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**ATTIC VENTILATION AND AIR SEALING:
A TECHNICAL REVIEW OF THE ISSUES**

Final Report

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ABSTRACT

This report was commissioned by the New York State Energy Research and Development Authority and the New York State Department of State to review the history and state-of-the-art of attic ventilation and air sealing. It includes a mathematical model that is used to examine the complex relationships between such variables as attic bypass leakage area, outside air temperature, household moisture production, and venting area. The primary recommendation is to reduce heat and moisture flows into the attic by permanently sealing all air leakage paths between the house and attic, especially in climate areas that experience sustained periods of low wintertime temperatures. It concludes that current attic ventilation codes, which omit reference to considerations of climate zones, are of marginal utility to the building or retrofit industry and are in need of revision. Recommendations for further research are included.

Key Words: Attic ventilation, air sealing, moisture, ventilation codes and standards

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SUMMARY

This paper summarizes research findings about the complex issues associated with attic ventilation and presents a mathematical model that enables graphing the relationships between such variables as attic bypass leakage area, outside air temperature, household moisture production, and venting area.

Much of the concern and controversy about the performance of attic insulation and ventilation approaches is due to difficulties in predicting air leakage rates between the house and the attic, and between the attic and outside. Additional uncertainties in formulating standards or recommending approaches include assessing the moisture-carrying capacity of different attics, including daily and seasonal moisture storage on wood surfaces, and defining design criteria such as indoor humidity.

Nonetheless, building codes, HUD standards, and ASHRAE "past practice" recommendations have led to relatively uniform attic ventilation standards. These standards usually require attics to have one square foot of net free vent area for every 300 square feet of insulated ceiling area. In many areas, twice as much ventilation (a ratio of 1 in 150) is required in buildings with flat roofs and cathedral ceilings or if there is no vapor barrier. These standards were developed in the 1940s based on limited field experiments.

Retrofit practice has been to add ventilation when adding insulation, frequently even if supposedly sufficient ventilation is already present. The high costs of adding the combination of soffit and ridge venting, the most effective system, have led to the widespread use of roof louvers, gable end vents, and turbine vents. These systems are quite dependent on site wind direction and speed and can suffer from short-circuiting and dead-zones. In areas with strict interpretation of the "vapor barrier" requirement, attic insulation retrofits sometimes fail cost-effectiveness criteria because of the high cost of added venting. Ironically, the venting is often either ineffective or unnecessary. Most houses would probably not have moisture problems even if left under vented according to current codes. On the other hand, houses with conditions conducive to moisture problems may still have damage directly above bypasses or in dead-zone areas, even when "adequate" venting is added.

The primary research on ventilation air flows was performed in 1962 by a research engineer for a company that manufactures attic vents (Hinrichs, 1962). This report compared alternative vent types and configurations and concluded that more venting was needed and continuous ridge and soffit venting was the best approach. Hinrichs provided tables, based on experimental results, which listed effective air flow rates for different vent types and wind speeds. He recommended a ventilation air flow of 0.8 cfm per square foot of ceiling area (achievable with a 1 in 144 ratio using continuous ridge and soffit vents), or about 400 cfm for a 500 square foot attic. This number was based on extreme conditions (5°F attic temperature, 74°F indoor air temperature

plus a 40% + relative humidity house).

Hinrichs' research is still cited as the primary source, although little guidance is given for adjusting those results to different sites or conditions. In reality, there is no guarantee that providing a specified area of passive ventilation openings will yield some desired level of ventilation. Predicting ventilation flow rates is difficult due to difficulties in modeling site-specific wind patterns, especially at shielded sites, and the unpredictable effects of wind speed and direction on a given system of vents. Additionally, even if the air flow provided by a ventilation system is known, the ability of the air to pick up moisture from the attic varies depending on its humidity and how much it is warmed when in the attic.

The most extensive field research on residential attic insulation thermal performance was conducted at Princeton University in the 1970s (Woteki and Dutt, 1977). The Princeton researchers discovered hidden heat loss paths which they called "thermal bypasses." They estimated that thermal bypasses increased attic heat loss rates three to seven times more than standard conduction equations predict. Other Princeton reports noted that air leakage from the house to the attic dramatically increases moisture transfer above the rates predicted solely from diffusion.

Until the 1980s, attic moisture research had generally not considered the effects of moisture storage. Moisture models determined if condensation would occur based on whether the roof deck temperature was below the dew point of the attic air. In reality, wood surfaces and even cellulose insulation in attics can store relatively large amounts of moisture, both in daily and seasonal cycles. In many circumstances, this storage capacity can protect the attic from moisture damage.

Current research indicates that bypass air leakage is the primary factor influencing heat and moisture transfer from the house into the attic. Indoor humidity and outdoor temperature are the most important factors to determine the wetting potential. Ventilation air flow, a function of wind regime and ventilation type, size, and placement, is the primary factor influencing moisture removal or drying potential. Wood moisture storage is critical in determining the carrying capacity and therefore potential consequences of the inflows and outflows in a given attic. Unlike indoor humidity and outdoor temperature, bypass air leakage is the hardest to measure of the relevant factors, yet it is the most important. A model of attic condensation indicates that sealing bypasses can reduce the need for attic ventilation dramatically.

Careful, permanent air sealing between the conditioned envelope and attics is strongly recommended to both save energy and avoid moisture problems in attics. Further field research and analysis designed to explore the interactions of the variables examined in this paper, plus the effects of solar loading, should be undertaken. The process of modifying codes to reflect such variables as climate should be begun immediately.

Section 1

OVERVIEW AND BACKGROUND

OVERVIEW OF THIS PAPER

This report gives an overview of the history and state-of-the-art understanding of attic ventilation and air sealing and recommends approaches to maximize cost effectiveness and minimize the potential for moisture damage while adhering to current building codes. The primary recommendation is to reduce heat and moisture flows into the attic by sealing all air leakage paths between the house and attic. Recommendations for further research are included.

BACKGROUND

Although attic insulation is one of the most common residential energy retrofits, little work has been done to measure actual performance. The traditional approach assumed the energy problem in attics was conductive heat loss and the solution was insulation. There was a concern that diffusion of moisture into attics would lead to rot, and the solution was ventilation. Most weatherization programs assumed that attic insulation was very straightforward with assured energy savings and moisture protection.

Unfortunately, the real world has proven to be more complex. Evaluations have indicated that energy savings from entire programs were less than the insulation alone was expected to produce. In the few evaluations of just attic insulation that have been accomplished, savings have averaged half the standard prediction.

In addition to disappointing energy savings, ventilation standards and approaches have also been questioned. Some attics have had no problems even when "under vented"

(according to traditional rules such as the 1 in 300 ratio) while other attics developed problems with presumably adequate venting. Researchers and concerned practitioners have wondered whether added venting may actually worsen attic moisture problems and increase energy use in some cases. The lack of adequate explanatory models and documented field experience has caused building engineers to question existing attic ventilation standards. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE), a major building science organization, altered its description of venting standards from "Recommended Good Practice" to "Past Practice" in 1981, and has made no new recommendations since then. These ventilation concerns are particularly important for flat roof and cathedral ceiling buildings (Tobiasson, 1988).

