions under which ASD systems might create back-drafting-induced spillage in practical residential applications, or exacerbate a pre-existing back-drafting condition. A key objective was to determine whether the risk of back-drafting might be predicted to be sufficiently low at specific combinations of house size and ASD exhaust rates, so that even in the absence of other information on the house or vent system characteristics, a radon mitigator might safely decide not to conduct spillage/back-draft testing under those conditions.

The focus is on gas-fired natural-draft furnaces and water heaters, since these are the combustion appliances most prone to back-drafting.

Approach

Basic Equation

The calculations use the power law equation commonly employed in characterizing the tightness of

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house shells, as described elsewhere (ASHRAE, 1993):

$$Q=c(\Delta p)^n \qquad (1)$$

or

$$\Delta p=(Q/c)^{1/n} \qquad (2)$$

where: Q is the airflow through the house shell (m^3/s); c is an empirical flow coefficient [$m^3/(s \cdot Pa^n)$], which depends upon the shell leakage area and the geometry of the shell openings; Δp is the pressure differential across the shell (Pa); and n is a dimensionless empirical flow exponent dependent on the flow characteristics through the shell openings. For the calculations here, a value of $n=0.66$ was used; this value is typical of those observed in the field, and was found to be the mean for 554 modern U.S. houses surveyed in one study (Sherman et al., 1986).

In these calculations, shell Δp values were computed using Equation 2 as exhaust flows Q (from the ASD system and from other exhaust appliances) and house leakage characteristics (i.e., values of the flow coefficient c) were systematically varied through a wide range of practical values. These computed shell Δp values were then compared against two selected values for the maximum mechanically induced shell depressurization, above which the exhausts might cause back-drafting in cooled combustion appliance vent stacks.

Maximum Allowable Mechanically Induced House Depressurization

Considerations in Selecting Allowable Depressurizations

The level of mechanically induced depressurization that will cause cooled-vent back-drafting in a given house depends upon many variables. These include variables that influence:

- the theoretical draft in the vent stack – including the height of the stack, the outdoor temperature, and an array of appliance and vent system variables that can affect the mean stack temperature when the appliance is off (e.g., the characteristics of any pilot light, the length of any uninsulated horizontal connectors, and the characteristics and location of the chimney);
- the thermally induced depressurization of the house at draft diverter height, which counteracts the theoretical draft – including the position of the draft diverter relative to the neutral pressure level, the outdoor temperature, and the indoor temperature; and
- the vent performance – including vent installation and maintenance parameters such as vent blockage, which could hinder performance.

With this large number of house-specific variables, any target value selected here as the maximum allowable mechanically induced house depressurization would be too conservatively low for some houses, and too high for others.

A companion issue is what exhaust appliances are present in a given house, what their exhaust rates are, and which of these exhausts are operating when the combustion appliance is off. A number of the intermittent exhausts might well not be operating when the combustion appliance is off, or might be operating too briefly to establish stable back-drafting. Again, any assumptions here regarding the characteristics of the house exhaust appliances will unavoidably be too conservative for some houses, and too lenient for others.

The two cases selected below are felt to represent depressurization levels and exhaust characteristics that are reasonably conservative (with the first case being somewhat more forgiving than the second). These cases are intended to provide perspective regarding the potential of residential ASD systems to create back-drafting. However, in view of the preceding discussion, it must be recognized that any given house might be more or less prone to back-drafting than would be computed from the selected cases.

An additional consideration is that this analysis cannot address spillage that might occur as the net draft is reduced, prior to the onset of back-drafting, i.e., prior to actual stable flow reversal.

Accordingly, while the analysis here is believed to provide useful insights regarding when ASD systems are more or less likely to contribute to spillage, it is clear *a priori* that the only way to *guarantee* the absence of spillage in *every* house would be to conduct suitable spillage tests for every ASD installation.

Focus on Cooled-Vent Back-Drafting

The two cases selected below focus on back-drafting of cooled (rather than hot) vents. The theoretical draft in a cooled vent (prior to the onset of back-drafting) might be 2 to 10 Pa or less, depending upon the temperatures outdoors and in the vent stack, and upon stack height. This draft is potentially subject to being overwhelmed by mechanical exhausts, resulting in back-drafting. Once such cooled-vent flow reversal begins with the appliance off, the hot combustion products can be hindered from entering the vent when the appliance cycles on, and a substantial amount of combustion product spillage could occur before the hot vent draft can be re-established (Moffatt, 1986).

