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LITERATURE REVIEW

1. Achenbach, P.R. and H.R. Trechsel. 1982. *Evaluation of Current Guidelines of Good Practice for Condensation Control in Insulated Building Envelopes*. Proceedings of the ASHRAE/DOE. Conference Thermal Performance of the Exterior Envelopes of Buildings II p 1090-1107.

Moisture problems in building envelopes can develop from six different sources of moisture; namely, use of wet materials in construction, capillary rise of ground moisture, leakage of rainwater or melted snow, condensation of water vapor, persistent high humidity conditions, and leakage of piped water. This paper is concerned with condensation caused by dew point temperatures occurring on or within building envelope constructions, and closely related phenomena. Condensation in building envelopes can be either a summer or winter phenomenon, although winter condensation has been given much greater attention in building standards and guidelines in the United States. Current standards and guidelines seek to control condensation by proper use of vapor retarders. Various criteria for the winter use of vapor retarders in building envelopes are based almost entirely on outdoor dry-bulb temperature and are not entirely consistent. However, a task group assembled to prepare recommendations for the Department of Energy on moisture control in retrofitted houses determined that house size, occupant density, air infiltration rate, type of heating system, and quality of workmanship affect the potential for winter condensation, in addition to outdoor temperature. The potential for summer condensation in building envelopes is confined principally to humid climates and fringe locations near the Gulf of Mexico and South Atlantic coasts of the United States, and to tropical or subtropical island locations. Summer condensation is limited to air-conditioned buildings, for the most part, although mold and mildew can develop without condensation when high humidities occur in buildings. Not all types of air-conditioning systems are effective in controlling relative humidity in humid climates.

2. Achenbach, P. R.; and H.R. Trechsel. 1982 Problem Definition Study of Requirements for Vapor Retarders in the Building Envelope. Germantown, MD: Trechsel (H.R.) Associates.

This document provides a state-of-the-art review and evaluation of current design criteria for vapor retarders. It also suggests general criteria for vapor and air leakage control in Navy building envelopes and recommends specific RDT&E to resolve conflicting criteria, develop remedial measures for existing buildings and prepare guidelines for new construct into prevent the types of moisture and fungus problems currently being experienced, particularly in tropical and subtropical.

3. Ackerman, M.Y., R.B Bannerot, and J.D. Dale. 1985. *A Study of Passive Solar Heating in a Northern Climate.* New York, NY: American Society of Mechanical Engineers.

A study of residential heating in a northern climate utilizing four downsized uninhabited test modules has shown that major reductions in purchased energy, relative to conventional housing, were obtained using moderately upgraded insulation and increased south glazing area. It was found, however, that the effective utilization of solar gains required the use of night window insulation and that the insulation effectiveness was a function of the integrity of the seal between window and insulation. A moderate amount of mass in the form of a direct gain wall while increasing the short term time constant of the structure significantly proved to be ineffective due to night cooling resulting from radiative losses to the windows. Tracer gas infiltration testing in conjunction with pressurization/depressurization techniques indicated that caulked joints and alternative air/vapor barrier placement were ineffective measures, resulting in marginal improvements in air tightness over conventional construction practices.

4. Ackerman, Mark Y., Per A Levin, and David J. Wilson. *Air leakage in the Perspective of International Standards*. Stockholm, Sweden: Royal Institute of Technology.

There exist a number of national standards and a draft international standard for the fan pressurization method for measuring air leakage. Although the standardized methods in principle are the same, the way of interpreting and presenting the results is different. In previous studies, houses that have a relatively large leakage area at a low pressure difference (4 to 10 Pa) still can seem comparatively airtight at a high pressure difference (50 Pa). This fact is a consequence of differences in the flow exponent in the power-law equation, which is the normal equation, used to fit to the data points, and can be a source of error when trying to compare the relative air tightness of houses. Extrapolating results from high-pressure differences to low pressures, which are out of the measured range, can thus result in substantial errors. Air leakage testing of windows normally starts at 50 Pa, which should be accounted for when trying to use these results as inputs in network air infiltration models. Measurement results on low-pressure air leakage are discussed in the paper and compared with high-pressure air leakage. Pressurization test data from105 tests in one house at the Alberta Home Heating Research Facility are the study of. The tests were made automatically over a seven-month period in low wind conditions. A wide range of pressure differences was tested and the results cover the test specifications for most standards. In addition to comparing standards, these tests were used to measure seasonal effects on air leakage in a wood-frame house with a plastic film air/vapor barrier. The results show some significant differences between the standards, and also a variation with month of test, indicating a seasonal variation in air leakage.

5. Air barrier details: How effective are they? 1992. Canada: Solplan Review, September.

A project was initiated to measure the air leakage through three typical details in wood frame walls: the header joist, electric outlets, and window openings. Three construction methods were tested: the poly approach, where a sealed internal polyethylene sheet and caulking provide the air barrier; an external air barrier approach using a continuous vapor permeable membrane sandwiched between two layers of external wall sheathing; and the airtight drywall approach (ADA), where the interior gypsum board finish along with framing and gaskets are the air barrier. Twelve sample panels using each of the three details were built using each of the construction approaches. A traditional wood-frame wall construction detail, with no effort made to create a continuous air barrier, was also built and tested for comparison. The samples were put in a test chamber so that air pressures could create infiltration or exfiltration through the panel under loads similar to those due to wind action. Measurements were made at several stages during construction of each sample to see the effect of different components on the air leakage. Overall, all but the traditional samples and the ADA electrical outlet panel exceeded the current tightness standards for glass and aluminum curtain walls. All three approaches could meet the airtightness standards of the R-2000 program. The total air leakage calculated for each approach is under 20% of that in traditional construction. Of the details tested, window detailing offers the greatest potential for increasing overall airtightness compared to traditional methods.

6. *Air barrier for the building envelope.* Proceedings no. 13. Ottawa, Canada: Institute for Research in Construction.

Proceedings of seminar-workshop on air barriers, covering definition and descriptions of the air barrier, the mechanism of air leakage, air impermeability, and air barrier requirements; wind and air pressures; air leakage control; and construction applications in residential and commercial construction, including metal air barrier systems, masonry wall and peel and stick membranes.

7. *Air barrier system details for houses.* 1994. Canada: Solplan Review; June-July.

Uncontrolled air leakage is a major source of problems in buildings. Excessive air leakage can lead to high-energy bills, uncomfortable drafts and cold interior surfaces. It can also contribute to structural damage caused by moisture condensation, and can adversely affect occupant health. A review is presented of air barrier systems for houses. An air barrier resists the flow of air over a normal range of air pressure imposed on a building and may include many components designed and constructed to reduce air flow through the building. A vapor barrier resists the diffusion of water vapor, and may consist of polyethylene, low permeability paints, or foil. The vapor barrier is always placed on the warm side of the construction, while the air barrier may be located on the interior or exterior. Attention to detail is key to achieving a successful air barrier. Air leakage can occur between foundation and sill plates, cracks between framing members, and penetrations in the header. Sheet air barriers can be wrapped over the header to provide a continuous air barrier. The floor joist assembly can be wrapped with polyethylene, and structural elements of the floor assembly are sealed or casketed. Penetrations into the exterior envelope of the house for electrical outlets and plumbing fixtures are potential sources of air leakage. Electrical boxes, windows, and heating ducts can all benefit from design to minimize the potential for air leakage

8. Air leakage control: Guidelines for Installation of Air Leakage Control Measures in Commercial Buildings. Ottawa, Canada: Public Works Canada Technology.

After an overview of the issues involved with regard to air leakage in commercial buildings and the potential cost benefits of air leakage control, this document presents specific guidelines on sealing and installation of air barriers. Sealing and installation methods and materials are described for various components of commercial buildings, including below-grade features, exterior walls, openings, interior walls, roofs, and shafts. It also includes an outline of the air leakage control design process and contracting procedures.

9. Air leakage control: Retrofit measures for high-rise office buildings. Ottawa Canada: Public Works Canada Technology.

The main objectives of this study are: To identify key parameters associated with air leakage in buildings; to determine the range of heating and cooling load energy savings associated with sealing the uncontrolled air leakage; to develop preparatory application guidelines for implementing air leakage control measures in office buildings; and to prepare a preliminary draft of best practices. After an introduction, the study reviews previous studies on air leakage control in office buildings and discusses four key factors: Building tightness, climatic influence, interaction of a building's heating/ventilation and air conditioning system, and the building's topographic environment. Section three presents application guidelines for air leakage control retrofit measures, including air barrier installation for some common scenarios and sealing details for roofs, windows, doors, and other penetrations.

10. Air Retarder (AR) Material or System for Low-Rise Framed Building Walls. 1995.

This specification is under the jurisdiction of ASTM Committee E-6 on Performance of Buildings and is the direct responsibility of Subcommittee E06.41 on Infiltration Performances. Current edition approved Jan. 15, 1995.

11. *Air sealing homes for energy conservation*. 1984. Canada: Marbeck Resource Consultants Ltd. p. 437.

This manual describes the air sealing of existing houses through the application of sealants, weather-stripping, air-vapor barriers, and other products and techniques. A section on the principles of air sealing covers the basic concepts of air exchange, moisture movement, and air sealing. In addition, it discusses the control of indoor air quality and the assurance of adequate combustion air supply in extremely well sealed homes. A section on assessment procedures identifies the procedures that can be used to assess individual houses to determine what air sealing measures should be undertaken. It provides an indication of priority amongst those measures and, by way of example, identifies a number of sealing packages for a variety of circumstances. A section on air sealing practices covers the various materials used for air sealing work, their characteristics, and their preferred applications. Sealing procedures are presented for each element of the house and for most situations or construction techniques likely to be encountered. Step-by-step instructions are provided in form of worksheets, which outline tools, materials, preparation, and application procedures for each case. The manual also contains a draft glossary of terms and appendices containing data sheets on various sealants and weather-stripping materials.

