SUCCESSFUL IMPLEMENTATION OF AIR TIGHTNESS REQUIREMENTS FOR RESIDENTIAL BUILDINGS

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ABSTRACT

Increasing the air tightness of homes is a cost-effective way to increase energy efficiency. But, as homes are made tighter attention must be paid to providing ventilation air to maintain a healthy environment and make up air for mechanical exhaust devices to maintain the safe operation of atmospherically vented appliances. In the year 2000 a new Minnesota energy code mandating stringent air tightness, mechanical ventilation, and make up air was successfully enacted. The new energy code has resulted in the construction of very energy efficient homes. Because nearly all homes built to the new code have high efficiency furnaces, they are likely to be much more efficient than would be expected by increasing air tightness alone. Minnesota's experience has shown that it is possible to implement a code requiring tight construction, as long as provisions are included for ventilation and make up air to avoid the potential harmful affects of depressurization.

INTRODUCTION

The desire for more energy efficient new homes has lead to energy code requirements for tighter homes. One consequence of air tightness is that air leakage is no longer a reliable source of fresh air for the home and its occupants. Much attention is being paid to the resulting need for mechanical ventilation to maintain healthy indoor air quality. However, the supply of make up air for vented combustion appliances appears to be getting relatively little attention.

In the year 2000 Minnesota adopted an energy code for one- and two-family dwellings mandating strict air tightness. Following the lead of Washington state and Canadian building codes the new Minnesota code also required mechanical ventilation. In a departure from the U.S. building code norm, make up air provisions, normally confined to mechanical codes, were amended to account for the fact that air tight buildings can not rely on infiltration alone to provide the make up air needed for mechanical exhausts and necessary for safe operation of vented combustion appliances.

While national model codes had for at least 18 years prior to Minnesota's 2000 code included warnings about the need to provide make up air for mechanical exhausts in homes, there is no indication that the residential construction or enforcement community paid any attention to make up air provisions in the U.S. The Minnesota code provided explicit and enforceable requirements for make up air, which changed industry practice.

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BOTH NEW AND EXISTING HOUSES ARE TIGHTER THAN WE MIGHT THINK

Problems with the supply of combustion air due to inadequate make up air for mechanical exhausts in homes have been discussed for at least three decades; problems started being reported nearly two decades ago.

A study of eight homes built in 1990 (Nelson, et al, 1993) identified serious combustion safety problems in a small sample of Minneapolis area new homes. Measured air tightness of the homes were all tighter than standard building practice at the time, averaging 4.2 air changes per hour at 50 Pascal (Pa). The estimated annual infiltration rates were low, averaging 0.27 air changes per hour relative to the 0.35 air changes per hour ventilation rate recommended by ASHRAE at that time.

In the 1993 study tests were conducted for the houses in the sample by turning on all exhaust fans including dryers and central vacuum cleaners. This condition was considered a "worst case" for vented combustion appliances. While at this worst case condition, natural draft furnaces and water heaters were turned on and checked for spillage. Any spillage after one minute of burner run time was considered a failure. Three of the five natural draft water heaters in the study were found to spill beyond the one minute limit under worst case conditions.

Measurements at combustion air inlets were found to have very low airflow rates. The report concluded that "…code approved combustion air inlets in Minnesota houses can not be relied upon to keep pressures induced by exhaust fans low enough to assure proper venting of natural draft appliances."

Another Minnesota study of both newer and older homes showed similar concerns. Bohac and Cheple (2002) compiled air tightness and appliance venting data from over 2500 Minnesota houses that had been retrofitted for soundproofing by the Metropolitan Airports Commission. The soundproofing work included the addition of insulation and air-tightening of the exterior building shell. The study was designed to provide information on ventilation needs and depressurization concerns for existing houses tightened under the program. Pre- and post-construction test data were analyzed to determine the frequency of combustion spillage and depressurization problems, and the need for mechanical ventilation for different housing types.