By comparison, the theoretical draft in a hot one- to two-story vent can be above 8 to 10 Pa, even with relatively mild outdoor temperatures and with some conditions that would reduce the mean vent temperature (such as uninsulated horizontal connectors leading to the vent stack and high excess air downstream of the draft diverter). With colder outdoor temperatures, hotter vent temperatures, and/or taller stacks, the hot theoretical draft can exceed 20 Pa. Except under extreme conditions (combinations of short stacks, reduced vent temperatures, very tight houses, and/or high exhaust flows), it is unlikely that mechanically induced depressurization would cause flow reversal in a properly installed and maintained hot vent.

The maximum allowable depressurizations used in Cases 1 and 2 below assume that the vent is properly installed and maintained. No adjustments to the allowable depressurizations have been made to compensate for any reductions in vent performance caused by, e.g., vent blockage.

Case 1: The CAN/CGSB-51.71-95 Case

Two Canadian standards (CSA, 1991; CGSB, 1995) specify that when open (natural-draft) combustion appliances are present in a dwelling, mechanical exhausts and fireplaces should depressurize the house by no more than 5 Pa relative to the outdoors. Inherent in these standards is the objective of reducing the risk of back- drafting the cooled vents when natural-draft combustion appliances have cycled off.

A specific protocol is defined for measuring the pressure differential across the house shell (CMHC, 1991; CGSB, 1995). The current protocol specifies the air-moving appliances to be operated during the test, including, among others: exhaust appliances intended for continuous operation (such as ASD fans); and specific intermittent exhaust fans (clothes driers, kitchen exhaust fans, and other intermittent exhausts rated at more than 75 L/s). Bathroom fans rated below 75 L/s are not operated. If the appliances create an incremental additional house depressurization greater than 5 Pa (beyond that already existing due to weather conditions), the house fails the test.

One of the two cases considered in this paper is based upon these criteria (maximum mechanical depressurization=5 Pa, bathroom fans not operated). This case is referred to here as "the CAN/CGSB-51.71-95 case," according to the spillage standard (CGSB, 1995).

Bathroom fans are excluded in the shell pressure measurement in part to help compensate for the fact that, in practice, intermittent exhaust fans will not all be operating simultaneously for any extended period. In addition, the consensus depressurization value of 5 Pa takes into consideration practical experience showing that, when a combustion appliance cycles on, the hot products of combustion can often re-establish th hot-vent draft within a short period of time in the fac of some degree of cooled-vent back-drafting.

Case 2: A More Conservative Case

For the current analysis, the computed mechanicall induced house depressurizations were also compare against a more conservative maximum of 3.5 Pa, calculated *with* the bathroom exhaust fans operating (in addition to the other exhaust appliances). This second approach does not provide any allowance for the fact tha intermittent appliances will generally not all be operating simultaneously, or for the ability of the combustio appliance to overcome cooled-vent back-drafting afte cycling on.

This more conservative 3.5 Pa maximum mechanica depressurization represents the total theoretical draf in a cooled two-story vent stack (about 5 Pa), minus th competing thermally induced stack depressurization o the house at draft diverter height (about 1.5 Pa). Thes pressures were calculated (ASHRAE, 1992; ASHRAE 1993) assuming:

- height from the draft diverter to the top of the ven stack=5.5 m;
- outdoor temperature=4°C;
- indoor temperature=20°C;
- mean temperature inside the vent=24°C with th combustion appliance off, warmed by the continuous 230 J/s pilot light; and
- height of neutral pressure level above draft diverter=2 m.

To account for heat losses through the furnace and duct walls, the 4°C increase of the vent temperature by the pilot light is about half that which would be calculated adiabatically. It is also about half that observed by others (Dumont and Snodgrass, 1990). Once stable back-drafting began, the inflow of outdoor ai would reduce the vent temperature to the outdoo value, and the theoretical draft would drop to zero. This calculation estimates the mechanical depressurization that would be required to establish that back-drafting in the 24°C vent.