12. *Airtightness of concrete basement slabs.* 1991. Winnipeg, Canada: G.K Yuill and Associates Ltd., December.

A study was carried out to develop and evaluate means of making basement floors airtight, with the objective of keeping out radon bearing soil air. The project included laboratory tests of the airtightness of several floor assemblies, and a field test of the airtightness of a floor in a house. In the laboratory tests, several arrangements of polyethylene films were tested, as seals of the floor-wall joint, and as crack seals. Also tested were concrete slabs without polyethylene films, and a concrete slab with a crack created and sealed with a water stop strip. Results of the tests showed that a lapped and caulked polyethylene film could be used successfully to make cracked concrete airtight. They also indicated that the use of a water stop could be a successful technique. In the field test, a lapped and caulked polyethylene air barrier was installed in the basement of a house, using techniques that could be applied by a house builder. A concrete floor was poured on top of the system. Airtightness testing showed that this air barrier was very successful in sealing the basement from the soil, and would reduce radon contamination by almost two orders of magnitude.

13. *An air barrier for the building envelope*. 1989. Saskatoon, Canada: National Research Council of Canada; Institute for Research in Construction, (Ottawa, ON) National Research Council Canada. (30 p) January.

A series of seminars called Building Science Insight '86 was held in cities across Canada, and the proceedings of these seminars are presented. Separate papers are included on principles of air and vapor barriers, wind and air pressures on the building envelope, air leakage control, and the design and construction of effective air barrier systems. Separate abstracts have been prepared for each of the four papers from the proceedings of this seminar.

14. Arundel, A, D. McIntyre, E. Sterling, and T.D. Sterling. 1986. Effectiveness of air vapor barriers combined with ventilated crawl spaces in decreasing residential exposure to radon daughters. Pittsburgh, PA: Air Pollution Control Association.

Radon gas is present in many homes. Concentrations may be increased in airtight, energy-efficient structures. This is especially true in cold climates where energy conservation is an important factor leading to the widespread application of sealing and tightening techniques both in older renovated homes and new construction. To reduce radon concentrations, it may be effective to ventilate crawlspaces and prevent infiltration of radon gas into the house by means of an air/vapor barrier. The authors report first results of comparing radon levels in homes with and without ventilated crawlspaces and air/vapor barriers. Radon emissions were measured in a tightly sealed home with ventilated crawlspaces and an air/vapor barrier and in two homes without such vapor barriers and ventilated crawlspaces, but differing in ventilation. Preliminary results suggest that use of ventilated crawlspaces and bottom side vapor barriers may reduce indoor radon levels by approximately 60%.

15. Aulisi, Susan. 1984. *Energy Conserving Housing: A Total Systems Approach To Passive Solar Design*: Energy Efficiency in Buildings and Industry. Rockville, MD: Adirondack Alternate Energy; Government Institute, Inc. p 638-650.

The paper discusses: 8505 a passive solar 'Low Energy Requirement' home, which incorporates an R37 insulation envelope and vapor barrier on all six sides of the structure, very heavy thermal storage, and an integrated air handling system. The houses are characterized by low air infiltration, stable humidity levels of 45-50 percent, and comfortable interior temperatures. Through the use of innovative construction techniques LER homes have avoided many of the limitations that have characterized energy efficient solar heated residences.

16. Bales, E., L.B. Bass, F.G. Odell, J.C. Thompson, and G.A. Tsongas. 1981. *Field study of moisture damage in walls insulated without a vapor barrier*. New York, NY: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Considerable uncertainty has existed over whether or not wall insulation installed without a vapor barrier causes an increased risk of moisture damage (wood decay) within walls. This paper describes the results of a study aimed at finding out if such a moisture problem really exists. The exterior walls of a total of 96 homes in Portland, Oregon were opened, of which 71 had retrofitted insulation (three types) and 25 were uninsulated. Field and laboratory test results are presented which show the absence of moisture accumulation, and wood decay fungi, or other indications of moisture damage in the walls of the test homes. Data on shrinkage and settling of insulation are also given, as are results of air leakage measurements by fan depressurization tests. The study concludes that the addition of wall insulation without a vapor barrier does not cause moisture damage in existing homes with wood siding in climates similar to that of Western Oregon. The overall advisability of future retrofitting of wall, insulation is discussed.

17. Bailey, D.W. and J. Flack. Patent. 1992. *Laminated, Thermal Insulation Panel*. Canada: CA 1293917 A Patent Assignee(s): Produits Isolofoam Inc., January.

A laminated thermal insulation panel for insulating the exterior of houses is provided which comprises a board made of expanded polystyrene permeable to water vapor and a membrane laminated over one side of the board. The membrane is impervious to air and moisture but permeable to water vapor, and is preferably made of non-woven spunbonded olefin. The membrane is joined to the board by an adhesive chosen for its compatibility with the board and the membrane. The adhesive is applied in a pattern to ensure permeability to water vapor, preferably in a plurality of strips. The adhesive preferably comprises, as an elastomeric base, a blend of polybutene and styrene-isoprene-styrene block copolymer, and as tackifying resins, a blend of synthetic hydrocarbon resins and rosin esters. When applying the laminated panels to the outside of a house, the joints between panels are sealed with an adhesive tape impervious to air and moisture, preferably comprising a permanent acrylic adhesive with an oriented polypropylene backing. The panel of the invention constitutes a barrier to air and moisture from the outside to the inside, while allowing water vapor to pass from the inside to the outside in order to prevent any condensation, moisture, and air infiltration within or through the wall assembly. A 47-mm thick panel of the invention has an R-value of 7. The laminated nature of the panels eliminates many of the problems associated with current practices of installing insulation panels and moisture/air barriers separately.

18. Bankvall, C.G. *Air Movements and the Thermal Performance of the Building Envelope*. Philadelphia, PA: Swedish National Testing Institute; ASTM special technical publication

This paper discusses how air movements will influence the thermal performance of the building envelope. To what degree will depend on the pressure situation in and around the structure, the permeability of the different materials, and the airtightness of joints between materials and building elements. In a multi-layer structure with a high thermal resistance, different parts have different functions in order to protect against unwanted airflow and ensure airtightness. Wind protection will give a degree of safety against airflow in the insulation, especially in situations involving large wind loads. Certain areas of the structure may be more sensitive and have a higher need for wind protection than others. In a similar way, the building envelope will be sensitive to air infiltration. The inside, (that is, the vapor barrier, inside board, and joints) will greatly influence the airflow and the heat losses from the envelope. Both types of increased heat losses from the building envelope (that due to air flow along the insulation and that due to air infiltration) will most influence envelopes with high thermal resistance. This type of envelope is typical of today's design in Scandinavia. The results and discussions presented in this paper are related to this.

19. Bankvall, Claes G. 1982. *Thermal Transmittance of Building Envelopes Influenced by Air Infiltration and Workmanship*. Conference Title: Energy Conservation in the Built Environment, Proceedings of CIB W67 3rd International Symposium. (Volume 3: Energy Conservation and the Building Envelope.), Dublin, Ireland

20. Bearg, D., C. Blumstein, J. Harris, and W.A. Turner. (eds.). 1984. *Super insulated retrofit in Maine: Theory and Reality*. Berkeley, CA: Lawrence Berkeley Lab; American Council for an Energy Efficient Economy.

During the summer of 1981, a 3600 square foot home located in an 8500-degree day climate was rebuilt using superinsulation concepts. The walls were insulated to R-26, ceiling to R-50, and crawl space to R-19. R-7 night insulation was used on most of the windows. Total energy consumption was monitored the following winter; both success and problems have been discovered. Larger than expected air infiltration and ice dam problems were identified. Annual fuel consumption appears to be 1.7 times the expected amount of 117 MBtu. The use of smoke tubes revealed that an inadequate floor and attic vapor barrier and excessive exfiltration appear to be the cause. The methods of retrofit, associated costs, and other planned changes are detailed. SF_6 tracer gas decay measurements and blower door measurements will be conducted and energy consumption measured to document the effects of further changes. Limited indoor air quality monitoring will be conducted, but the addition of an air-air heat exchange is not planned at this time.

21. Beckman, J., and G. Proskiw. 1989. *Airtightness Performance of Twenty Detached Houses over a Two-Year Period Flair Homes: Project report no.5*. Winnipeg, Canada: UNIES Ltd.; Energy, Mines and Resources Canada. p. 62.

Airtightness tests were performed on 20 new houses over a 2-year period in Winnipeg. The houses were constructed with a variety of air/vapor barrier systems and 3 different types of main walls. Polyethylene was used as the air/vapor barrier in 6 of the houses while the remaining 14 used the airtight drywall approach (ADA). The houses had similar floor plans and were constructed by the same builder. Both the polyethylene and ADA systems were found to be capable of meeting the airtightness requirements of the R-2000 standard with the tightest structures being double wall houses. No significant or permanent change in airtightness was observed for any of the houses over the monitoring period. Application of stucco as an exterior finish was found to improve airtightness of the ADA houses, but not of the double wall houses with polyethylene vapor barriers. Consistent sources of air leakage in the ADA houses were found to be the electrical outlets on exterior walls. Window leakage was also noted in many houses and the frequency of this leakage increased over the monitoring period. A significant leakage source was found to be an integrated mechanical system, which ducted in large volumes of outdoor air. It was also concluded there is a need to re-examine the design pressure requirements for residential air barrier systems. Specifically, this should investigate how transient wind-induced pressure loads are resisted by air barrier systems and whether some portion of the load is taken by other envelope components. An air leakage detection system was proposed consisting of a simple non-instrumented blower, which would be suitable for use by builders to aid in the construction of low leakage houses.

22. Berglund, B.L., H.N. Berglund, and L.G. Berglund. Thermal performance of two technically similar super-insulated residences located at 61 N and 41 N latitude. San Francisco, CA.