Much of the concern and controversy about the performance of attic insulation and ventilation approaches is due to the difficulties in predicting air leakage rates between the house and the attic, and between the attic and the outside. Additional uncertainties in formulating standards or recommending approaches include assessing the moisture-carrying capacity of different attics including daily and seasonal moisture storage on wood surfaces, and defining design criteria such as indoor humidity. Current research projects are starting to shed light on some of these questions, but it may be years before results are confirmed and codes start to change. Accordingly, until more research results are available it is perhaps appropriate to concentrate on actions that can be taken based on the best current knowledge.

Section 2

HISTORY AND PRINCIPLES OF ATTIC VENTILATION AND AIR SEALING

HISTORICAL DEVELOPMENT OF ATTIC VENTILATION STANDARDS

A set of early attic ventilation paper abstracts has been compiled by William Rose of the University of Illinois (Rose, 1990). This compilation is summarized below.

Attic insulation was not commonly used until the 1930s, at which time U.S. Department of Commerce reports started to recommend attic ventilation to reduce potential moisture accumulation in cold climates. Forest Products Laboratory reports in 1937 and 1939 recommended ventilation and noted that some insulation companies were including ventilation when insulating. They noted that effective ventilation can be difficult to achieve, particularly in flat roof buildings, and may increase heat loss. They warned that unless ventilation can be provided, high indoor winter humidities are unsafe for building durability. Several other reports from the 1930s and early 1940s recommended attic insulation but made no mention of ventilation.

The first significant ventilation studies were made by F.B. Rowley of the University of Minnesota. Under fairly extreme conditions (-10°F outside, 40% RH inside) Rowley found that a ventilation ratio of 1 in 1152 (1 square foot of vent area per 1152 square feet of ceiling area) led to condensation, but a ratio of 1 in 576 did not. A 1946 University of Illinois report recommended a ventilation ratio of 1 in 250, without citing sources. A 1947 report by Professor Rowley noted that ventilation is not needed if a vapor barrier is installed and it is preferable to stop the moisture from reaching the attic rather than trying to vent it away. He proposed a ventilation ratio of 1 in 576, well distributed. Rowley also noted that sealing a leaky attic hatch eliminated condensation in one attic and that the attic heat loss was much greater than expected.

In 1948, the Housing and Home Finance Agency (HHFA) issued a series of reports on attic ventilation research by Ralph Britton. A test structure was built with a 1 in 300 venting ratio and tentative conclusions indicated that ventilation was adequate. That same year, HHFA issued a technical bulletin that cited Britton's work and recommended that builders use a 1 in 300 ratio for attic ventilation. Another HHFA bulletin that year describes three homes, two of which had no ventilation and experienced no moisture problems. The report noted the importance of indoor relative humidity on attic moisture. Research was also conducted at Penn State University in the late 1940s. In 1949, HHFA codified venting requirements at 1 in 300 and 1 in 600 for lofts and attics respectively. In 1951, the American Society of Heating and Ventilation Engineers (ASHVE, the precursor to ASHRAE) guide started to provide ventilation recommendations.

Rose's abstracts demonstrate that attic ventilation requirements were developed to avoid moisture buildup, and particular venting ratios were selected partly by chance because they certainly would have varied depending on the researchers' specified test conditions.

VENTILATION FOR SUMMER COOLING AND ICE DAM PREVENTION

In addition to its role in reducing roof moisture buildup, attic ventilation has also been promoted for reducing summer attic temperatures and as a solution for ice damming.

Reducing summer attic temperatures through ventilation has been advocated to reduce heat gain into the living space (reducing cooling loads) and to lower roof temperatures (potentially extending roofing or sheathing longevity). However, according to research, ventilation has very little effect on summer cooling loads if the attic is well insulated (McQuiston et al, 1984). The ventilation will reduce attic air temperatures, but reasonable insulation levels will make the resultant effect on cooling loads small. Additionally, most of these attic air temperature reductions from venting will occur

with relatively little vent area. Ventilation is also unlikely to significantly affect roof sheathing temperature. Best estimates of this impact are 5-8°F. These findings make sense since the principal mode of summer heat transfer in an attic is radiation. Therefore, even if ventilation can lower the attic air temperature significantly, it has relatively little effect on ceiling heat gain or roofing temperature.

Ice damming is ice buildup at the eaves caused by heat loss from the attic that melts snow, the water from which refreezes at the colder eaves. Ice dams can extend under shingles and cause water leakage on to the ceiling underneath. Ventilation is promoted to keep the roof colder over the insulation, preventing snow from melting during periods that are cold enough to experience re-freezing. But if the ceiling is well insulated and airtight, then the attic should stay very cold and ice dams should not be a problem. This alternative solution may not work well in areas with heavy snow loads because the snow may provide enough insulation to warm the roof and still cause ice dams, particularly for cathedral ceilings. Solar gain on gable end walls may also warm an attic sufficiently to melt snow and cause ice dams. Therefore, in new construction, ventilation may be a wise precaution, especially in climates with high snow loads. But an airtight super-insulated ceiling would still most likely provide the best protection and performance. In retrofit situations, stopping bypass air leakage and improving insulation quality may be sufficient, and certainly more cost-effective, than adding continuous ventilation (Ireton, 1990).

VENTILATION EFFECTIVENESS

There has been little research on predicting the actual ventilation air flows of given vent types and areas at a particular site. The primary research on ventilation air flows was performed in 1962 by a research engineer for a company that manufactures attic vents (Hinrichs, 1962). This report compared alternative vent types and configurations and concluded that more venting was needed and continuous ridge and soffit venting was the best approach. Hinrichs provided tables, based on experimental

results, which listed effective air flow rates for different vent types and wind speeds. Hinrichs recommended a ventilation air flow of 0.8 cfm per square foot of ceiling area (achievable with a 1 in 144 ratio using continuous ridge and soffit vents), or about 400 cfm for a 500 square foot attic. This number was based on extreme conditions (5°F attic, 74°F 40%+RH house). Interestingly, in the question and answer attachment to the paper, Hinrichs noted that vapor barriers are insufficient for moisture control because air leakage is two to six times more important than vapor diffusion. He listed several air leakage sites such as plumbing stacks, ceiling light fixtures, and attic hatches.

Hinrichs' research is still cited as the primary source, although little guidance is given for adjusting those results to different sites or conditions. In reality, there is no guarantee that providing a specified area of passive ventilation openings will yield some desired level of ventilation. Predicting ventilation flow rates is difficult due to the generally poor ability to model site-specific wind patterns particularly at shielded sites, and the unpredictable effects of wind speed and direction on a particular system of vents. (Section 4 summarizes the most recent research on this topic.) Additionally, even if the air flow provided by a ventilation system is known, the ability of this air to pick up moisture from the attic will vary depending on its humidity and how much it is warmed when in the attic.

Passive Attic Ventilation System Comparisons

Passive ventilation systems rely on natural pressure differences to provide the driving force for air flow. These pressure differences include the wind and, if vents are placed at high and low locations, the stack effect induced from attic heating due to solar gain. Systems that respond to both of these driving forces are more likely to provide continuous ventilation air. In evaluating a ventilation approach, the primary consideration is to provide an even flow throughout the attic, minimizing short-circuiting (direct flows between two vent openings) and dead zones (areas with little

or no air flow). Vents must also be designed to prevent entry of rain, snow, insects and vermin.