Wind effects at the vent stack discharge, which would usually increase the draft, were disregarded.

With colder outdoor temperatures, warmer vents, taller vent stacks, lower neutral pressure levels, or cooler houses, the maximum allowable mechanically induced house depressurization would increase above 3.5 Pa, to 7 Pa and greater. With milder temperatures, cooler vents, one-story vent stacks, higher neutral levels, and warmer houses, this value could decrease below 2.5 Pa. The value of 3.5 Pa is selected as being conservative but reasonable.

The assumption that all intermittent exhaust appliances (including bathroom fans) will be operating simultaneously represents a more severe situation than would be encountered in practice. This is consistent with the philosophy of making the Case 2 approach conservative.

The assumption of simultaneous intermittent exhausts also represents an attempt to account for a number of other exhaust sources that can be present, but for which it is difficult to make generalized assumptions in a computational effort such as this. These other sources include intermittent exhausts (e.g., high- exhaust kitchen ranges, open fireplaces, and wood stoves) and continuous exhausts (e.g., as created in a basement or furnace room by the return ducting to a central forced-air furnace).

These other depressurization sources *are* accounted for in the Canadian test protocol (CMHC, 1991; CGSB, 1995). Thus, the consideration of this more conservative case might be viewed as an attempt in this computational analysis to compensate for the omission of certain depressurization sources that the test protocol would be able to address in practice.

House Sizes

Three house sizes were selected, to represent a range of possible field situations.

- 100 m^2 of floor area, representing a small house. Or, this area could represent the case where the combustion appliances and the ASD system are inside a basement that is isolated from the remainder of the house. When there is forced-air supply and return ducting penetrating the shell between the basement and the adjoining living space, it is unclear how well the basement would in fact be isolated pressure-wise, even if the basement door remained closed.
- 190 m^2 of floor area, representing a moderately sized house.
- 280 m^2 of floor area, representing a somewhat larger house.

House Normalized Leakage Areas

Five values were selected for house tightness. These values are expressed in terms of the effective leakage area (ELA) of a bell-mouthed nozzle (discharge coefficient=1.0) at 4 Pa, and are normalized on the basis of the total floor area of the conditioned space (including basements).

- 0.7 cm^2 ELA at 4 Pa per m^2 of floor area, representing a super-tight house meeting the specifications of the tightest leakage class defined in ASHRAE Standard 119-1988 (ASHRAE, 1988). This tightness also meets the specifications of the Canadian R-2000 program: 1.5 air changes per hour at 50 Pa, or 0.7 cm^2 equivalent leakage area (EqLA) of a sharp-edged orifice (discharge coefficient=0.61) at 10 Pa per m^2 of house envelope area (including exterior walls, top-story ceiling, and bottom-story floor) (NRCan, 1994).
- 2.0 cm^2/m^2, generally representing the range observed in new construction (excluding super-tight houses) in cold climates (Moffatt, 1986; Sherman et al., 1986; Hamlin et al., 1990; CMHC, 1995; Grimsrud et al., 1996).
- 3.5 cm^2/m^2, which appears to be reasonably representative of the range observed in new construction in less cold climates, according to published (Hamlin et al., 1990; Cummings et al., 1992) and unpublished sources.
- 5.5 cm^2/m^2, representing less tight new construction, and more tight construction among modern (but not new) houses in less cold climates (Moffatt, 1986; Sherman et al., 1986; Hamlin et al., 1990).
- 9.0 cm^2/m^2, representing older, post-World War II houses (Sherman et al., 1986; Cummings et al., 1992; Sherman and Dickerhoff, 1994).

Mechanical Exhausts other than the ASD System

As shown by Equation 2, house depressurization does not increase linearly with exhaust flow, but is proportional to flow to the power $1/n$ (i.e., to the power of about 1.5). Thus, the incremental additional depressurization created by a given ASD exhaust flow will depend upon the magnitude of other exhausts which are occurring simultaneously.