Two super-insulated contemporary residences constructed in 1992 in different climatic regions had the same designer, followed the recommendations of the Alaska Craftsman Home Program and have identical envelope details. One located on a mountainside in Anchorage, AK, has a 180 m^2 floor area and 6100 C heating degree-day winters while the other with 128 m^2 is in Lebanon, CT, with 3400 C degree-days. The walls are 29 cm thick (R = 7.2 m^2 K/W) and insulation in the roof is 61 cm thick (R = 13.2). Wall construction minimizes thermal bridging and includes a vapor barrier and a polyester fabric air barrier. The Alaskan residence has floor heating while the Connecticut house has baseboard heating, supplied from gas and oil-fired boilers respectively. Both houses have mechanical ventilation with heat recovery and substantial window areas on the south sides for solar heating assistance. The energy consumption normalized for area and weather differences is about 30% less for the Alaskan house. About half of this difference is due to a less-efficient boiler, a quarter to the proportionately smaller roof and the remainder to increased air leakage of a fireplace and additional entrances of the Connecticut house. The Alaskan residence won the 1992 Governor's Award for Excellence in Energy Efficient Design.

23. Besant, R.W., R.S. Dumont, and G. Schoenau. 1979. Saskatchewan House: 100 percent Solar in a Severe Climate.

The Saskatchewan Conservation House in Regina, Canada, receives 100% of its heating primarily from passive heat gain. The house incorporates insulation levels three-fold the current Canadian standard, caulked and sealed vapor barriers with an air-to-air heat exchanger utilizing plastic sheeting, south facing windows, a waste water heat exchanger for laundry and bath water, and an active system of 192 ft^2 of vacuum tube collectors with 2,800 gal water storage. Insulated shutters are used on all the windows. Problems have developed with controls for the active heating system that was designed to supply 100% of the space heating. Infiltration was measured at 5% air change/hr. The heat storage capacity, energy consumption, performance estimates, and system components of the house are reported in detail.

24. Bielek, Milan; Pavol Kalinay and Zoltan Polak. 1984. Experimental Investigation of Physico-Mechanical Properties of Window Sealing Profiles.

This study deals with research on window sealing profiles of Czechoslovak make manufactured of different materials and using as basis the theory of the general phenomenon of air filtration. The laboratory technique and the experimental research of volume air flow through the window sealing profiles under various conditions of their compression and air pressure differences defined by the boundary conditions for the physical analysis of the influence of wind on buildings and structures in the climate of Czechoslovakia are described. An algorithm was developed in order to determine further physic-mechanical characteristics of the air filtration theory of buildings represented by numerical relationships and graphical means which allow a quick orientation for the designer charged with the selection and the design of window sealing profiles, the choice of the shape of wind barriers and the design of the outer parts of buildings.

25. Braun, B., and J. Hansen. 1995. *Urethane foams and air leakage control.* Home Energy v 12:4. Coden. Jul Aug p 25-28

Urethane foams can be a key component in a continuous, high performing air barrier and have high R-values when used as insulation. The topics include the following: hole versus gap fillers; one component foam; two-component foam; applying the foam pointers codes and standards.

26. Brick veneer walls - Proposed Details to Address Common Air and Water Penetration Problems. Plainville, MA: R.J. Kenney Associates, Inc.

Common problems with brick veneer walls include inadequately sealed Flashing, poorly draining cavities, excessive air infiltration, and large thermal bridges through the back-up walls. This paper proposes brick veneer wall details that directly address these problems and which provides a durable wall assembly that is expected to retain its weather resistance and thermal properties for the life of the wall. It is proposed that a properly sealed air barrier membrane be applied at the back of the cavity and that glass fiber drainage insulation be installed in the cavity, the full depth of the cavity.

27. Brown, W.C., and M.E. Lux. 1989. *Air leakage control, an air barrier for the building envelope: Proceedings of building science insight '86.* Ottawa, ON: National Research Council of Canada; Institute for Research in Construction.

Present knowledge about effective air barrier systems for buildings is reviewed from the viewpoint of air leakage. The consequences of an ineffective air barrier system include the adverse effects of air leakage on building performance. For example, energy use associated with air infiltration may account for more heat loss than is occurring by conduction through the wall insulation. Air exfiltration may also cause loss of temperature and humidity control in interior spaces, and condensation of moisture in infiltrating air can reduce the service life of materials in the building envelope. An effective air barrier is a continuous system made of materials, joints, and assemblies, with effective sealing at all junctions so that the line of airtightness extends over the whole envelope in all its dimensions. Air barrier systems must be built in stages and use materials impermeable to air flow. Two categories of airflow diffuse (continuous flow through a material) and channel (through passages in the building envelope) flow, must be controlled. Test methods for determining air leakage rates are described, including standard procedures for testing materials and assemblies. Some permissible leakage levels for windows, doors, and walls are presented.

28. Brown W.C., G.A. Chown and M.C. Swinton. 1990. Building Science Insight Series: “Small Buildings—Technologies in Transition: Controlling the Transfer of Heat, Air and Moisture Through the Building Envelope. National Research Council Canada Ottawa, Canada: (NRCC 3233)

29. Brown, W.C, G.A. Chowan and M.C. Swinton. 1990. Controlling the Transfer of Heat, Air and Moisture through the Building Envelope, Small Buildings: Technology in Transition, NRC Canada

30. Brown, W.C., and K. Ruberg. 1988 *Window Performance and New Technology: Proceedings of Building science insight '88*. Ottawa, Canada: National Research Council of Canada, p 17-28 (80 p) August.

Window performance factors discussed in this paper include those that arise because of the light transmission properties of windows as well as those that are applicable to opaque walls. Discussion is presented in three major areas: windows as energy filters, as part of the building envelope, and as a building component. Historically, windows have been installed primarily to provide light and a view, and other performance factors were balanced against this. After light and view, the most commonly used performance criterion is thermal performance, involving heat transmission (heat loss from a heated interior to a colder exterior, and solar gain) and surface temperature factors (moisture condensation and its effects on the durability of the window system). As part of the building envelope, windows must be able to withstand structural stresses and must function as air, vapor, and water barriers. Once installed, they must conform to expected modes of operation as modes of egress and as means for ventilation.

31. Brunsell, Jorn T.; Sivert Uvslokk, and Bjorn Vik. 1983. *Air tightness and Thermal Insulation of Buildings: Research in Progress at the Norwegian Building Research Institute (NBI.)* Gavle, Sweden: National Swedish Institute for Building Research. P. 57-64.

Air infiltration in buildings is both measured by the tracer gas method and calculated by means of the computer program ENCORE. Calculations show satisfactory correlation at low wind speeds. At higher wind speeds, the calculated values of air infiltration are too high, mainly due to insufficient knowledge of air pressure differences in ventilated multi-layer constructions. Testing on 10 wood frame domestic houses shows no significant difference in total air leakages in houses with thin and thick polyethylene film used as water vapor barrier.

32. Buckley T., R.C. Diamond, H.E. Feustel, J.A. McAllister, and C. Patullo. *Affordable housing through energy efficiency: The North Gate Story*. Berkeley, CA.: Lawrence Berkeley Lab.

In this paper we evaluate a comprehensive retrofit and rehabilitation Effort to improve the comfort, affordability, and energy efficiency of 336 low-income housing units. The units had complete shell retrofits, including new siding, air-infiltration barriers, new windows and doors, and both roof and foundation insulation. In addition, the existing electric-base board heating system was replaced with a new gas-fired boiler for each apartment. New programmable thermostats, refrigerators, and tenant education were also included in the retrofit package. The evaluation of the project included pre- and post-retrofit utility bill analysis, computer simulation to evaluate the cost and saving of the individual measures, and a comprehensive survey of the residents regarding their comfort, behavior, and satisfaction with the retrofits. The analysis has shown energy savings of more than 20% for the shell measures, with a reduction in utility bills of nearly 50% from the combined measures. The resident survey shows high tenant satisfaction with the retrofits.

33. Bumbaru, D., R. Jutras, and A. Patenaude. *Air Permeance of Building Materials*. 1988. St. Laurent, Canada: AIR-INS, Inc. June. (229 p.)

The need for improved air tightness of the building envelope is now accepted. Air infiltration and exfiltration through the building envelope has been blamed for the premature failure of many new wall systems. To achieve air tightness of a building envelope, an air barrier system should be designed to perform the unique function of resisting air infiltration and/or air exfiltration. To accomplish this, the system must have the following attributes: continuity, strength, air impermeability and durability. Among the above aforementioned attributes, the air impermeability of building materials used to build the air barrier system is certainly the first characteristic to evaluate in order to set limitations. Tests were conducted on orifice plates and building materials. A total of 126 specimens from 36 building materials were tested at static pressure differentials varying from 25 to 100 pascals. These trials indicated that the test method developed was in close agreement with the test method developed by the Institute for Research in Construction. The method is capable of measuring a wide range of airflow rates with reasonable accuracy. In pressure differentials between 25 and 100 pascals, the airflow regime was shown to be mainly laminar.

34. Burch, D. 1995. *An Analysis of Moisture Accumulation in the Roof Cavities of Manufactured Housing.* Gaithersburg, MD: NIST Building and Fire Research Lab. p 156-177.

35. Burch, M. Douglas. 1995. *An Analysis of Moisture Accumulation in the Roof Cavities of Manufactured Housing*. (STP 1255) Philadelphia, American Society for Testing and Materials, pp. 156–177.

A detailed computer analysis is conducted to investigate whether moisture problems occur in the roof cavity of manufactured homes constructed in compliance with the current Department of Housing and Urban Development (HUD) Standards for manufactured housing. The current HUD Standards require a ceiling vapor retarder, but do not require outdoor ventilation of the roof cavity. In cold climates, the analysis revealed that moisture accumulates at lower roof surface and poses a risk of material degradation. The analysis found the following combination of passive measures to be effective in preventing detrimental winter moisture accumulation at lower surface of the roof: (1) providing a ceiling vapor retarder; (2) sealing penetrations and openings in the ceiling construction, and (3) providing natural ventilation openings in the roof cavity. In addition, the performance of a roof cavity exposed to a hot and humid climate is investigated. The analysis revealed that outdoor ventilation of the roof cavity causes the monthly mean relative humidity at the upper surface of the vapor retarder to exceed 80%. This condition is conducive to mold and mildew growth.