Considering particular ventilation strategies, the combination of continuous ridge and soffit vents is generally accepted as providing the greatest assurance of even and continuous ventilation air flow. Unfortunately, this approach is also the most expensive, often comparable to the cost of insulating. A typical attic retrofit includes some combination of gable vents, roof louver vents, soffit vents, and turbine vents. The following descriptions of passive venting strategies are based more on anecdotal evidence and a consensus of practitioners than on actual measurements (see Forgues, 1985 for a more detailed discussion of attic venting strategies):

- Gable vents, usually consisting of a set of horizontal louvers shaped to discourage the entrance of precipitation, are installed on vertical surfaces in the attic. They can provide high flow rates but depend strongly on wind direction. They are inexpensive and are often the only existing ventilation, however they do not usually provide good air flow at lower portions of the attic unless combined with soffit vents. They do not get covered with snow but may allow entry of wind-driven snow in some circumstances if not properly re-designed when installed (some contractors fasten a thin layer of fiberglass over the opening and fabricate a drip tray with flashing in order to avoid snow entry). Contractors report commonly finding plastic over gable vents installed by homeowners to solve this problem. The large air flows through gable vents have also been reported to create suction at roof louvers and thus draw snow into the attic.
- Roof louvers, sometimes called mushroom vents, are mounted on sloping portions of roofs near the peak. Used alone, they can leave dead zones and may create localized moisture problems as moister air escapes through them. They are more effective if used high near the ridge and in combination with low venting such as soffit vents. Because roof louvers usually provide only 40 to 80 square inches of net free vent area each, it is often impractical to install enough of them to meet code. In regions with high snow loads, roof louvers may become completely covered in snow rendering them useless during the coldest weather.
- Soffit vents are installed in soffits, of course. They may be continuous or may consist of a series of individual vents, particularly common in retrofits. They depend less on wind direction than most other types of venting and can provide nearly continuous ventilation air directly up along the roof deck when used in combination with higher venting, such as ridge or roof louvers, which promotes stack effect (i.e. buoyancy-induced) flows within the attic. Many soffit vents,

particularly the perforated and button types, provide limited free vent area and can therefore be ineffective or too expensive a retrofit for meeting codes.

- Turbine vents, mounted in the roof, are designed to use the wind to draw air from the attic. The suction they create can increase air leakage through bypasses, exacerbating moisture problems. But if the ceiling is tight this concern is lessened. Turbine vents may provide greater flow per unit area than passive roof louver vents; however, failure of the spinning mechanism could lead to rain and snow penetration.
- Ridge vents, mounted along the peak of a roof, are effective when used with soffit venting. They are relatively insensitive to wind direction and can provide even air flow across the roof deck throughout the attic. Rain and snow entry may be a problem if they are not properly designed. They can also be rendered useless when covered under high snow loads -- a serious problem in extreme climates. They are an expensive retrofit.

The Problem of Flat Roofs

Flat roofs are generally an unforgiving construction assembly and difficult to ventilate. Because of the short distance from the ceiling to the roof deck, there is little opportunity for dilution of moist bypass leakage air through mixing with drier attic air, and therefore there is a greater opportunity for moisture buildup. In contrast to a sloped roof where moisture can drain down the slopes or evaporate on the way to the eaves, melted frost will drip onto the ceiling.

Flat roofs have limited exposure to perpendicular wind and insufficient height to create much stack effect. Passive venting strategies such as mushroom, gooseneck, and breather vents rely on wind-induced pressure differences at different points on the flat roof surface to induce ventilation flows. But the roof cavity may be relatively airtight to the outside and therefore play a significant role in preventing bypass air leakage, so the addition of vents can lead to increased bypass leakage and increased moisture problems (Tobiasson, 1988). They are also subject to possible rain and snow entry and roof leaks. Unfortunately, there are few economical retrofit alternatives for flat

roof cavities. Sealing bypass leaks is crucial in these houses, particularly if ventilation is added.

Active Attic Ventilation Systems Options

Because of the unreliability of passive ventilation, some researchers and practitioners have used active attic ventilation systems (i.e., fans). Many houses have attic exhaust fans that are controlled thermostatically to operate above a certain temperature. The purpose of these fans is to reduce attic temperatures in the summer and therefore reduce cooling requirements in the living space. But as noted previously, if an attic is well insulated then reducing its air temperature through ventilation will have only a small effect on cooling loads. However, if there are bypasses then the fan may actually function as a whole house ventilation system, which could provide effective cooling at night. Some of these fans are quite powerful (1000+ cfm) and there have been reports of combustion appliance backdrafting caused by the house depressurization created by these fans (Fitzgerald, 1992).

Active ventilation to reduce winter moisture buildup has been used in flat roof buildings in Canada and elsewhere (Tamura et al, 1974 and Tobiasson, 1988). Tamura's strategy was to pressurize the roof with outdoor air in order to counteract the house's stack effect and reduce bypass leakage. This approach was fairly successful for the houses studied, but Tamura had concerns about the maintenance and operating costs of the fan, the possibilities of flow reversal down the bypasses leading to wall condensation and increased heating costs. Tamura also investigated using an exhaust fan in the house to reduce the stack effect across the ceiling and lower indoor humidity. This approach also appeared promising.

Current Canadian research (Forest and Walker, 1992) is investigating active attic ventilation in standard sloped roof attics. Their strategy is to operate an attic exhaust fan between 10 AM and 4 PM, which is a period of high solar gain and therefore high

attic absolute humidity (see Moisture Storage section below). Preliminary results indicate that a 345-cfm exhaust fan did increase attic air change rates but did not always dominate over natural ventilation. Other researchers (Kinney, 1992) have considered various "smart" ventilation approaches that provide ventilation (either active, solar, or passive) when needed and most effective based on temperature and/or humidity conditions. No published results are available.

HOUSE-TO-ATTIC AIR LEAKAGE

The moisture and, to some extent, thermal implications of house-to-attic air leakage were first noted by Rowley as previously mentioned.. While research reports in the early 1960s (Wilson, 1961; Hinrichs, 1962; Hutcheon, 1963) indicated that air leakage is indeed more important than vapor diffusion, few practitioners paid attention. Energy was inexpensive and the combination of low insulation levels, leaky houses with low relative humidities, and standard attic ventilation resulted in few moisture problems outside of very cold climates.

The energy crises of the 1970s increased the search for effective conservation options. At the same time, higher levels of attic insulation combined with tighter houses and tighter roof construction produced colder attics, moister houses, and less actual attic ventilation. Moisture problems became more common even in presumably well ventilated attics.

Attic Bypasses And Heat Loss

The most extensive field research on residential attic insulation thermal performance was conducted at Princeton University in the 1970s (Woteki and Dutt, 1977). The Princeton researchers discovered hidden heat loss paths that they called "thermal

bypasses." These bypasses include air leakage from the house to the attic and convective loops. Many common bypass leakage paths have been discovered, including:

- Chaseways for plumbing, chimneys, ducts, and wiring.
- Partition walls open to the attic due to ceiling height changes, soffits, balloon framing, pocket doors, and cracks between sheetrock and top plates.
- Kneewall floor intersections in story-and-a-half houses.
- Attic ductwork.
- Miscellaneous leaks such as ceiling light fixtures and attic access hatches.