For these calculations, representative values of the actual exhaust rates of various exhaust appliances were estimated from values reported in the literature (CMHC, 1995; Cummings et al., 1992; Moffatt, 1986). These exhaust rates are generally below the rated flows of the appliances, due to the flow resistance created by the ducting. The actual exhaust rate for a particular type of appliance in a given house can vary dramatically, depending upon the performance curve of the specific fan and the details of the specific installation. Recognizing the uncertainty created by this broad range that exists in practice, the representative net exhaust rates to the outdoors selected for these calculations were:

- bathroom exhaust fan – 20 L/s;
- standard kitchen range hood exhaust – 50 L/s;
- clothes drier – 50 L/s.

High-exhaust range hoods commonly have exhaust rates on the order of about 120 L/s, and open wood-burning fireplaces about 80 L/s. Since the house is being depressurized by the mechanical exhausts, there will be no naturally induced exfiltration flows influencing the calculations.

The total "worst-case" exhaust rates from the different house sizes, i.e., if all exhaust appliances were being operated simultaneously, were assumed to be as follows, for houses other than the super-tight (0.7 cm^2/m^2).

- 100 m^2 – a basement containing a clothes drier and a bathroom exhaust fan. For Case 1, as discussed above, only the drier was considered (50 L/s); for Case 2, the bathroom fan was also addressed (giving 70 L/s total).
- 190 m^2 – a house containing a drier, a kitchen range hood, and a bathroom fan (100 L/s total for Case 1, 120 L/s total for Case 2).
- 280 m^2 – a house containing a drier, a range hood, and two bathroom fans (100 L/s total for Case 1, 140 L/s for Case 2).

For super-tight houses, it was assumed that, consistent with the practices representative of the R-2000 program, bathroom ventilation is implemented using the heat recovery ventilator (HRV) specified for these houses, so that the net exhaust by bathroom fans is zero. Likewise, kitchen range hoods are recirculating units, accompanied by ventilation of the kitchen using the HRV, so that net kitchen exhaust is also zero. Accordingly, the only net exhaust from the super-tight house is from the clothes drier (50 L/s), which is the same for all three house sizes.

All of the non-ASD exhaust rates listed above were assumed to be those that would exist when there is no pressure differential between indoors and outdoors. As the house became depressurized, the flow through each exhaust fan was reduced by 0.25 L/s per Pa of house depressurization. This figure is a representative value derived from analysis of a range of actual and hypothetical fan performance curves for these appliances. This flow correction reduced computed house depressurizations by 0% to 20%, a small amount in comparison with the uncertainty already inherent in selecting the representative exhaust rates for each appliance.

Amount of House Air Exhausted by the ASD System

Depending upon the capacity of the ASD fan, the permeability of the sub-slab region, and the tightness of the house shell below grade, total exhaust flows from ASD systems are typically in the range of 10 to 70 L/s. Depending upon the tightness of the shell below grade, between 20% and 80% of this total flow is drawn from inside the house (Henschel, 1993).

For these calculations, three values were selected for the amount of air drawn out of the house by the ASD system, representing the range that might be encountered in practice.

- 5 L/s – representing the case where total ASD flow is toward the lower end of the observed range (10 L/s), and the percentage coming from the house is 50%, a typical value.
- 12 L/s – representing the case where total flow is at a commonly observed value (25 L/s), and the percentage from the house is 50%.
- 35 L/s – representing the case where the total flow is at the upper end of the range (70 L/s) and the percentage from the house is about 50%; or the case where the total flow is not so high (50 L/s) but the percentage coming from the house is toward the higher end of the range (70%).

Results and Discussion

Case 1: The CAN/CGSB-51.71-95 Case

The complete results for Case 1 are presented in Table 1. The table shows the "worst-case" mechanically induced depressurizations with and without the ASD system operating, for the different ASD exhaust rates out of the house. The shading indicates cases where the total mechanical depressurization is greater than 5 Pa; i.e., where the ASD system would be predicted to be exacerbating or creating the potential for cooled-vent back-drafting of natural-draft appliances according to the Case 1 assumptions.

Table 2 presents the Case 1 results in terms of the minimum ELA (the maximum tightness) that could be tolerated for each ASD exhaust rate for each house size, before the 5 Pa maximum house depressurization would be exceeded.