36. Burch, D. M., and W.C Thomas. *Analysis of Moisture Accumulation in a Wood-Frame Wall Subjected to Winter Climate*. Gaithersburg, MD: National Institute of Standards and Technology (BFRL); Building Environment Division.

A transient, one-dimensional, finite-difference model is presented that predicts that coupled transfer of heat and moisture in a multi-layer wall under non-isothermal conditions. The model can predict moisture transfer in the diffusion through the capillary flow regimes. It has a provision to account for convective moisture transfer by including embedded cavities that may be coupled to indoor and outdoor air. The model is subsequently used to predict the time-varying average moisture content in the sheathing and siding of a wood-frame wall as a function of time of year. The effect of several construction parameters on the winter moisture accumulation is investigated. The parameters include the interior vapor retarder permeance, sheathing permeance, exterior paint permeance, indoor air leakage, and the amount of insulation 5/7/10 (Item 10 from file: 6)

37. Burch, D.M. 1993. *Analysis of moisture accumulation in walls subjected to hot and humid climates.* Gaithersburg, MD: National Institute of Standards and Technology.

A detailed computer analysis was conducted to investigate the moisture accumulation in walls subjected to a hot and humid climate (Lake Charles, LA). The analysis revealed that the use of low-permeability wallpaper (e.g., vinyl wallpaper) causes moisture to accumulate within adjoining gypsum board. At this location, the surface relative humidity can rise above 80% and approach a saturated state, thereby providing a conductive environment for mold and mildew growth. A variation of parameters was carried out to investigate which parameters are important. Para meters found to have a significant effect included indoor temperature, permeance of the wallpaper, the amount of outdoor infiltration, the permeance of exterior construction, and the initial moisture content of the construction materials. Parameters found to have a less important effect included orientation, insulation thermal resistance, the permeance of exterior paint, and the type of wall construction. Based on the analysis, the following practices for controlling moisture accumulation in walls exposed to hot and humid climates are recommended. Vapor retarders should not be used at interior surfaces. An exterior vapor retarder should be installed in the construction. Installing an exterior air barrier and eliminating negative pressurization of the indoor space should minimize the infiltration of outdoor air into the construction. Construction with moist materials should be avoided. The indoor space should not be cooled below its design set point temperature.

38. Burch, D.M. and A. TenWolde. *Computer Analysis of Moisture Accumulation in the Walls of Manufactured Housing.* Gaithersburg, MD. National Institute of Standards and Technology.

Detailed computer analysis was conducted to investigate the effectiveness of three alternative practices for controlling moisture accumulation in the walls of manufactured housing during the winter. The three practices included (1) providing an interior vapor retarder, (2) using permeable sheathing and siding, and (3) providing an outdoor ventilated cavity. The current HUD Manufactured Home Construction and Safety Standards do not require a vapor retarder for practices 2 and 3. The analysis was carried out for a cold winter climate (Madison, WI), an intermediate winter climate (Boston, MA), a mild winter climate (Atlanta, GA), and a Pacific Northwest climate (Portland, OR). The practice of providing a vapor retarder was found to be effective in all four climates. The moisture content of the siding was always considerably below fiber saturation. On the other hand, the practice of using permeable sheathing and siding and the practice of providing an outdoor ventilated cavity were not always effective in colder climates. Moisture accumulated above fiber saturation, and free liquid water existed within the pore structure, providing a potential for material degradation. A detailed computer analysis was also conducted of moisture accumulation in manufactured housing walls in a hot and humid climate (Lake Charles, LA). During the summer, moisture from the outdoor environment is transferred into manufactured housing by diffusion and, more important, infiltration. As the interior layers of the construction cooled by air conditioning. When an interior vapor retarder is used in the construction, the relative humidity at the outside surface of the vapor retarder can approach saturation, thereby providing an environment.

39. Burch, D.M. 1992. *Controlling Moisture in the Roof Cavities of Manufactured Housing*. NISTIR 4916, Building and Fire Research Laboratory, National Institute of Standards and Technology, U.S. Dept. of Commerce, prepared for U.S. Dept. of HUD, November.

40. Burch, D.M. 1992. *Controlling Moisture in the Walls of Manufactured Housing.* NISTIR 4981. Building and Fire Research Laboratory, U.S. Dept. of Commerce, prepared for U.S. Dept. of HUD.

41. Burch, Douglas M. 1995. Manufactured Housing Walls That Provide Satisfactory Moisture Performance in all Climates, Building and Fire Research Laboratory. U.S. Dept. of Commerce, prepared for U.S. Dept. of HUD.

42. Burch, D. M., Tsongas, G. A, et al. 1996. *Mathematical Analysis of Practices to Control Moisture in the Roof Cavities of Manufactured Houses.* NISTIR 5880, Building and Fire Research Laboratory, National Institute of Standards and Technology; U.S. Dept. of Commerce, prepared for U.S. Dept. of HUD.

43. Burch, Douglas M. and Anton TenWolde. 1993. *Ventilation, Moisture Control, and Indoor Air Quality in Manufactured Houses*. A Review of Proposed Changes in the HUD Standards and a Proposal for Revised Standards. AQ-11, prepared for HUD, February.

44. *Canadian housing experience '99* 1999. Ottawa, Canada: Proceedings of the 5. Canada-Japan housing R and D workshop; Natural Resources Canada Publication, p 271-278 (496 p)

In part 1, of this report, regional Classifications for Moisture Control in Japan moisture control guidelines for maintaining efficient and durable wall assemblies were proposed, based on the criteria of the summertime mean water potential and winter mean temperatures. In part 2, the influence of air leakage on wetting and drying characteristics of envelopes on the proposed regional classification system is discussed. A series of wall assemblies are recommended as appropriate for various regions of Japan. In this classification system, wall B with a polyethylene barrier should only be used in region A. The potential for moisture damage represented by the cumulative ratio for high relative humidity does not differ in a big way from wall B whether a primer or polyethylene barrier is used whether in summer or winter. Previous work indicates that the relative humidity of wall C is maintained at low levels throughout the year in all regions. Wall D which uses a desiccant board finished with a vapor barrier primer performs well in all regions, except E, during the summer, but experiences moisture problems in colder regions A and B during the winter. If a vapor barrier and air barrier are properly installed in wall E, the risk of moisture damage is minimized in regions A to D throughout the year.

45. Carll, Charles. Vyto Malinauskas, and Anton TenWolde. *Airflows and Moisture Conditions in Walls of Manufactured Homes.* Madison, WI: USDA Forest Service.

Unintentional airflow in exterior framed walls frequently causes diminished thermal performance. Furthermore, even very small infiltrative or exfiltrative airflows with little or no effect on the thermal performance are capable of voiding the moisture protection provided by a vapor retarder. Combined with high indoor or outdoor humidity, such walls may accumulate excessive amounts of moisture. However, more data were needed on airflows in and through wall assemblies and the effect of airflows on moisture conditions in walls. Twenty wood frame walls of ten different designs, characteristic of walls of manufactured homes, were constructed and installed in a test building near Madison, Wisconsin. In-place pressurization and depressurization tests were performed to separately determine air tightness of the interior and exterior membranes of the wall. This paper describes the methodology, equipment, and results of these measurements. Air pressure differences across these walls were monitored during an entire winter season, along with temperatures and moisture conditions in the walls. This paper describes the instrumentation and methodology used in these measurements. The measurements showed that providing wall cavity ventilation may cause pressurization of the wall cavity and can lead to a significant increase in air leakage and heat loss without reliably providing the intended protection from moisture accumulation in the cavity. Although several of the walls experienced condensation and mold growth, the moisture conditions in the walls showed no clear correlation with air tightness or with the amount of air flowing through the wall. Indoor humidity correlated strongly with wall cavity moisture conditions, suggesting that indoor humidity control is the most effective strategy to prevent excessive moisture accumulation in the Exterior building envelope during winter.

46. Carmody, John and Joseph Lstiburek. 1991. *Moisture Control Handbook: New Low-rise, Residential Construction.* RP02Y Energy Design Update. Prepared for Oak Ridge National Laboratory. Cutter Information Corp., October.

47. Carmody, John and Joseph Lstiburek. 1991. *Moisture Control Handbook: New, Low-Rise Residential Construction.* Washington, D.C.: U.S. Department of Energy Conservation; Renewable Energy Office of Buildings; Community Systems Building Systems Division

48. Chase, V.D. 1980 Indoor pollution: a potential problem in energy-saving houses. . United Kingdom: Atmos Environ.

Many researchers believe that the increasing implementation of energy conservation steps in residential homes is causing an indoor air pollution problem. Experiments in several government and private energy-efficient test houses that are determining the impact of energy conservation measures on indoor air infiltration are reported. Factors shown to reduce the rate of indoor air infiltration substantially and to cause an accumulation of indoor pollution include the use of vapor barriers, weatherstripping, and caulking devices. Mechanical ventilation could be the solution to most indoor air pollution problems.

49. CMHC research project: Testing of air barriers construction details. 1991. Ottawa, Canada: Canada Mortgage and Housing Corp., August.