Convective loops are enclosed spaces that allow air to circulate from below the insulation, where it is warm and therefore rises, to above the insulation, where it is cooled and sinks back again. This pattern creates a loop that transfers heat around insulation. The Princeton researchers found that a large convective loop formed inside cinder block common walls in townhouses.

The Princeton researchers estimated that thermal bypasses increased attic heat loss rates three to seven times more than standard conduction equations predict. Other Princeton reports noted that air leakage from the house to the attic would dramatically increase moisture transfer above the rates predicted solely from diffusion.

MOISTURE STORAGE IN ATTICS

Until the 1980s, attic moisture research had generally not considered the effects of moisture storage. Moisture models determined if condensation would occur based on whether the roof deck temperature was below the dew point of the attic air. In reality, wood surfaces in the attic can store relatively large amounts of moisture both on daily and seasonal cycles.

Models of attic moisture behavior have generally assumed that the attic air is a mixture of indoor and outdoor air and, therefore, the absolute humidity should be between (i.e., a weighted average of) the indoor and outdoor absolute humidity. According to Princeton research (Ford, 1982), attic air often had a greater moisture content than either the inside or outside air. Ford suggested that this apparently anomalous behavior may have been due to daily condensation and evaporation cycles; however, this seemed unlikely.

Short-term Moisture Storage At Wood Surfaces

Research at Lawrence Berkeley Laboratory (Cleary, 1984) found an alternative explanation for Ford's findings: wood surfaces have significant short-term moisture storage capacity. Cleary recognized that there is a boundary layer at wood surfaces. The outer edge of this boundary layer is in equilibrium with the surrounding attic air based on *absolute* humidity. The inner edge of this boundary layer, at the wood, is in equilibrium with the wood moisture content based on *relative* humidity. Table 2-1 shows a range of these equilibrium values (Wood Handbook, 1974).

Table 2-1. Relative Humidity and Wood Moisture Content Equilibrium Values							
Air Relative Humidity %	30	40	50	60	70	80	90
Wood Moisture Content %	6	8	10	11	13	17	21

For example, wood with an 11% moisture content is in equilibrium with air at 60% RH. This correspondence remains essentially the same over a wide range of temperatures and wood species. Under constant conditions, this equilibrium is maintained and the boundary layer is uniform. But under actual dynamic conditions, the temperature of the wood changes rapidly because of solar gain and night sky radiation while the moisture content of the wood changes slowly.

Because the relative humidity of the air at the wood surface stays approximately constant but its temperature changes, the *absolute* humidity of this air must also change rapidly. These changes cause moisture to be adsorbed and desorbed at the wood surface and to convect across the boundary layer into or out of the attic air.

In simpler terms, this process is just that of the wood surface drying when heated and wetting when cooled. The result is high absolute attic humidity during sunny afternoons and low absolute humidity at night. Cleary found that this diurnal cycle was a dominant factor in determining the attic air absolute humidity at a given hour and also led to the attic actually *gaining* moisture from night ventilation.

The development and laboratory validation of a thermal and moisture model of attic behavior at the National Bureau of Standards (Burch, 1984) confirmed Cleary's hypothesis. Burch's thermal model involved solving heat balance equations at three points in the attic (the floor, air, and underside of roof deck) and included both conduction and bypass air leakage. The moisture component of the model used the results of the thermal model and included diffusion, air leakage, and Cleary's wood surface storage equations. While the model's general utility was restricted by its requirement for specification of bypass and ventilation air flows and wood moisture content, it provided a valuable test of underlying assumptions and Cleary's work. The model performed fairly well in a controlled environment.

Burch concluded that wood surfaces below the attic air dew point will not experience condensation until moisture adsorption has led to an equilibrium with the attic air (at about 28% moisture content). But as noted by Cleary, condensation may still occur if conditions change rapidly and either the slow diffusion rate within the wood creates a moisture content gradient or the transfer rate across the boundary layer exceeds the surface adsorption rate capacity. This latter effect may occur at very low temperatures and result in frost formation on

the roof deck even though the wood moisture content is below the saturation point. Still, Burch and Cleary's research indicates that attics are more "forgiving" than previously thought, and attic ventilation design criteria that don not include this storage effect will generally be too conservative.

Seasonal Moisture Storage

A field study at Princeton (Harrje et al, 1985) measured attic wood moisture content over the course of a year and found that the moisture content varied dramatically. In one house, the north slope roof sheathing cycled from a winter high moisture content of 20% to a summer low of about 5%, indicating that approximately 1200 pounds of moisture was stored in the roof deck during the winter and released in the spring and summer. If a typical household produces about 20 pounds of water vapor per day and half of this moisture convects and diffuses into the attic, then the wood surfaces in this attic would be capable of storing about four months of fall and winter moisture load.

Harrje also found that the south slope reached a winter peak of just 11% moisture content, which indicated that solar gain plays a significant role in avoiding moisture buildup. The plywood roof sheathing showed no signs of damage except for some delamination directly above a major bypass. Even higher moisture levels, cycling from 10% to 44%, were found at a second house which had tongue-and-groove roof sheathing. This house had noticeable mold growth and condensation in the attic, yet there was no evidence of rot. The high moisture-carrying capacity of solid wood sheathing provided a more forgiving construction to avoid serious moisture damage. Based on these observations, Harrje concluded that "avoiding condensation may be an unnecessarily severe design constraint."

Moisture Storage And Insulation Materials

Wood construction materials may not be the only potential site for moisture storage in attics. Cellulose insulation is similar to wood in its ability to store moisture and may provide significant short-term storage capacity because of its large surface area. Some researchers and practitioners have reported finding attics with "damp" cellulose that may have helped avert moisture problems (Fitzgerald, 1992). In contrast, fiberglass does not store moisture and there have been reports of frost formation within fiberglass caused by temperature gradient reversals (Nelson, 1992).

Vapor Drive Maps For Assessing Seasonal Storage Potential

The moisture storage capacity of wood in an attic has caused some researchers to change the design criteria for attic ventilation. Instead of trying to avoid condensation or high moisture content levels during the most adverse conditions of the year (late winter), researchers have started to focus on avoiding long-term moisture buildup that may lead to roof deck failure.

A vapor drive map (Tobiasson and Harrington, 1986) is a useful device for examining the seasonal and annual wetting potential and drying potential of a building with a given relative humidity in a given climate. A vapor drive map graphically represents the vapor pressures that act to wet and dry roofs. It is created for a specific geographic location using typical year weather data and a specified indoor temperature and humidity. These maps show that in most locations, any moisture that accumulates in an attic during the winter due to a vapor pressure difference can leave by the same route in the summer. A map can be summarized by the ratio of wetting to drying potential, which is typically below one in the contiguous United States. This ratio indicates that wetting will be seasonal, not progressive. Some ratios cited for 45% indoor RH include 0.2 in Washington DC, 0.9 in Minneapolis, and 3.2 in Fairbanks. Tobiasson noted that

"the objective is to limit seasonal wetting to an acceptable level. This level will vary with the moisture sensitivity of the materials present."

Vapor drive maps can also be used to highlight the dominating effects that indoor relative humidity and outdoor temperature can have on moisture buildup potential. Houses with low (30%) winter indoor humidities common in older leaky houses, or in mild climates (40°F in January) rarely have attic moisture problems unless the roof leaks. Roof deck temperatures rarely drop below the dew point of the indoor air, so condensation can not occur regardless of the amount of bypass leakage. The vapor drive is not strong enough to create problems.