Air leakage data on the houses before air tightening found an average leakage of 1082 liter/second (L/s) at 50 Pa (2293 cfm50). The retrofit work resulted in an average air leakage reduction of 27% and the fraction of houses requiring mechanical ventilation increased from 30% to 80%. Combustion spillage tests for houses that had not yet received the improvements showed that about 20% of natural draft water heaters and 10% of natural draft furnaces failed a worst-case spillage test. Bohac and Cheple (2002) observed that weatherization treatment significantly tightens houses. They found that in both looser and tighter homes the maximum depressurization for which any type of combustion equipment with a properly sized vent system should be able to vent properly is affected by tightening:

- for tight homes where the maximum depressurization for proper venting is 3 Pa, the percentage of homes where appliances would fail to vent properly doubled after tightening, and
- for looser homes where the maximum depressurization for proper venting is 5 Pa, the percentage of homes where appliances would fail to vent properly also doubled after tightening.

They also noted that at that level of depressurization about 25% of water heaters will fail spillage criteria when tested under a variety of outdoor conditions.

There was no indication in either of these studies, nor of the author's recollections of building practices at that time, that make up air for mechanical exhausts was being provided for new homes. This is despite the fact that codes in place at the time contained strong (if not explicit) language requiring provisions to provide make up air. At the time of the 1993 Nelson study, and likely before, the Minnesota building code referenced the 1992 edition of the National Fuel Gas Code (NFPA54/ANSI Z223.1), which included the following provisions:

> A.5.3 Special Conditions Created by Mechanical Exhausting or Fireplaces. Operation of exhaust fans, ventilation systems, clothes dryers, or fireplaces may create conditions requiring special attention to avoid unsatisfactory operation of installed gas utilization equipment.
>
> 5.3.1 (g) Air requirements for the operation of exhaust fans, kitchen ventilation systems, clothes dryers, and fireplaces shall be considered in determining the adequacy of a space to provide combustion air requirements.

The Minnesota State Energy Office was authorized to promulgate the state energy code between the years 1980 and 2000. Beginning in the early 1990's discussions between the State Energy Office, investigators studying the residential construction industry, and the home building community began expressing concern that, while tight construction provides energy saving benefits, codes should not mandate increased air tightness without first addressing safety concerns. A 1992 communication (The Energy Conservatory, 1992) urged the State Energy Office to postpone adoption of rules that might result in increased air tightness until combustion and ventilation air were adequately addressed in the code.

CONSIDERATION OF DEPRESSURIZATION AND SAFETY FROM SPILLAGE

In the past residential structures had sufficient air leakage so that neither indoor air quality nor make up air for vented combustion appliances were of concern. However, with modern houses of very tight construction, natural ventilation and traditionally specified make up air for appliances may be inadequate. There are three variables that affect the safe operation of installed vented combustion appliances:

1. the house air tightness,
2. the exhaust rate of installed fans, and
3. the depressurization tolerance of combustion appliances.

A house air leakage rate (the inverse of the air tightness) can be quantified by inducing a pressure difference between the interior and exterior of the house and measuring the airflow necessary to maintain this pressure difference. The common tool used for measuring air tightness is the blower door, which accurately measures air pressure difference and flow rate. The blower door measurements, reported at 50 Pascal, can be combined with a factor representing house dimensions to yield the comparable air tightness value expressed as $L/s/m^2$ @ 50Pa (cfm/sf @ 50PA), ach 50, and liter/second 50 (cfm 50).

A house may become depressurized when air is mechanically exhausted (e.g. through a bathroom exhaust fan) and there is no intentional accommodation to replace the exhausted air. Leaks and intentional "passive" openings will alleviate depressurization, but if the exhaust flow is high significant depressurization will occur. The amount of depressurization is a function of the net air flow exhausted and the house air tightness. For a given house, the tighter it is (small house air leakage rate), the less air flow will be needed to maintain a depressurization of 50 Pa).