The airtightness of building envelopes is important in controlling comfort and energy usage in houses. Leakage generally occurs through construction details, where there are joints or connections between materials, or where there are penetrations for services or other components. A study was conducted to quantify the air leakage characteristics of three such details in wood-frame walls: the header joist, the electric outlets, and the window opening detail. Three construction methods employed to achieve airtightness were evaluated: the sealed internal membrane approach (POLY); the external air barrier approach using a continuous vapor permeable membrane sandwiched between two layers of wall sheathing (EASE); and the airtight drywall approach (ADA). Test panels containing the details were subjected to air leakage testing at pressure differentials from 50 to 1,000 pascals. Measurements of airflow were made and evidence of failure of the barrier due to pressure loading was noted. Leakage rates for the header detail with the POLY, EASE and ADA panels were 24%, 18% and 10% respectively of that for the reference panel. For the electrical outlet joint, leakage rates for POLY and EASE panels were 24% and 36%, while the ADA panel had higher leakage rates than the traditional panel. For the window detail, leakage rates were lowest for the ADA panel and similar for the POLY and EASE panels; all were less than 15% that of traditional panels.

50. CMHC research project: Testing of air barriers construction details. 1991. Ottawa, Canada: Canada Mortgage and Housing Corp.

This project was conducted to quantify the air leakage characteristics of the header joist, the electric outlets, and the window openings in wood-frame walls. The study evaluated the sealed internal membrane method, where polyethylene sheet and sealant provide the air barrier; the external air barrier method, which uses a continuous vapor permeable membrane (spun-bonded olefin film), sandwiched between two layers of external wall sheathing; and the airtight drywall method, where the interior gypsum board finish, together with framing materials and gaskets, are used as the air barrier. In addition, the traditional approach to wood-frame wall construction, where no special attention is given to achieving a continuous air barrier, was evaluated for comparison.

51. CMHC research project: Testing of air barrier construction details II. 1993. Ottawa, Canada: Canada Mortgage and Housing Corp. March.

Air leakage control through the building envelope of wood framed houses is more important than ever. This is because owners expect better temperature control, higher indoor humidity in winter, low energy consumption and building durability. The leakage of air is controlled by the air barrier system. There are several new technologies to construct an air barrier system for the building envelope. These

are the Poly Approach, the Air Drywall Approach (ADA) and the EASE system. Primarily the building community without significant research and development undertook the development of these systems. While it is believed that these methods improve airtightness it is not known if the improvement is marginal or significant. A study was conducted to determine actual performance of several different types of construction details for each of the different approaches. Each of these details was designed and constructed using one of the air barrier methods and tested in the laboratory. The test details included sill plate, the partition wall, the stair stringer, the electrical outlets, the bathtub detail, the plumbing stack detail, the metal chimney detail, the bathroom fan detail and the EASE wall system. The test results revealed that the Poly, ADA and EASE approaches reduce air leakage by a factor of six, if applied with a modest degree of workmanship. Further, certain Poly details are to be reconsidered because they lack adequate support against design wind load pressures.

52. Colantonio, Antonio. *Air-Leakage Effects on Stone Cladding Panels Public Works and Government Services.* Ottawa, Canada: Thermo sense XVII: An International Conference on Thermal Sensing and Imaging Diagnostic Applications.

This paper looks at the effects of air leakage on insulated stone clad pre cast panels used in present day construction of large commercial buildings. The building investigated was a newly built twenty-story office building in a high-density urban setting. Air leakage was suspected as a possible cause for thermal comfort complaints at isolated locations within the perimeter zones of the building. During the warrantee period the building owner asked for a quality control inspection of the air barrier assembly of the building envelope. Infrared thermography was used to locate areas of suspected air leakage within the building envelope. In order to differentiate thermal patterns produced by air leakage, conduction and convection as well as radiation from external sources, the building was inspected from the exterior; (1) after being pressurized for three hours, (2) one hour after the building was depressurized and (3) two and a half hours after total building depressurization was maintained by the building mechanical systems. Thermal images from similar locations were correlated for each time and pressure setting to verify air leakage locations within the building envelope. Areas exhibiting air leakage were identified and contractors were requested to carry out the necessary repairs. The pressure differential across the building envelope needs to be known in order to properly carry out an inspection to identify all locations of air leakage within a building envelope. As well the direction of the air movement and the density of the cladding material need to be accounted for in the proper inspection of these types of wall assemblies.

53. Colantonio, Antonio. 1999. *Identification of Convective Heat Loss on Exterior Cavity Wall Assemblies*. Quebec, Canada: Conference Title: Proceedings of the 1999 Thermosense XXI Conference, Orlando, FL

Most present day low and medium rise buildings constructed in Canada use some form of cavity wall design for their exterior walls. These types of wall assemblies use a broad range of cladding materials such as brick, stone, wood, sheet metal, porcelain enamel or metal panels, cementitious materials and plastics. The interior assemblies of these walls include the air barrier, vapor barrier and insulation layers. The cladding is separated from the interior wall assembly by an air space of varying thickness. Dependent upon the temperature differential between the interior and exterior, the temperature between the outer surface of the interior wall assembly and the inner surface of the exterior cladding under conditions in which air movement is restricted will give rise to convective heat loss mechanisms. This paper will look at how these convective heat loss patterns manifest themselves as thermal patterns on exterior surfaces of cladding materials. Similar details will be illustrated under various pressure differential conditions through the entire building envelope assembly. Various types of exterior wall assemblies will be discussed.

54. *Commissionable air barrier system for the building envelope*. Ottawa, Canada: Canada Mortgage & Housing Corporation; Housing Innovation Division.

This report explains and illustrates the steps to be taken to design, construct, and commission the air barrier system of a building envelope. The introduction explains the cause & effect of uncontrolled leakage and reasons why some buildings do not perform as expected, and proposes a conceptual approach for developing a commissionable air barrier system. Part 2 discusses performance requirements of air leakage control and proposes requirements for use in engineering the air barrier system. Part 3 explains and illustrates a design procedure to account & certify the feasibility of the air barrier system design, a construction method to incorporate the air barrier system technology and progress review & testing, and a method of commissioning the air barrier system. Part 4 is a conceptual plan for a manual that describes the system, explains monitoring & testing, and suggests maintenance where required. Part 5 reviews the current situation, how to attain a commissionable air barrier system, and areas of research & development to improve knowledge & skill in providing performing & durable air barrier systems.

55. *Comparison of airtightness retesting results*. 1988. Ottawa, Canada: Buchan, Lawton, Parent Ltd., Energy, Mines and Resources. P. 15.

Polyethylene vapor barrier and airtight drywall are two methods used by the building industry to reduce air leakage in residential homes. Concern has been expressed that polyethylene air/vapor barriers degrade over time. This concern has led various agencies to test and retest homes for air leakage. This report is the compilation of the data collected as a result of that testing. Raw data were collected on 145 homes from various sources. Data were screened and the tests of homes were omitted from the analysis if, the fan tests were done on the same house by different firms, if the construction of the house was not sufficiently complete, or if the initial air change rate per hour (ACH) was greater than 3. With these omissions from the database, 90 homes remained to be analyzed. The 90 homes were separated into two groups, those with an initial ACH less than 1.5 and those with an initial ACH in two tables which included the ACH, the time in months, the percentage change, and the difference in change between the first test and each subsequent test. These data indicate a relatively minor average change in airtightness. Keeping in mind the quantity of data collected and the time period examined, there is no indication that significant problems exist that would necessitate a change to the current building practice.

56. Condren, S. J. 1982. *Vapor Retarders in Roofing Systems: When Are They Necessary?* ASTM Conference: Moisture Migration in Buildings. Conference Location: Philadelphia, PA

57. *Consumer's guide: Keeping the Heat*. 1994. Ottawa, Canada: Natural Resources Canada; February.

A guide is presented to aid in retrofitting houses with insulation, caulking, and weather-stripping, and other improvements to help reduce heat losses and conserve energy. After an introduction on the fundamentals of air, heat, and moisture flow within houses and the house as a system, materials used for insulation, air barriers, and vapor barriers are described. Health and safety considerations regarding use of these materials are indicated. Directions are then provided on comprehensive air leakage control, on installation of insulation in roofs, attics, basements, and walls, and on upgrading of windows and doors. Recommendations are given for operating the heating system, ventilation system, and other features (such as heat recovery systems) for maximum energy efficiency.

58. *Controlling Internal Moisture Problems in the Home*. 1984. Cooperative Extension Service, Clemson University.

59. *Controlling Moisture in the Roof Cavities of Manufactured Housing*. 1992. U.S. Department of Commerce. National Institute of Standards and Technology. (NISTIR 4916)

60. *Controlling Moisture in the Walls of Manufactured Housing*. 1992. U.S. Department of Commerce. National Institute of Standards and Technology. (NISTIR 4981)

61. Cromer, C. J. *Instrumentation for Side-by-Side Testing of the Energy Attributes of Mobile Homes.* Cape Canaveral, FL: Florida Solar Energy Center; Residential Conservation Demonstration Program.

Two 14 x 70 ft (nominal) mobile homes located at Tallahassee, Florida Have been monitored for energy use on a side-by-side basis. One home had typical HUD approved insulation values: (1) R-7 in the walls, (2) R-11 in the floor, (3) R-14 in the roof and, (4) insulated doors. The second home had: (1) R-13 in the walls (increase of R-6), (2), R-18 in the floor, (3) R-22 in the roof, (4) insulated door, (5) storm windows (increase of R-16), (6) air infiltration barrier in the walls, and (7) an additional R-7 hot water tank insulating jacket. The second home had a smaller capacity refrigerator (14.1 cu. ft.), while the first home had a refrigerator of 15cubic feet. Each home's energy use was monitored by individual kWh meters in four power consumption circuits: (1) heat/AC, (2) refrigerator, (3) hot water and, (4) lights/range. A kWh meter separately monitored the power usage of all instrumentation. The homes were unoccupied, but occupancy is simulated in each home by a microcomputer system that switched the lights and range and drew hot water such that occupancy usage is identical for both homes. Internal loads similar to those created by a family of four were simulated. The microcomputer also monitored kWh, Btu and gallon use and the seconds the exterior doors are open. Results after one year indicate a measured reduction in energy consumption of approximately 10% in the extra-insulated mobile home. This provides a straight payback for the total energy package of 4.1 years. However, the additional infiltration barrier in the walls provided no reduction in air infiltration. If this costly and apparently ineffective option is removed from the energy package, the straight payback becomes about 2.5years. Actual consumption data, separate component analysis, and a completed prescription of instrumentation and method are provided along with the software developed for the microprocessor.