Some researchers and practitioners believe that designing to avoid progressive wetting may be insufficient because short-term moisture buildup in cold climates can lead to frost formation, which can melt onto the ceiling below during a warm snap. Therefore, while moisture storage may often help avoid problems, short-term considerations are still important, particularly in cold climates.

Section 3

THE STATE OF THE PRACTICE

ATTIC VENTILATION PRACTICE

Building codes, U.S. Department of Housing and Development (HUD) standards, and ASHRAE "Past Practice" recommendations have led to relatively uniform attic ventilation standards. These standards usually require attics to have 1 square foot of net free vent area for every 300 square feet of insulated ceiling area. In many areas, twice as much ventilation (a ratio of 1 in 150) is required in flat roofs and cathedral ceilings or if there is no vapor barrier.

Retrofit practice has been to add ventilation when adding insulation, frequently even if supposedly sufficient ventilation is already present. The high costs of adding the combination of soffit and ridge venting, the most effective system, have led to the widespread use of roof louvers, gable end vents, and turbine vents, systems that are much more dependent on site wind direction and speed and can suffer from short-circuiting and dead-zones. In areas with strict interpretation of the vapor barrier requirement, attic insulation retrofits sometimes fail cost-effectiveness criteria because of the high cost of added venting. Ironically, the venting is often either ineffective or unnecessary or both. Most houses would probably not have moisture problems even if left undervented (see Section 5). Houses with conditions conducive to moisture problems may still have damage directly above bypasses or in dead-zone areas, even when so called "proper" venting is added.

FIXING ATTIC BYPASSES

The Princeton work on attic bypasses in the 1970s was well publicized among weatherization practitioners and simple and inexpensive methods for fixing most thermal bypasses in accessible attics -- those with hatches or doors -- are now

available (for example, see Massachusetts Audubon Society 1985 and Marbek Resource Consultants, 1983). Most techniques involve air-sealing the leakage paths from the attic using caulk, foam, and rigid materials. Knowledgeable practitioners recognize that sealing bypasses leads to both increased energy savings and reduced chances of moisture problems. The work is generally straightforward and inexpensive, usually less than \$100 per attic.

The Challenges Of Limited-Access Attics

In limited access attics (e.g., those with flat roofs or cathedral ceilings) and floored attics, proper approaches for fixing bypasses are not as well-established and the work can be expensive and difficult if the right techniques are not used; however, the effectiveness of insulating and venting without sealing bypasses is questionable. Researchers, program managers, and practitioners have wondered whether adding vents, required by code and a standard part of insulating an attic, will increase bypass air leakage so much that insulating may actually increase fuel bills and create moisture problems. Additionally, moisture problems may be greatest if some but not all of the bypasses are sealed because the remaining leakage would be into a colder attic.

In limited access attics, these concerns are heightened by the difficulty in achieving good insulation coverage. Many contractors attempt to blow insulation into these attics from the vent holes without entering the space, a practice that inevitably leads to poor coverage and unsealed bypasses. The proper approach to flat roof attics has been the subject of conjecture and debate (Wilson, 1989). The primary questions concern finding effective treatments and determining which bypass, insulation, and ventilation methods lead to cost-effective savings while minimizing moisture damage potential. Recent research has found that high density cellulose insulation can often act as an effective air barrier (see Section 4).

Section 4

STATE OF THE ART AND RESEARCH

According to the current state-of-the-art understanding of attic performance, the attic is a dynamic system of thermal and moisture transfer and storage that is strongly influenced and often dominated by bypass and ventilation air flows. However, accurate validated models with readily measurable inputs do not exist.

The main obstacles to understanding and predicting attic performance are related to uncertain inputs and models for air flow and moisture storage. There is a lack of well-documented field data and of useful, validated models. The development of adequate air flow models has been hampered by the difficulty of measuring or even estimating building component air tightness in addition to the general difficulties in modeling wind effects. Moisture storage modeling lacks adequate data for the properties of common materials, particularly under dynamic conditions.

Recent research efforts have used a combination of field data collection and monitoring, and model development and validation to help address these areas of uncertainty. Projects have been undertaken by Don Fugler at Canada Mortgage and Housing Corporation (CMHC), Bill Rose at the University of Illinois, and the author of this report, Michael Blasnik, at GRASP, a Philadelphia-based non-profit group.

CURRENT RESEARCH: CANADA MORTGAGE AND HOUSING CORPORATION

Canada Mortgage and Housing Corporation (CMHC) has sponsored a series of research projects on attic moisture problems and ventilation system effectiveness. The primary completed project (CMHC, 1991) was a field study of 20 houses that involved:

- The development of a dual-blower door technique for measuring attic ventilation and house-attic interface airtightness.
- Spot measurements of attic air change rates with tracer gas.

- Repeated measurements of attic wood moisture contents and relative humidities.
- Measurement of other house and attic characteristics.
- Limited comparisons between an attic model and measured data.

The air tightness measurements indicated that the house-to-attic interface leakage averaged about 27 square inches of effective leakage area (ELA, converted by the author using the LBL-defined 4 Pa leakage area with $C_d = 1$; see ASHRAE *Fundamentals*, Chapter 23), equivalent to about 500 cfm₆₀. This leakage represented about one third of the average whole house leakage. The interface leakage was fairly consistent, with half of the houses having between 23 and 33 square inches of interface ELA. Attic ventilation ELA averaged about 240 square inches, but varied widely from estimates based on actual installed net free vent areas. These discrepancies were attributed to a combination of background leakage (unintentional openings) and difficulties in estimating soffit vent areas.

Air change rates measured with tracer gas varied widely from house to house and even from test to test. Half of the houses had attic air change rates below 5 air changes per hour (ach), while 30% had air change rates of 10 to 15 ach. There was little relationship between air change rates and other measured factors for these houses. Wind speeds, adjusted for wind direction and exposure, had a weak correlation with attic air change rates. Similarly, attic ventilation ELA had a poor correlation, explaining only about 7% of the variability in air change rates. These poor correlations were attributed to varying weather effects.

Attic wood moisture content measurements indicated that many houses had very wet attics with sheathing moisture contents of more than 30% in mid-winter. The attics generally dried out during the summer to acceptable levels except for some houses in wetter areas of the country. Houses with higher indoor relative humidities, some with humidifiers, tended to have wetter attics. The CMHC also observed that houses with

mushroom-type vents and houses with few exit points for exfiltrating attic air tended to have localized wetting near the vents.

Moisture content levels for individual houses tended to vary widely and sometimes inexplicably. There was almost no discernible relationship between attic wood moisture content and any other factor investigated such as attic ventilation leakage area or interface leakage area, although the latter exhibited a somewhat stronger relationship. Attempts at comparing spot measurements with modeled results found negligible agreement.

The report grouped the houses into three categories: wet, dry, and neither. Independent analysis of the CMHC report by the author of this study found that wet attics were much more likely than dry attics to have fiberglass batt ceiling insulation and have two stories. Fiberglass batts may be associated with greater moisture problems because they do not provide an air barrier or any moisture storage capacity. Half the wet attics were undervented (less than 1 in 300 venting area) compared to a third of the dry attics. Vapor barriers were equally present for wet and dry attics (75% and 66% respectively). These observations are consistent with the belief that having "enough" vents will not ensure protection from moisture problems, and having "too few" vents will not necessarily lead to moisture problems. In general, the study confirms that attic moisture levels are difficult to predict and standard venting ratios and vapor barriers are unlikely to be, in any simple sense of the expression, "the solution."