Table 2 predicts that, even at the worst-case ASD exhaust rate of 35 L/s out of the house (about 70 L/s total system flow), typically sized houses (190 to 280 m^2) should not encounter back-drafting of natural-draft appliances until the normalized ELA drops below 1.6 to 2.3 cm^2/m^2, based upon the assumptions of this analysis. This range is representative of new houses in cold climates. Even the 100 m^2 house would have to be tighter than 2.8 cm^2/m^2 at maximum ASD flow to exceed 5 Pa, tighter than new construction in temperate climates.

The majority of the U.S. housing stock is much leakier than this. A review of data from over 12,000 U.S. houses suggests a mean greater than 10 cm^2/m^2 (Sherman and Dickerhoff, 1994; Sherman and Matson, 1997). Thus, in the large majority of cases, cooled-vent back-drafting should not be a problem, even at maximum ASD flows in small houses and isolated basements, under the assumptions of Case 1.

Table 1 Estimated mechanically induced house depressurizations (ASD systems plus other exhausts) for the CAN/CGSB-51.71-95 case (5 Pa maximum allowable depressurization, bathroom fans excluded)

House floor area (m^2)	ELA @ 4 Pa, per unit floor area (cm^2/m^2)	"Worst-case" exhaust rate of appliances other than ASD (L/s)		"Worst-case" mechanical depressuriz. with ASD off (Pa)	Depressurization added by ASD system (Pa) when air being exhausted from house by ASD is:					
					5 L/s		12 L/s		35 L/s	
		Nominal[1]	Actual[2]		ASD Adds	Mech. Total[3]	ASD Adds	Mech. Total[3]	ASD Adds	Mech. Total[3]
100	0.7	50	41–46	16.4	2.8	18.9	6.8	22.4	21.4	35.3
190	0.7	50	46–48	6.7	1.1	7.7	2.7	9.2	8.5	14.8
280	0.7	50	48–49	3.8	0.6	4.4	1.5	5.3	4.8	8.4
100	2.0	50	48–49	3.7	0.6	4.3	1.4	5.1	4.6	8.2
190	2.0	100	97–98	4.0	0.3	4.3	0.8	4.7	2.3	6.3
280	2.0	100	98–99	2.2	0.2	2.4	0.4	2.7	1.3	3.5
100	3.5	50	49-50	1.6	0.3	1.9	0.6	2.2	2.0	3.6
190	3.5	100	99	1.7	0.1	1.9	0.3	2.0	1.0	2.7
280	3.5	100	99-100	1.0	0.1	1.0	0.2	1.2	0.6	1.5
100	5.5	50	50	0.8	0.1	0.9	0.3	1.1	1.0	1.8
190	5.5	100	99–100	0.9	0.1	1.0	0.2	1.0	0.5	1.4
280	5.5	100	100	0.5	<0.1	0.5	0.1	0.6	0.3	0.8
100	9.0	100	99	1.1	0.1	1.2	0.2	1.3	0.6	1.7

Shaded numbers highlight cases where mechanically induced depressurization in the space (by ASD plus other exhaust sources) exceeds 5 Pa, as discussed in the text.

Footnotes:

[1] Assumed combined exhaust rates of kitchen range and/or clothes drier fans when there is no pressure differential between indoors and outdoors.

[2] Corrected combined exhaust rates, accounting for house depressurization relative to outdoors.

[3] Total depressurization with the ASD operating sometimes does not equal the sum of the depressurization with the ASD off plus the ASD contribution, due to: a) rounding to the nearest 0.1 Pa; and b) for 0.7 cm^2/m^2 houses, reductions in non-ASD exhaust flows resulting from ASD-induced house depressurization.

On the other hand, Table 2 also predicts that back-drafting could occur even at minimal ASD flows, if the ELA were 1.2 to 1.7 cm^2/m^2 or less, depending upon house size. While such ELAs are substantially below the U.S. average, they do represent values that will be encountered in the housing stock (especially in new construction in cold climates), and they are not as low as values representative of super-tight houses.

Thus, while ASD-induced back-drafting would be predicted to occur in only a limited fraction of U.S. houses, it can occur in some cases even under the more forgiving Case 1 assumptions. Thus, it cannot be ignored. Without data on the ELA distribution among the U.S. housing stock, it is impossible to estimate the fraction of houses that are tighter than the 1.2 to 2.8 cm^2/m^2 range for which a potential problem would be predicted from Table 2. Nationally, the fraction is probably small, although it could be higher in cold climates.