In reality houses rarely operate under conditions that would cause a depressurization of 50 Pa. As discussed below much lower values of depressurization will cause many vented appliances to not function properly. Thus, computing airflows that would cause smaller levels of depressurization is important. In reality the relationship between pressure and airflow is not linear, but a linear relationship will be shown here for simplicity of illustration. Equation 1 (The Energy Conservatory, 2007) is used to make such adjustments. For any pressure (or depressurization level) "i", the airflow at pressure *i* is computed by multiplying the airflow at 50 Pa by the ratio of the actual pressure to 50 Pa raised to the 0.65 power. Solving Equation 1 for the depressurization, P*i* yields Equation 2.

<u>Equation 1</u>

Airflow @ *i* pressure = Airflow @ 50 Pa x (P*i*/50)^0.65

where

P*i* = pressure (or depressurization) value "i" in Pascal

<u>Equation 2</u>

Depressurization (P*i*) = 50 x ((Airflow @ *i* pressure) / (Airflow @ 50 Pa))^1.538

Figure 1 employs equation 2 to show a simplified relationship between net exhaust flow rates and depressurization values for a 2500 sq. ft home having the three air tightness values given in Table 1:

TABLE 1: Air Tightness Values for a 232 sq meter (2500 sq ft) Home

Air tightness	ach @ 50Pa	L/s @ 50Pa	cfm @ 50Pa
Tight	1.5	340	720
Medium	3.6	816	1728
Loose	7.2	1631	3456

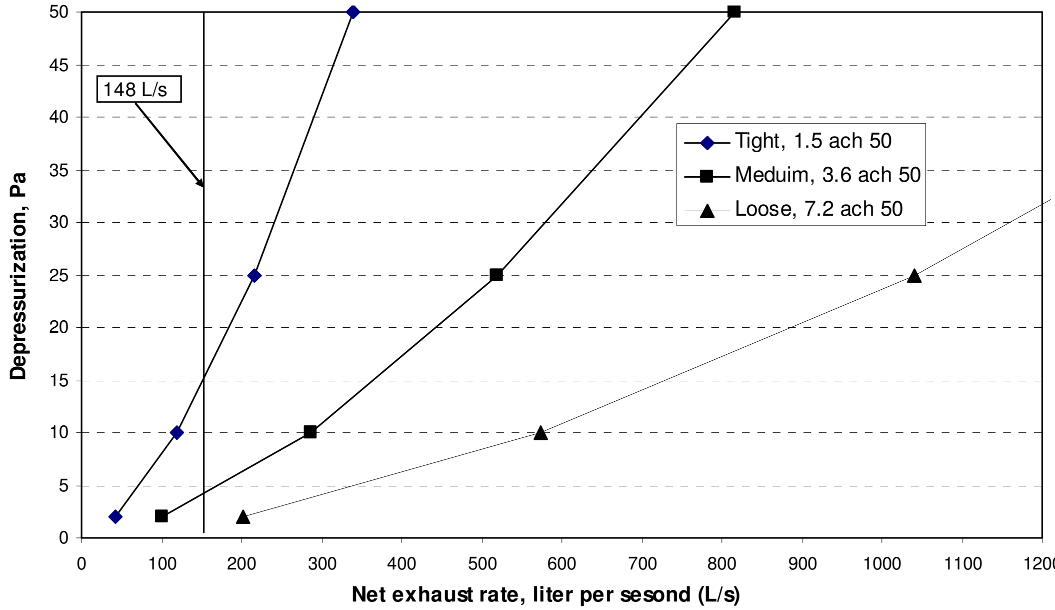

FIGURE 1: Depressurization as a Function of Net Exhaust Rate for Three Levels of Air Tightness

TABLE 2: Unit Conversion Values for Figure 1

L/s	100	200	300	400	500	600	700	800	900
cfm	212	424	636	847	1059	1271	1483	1695	1907

Note in Figure 1 that the tightest house (1.5 ach 50), a single fan exhausting 148 L/s (314 cfm), which could be a typical kitchen range hood on "high" setting, can result in a depressurization value of 15 Pa. As will be discussed later, this level of depressurization can be problematic for the safe operation of many vented combustion appliances.