62. Cummings, J.B., P.W. Fairey, C.A. Gaston, E. Gordon, B.B. Mckendry, N.N. Moyer, and C.R Withers. 1996. *Field Measurement of Uncontrolled Airflow and Depressurization in Restaurants*. Cocoa, FL: Florida Solar Energy Center; (ASHRAE.) 102 (p.1) 859-869.

Field investigations were done in seven restaurants (sub-sample of a study of 63 commercial buildings) to identify uncontrolled airflows and pressure imbalances. Testing included building airtightness tests, identification of building air barrier locations, duct system airtightness, characterization of pressure differentials, building airflow balance, and infiltration/ventilation rates. All restaurants were found to operate at negative pressures that ranged from -0.003 in. w.c. (-0.8 Pa) to -0.173 in.w.c. (-43 Pa) and averaged -0.051 in. w.c. (-12.7 Pa) under normal operation. The variables that affect depressurization are large exhaust fans, missing or undersized make up air, intermittent outdoor air caused by the cycling of air handlers, dirty outdoor air and make up air filters, and building airtightness. These uncontrolled airflows and pressure imbalances impact energy use, ventilation rates, sizing of heating and air-conditioning systems, indoor comfort, relative humidity, moisture damage to building materials, mold and mildew growth, operation of combustion equipment, and indoor air quality.

63. Curtis, F.A., J.W. Evans, and R.E. Mellin. 1982. *Greenhomes: Passively Ventilated Energy Efficient Houses*. Winnipeg, Canada: The Solar Energy Society of Canada Incorporated.

Dogma defines super-insulated houses as those with: very high levels of insulation, very tight vapor and air infiltration barriers located on or towards the inside surface of the insulation, and an air to air heat exchanger for maintaining air quality, reducing moisture levels within the house, and recovering heat from exhaust air in the process of ventilation. Theoretical studies and experience with the performance of the Newfoundland greenhome lead us to make two proposals. First, super insulated houses can be passively ventilated without significant loss of thermal efficiency. Second, the very tight air-vapor barrier is unnecessary if a windscreen, in the form of a greenhouse, is placed on the outside of the building. A "green home" is a super-insulated house surrounded by a greenhouse. The greenhouse not only eliminates the wind pressure on the house but also elevates the temperatures of the air around the house. By venting interior air out of a chimney a slight negative pressure is created within the house, this encourages fresh prewarmed air from the greenhouse to infiltrate into the house. The rate of infiltration can be controlled by controlling the rate of venting.

64. Dale, J.D. 1987. *Better Home Comfort Saving Energy and Money with Better Home Design.* . Affiliation: Univ. of Alberta C.G.A. 1987 Marketing Conference. Corporate Source: Canadian Gas Association, Don Mills, Ontario, Edmonton, Canada Conference Date: 18 Oct 1987 p 42

Field experiments are described which were conducted at a test facility in Alberta having six electrically heated houses with various levels of insulation and other energy conserving measures. It was found that increased insulation levels decreased the heating energy requirements, although the savings from one level to the next were not as large as one might expect. Basement heat losses can be 30-40% of total losses, for uninsulated basements, and air infiltration accounts for 20-35% of total losses in uninhabited houses. Furnace flues were found to be the dominant factor in air leakage. Careful, expensive air/vapor barrier installation methods did not significantly improve airtightness compared with more conventional methods. To utilize passive solar gains properly, well-sealing insulating shutters are necessary. Good agreement was obtained between field and laboratory seasonal efficiency ratings of natural gas furnaces. To present the energy conservation results in a more meaningful manner, the results on potential energy savings were scaled to typical full-size houses. Four designs were compared, ranging from one with minimal levels of insulation and other features to a super insulated house with tight construction, heat recovery ventilation, multiple glazed windows, and a high efficiency furnace. Two locations were used, Edmonton and Toronto. Economic analysis showed that for current costs of construction, equipment and energy, the more advanced designs are not necessarily a good investment, the payback period being more than 8 years. A compromise is recommended to trade off increased construction costs against money saved through reduced energy consumption.

65. Department of Housing and Urban Development. 1998. Manufactured Housing and Standards Division and The National Conference of States on Building Codes and Standard: The Essentials of Moisture Control Through a Building Envelope. Washington, D.C.: U.S., February.

66. Derome, Dominique and Paul Fazio. Large-scale Testing of Two Flat Roof Assemblies Insulated with Cellulose.

A laboratory test using a large-scale environmental chamber has been carried out on two flat roof models fully insulated with cellulose fiber. These two models represent the most representative single-cavity flat roofs, built in Montreal between 1930 and 1970, being insulated as part of an energy conservation program. The insulating strategy consists of packing cellulose fiber in the cavity. The goal of the test program was to determine the risk of rotting of the wood structure and moisture accumulation in the roof assembly. The test was performed using real-scale huts that were exposed to 6 months of winter and summer conditions. Two roof assemblies were each divided into five roof cavities. The main variables were the mode of moisture transfer (diffusion only and diffusion combined with air exfiltration), type of vapor barrier, and air leakage paths. The construction of the huts and the monitoring plan are described. The results of the 6-month test program using seven simulated climatic conditions are presented. Wetting and drying curves for different parts of the assemblies as well as the levels of exposure to moisture are presented and analyzed.

67. *Design Aspects Of Cold Stores*. New Zealand: Meat Industry Research Institute of New Zealand, Process Technology Division; Transactions of the Institution of Professional Engineers New Zealand; Electrical/Mechanical/Chemical Engineering Section v 12 n 3 Nov 1985 p 139-146.

The importance of cold stores for New Zealand's food exports is discussed and various design criteria are specified. Construction methods are reviewed, including both traditional separate insulation/vapor barrier systems and modern metal-sheathed cellular foam plastic panels. Air infiltration through open doors is a major factor in the design, operation and performance of cold stores; yet infiltration is difficult to predict. Using tracer gas techniques test results are given for infiltration rate sunder a variety of conditions. From these results, good estimates can be made of the refrigeration loads generated by air infiltration.

68. *Design and performance of walls with SPF*. 1998. Journal of Thermal Insulation and Building Envelopes.

The design and performance of an SPF wall as an air barrier. Systems were evaluated when applied to two popular systems, namely, fiberboard sheathing covered with a spun bonded olefin (SBO) and strapping, and gypsum with finished joints. The SPF wall was evaluated based on the air leakage of the air tightness plane, barrier continuity, structural design, and materials standards. 5/7/33 (Item

69. Desmond, R.M., D.T. Grimsrud, and F.J. Offermann. *Residential Air Leakage and Indoor Air Quality in Rochester.* New York. Berkeley, CA: California University; Lawrence Berkeley Lab.

A sample of 58 occupied homes in Rochester, New York, most of which incorporated special builder-designed weatherization components, were studied to assess (1) the effectiveness of construction techniques designed to reduce air leakage; (2) the indoor air quality and air-exchange rates in elected tight houses; and (3) the impact on indoor air quality of mechanical ventilation systems employing air-to-air heat exchangers. The specific leakage area was measured in each house using the fan pressurization technique. Houses built with polyethylene vapor barriers and joint-sealing were as a group 505 tighter and had a 30% lower over all average heat loss coefficient (W/ exp 0 C-m exp 2) than a similar group of houses without such components. Mechanical ventilation systems with air-to-air heat exchangers were installed in nine relatively tight houses, some of which had gas stoves and/or tobacco-smoking occupants. Air-exchange rates and indoor concentrations of radon (Rn), formaldehyde (HCHO), nitrogen dioxide (NO_2), and humidity, were measured in each house for one-week periods with and without mechanical ventilation. More detail and measurements including concentrations of carbon monoxide, and inhalable particulates were made in two of these houses by a mobile laboratory. In all nine houses, air-exchange rates were relatively low

70. Diamond, R. C., J.B. Dickinson, and R.D. Lipschutz. *Infiltration and Leakage Measurements in New Houses Incorporating Energy-Efficient Features*. Berkeley, CA: California University; Lawrence Berkeley Lab.

In order to increase energy efficiency in new residential housing, building contractors are using a number of recently developed infiltration-reducing construction techniques. One of these techniques is the installation of a continuous vapor barrier. A second technique is the selective sealing of infiltration sites with polymeric foam caulk following completion of the rough framing of a house. Measurements of leakage areas and infiltration rates in houses incorporating such energy-conserving measures can provide important information about their effectiveness. Houses with energy efficient designs in Eugene, Oregon and Rochester, New York were measured for effective leakage area using blower door fan pressurization. Air exchange rates were determined by tracer gas decay analysis. Fan pressurization measurements were made on 13 new houses in the San Francisco Bay area that had been partially sealed with polymeric foam sealant. A similar group of 13 new houses that had not been sealed were measured as controls. The results of these measurements were used in conjunction with an infiltration model developed at Lawrence Berkeley Laboratory to predict average annual and heating season infiltration rates. Specific leakage areas (leakage area per unit floor area) for the Eugene uses averaged 45% of that measured in post-1975 California housing. The energy-efficient Rochester houses were found to be 50% tighter (in terms of specific leakage area) than their non-energy efficient counterparts in the same area. Excluding leakage in the heating duct system, the average specific leakage area (leakage area per unit floor area) of the houses sealed with polymeric foam was 3.4 cm exp 2 /m exp 2 (s.d. = 0.7) while the control group averaged 4.2 cm exp 2 /m exp 2 (s.d. = 1.1), a 19% difference. This difference was found to be statistically significant at the 95% confidence level.

71. Di Lenardo, B. 1999. *Performance Assessment of Air Barrier Systems*. Ottawa, Canada: National Research Council of Canada.