Depending upon the house size, the ELA, and the ASD exhaust rate, the ASD system can sometimes *create* a risk of back-drafting. That is, a house that is below the 5 Pa maximum with the ASD system off can be raised above that maximum when the system is turned on. For example, referring to Table 2, a 190 m^2 house with an ELA of 2.0 cm^2/m^2 – below 5 Pa with the system off – would be predicted to rise above the maximum if the ASD exhaust out of the house exceeded 20 L/s.

But if the ELA of that 190 m^2 house were 1.6 cm^2/m^2, the threat of back-drafting would exist even without the ASD system, due to the non-ASD exhausts. The system would then be *exacerbating* a pre- existing back-draft condition.

Table 1 predicts that super-tight houses (0.7 cm^2/m^2) could often exceed the 5 Pa maximum which could back-draft natural-draft appliances. Such houses will commonly have induced-draft or sealed combustion appliances, for which 5 Pa of depressurization will not create a problem. However, in small houses or isolated basements of this tightness, or with high ASD exhausts, Table 1 suggests that the house depressurization might sometimes exceed even the 10 Pa limit specified in CAN/CGSB-51.71-95 for induced-draft appliances (with both continuous and intermittent exhausts operating). It might also sometimes exceed the 20 Pa limit for sealed units. A radon mitigator should be alert to this potential problem when working in houses known to be super-tight.

Case 2: A More Conservative Case

Table 3 summarizes the results for the Case 2 assumptions, in the same format as Table 2.

The more conservative Case 2 assumptions predict that the normalized ELA would have to increase to 2.6 to 3.4 cm^2/m^2 in the 190 to 280 m^2 houses before house depressurization would be maintained below the 3.5 Pa maximum at the 35 L/s ASD house exhaust rate. This compares with 1.6 to 2.3 cm^2/m^2 to maintain the houses below 5 Pa in Case 1. In the 100 m^2 house or isolated basement, the Case 2 ELA for the 35 L/s exhaust increases to 4.4 cm^2/m^2 (compared to 2.8 cm^2/m^2). Thus, even using the more conservative Case 2 assumptions, it would be predicted that natural-draft appliances should often not back-draft when the house tightness is representative of new construction in temperate climates (3–4 cm^2/m^2) or leakier, even under the highest flows that might be expected in ASD systems.

The 4.4 cm^2/m^2 ELA required to avoid back-drafting at worst- case ASD exhaust rates in small houses and isolated basements is still well below the >10 cm^2/m^2 mean reported for over 12,000 U.S. houses. Thus, even using the more conservative assumptions, the majority of the existing housing stock should not encounter a back- drafting problem.

On the other hand, Table 3 also predicts that at ELAs below 2.1 to 2.6 cm^2/m^2, back-drafting could occur even at minimal ASD flow in the two largest houses, according to the Case 2 assumptions. These ELAs are representative of those encountered in new construction in cold climates (as well as in individual older cold-climate houses).

Thus, like Case 1, the Case 2 assumptions also lead to the prediction that ASD-induced back-drafting would occur in a limited fraction of U.S. houses. However, under Case 2, this fraction is increased, as expected.

The Need for Spillage/Back-Draft Testing

Tables 2 and 3 predict that back-drafting could potentially occur even in a relatively large house and at low ASD flows, if the house is tight enough. Thus, even if all of the assumptions used in this analysis were universally applicable, a mitigator would require ELA data for comparison against Table 2 or 3 to determine whether back-draft testing is required in a given house. It would not be possible to use readily observed parameters such as house size or ASD system flow rate to make this decision.