If house tightness is the first variable, the second is the exhaust rate of installed fans. Clothes dryers, bath fans, range hoods, and central vacuum equipment are major mechanical exhausts typically found in new homes. The flow rate of some of these exhausts would be derated in a highly depressurized environment of 50 Pa but not at the depressurization levels of 5 Pa to 10 Pa which are shown below to be of concern.

The third variable is the numerical value of depressurization that can be tolerated by an atmospherically vented combustion appliance. "Depressurization that can be tolerated" means the lessor of the following:

1) the negative pressure environment that a vented combustion appliance can fire from a cold start and within three minutes will establish normal draft, or
2) the negative pressure that, when imposed on a firing appliance, will not cause the appliance to back draft.

Addressing depressurization is especially important because atmospherically vented combustion appliances are allowed by building codes and are widely installed. Sealed combustion appliances are accepted as the solution to back drafting problems. Since at least 1992, model mechanical codes have included requirements for make up air when large spot exhaust fans are installed.

A common field test that demonstrates how these three variables come together in a house is the "worst case depressurization" test. In the worst case depressurization test all exhausting fans are activated to their maximum setting. Vented combustion appliances are in some cases started during the test and in other cases allowed to warm up the flue prior to the test. From the time the exhaust fans are turned on all vented appliances are observed to determine whether proper venting is established or can be maintained. While coincident operation of all fans is unlikely, the test is done at this condition because the hazard that could be created by back drafting appliances is so significant that the "worst case" scenario must be assumed.

Published Canadian standards define depressurization tolerance for a variety of combustion appliances. The Canadian Spillage Test (CAN/CGSB, 1995) and CSA Standard F326 specify a depressurization limit of 5 Pa for natural draft appliances. The Canadian General Standards Board Standard 51.71 specifies the depressurization limit for closed, controlled combustion wood burning appliance as 7 Pa. Additionally, CSA Standard F326 sets a very high limit of 50 Pa depressurization for direct vented appliances.

WHAT WE DID IN MINNESOTA

Since its inception in January 1976, the Minnesota energy code has been amended to increase the thermal performance of new homes. In the mid-1980s studies (B.D.Nelson, et al, 1986) began to show that air tightness was at least as important as R-value for achievement of high energy performance in residential buildings. Over the following years, amendments to the Minnesota energy code emphasized air tightness. In 1994 the Minnesota code was amended to require a minimum standard of "Category 2," with a minimum increased air tightness requirement over the previous code (e.g. sealed recessed light fixtures). A voluntary "Category 1" standard was included in the code that described additional air tightening measures that could be done, but if any of those measures were done, then a mechanical ventilation system would be required.

Following adoption of the energy code with the Category 2 requirement and the Category 1 alternative, an informal Residential Ventilation Task Force (RVTF) consisting of persons involved in the housing industry was organized to sort out how future energy codes might be changed so that homes could be built tighter to save energy while preserving occupant safety and building durability. The RVTF presented its recommendations to the Minnesota State Energy Office (SEO) in early 1997.

In late 1997, the Minnesota SEO proposed energy code amendments for 1 and 2 family dwellings that mandated substantial air tightening and mechanical ventilation. The proposed amendments also mandated that make up air be provided for exhaust fans that may be installed in the house. The amount of make up air required was based on the depressurization tolerance of the installed vented combustion appliances. Although combustion air had previously been addressed in the state mechanical code, the need for make up air to account for the affects of exhaust fans installed in the home had not been addressed.