This paper outlines the expected air leakage performances of air barrier systems, which has no correlation to whole-house; air leakage values, but instead examines the airflow through the air barrier materials within the insulated portion of a wall. As the 1995 National Building Code of Canada (NBCC) requires that air barrier systems be installed in buildings to control air leakage and certain requirements have to be met, the Canadian Construction Materials Centre (CCMC) developed a technical guide outlining required system air leakage performance and test protocol to determine if compliance has been achieved. CCMC evaluates proprietary air barrier systems at the request of the building sector. Testing covers structural capacity, deflection requirements and durability of air barrier systems. Materials used in a system must be installed properly in the field so that they perform as evaluated in order to meet the requirements of the NBCC.

72. Dixon, R., and H.A. Ingley. 1981. Investigation of Mobile Homes for Air Conditioning and Heating Performance: Evaluation of Zone 1 Mobile Home Thermal Envelopes. Gainesville, FL: Florida University; Solar Energy Lab.

This report presents an evaluation of Zone 1 full - size mobile home winter - spring thermal envelopes. The task involved an experimental analysis of day and night thermal performance evaluation of these homes for compliance with HUD Mobile Home Standards Subparts F and H '3'. Existing instrumentation installed in the two HUD - provided mobile homes was modified in order to conduct winter - spring testing on the mobile homes' furnace air delivery, fuel supply, and thermal envelope. The experimental parameters manifested during this phase included climate conditions; interior temperatures; interior humidity; heat flow through walls, ceiling, and floor; condensation in the internal structure; infiltration rates; and energy consumption of the heating equipment. These data were subsequently used to analyze the thermal performance of the mobile home envelope and the energy consumption associated with conditioning the interior space. Also presented are the results of an evaluation of the effects of improved insulation and vapor barrier strategies on thermal performance and condensation, the impact of transportation on thermal performance, and evaluations of four selected shading devices.

73. Dumont, R.S. and H.W. Orr. 1987. *A Major Energy Conservation Retrofit of a Bungalow*. Saskatoon, Canada: National Research Council of Canada; Institute for Research in Construction. p 44.

Construction details are presented for a major energy conservation retrofit of a bungalow. The procedure involved the addition of a well sealed air-vapor barrier to the exterior walls and roof of the house and addition of about 300 mm of glass fibre batt insulation. Insulation was also added to the interior of the basement walls and an additional layer of glass was added to each window. The air leakage of the house as measured by pressure tests was reduced from 2.95 air changes per hour at 50 pascals to 0.29 at 50 pascals, a reduction of 90.1%. Before and after measurements were taken of the space heating requirements of the house. The design heat loss of the house was reduced from 13.1 kW at -34^0 C to 5.45 kW by the retrofit. As the retrofit procedure involved major alterations to the entire envelope of the structure, costs for the total retrofit were high. The total cost for the project, which included upgrading the shingles and the stucco on the house, was $23,700 in 1984 dollars. The energy conservation related costs were $17,200.

74. Dumont, R.S. 1994. *An Overview of Insulation and Airtightness in Wood Frame Construction*. Ottawa, Canada: Innovations technology. Resources, Canada.

The most common framing technique for North American wood frame houses was the use of 2x4-in. studs on 16-in. centers with R12 insulation in the cavity. Since 1975, a number of different wall systems have been developed incorporating improved insulation levels and improved airtightness. A technique using 2x6 studs spaced 24 in. Apart minimizes the use of wood and increases the amount of insulation. Variations on the 2x6 wall include the use of exterior insulating boards and the use of

horizontal 2x3 strapping on the inside of the wall with a vapor barrier sandwiched between. This latter technique allows two parallel walls to be built, with wiring on the warm side of the vapor barrier thus reducing air leakage. Below grade, insulation is now commonly installed on the exterior and/or interior of a concrete basement wall. Air leakage in wood frame houses has been found to be greatest between the intersection and the interface of building components, such as wall-floor intersections. Two major approaches are used to control air leakage: polyethylene vapor barriers and solid-material air barriers (also called the airtight drywall approach). Improved sealing techniques have been developed which can reduce leakage to less than 1 air change per hour (ACH) at a 50-pascal pressure differential. Canadian R2000 houses commonly have airtightness levels below 1 ACH at 50 pascals.

75. Ellis, W. and T. Kusuda. *Vapor Condensation in Air-Pervious Insulation.* (Final report). Washington, D.C.: National Bureau of Standards.

Theoretical and experimental studies were conducted on moisture accumulation problems in air-pervious insulation subjected to a steep temperature gradient. The principal test wall studied was a wooden partition for a cold storage installation consisting of warm-side vapor barrier, six inches of fibrous glass insulation, and a one-inch fibrous-glass interior finish board. Experimental data indicated that moisture accumulation became serious only when the vapor barrier was punctured both at the top and bottom of the test wall, thus causing a convective air in-flow at the top and outflow at the bottom. The data further showed that with this type of leakage, most of the moisture accumulation occurred only at the top region of the wall. A small-scale apparatus was used to test the moisture accumulation and drying-out performance of tube-type specimens that represent a portion of an insulated exterior wall subjected to simultaneous flow of air, moisture, and heat. These test results show that a slight air pressure differential across the insulation has much stronger influence on the vapor condensation problem than the much higher water vapor pressure differential.

76. Elovit, Kenneth M. 1999. *Understanding What Humidity Does and Why*. ASHRAE Journal, Volume 41, No. 4, Pp 84–90, April.

77. Energy Conservation and House Basements: A. Review of the Effects of Energy Conservation Measures on Low-Rise Residential Basements. 1982. Toronto, Canada: Middleton Associates. p. 143. October.

This study examines techniques of saving energy in the construction and retrofitting of basements in low-rise residential buildings. The principal types of basement construction are reviewed with attention to inherent structural problems relevant to the installation of thermal insulation. The soil conditions can often threaten the long-term integrity of the basement. Once the insulation is placed adjacent to the basement walls, it can change the soil and water behavior and cause structural damage. The diverse techniques for installing basement insulation are examined, whether applied externally or internally, and their relative advantages and disadvantages are compared. The problems in installing vapor barriers are also described. A final section discusses the economics of basement installation. This section confirms the economic advantages of insulating basements, where the cost can be recuperated in 1.2 to 7.3 years, depending on the local climate, heating costs, and type of insulation installation. An annotated bibliography is included.

78. Energy Design Update: selected articles.

- *Air and Moisture Leakage Through Recessed Ceiling Light Fixtures*; January 1994.
- *Controlling Crawl Space Moisture- What Works and What Doesn't*; July 1991.
- *The Effect of Nail Holes and Other Defects on Vapor Retarder Performance*; August 1992.
- *The Effect of Vapor Retarders on Wall Drying Time*; September 1996.
- *Head-Scratcher of the Month- Housewrap-Induced Moisture Problems*; *August 1996.*

- *Moisture Accumulation in Walls Without Vapor Retarders*; May 1992.
- *Moisture Flow Through (and/or Around) Foam Basement Insulation*; April 1991.
- *Moisture Control in Attics*; November 1992.
- *Moisture Control in "Cathedralized" Attics and Cathedral Ceilings; September 1995.*
- *Mold and Mildew in Warm, Humid Climates*; February 1992.
- *On Outdoor Air for Moisture-Control Ventilation*; November 1994.
- *The Reliability of Vapor Barrier Paints*; May 1995.
- *R-Value of Moist Cellulose Insulation*; May 1992.
- *"Smart" Vapor Retarder Can Change Its Permeability*; February 1999.
- Studies Cite Rain Penetration as Significant Moisture Source in Wood Walls; December 1990.
- *Weighing Hygrothermal Design Strategies for Steel-Framed Homes (Part 2)*; January 2000.

79. *Energy Efficient Housing - a Prairie Approach.* 1980. Saskatoon Canada: Saskatchewan University, Dept. of. Mechanical Engineering. p. 31.

This booklet provides information on a number of practical measures that can be undertaken to conserve energy in houses in the Canadian prairie provinces. It concentrates on improving air tightness, insulation, and passive solar gain, showing how it is possible to reduce average space heating requirements by 90%. Diagrams and explanations are given on the installation of vapor barriers; sealing and weatherstripping; special procedures around doors, windows, vents, and chimneys; construction and installation techniques for insulation of walls, roofs, and floors; utilizing south-facing windows for maximum solar gains; and retrofitting insulation on to exterior walls. Other topics more briefly described are energy-efficient water heating and energy conservation through optimum usage of electricity.

80. Ferrante, Vic, Siavash Fravardin, et. al. 1998. *The Essentials of Moisture Control*. Manufactured Housing and Standards division; Office of Consumer and Regulatory affairs; Dept. of Housing and Urban Development, February 27.

81. Field Performance of Energy-Efficient Residential Building Envelope Systems. 1992. Ottawa, Canada: Unies Ltd.

The airtightness of 24 new houses was measured on a regular basis over periods of up to three years to evaluate the structures' air barrier systems and to study the possibility of air barrier degradation, as would be indicated by an increase in the measured air leakage rate. Ten of the houses were built with the polyethylene air barrier system and 14 using an early version of the airtight drywall approach (ADA). The 24 project houses were architecturally similar and of approximately equal size and general layout; stucco was the predominate wall finish.

82. Flanders, Stephen N., James A. Rioux, and Grenville K Yuill,. 1997. *Impact of Changes to Building Air Tightness on HVAC costs*. College, PA: Pennsylvania State University, Journal of Architectural Engineering. p. 164-169; December.