Of course, the assumptions behind Tables 2 and 3 are *not* universally applicable. House and vent system parameters would vary from house to house, impacting theoretical stack draft, thermally induced house depressurization, and vent performance, as discussed earlier. Also, the actual exhaust appliances and their capacities would vary. To be rigorous, all of these

Table 2 Selected results for case 1, the CAN/CGSB-51.71-95 case (5 Pa maximum allowable depressurization, bathroom fans excluded)

ASD exhaust out of house/ (approx. total ASD system flow) (L/s)	Minimum ELA @ 4 Pa, per unit floor area (cm^2/m^2), to ensure house depressurization <5 Pa for house floor area of		
	100 m^2	190 m^2	280 m^2
0 / (0) (ASD off)	1.6	1.7	1.2
5 / (10)	1.8	1.8	1.2
12 / (24)	2.0	1.9	1.3
20 / (40)	2.3	2.1	1.4
35 / (70)	2.8	2.3	1.6

Table 3 Selected results for case 2, a more conservative case (3.5 Pa maximum allowable depressurization, bathroom fans included)

ASD exhaust out of house/ (approx. total ASD system flow) (L/s)	Minimum ELA @ 4 Pa, per unit floor area (cm^2/m^2), to ensure house depressurization< 3.5 Pa for house floor area of		
	100 m^2	190 m^2	280 m^2
0 / (0) (ASD off)	2.9	2.6	2.1
5 / (10)	3.1	2.7	2.1
12 / (24)	3.4	2.9	2.2
20 / (40)	3.7	3.1	2.4
35 / (70)	4.4	3.4	2.6

parameters would have to be analyzed, in addition to ELA measurements.

This combination of house-specific parameters can be addressed rigorously only through suitable spillage and back-draft testing in the particular house. Thus, in practice, a spillage/back-drafting test would likely be warranted for every ASD installation. This is true even though the reasonably conservative analysis in this paper suggests that ASD-induced back-drafting should not be a common problem except in relatively tight houses.

If ELA data *were* available for a given house, the ELA would have to be conservatively *higher* than the values in Table 2 or 3 before spillage and back-draft testing could reasonably be omitted. Even though the assumptions used in deriving the two tables are considered to be reasonably conservative, they might not be conservative enough for any given house.

Conclusions

1. Even with the more conservative of the two sets of assumptions considered here, it is predicted that ASD systems would *not* create back-drafting of natural-draft gas-fired appliances, or exacerbate a pre-existing back-drafting problem, in a potentially large majority of the existing U.S. housing stock.
   As long as the leakage area of a typically sized house were greater than about 3 to 4 cm^2 (@ 4 Pa) per m^2 of floor area (6–8 air changes per hour (ACH) @ 50 Pa), even the highest likely ASD exhaust flows should not create or exacerbate back-drafting under the more conservative assumptions. If the ASD system were in a small house (100 m^2) or an isolated basement, the leakage area would have to be greater than about 4 to 5 cm^2/m^2 (8–10 ACH @ 50 Pa). By comparison, the mean ELA for a sample of over 12,000 U.S. houses is reported to be >10 cm^2/m^2.
2. On the other hand, even with the more forgiving of the two sets of assumptions considered here, it is predicted that ASD systems *could* create or exacerbate back-drafting of natural- draft appliances, even at minimal ASD exhaust flows and in large houses, in some fraction of the housing stock.
   Even at minimal ASD flow in the largest houses considered (190–280 m^2), back-drafting would be predicted under the more forgiving assumptions at ELAs below 1 to 2 cm^2/m^2 (2–4 ACH @ 50 Pa). With the more conservative assumptions, these ELAs rise to 2.1 to 2.6 cm^2/m^2 (4–5 ACH @ 50 Pa). These ELAs are representative of new construction in cold climates (as well as individual older cold-climate houses), an important if not large component of the total housing stock.
3. It is not possible to use readily observed parameters such as house size or ASD system flow rate to determine reliably whether the installation of an ASD system might be creating or exacerbating spillage or back-drafting. Spillage/back-draft testing would be needed for essentially all installations where natural-draft appliances are present, even though this analysis suggests that ASD-induced back-drafting should not be a common problem. Only when the ELA of a given house is known to be conservatively greater than the applicable value in Table 2 or 3 might spillage/back-draft testing be omitted.
4. When an ASD system is installed in a house that is known to be super-tight (meeting the tightness criteria of the R-2000 program or of Leakage Class A defined by ASHRAE 119-1988), a mitigator would be well advised to consider back-draft testing even when the house has induced-draft or sealed combustion appliances. This is especially advisable if the ASD system is found to have a relatively high exhaust flow. In such cases, the target maximum house depressurizations would be the levels (10 and 20 Pa, respectively) specified in CAN/CGSB-51. 71–95.

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