Five days of public hearings ensued, with extensive testimony from the all sides of the construction industry. A small group of Minnesota building researchers who had served on the RVTF were particularly helpful in simplifying the SEO's original proposed make up air requirement. Administrative Law Judge Richard Luis (Luis, 1998) approved the code's adoption. After some delays imposed by the legislature, the new code took effect April 15, 2000.

The Minnesota code was based on ventilation standards that existed in Washington and Oregon. However, Minnesota's was the first building code in the U.S. to include consideration of depressurization. The RVTF had suggested a basis for the make up air provisions of the code be a model house with conditioned floor area of 232 sq m (2500 sq ft) and with an air tightness level representing the tightest house that would be built under the new code of 1.5 ach @ 50Pa (240 L/s @ 50 Pa).

The specific make up air requirements in the code were prescribed based on depressurization limits in one of four "paths" shown in Table 3.

TABLE 3: Depressurization Tolerance for Four Prescriptive Paths

Path	Appliance	Depressurization tolerance
0	Direct vented appliance	50 Pascal
1	Closed controlled combustion wood burning appliances	7 Pascal
2	Atmospherically vented furnaces or boilers and decorative wood-burning appliance	5 Pascal
3	Atmospherically vented water heater	2 Pascal

The four prescriptive Paths designate the amount of make up air required for mechanical exhausting devices in the house. The quantity of make up air permitted to be available by infiltration and passive openings was limited for each of the prescriptive paths. A requirement was inserted that make up air needed in excess of these amounts must be made up by a powered make up air source.

No test standard existed at the time to determine whether or not an appliance could function properly at 50 Pascal depressurization. Thus the energy code provided a mechanism whereby manufacturers could self-certify that one or more of their particular models of appliances could tolerate a 50 Pa negative pressure. Several manufacturers of fossil fuel and solid fuel vented appliances took advantage of this opportunity.

The code also prescribed how make up air was to be provided. Tables in the code specified the sizes of passive openings required and the air flow requirements of powered make up air. The code includes a table of required make up air duct diameters for each prescriptive path that specified the airflow amount that could be relied upon to come through that duct at the pressure identified for that path.

As discussed earlier, the 2000 Minnesota code was not the first to recognize that make up air is needed for mechanical exhausts in new homes. What the Minnesota code did differently was to:

- explicitly denote when make up air is needed,
- specify how much make up air is required, and
- stipulate how the make up air is to be provided.

Specific details on the prescriptive elements of the four prescriptive paths were located in Minnesota Rules Part 7672.0900. This rule part has since been repealed and replaced with provisions in the state mechanical code (Minnesota Office of the Revisor of Statutes, 2004) but the original Paths are still available for inspection (Minnesota Office of the Revisor of Statutes, 2000).

DISCUSSION

Minnesota homes built under the 2000 energy code are significantly more energy efficient than would be expected accounting for the reduction of infiltration alone. The 2000 code appears to have created some change in the Minnesota home building industry. To avoid the complex make up air requirements required for each of the paths except path zero, virtually all builders install sealed combustion heating appliances and either sealed combustion or electric water heaters. While the National Appliance Energy Conservation Act of 1987 (amended) preempts states from adopting regulations regarding the energy use of specified appliances, the new energy code strongly incentivized high efficiency (sealed combustion) space heating by requiring an extra measure of safety.

A follow up study in 2002 (Shelter Source, 2002) examined specific building performance issues in Minnesota homes built during the time of transition in building practices and energy code changes. The study included homes built in 1994, 1998, and 2000 (under the 2000 energy code). Though a relatively small sample was examined (43 homes), the study indicated that the homes built under the later codes were found to be progressively tighter (Figure 2).