Another CMHC ongoing research project is currently focussing on detailed modeling of attic air change rates and thermal and moisture performance (Forest and Walker, 1992). A two-zone air flow model was developed and detailed measurements made in two test attics have shown that it is a good predictor of ventilation and bypass flows, generally within 15% of the average measured flow. The ventilation model also

shows good agreement for the impact of wind direction on flow rates. Forest and Walker noted that the model requires accurate measurement of the interface and ventilation leakage characteristics. This project is continuing with the development of detailed thermal and moisture modeling. Initial thermal model results have been promising.

CURRENT RESEARCH: UNIVERSITY OF ILLINOIS

William Rose at the University of Illinois is currently conducting a multi-year detailed study of attic ventilation and moisture buildup in a series of controlled test attics. He is particularly interested in determining the impacts of ventilation or lack of ventilation on moisture levels and roof temperatures, as they affect shingle longevity. Sophisticated monitoring equipment was designed for the project and detailed model validation studies will be performed.

While this work is incomplete, preliminary observations have been made, with caution. The unvented attics were consistently *drier* than the vented attics until a few very cold days, when the unvented attics had some frost buildup while the vented attics did not. This observation has not yet been explained but could be due to rapid desorption of moisture from the roof sheathing, the water vapor being unable to escape quickly enough in the unvented attics. Differences in shingle and roof deck temperatures were generally very small between the vented and unvented attics, as expected, since convection is not the primary heat transfer mechanism on the inner side of a hot roof deck.

CURRENT RESEARCH: GRASP

The Grass-Roots Alliance for a Solar Philadelphia (GRASP) has performed two research projects sponsored by the Pennsylvania Energy Development Authority on attic insulation and ventilation performance in older flat roof masonry rowhouses in

Philadelphia. The projects were designed to improve energy savings from insulation retrofits while minimizing potential moisture problems. The key research objectives were to quantify the heat loss associated with the numerous bypasses in these very small attic spaces, typically ranging from 8 to 30 inches high rear to front, and to find a cost-effective way to seal these bypasses.

The first project involved intensive measurement, monitoring, and analysis of different insulation and ventilation methods in six rowhouses (Blasnik, 1990). An attic model was developed that extended Burch's model by explicitly modeling air leakage rates and attempting to account for thermal mass effects. A simple procedure requiring only one blower door was developed to measure attic ventilation and house-to-attic interface air tightness. This approach relies on several assumptions and careful pressure measurements, which make the results potentially less accurate than the CMHC dual-blower door approach (although comparisons between the two approaches have not been made).

This project also sought to find and test alternative approaches to sealing bypasses in these minimum-access attics. By far, the most effective technique involved dense-packing cellulose in the inaccessible rear portions of the attic, combined with crawling to and directly air-sealing all accessible bypasses in the front of the attic. This approach resulted in almost complete elimination of bypass leakage at an incremental cost of about \$0.20 per square foot.

The attic model generally performed well in predicting attic heat loss rates and moisture levels. Moisture problems could not be created in these houses, even with unsealed bypasses and unvented attics, because of the low relative humidities common to leaky houses (generally about 30%), the mild climate (base 65 heating degree days = 4800), and the large moisture-storage capacity of rough-sawn board roof decks. The attic modeling indicated that moisture problems would be difficult to create without significantly higher indoor relative humidities. The model also predicted

that, on average, energy savings should double using the dense-packing approach compared to standard approaches that just provide good coverage. The model also predicted that failing to seal the bypasses and adding roof vents would still lead to cost-effective energy savings, although they would be much reduced in all but the most extreme circumstances.

The second GRASP project involved larger-scale replication of the first project's results. Two groups, each having approximately 35 houses, were insulated with the "standard" and new approaches. Energy savings were measured based on weekly heating usage. The dense-pack houses saved more than twice as much energy as the standard approach houses (18% compared to 8% of heating usage). The extra savings, worth \$80/year, provided a payback of less than two years on the incremental cost of \$120.

These results are consistent with the expectations from the first project. The savings differences between the two approaches were particularly large for houses that already had some previous insulation, with the new approach saving almost as much as it did in uninsulated houses while the standard approach saved very little.

Section 5

ATTIC VENTILATION AND AIR SEALING: WHAT MATTERS MOST?

CLARIFICATION BY SENSITIVITY ANALYSIS

While the discussions thus far about attic insulation, ventilation, and air sealing may seem confusing, they indicate that the state-of-the-art understanding is still developing. Sensitivity analysis is one technique that can sometimes clarify complex systems and identify key parameters. An analysis was made for this report that examined the factors related to attic performance, surveyed available research for approximate values of key inputs, and used a simplified model to identify the relative importance and interactions of these modeled factors.

FACTORS AFFECTING ATTIC PERFORMANCE

Attic heat loss and moisture levels depend on house characteristics and indoor and outdoor climatic conditions. The primary house characteristics are:

- Ceiling (or house/attic interface) construction: R-value, area, air-tightness, and moisture vapor permeability.
- House height, roof geometry, roof vent size and placement, and wind exposure (pressure coefficients).
- Attic moisture storage potential (exposed wood and insulation).

The climatic conditions are:

- Indoor: temperature, relative humidity.
- Outdoor: temperature, humidity, wind speed and direction, insolation.

Current research indicates that bypass air leakage is the primary unknown factor influencing heat and moisture transfer from the house into the attic. Indoor humidity

and outdoor temperature are the most important factors to determine the wetting potential. Ventilation air flow, a function of wind regime and ventilation type, size, and placement, is the primary factor influencing moisture removal or drying potential. Wood moisture storage is critical in determining the carrying capacity and, therefore, potential consequences of the inflows and outflows in a given attic. Besides specifying indoor humidity and outdoor temperature, bypass air leakage is probably the most amenable of these factors to measurement and modeling, and perhaps the most important.

QUANTIFYING BYPASS AIR LEAKAGE

There are two primary unknowns influencing the air flow through attic bypasses: the amount of bypass leakage area and the pressure differences that act across these leaks. The relationship between flow and pressure at low natural pressures is not well understood either.

Due to the difficulties in measuring bypass leakage area, few measurements have been made. Measurement techniques that have been used include: dual-blower door tests that manipulate and balance pressure differences between the house and attic (CMHC, 1989); estimated component leakage areas summed and reconciled to whole-house totals; taping over individual leaks and measuring changes in whole-house leakage; and a single-blower door technique which involves measuring relative pressure drops and adding a known leak to the flow path (Blasnik, 1990).