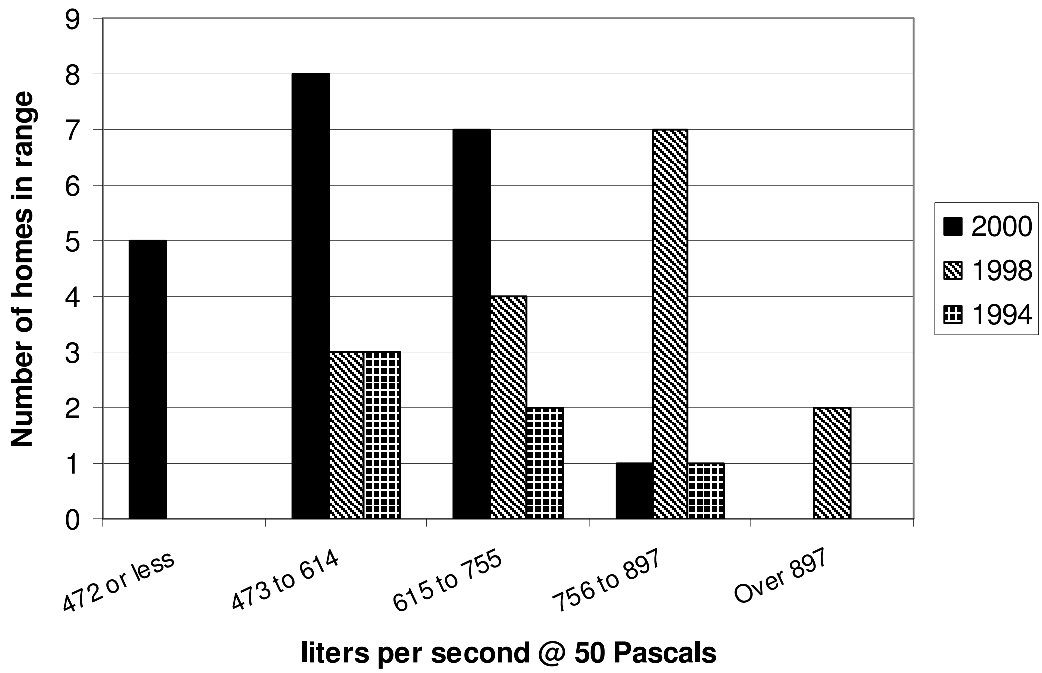

FIGURE 2: Air Tightness of Homes in the Shelter Source Study

Of the 43 homes in the Shelter Source study, a total of:

- 21 homes were built under the 2000 energy code,
- 16 homes were built under the 1998 energy code, and
- 6 homes were built under the 1994 energy code.

The Shelter Source study also found:

- Mechanical ventilation systems of this sample set are meeting or exceeding the minimum airflow requirements of the new energy codes.
- Despite being less airtight, homes built in 1994 and those built in 1998 to Category 2 standards in this sample were more susceptible to combustion safety issues than those built in 1998 to Category 1 standards and the 2000 energy code.
- Savings in heating and cooling costs offset the additional expense for energy upgrades to comply with the improved energy code in most homes reviewed.

It was noted earlier that the new energy code influenced virtually all home builders to install sealed combustion heating appliances. Although many anecdotal comments from builders, builder educators, and code inspectors have been heard without a single challenge to this hypothesis, additional efforts were made to confirm its validity.

Following adoption of the 2000 energy code the question arose whether energy utilities should be offering incentive rebates to promote high efficiency furnaces in new homes. The basis for the question was that the new energy code probably offered sufficient incentive for sealed combustion furnaces, and a rebate for a purchaser of such equipment for a new home would likely classify them as a “free rider,” i.e., receiving an incentive for doing something they would have done anyway. In 2006, Department of Commerce conducted a web survey of building inspectors to identify the efficiency of the HVAC systems that were being installed in new residential construction. Fifty two building officials responded, representing different cities in Minnesota and 5293 HVAC systems that had been installed in new single family houses built in the year before the survey took place. Survey respondents reported that 93% of the new single-family homes within their jurisdiction included high efficiency sealed combustion HVAC systems and those systems had average efficiency ratings at or above 92%.