The results from available sources (CMHC, 1991; Blasnik, 1990; Reinhold and Sonderegger, 1983; Saunders, 1982; Bassett, 1986; Liddament and Allen, 1983) were converted to effective leakage areas (using the LBL definition). Only two sources provided more than six measurements: CMHC provided dual-blower door measured data on 18 houses as previously described, and Reinhold presented estimated data on 28 houses. The CMHC study found a median leakage area of 27 square inches

(approximately 500 cfm_{h0}, equal to 34% of whole-house leakage) and the Reinhold study found 23 square inches. The small amounts of data from the other studies generally indicated that these are reasonable estimates of typical values for cold-climate houses built within the past 30 years. The ASHRAE Handbook of Fundamentals estimates that about 18% of whole-house leakage area is through the attic, although according to the CMHC data this estimate appears low. The GRASP research found interface leakage areas three to four times greater than the CMHC study. These extremely high rates still only accounted for about 25% of the whole-house leakage, indicative of the very large bypasses, such as duct chases, and air leakage problems common in flat roof rowhouses 70 to 100 years old.

House-to-attic interface leakage areas can be converted into approximate natural air flow rates using an approach similar to the LBL infiltration model (ASHRAE Handbook of Fundamentals, Chapter 28). This analysis was performed using the CMHC average measurement and indicated that at a winter temperature difference of 40°F, bypass leakage can be expected to be about 50 cfm. This air flow rate would more than triple the heat loss rate of a 600-square-foot R-30 ceiling, and would increase the moisture transfer by more than 18 fold compared to vapor diffusion through a ceiling without a vapor barrier. These estimates indicate the large impact that typical bypasses can have on attic performance.

Therefore, while accurately predicting attic thermal performance may be difficult because of many problems inherent in modeling air flow, this simple example leads to the conclusion that bypasses must be fixed.

A SIMPLE ATTIC MODEL

A steady-state attic thermal and moisture model was developed as an interactive spreadsheet for sensitivity analyses. Bypass air leakage is specifically modeled, but moisture storage, solar gain, and wind effects are not. The model was designed to

determine the amount of net free ventilation area required to prevent condensation on the roof deck (excluding moisture storage effects) in mid-winter.

The model requires these inputs: indoor temperature and moisture vapor production rate; whole-house air leakage rate (in the common weatherization program units of cfm_{50} , where one square inch of ELA_4 is equal to about 18.2 cfm_{50}); ceiling area, R-value, perm value, and airtightness (in cfm_{50}); average January outdoor temperature and relative humidity; roof area, R-value, and leakage area; and house height. Conduction into and out of the attic is calculated using standard formulas. Indoor relative humidity can be specified or calculated based on the moisture production rate and the estimated natural infiltration rate. Whole-house and bypass air leakage rates are calculated using the two most common air leakage models; the LBL infiltration model and the Canadian AIM-2 model. Only the stack-effect portions of these models are used and the two results are averaged for each estimated flow.

Each model calculates the neutral pressure plane height and driving forces based on the leakage distribution and the indoor-outdoor temperature difference. The heat and moisture transfer associated with this air leakage is then calculated using standard equations. The temperature of the attic and roof deck are then determined by solving the heat balance equation. The air flow required from attic ventilation to avoid roof sheathing condensation is then calculated. The model is re-solved iteratively adding the calculated ventilation air flow at each step until it converges. The required net free ventilation area is then calculated to provide the needed flow based on Hinrichs' research, assuming a 7.5 mph wind and adjusted as indicated in Ford's thesis.

Although this model is steady state and omits several important factors such as solar gain and moisture storage, it can help determine the relative importance of the modeled parameters. For example, Figure 5-1 shows the impact of bypass leakage area on the required net free vent area at four different specified indoor relative

humidities for a two-story house having 600 square feet of R-30 ceiling insulation and no vapor barrier in a climate with an average January temperature of 30°F.

The horizontal line in Figure 5-1 represents a standard 1 in 300 venting ratio. This figure illustrates the large impacts and interactive nature of indoor humidity and bypass leakage. At typical

bypass leakage rates of 200 to 700 cfm₅₀, the indoor relative humidity has a large influence on venting requirements. For the given design criteria and model, the following observations about the impact of indoor relative humidity can be made:

Figure 5-1. Venting vs. Bypasses at Four Indoor Relative Humidities, $T_{out} = 30^{\circ}\text{F}$.

- If the indoor RH is 30% or less, venting at a 1 in 1000 ratio should be fine.
- If there are no bypasses, then a 1 in 1000 venting ratio is sufficient at any indoor RH.
- At 35% RH, a 1 in 300 venting ratio should be fine even if bypasses are large.
- At 45% RH, the effect of bypass leakage is greatest. For example, sealing 600 cfm₅₀ of bypass leakage down to 200 cfm₅₀ has the same impact on moisture buildup as adding about three square feet of ventilation.

It should be noted that these conclusions are conservative because they do not consider moisture storage or solar gain; however, they do not consider night sky radiation either. Additionally, it is unrealistic to specify an indoor relative humidity

because it would certainly vary with bypass leakage. Only tight houses are likely to be capable of maintaining 45% indoor relative humidity in the middle of winter.

Figure 5-2 shows the same relationship but with indoor relative humidity modeled as a function of moisture production rate and whole-house infiltration rate. Curves are shown for four different moisture production rates with the average outdoor temperature set at 20°F and the whole-house air leakage rate at 1600 cfm₅₀ plus bypass leakage (fairly tight). For comparison, the typical household produces about 25 pounds per day of moisture.

The figure shows the large effect of moisture production rate on attic moisture buildup. Clearly, controlling excessive indoor moisture sources whether behavioral, such as air drying of clothes or firewood, or structural, such as wet basements or crawlspaces, can be a very effective attic moisture control strategy.

Figure 5-2. Venting vs. Bypasses at Four Moisture Production Rates, $T_{out} = 20^{\circ}\text{F}$, $\text{cfm}_{50} = 1600 + \text{Bypasses}$.

While the increase in venting requirements as bypass leakage increases is an expected feature of Figure 5-2, the relatively rapid decline in venting needs above a certain level of bypasses is notable. This decline is caused by a combination of the attic warming from bypass leakage and the house air getting dryer from the increased overall house air leakage rate. For this scenario, the peak venting needs tend to occur at lower-than-average bypass leakage rates of 100 to 400 cfm₅₀. This finding implies that

sealing bypasses only partially, while still saving energy, may actually increase attic moisture problems.

Because outdoor temperature has a dominant role in determining the roof deck temperature and also affects indoor humidity levels (through its impacts on whole-house air leakage rates and outdoor air moisture levels), the sensitivity of venting requirements to changes in outdoor temperature was also explored. Figure 5-3 shows the relationship between

Figure 5-3. Venting vs. Bypasses at Four Outdoor Temperatures, $\text{cfm}_{50} = 1600 + \text{Bypasses}$, Moisture Production = 30 lb/day.

bypass leakage and venting requirements at four different outdoor temperatures. The whole-house air leakage rate is again set at 1600 cfm_{50} plus bypass leakage and the moisture production rate is set at 30 pounds per day.

This figure illustrates the large potential for moisture problems and the critical importance of sealing all

bypasses in very cold climates. The apparently large venting needs (a venting ratio of about 1 in 75) when the average outdoor temperature is 0°F and bypass leakage is relatively low (250 cfm_{50}) implies that many attics in cold climates with "standard" venting should be suffering severe condensation and moisture buildup problems. However, if moisture production rates are lower or houses are leakier than assumed, problems would be less severe. Additionally, moisture storage and solar gain are not included in the model.