Also in 2006 Department staff conducted telephone interviews with five of the largest HVAC wholesale-distributers in the state to find out how often orders from new home builders did or did not specify sealed combustion furnaces. The distributers contacted said that since the new energy code of 2000 went into effect, the vast majority of bid requests for new home HVAC installations were for a sealed combustion furnaces and the systems supplied by the distributors were typically rated at 92% or higher efficiency.

Another look at houses built to the 2000 Minnesota energy code was made possible by a residential testing and rating program conducted by the Builders Association of Minnesota (BAM). The federal Energy-Efficient New Homes Tax Credit for Home Builders provided up to a $2,000 tax incentive for new homes certified to provide a level of heating and cooling energy consumption at least 50% below that of the 2004 Supplement to the 2003 International Energy Conservation Code. In conducting this certification program BAM (Linner, 2008) certified more than 450 homes for the federal tax credit. Very few of these homes were built with energy features exceeding the requirements of the 2000 Minnesota energy code.

Of the homes tested by BAM for this program, 148 were also HERS rated. The average HERS rating was 61, which is 24% better than needed to qualify for an ENERGY STAR label in Minnesota. Of the 148 HERS-rated homes that had natural gas furnaces, all were sealed combustion, with an average AFUE was 92.4. The average infiltration rate for the HERS-rated homes was 867 cfm 50.

In some respects a downside of the Minnesota code change is that the make up air provision of the new code is likely responsible for discouraging the choice of natural gas water heaters by new home builders, resulting in a higher market share of electric water heaters (American Gas Association, 2001). Natural gas sealed combustion water heaters might seem to be a solution, but due to high cost are still not prevalent in Minnesota. In the service territory of a major Minnesota gas utility, the market penetration for natural gas water heaters in new homes fell from a pre-2000 level of above 90% to below 76% following the implementation of the new energy code. In the short term this meant higher pollution emissions from predominately coal-based electrical generating facilities. In the long term this trend will place added demand on Minnesota's need for installed electrical generation and transmission capacity.

In the current Minnesota building code the make up air provisions have been moved from their initial location in the energy code to the state's mechanical code. The make up air provisions have been expanded beyond one- and two-family structures to include three story and less townhouse structures.

CONCLUSIONS

Changes in new home construction led to major revisions of the Minnesota energy code in 2000. Writers of energy codes adopted earlier than Minnesota's 2000 code had recognized the need for mechanical ventilation. Yet Minnesota's code was the first to include specific provisions mandating make up air when the safe operation of certain combustion appliances is threatened. Minnesota's residential energy code provides a model for significantly improving both energy performance and the indoor environment. As a result, residential energy code writers should no longer require increasing levels of air tightness without considering how air tightening affects other parts of the building.

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NOMENCLATURE

Liter per second (cfm) 50 – the airflow through a blower door with a pressure difference (indoor to outdoor) of 50 Pascal.

Ach 50 – air changes (of the conditioned volume of the house) per hour with a blower door creating a pressure difference of 50 Pascal

HERS – Home Energy Rating System, RESNET.

AFUE – Annual Fuel Utilization Efficiency.

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Availability of Select References

The 2000 Minnesota Residential Energy Code, Minnesota Rules Chapter 7672: http://www.dli.mn.gov/CCLD/EnergyConservation.asp

The Minnesota Mechanical Code, Minnesota Rules Chapter 1346: https://www.revisor.leg.state.mn.us/rules/?id=1346. Note that the Minnesota amendments for IFGC Appendix E, Worksheet E-1, Residential Combustion Air Calculation Method begin on page 101.

Report of the Administrative Law Judge in the matter of Proposed Rules of Department of Public Service Relating to the Energy Code, Minn. Rule Chapters 7670 to 7678, 1998: http://www.oah.state.mn.us/aljBase/390011394.rr.htm