The attic model was also used to examine the effect of house airtightness on indoor relative humidity and, therefore, attic venting requirements. Figure 5-4 shows the relationship between bypass leakage and venting requirements for houses at four different levels of airtightness (each value is for the entire house except the bypass leakage). The outdoor temperature is set at 20°F and the moisture production rate is again at 30 pounds per day. The figure shows that only tight houses are likely to have high enough relative humidity levels to create attic moisture problems. Consistent with GRASP's research in Philadelphia, leaky weatherization program houses are unlikely to experience moisture problems because of their low indoor relative humidity. However, if weatherization air sealing is very effective, then a house may become tight enough to experience attic moisture problems even if the attic had already been insulated and the program did no attic work.

While the preceding analysis is based on a simplified and conservative steady-state model that ignores solar gain and moisture storage effects and uses assumptions about the air flow that attic vents will provide, the results still help illustrate the trade-offs among moisture production rates, house tightness, indoor

humidity, outdoor temperature, bypass leakage, and ventilation requirements. Many reasonable combinations of these factors indicate that moisture problems are unlikely and standard venting requirements are too great. For example, even a fairly tight house (2000 cfm₅₀) with 20% of its leakage through bypasses in a 20°F winter

Figure 5-4. Venting vs. Bypasses at Four House cfm₅₀ Levels, T_{out} = 20°F, Moisture Production = 30 lb/day.

climate needs only a 1 in 1000 venting ratio if moisture production rates are average (25 lb/day). Conversely, severe problems could occur in a standard vented attic in a tight house located in a cold climate with moderate bypasses and high moisture production.

Ventilation requirements are clearly a strong function of climate and site conditions. Wide variations in site conditions make it particularly difficult to develop appropriate venting standards. This difficulty is compounded by the weak relationship between net free vent area and actual attic air changes found in CMHC's field research. Therefore, sole reliance on attic vents in general, and venting ratios in particular, is inadvisable for controlling attic moisture buildup. **An appropriate strategy needs to include thorough bypass sealing combined with the control of any excessive indoor moisture production.** This latter goal may be accomplished through basement and crawlspace moisture control, occupant education, spot ventilation or even dehumidification, and fixing bathroom fans vented into attics. The level of effort and expenditure for a given house should be a strong function of climate and evidence of existing problems. Efforts should also increase when any of the key factors (particularly moisture production rate and house airtightness) are conducive to problems.

Section 6

RECOMMENDED PRACTICE

While current knowledge about attic moisture buildup and the impact of added ventilation may be imperfect, consensus among researchers and practitioners concerning certain issues and methods is emerging.

Clearly the first priority in order to save energy and avoid moisture problems is to seal attic bypasses, both in existing dwellings and in new construction. Energy savings can be doubled and venting requirements substantially reduced. Sealing bypasses is cheap and easy in standard accessible, unfinished attics. The dense-pack and crawl approach to deal with flat roof attics has been effectively demonstrated. The same dense-packing method can also be used in cathedral ceiling, floored attics, and a variety of other difficult circumstances. If bypasses are not sealed, attic insulation is still likely to be cost-effective in previously uninsulated houses, but savings will be reduced and moisture problems may develop. Adding insulation on top of existing insulation without sealing bypasses is unlikely to be cost-effective because the heat loss is dominated by air leakage, which regular insulation does not significantly reduce. The primary remaining question is the attic moisture control and venting strategy *after bypasses have been sealed*.

When bypasses are sealed, concerns about added heat loss due to attic venting are reduced. The primary concerns are ventilation effectiveness, building codes, and costs. When retrofitting attic insulation, the existing vent area is usually summed and compared to the 1 in 300 ratio of net free vent area to ceiling area. If current venting does not meet building codes or there are moisture problems, additional venting is advisable. The cause of any existing attic moisture problem should be investigated and remedied and opportunities to reduce indoor moisture production rates pursued. The solution is often as simple as properly venting a bathroom exhaust fan or sealing a large bypass directly under the problem area.

When a need for ventilation has been established, often for code compliance, then the venting strategy should be designed to provide maximum effective ventilation air flow when needed at minimum cost, while avoiding roof leaks and rain, snow, and vermin entry. Because no passive ventilation system can guarantee adequate air flow, any attic with a moisture problem that has not been fixed will probably need a followup visit to inspect for further damage and to assess drying. In flat roof houses with high indoor relative humidity, forced ventilation may be worth considering if thorough bypass sealing or moisture production source control are deemed infeasible. In most cases, moisture problems will not occur if bypasses are well sealed; therefore, venting is primarily used to meet codes and a least-cost strategy should be pursued.

Section 7

RECOMMENDED RESEARCH

While a number of research efforts are underway to improve the state-of-the-art understanding of attic ventilation, there are steps that need to be taken to properly apply results. One void in the knowledge base is large-scale documented field information. This information could be relatively simple to collect as part of a weatherization program. Simply noting whether or not a house has an existing attic moisture problem could be quite valuable when combined with basic building information. Information that should already be collected or could easily be collected includes:

- **Basic house information:** style, age, size, number of stories, and type of heating system.
- **Energy consumption history.**
- **Attic information:** type and size, existing attic insulation type and amount, types of large bypasses, type of roof sheathing, and existing ventilation type and amount.
- **Moisture damage:** description of type and location (mold, rot, etc.), and probable cause if obvious (e.g., bathroom exhaust fan disconnect, bypass).
- **Blower door test results on the whole house.**

Additional information which would be useful and relatively inexpensive to collect includes:

- **House moisture information:** sources such as houseplants, clothes drying, wood drying, number of occupants, basement or crawlspace moisture, site drainage, humidifier/dehumidifier usage, and bathroom exhaust fans.
- **Attic orientation, vent locations, and local wind shielding.**
- **Occupant interview information on moisture problems and other house changes that have occurred.**

- More detailed diagnosis of causes for any observed attic moisture problems.

After the information has been collected on a fairly large sample of houses, then a sub-sample could be selected for intensive study. This sub-sample should include only houses with moisture problems; however, a small sample of comparable houses without problems would also be desirable. The moisture sources in these houses should receive more intensive investigation of moisture sources and some combination of diagnostic tests and short-term monitoring should be accomplished.. The ventilation and house-to-attic interface airtightness should be measured, perhaps with the single-blower door technique. Wintertime house and attic humidities and temperatures should be at least spot-measured if not monitored for several months. Attic wood moisture content should be spot-measured, perhaps monthly for a winter. If possible, some limited tracer-gas testing would be useful.

The information collected in the larger sample and the sub-sample should be summarized and analyzed for patterns. Characteristics associated with moisture-problem houses should be identified and used to provide improved field approaches for dealing with likely problem houses. Various retrofits could be tried on some of the houses and the impacts checked or monitored. Because a large database of this type of information does not exist, it would be valuable not only for the weatherization program, but also for researchers, code organizations, and other practitioners.

The existence of short-term techniques like the measured performance rating (MPR) system for quantifying changes in the overall effective heat transfer coefficient (UA) of the envelope and the effective system efficiency of the heating system suggests a second research agenda related to attic air sealing. Using techniques similar to those employed by GRASP in the flat roof research discussed in Section 4, it may be useful to explore the effect of changes in the attic ELA on overall envelope UA during electric coheating and furnace cycles. This research could be undertaken on a small sample of unoccupied houses of the kind weatherized by the New York State weatherization

program. The result would be helpful in quantifying the energy consequences, as well as the convective and moisture consequences, of attic air sealing.

Section 8

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