Air leakage is generally the most significant factor in small-building energy consumption. This study determined if reducing air leakage in pre engineered metal buildings would be cost-effective. The effects of air-retarder treatments on owning and operating costs were examined for two different sizes of buildings that were thermally modeled using a building energy analysis computer program, BLAST. The annual energy consumption and peak loads were then produced by BLAST to find the fuel consumption for each building and the system sizes needed for adequate climate control. A detailed cost estimate was done on the mechanical system based on the required equipment size for each air-retarder treatment used. Life-cycle costs were determined for two types of air retarder and one case without an air retarder at four locations in cold and hot climates, and for five air exchange rates. A payback analysis illustrated the cost-effectiveness of the air-retarder treatments. Both air-retarder treatments proved cost-effective for both buildings. They provide immediate savings in system first cost because of the reduction in heating, ventilating, and air conditioning (HVAC) system size, as well as long-term energy and operation cost savings. Furthermore, even if the HVAC system size was not reduced, use of air retarders still had a short payback period in both warm and cold climates.

83. Fowler, C. S., S.E. McDonough, D.C. Sanchez, and A.D. Williamson. July 1993-August 1994. *Recommended Standards and Practices for Radon Resistant Passive Construction in Slab-on-Grade Houses*. Birmingham, AL: Prepared for Southern Research Institute.

The paper gives results of a study to evaluate the effectiveness of the features of a draft standard (developed by the State of Florida) for controlling radon entry in new houses built over relatively high radon potential soils. Special attention was given to foundation preparations and lab placements to ensure that the draft standard requirements were being met and to identify areas or practices that would assist in achieving the desired results. The combination of using a high-range water-reducing and mixture in the concrete mix, slab reinforcement at re-entrant corners and around large work spaces, and such prescribed activities as vapor barrier and slab penetration sealing performed well in achieving the objective. Recommendations are made for more specific code language and guidance. 5/7/9 (Item 9 from file: 6)

84. *ASHRAE Fundamentals Handbook*. 1997. ASHRAE, (chapters 22-25).

85. Garst, Mike. 1998. *Are Your Customers Comfortable? Issues in Dealing with Humidity Control*. Lennox Industries, Inc. Air Conditioning, & Refrigeration News, January.

86. Goodrow, J.T., D.C. Jones, and D.G. Ober. Thermal Performance Characterization of Residential Wall Systems Using a Calibrated Hot Box with Airflow Induced by Differential Pressures. Cambridge, MA: Holometrix, Inc.

ASTM E 283 ad ASTM E 1424 in conjunction with ASTM C 976 were used to study the effect of airflow on thermal performance of the wall. A typical residential 2×4 stud wall was constructed and placed on top of a sub floor, making a 2.44×2.74 m (8 by 9 ft) test specimen. This base wall assembly was then covered with two types of XPS sheathing, various house wraps, a 15# felt, and a polyethylene vapor retarder film in 40 different configurations and tested individually per ASTM E 283 and per ASTM C 976. For 24 of the 40 C 976 tests, a differential pressure was induced across the test wall as per and ASTM E 1424. Airflows ranged from undetectable airflow at 0·Pa ΔP to 1.63 L/s m^2 for the base wall assembly alone. Difference in airflow resistance performance between the ASTM E 283 and ASTM E 1424 test methods were noted. Thermal testing results incorporating both ASTM C 976 and ASTM E 1424 for tests 1--28 produced apparent thermal conductance’s (C-values) in the range of 0.40 $W/m^2 \cdot K$ for a undetectable airflow level to 1.81 W/m^2 K for an airflow of 1.53 L/s m^2 for the base wall assembly alone with a 20-Pa Δ P. The calculated C-value for this base wall assembly was 0.40 W/m^2 K. Test results reveal that airflow rates as low as 0.2 L/s m^2 could produce a 46% increase in apparent C-value. Similar thermal performance differences were revealed when thicker shiplap XPS sheathing was used. Tests were also conducted using an Air-Tight Drywall configuration showing the effect of wind washing on thermal performance. By sealing the gypsum drywall on the base wall assembly tested, the apparent C-value, when exposed to a 12.5 Pa wind pressure, was found to be equivalent to a base wall assembly configuration which allows 0.15 $L/s \times m^2$ airflow to 5/7/75.

87. Hagan, D.A. and R.F. Jones. 1982. *Thermal Performance of the Blouin Super Insulated House*. Architectural and Building Systems Division, Brookhaven National Laboratory, Upton, NY. ASHRAE, Atlanta, GA.

An evaluation of the design and thermal performance of a superinsulated residence in South Royalton, VT, is made. Data were acquired by a Solar Energy Research Institute (SERI) Class B monitoring system during 60 days of March, April, and May of 1982. In addition, air infiltration is measured using the fan pressurization technique, and effectiveness of the air-to-air heat exchanger is analyzed. The house design is a copy of the colonial "saltbox". Included are R-40 (RSI-7.2) walls, R-57 (RSI-10.0) ceiling, R-25 (RSI-4.5) pressure-treated wood basement walls, R-9 (RSI-1.5) sliding window shutters, a caulked polyethylene vapor barrier, and a site-built air-to-air heat exchanger. Reported on are the data acquired and an analysis of the thermal performance based on these results. Several possible modifications to the building design are suggested. It is concluded that the measured building thermal parameters are within acceptable error bounds of the calculated values.

88. Hagentoft, C.E.; E Harderup. 1996. Moisture Conditions in a North-Facing Wall with Cellulose Loose Fill Insulation Constructions with and without Vapor Retarder and Air Leakage. Goteborg, Sweden: Chalmers University of Technology, Journal of Thermal Insulation and Building Envelopes, p 228-243.

This paper presents calculated moisture conditions of a wall exposed to a climate equivalent to the North of Sweden. A north facing timber wall with a brick facade and cellulose loose fill thermal insulation is studied both with and without vapor retarder and air leakage. If the vapor retarder is eliminated from the construction, the moisture levels will increase to unacceptable high values. The construction becomes sensitive to the choice of facing materials and the indoor moisture supply. Air leakage carrying moist air into the construction leads to unacceptably high values even for moderate indoor moisture supplies.

89. *Heat and Moisture Transfer in Wood-Based Wall Construction: Measured Versus Predicted*. 1995. U.S. Department of Commerce. National Institute of Standards and Technology. (NIST Building Science Series 173).

90. Hendricks, L.T. *Stop Energy Loss and Moisture Build-Up Cold.* St. Paul, MN: Univ. of Minnesota. Home Energy. Jul-Aug 1991 p 14-20

With the advent of tight and even super tight homes in the quest for energy efficiency have come new concerns about side effects not experienced in the past. Air barriers, while a crucial factor in the heating efficiency of a house, need to be part of a thoughtful strategy that will take other factors into account, like vapor movement. Put differently, while air infiltration is commonly considered an energy problem, ex-filtration of humid air is a materials and structural threat. And because the problems that architects and builders encounter in cold climates are often just exaggerated versions of similar problems found in milder climates, the solutions discussed here may be useful in milder regions as well. This article briefly describes some aspects of utilizing cold climate air sealing techniques and materials. Techniques for sealing walls include two that use polyethylene (poly), and a third utilizing the wall itself as a barrier. Wind barriers and ceiling barriers are also discussed.

91. Henning, G. N. 1983. Energy Conservation with Air Infiltration Barriers.

92. Hildebrand, G. Development of Test Procedures and Methods to Evaluate Air Barrier Membranes for Masonry Walls. Ottawa, Canada: Canada Mortgage and Housing Corporation; Project Implementation Division.

Investigation of 15 'as installed' air barrier systems for initial air leakage, membrane adhesion under gust wind load and sustained wind load, membrane performance under stack effect (creep) load, membrane uniformity, and prescriptive data. The project was carried out in two phases; with phase I evaluating nine air barrier membranes (23 block wall substrates) and phrase II evaluating six air barrier membranes (15 block wall substrates) and a blank block wall (no membrane).

93. Hintenlang, D.E., F.T. Najafi, E.C. Roessler, and A. Shanker. 1994. *Evaluation of Building Design, Construction, and Performance for the Control of Radon in Florida Houses*. Gainesville, FL.: Florida University; Dept. of Nuclear Engineering Sciences.

The report gives results of a study of eight houses throughout their construction in North Central Florida. Each house was built in compliance with the proposed radon resistant construction standard being developed by the Florida Department of Community Affairs. Each house was monitored for at least 6 days after construction, operating in three different heating ventilation, and air-conditioning (HVAC) system configurations. Continuous measurements of indoor radon concentrations, house ventilation rates, cross-slab differential pressures, and interzone differential pressures provided time-resolved radon entry rates and a performance index for passive radon barriers. Radon entry rates were found to be relatively constant throughout the measurement periods and for the different house operating conditions, implying that the passive radon barrier eliminates most convective entry.

94. Hollowell, C.D., F.J. Offermann, (Lawrence Berkeley Lab., CA), J.E. Rizzuto, G.D. Roseme. 1981. *Low-infiltration housing in Rochester, New York: a Study of Air Exchange Rates and Indoor Air Quality*. International symposium on indoor air pollution, health and energy conservation. Extended summaries.

The results of measurements of leakage area, air-exchange rate, and concentrations of Rn, NO_2, HCHO, and RH in the ten houses selected for a detailed study of indoor air quality are summarized. In the full sample of 60 houses, the specific leakage area varied from 1.3 to 9.0 cm/m^2. Of the 49 houses built by one of the builders, the 36 houses with special weatherization components, (e.g., polyethylene vapor barriers in the outside walls and sealing of all joints and electric outlets) had an average specific leakage area of 2.8 cm^2m^2 which is 35% lower than the 4.3 cm^2m^2 average measured in 13 similar houses without such components. The indoor concentrations of Rn, NO_2, HCHO, and RCHO measured during both ventilated and unventilated periods were below the various guidelines presently used to assess indoor air quality. (DT)

95. Hosni, Mohammad H., Jerry M. Sipes, and Michael H. Wallis. *Experimental Results for Diffusion and Infiltration of Moisture in Concrete Masonry Walls Exposed to Hot and Humid Climates*. Manhattan, KS: Kansas State University; ASHRAE Annual Meeting.

This paper presents experimental test results for heat and Moisture migration in walls exposed to hot and humid climates. The research was conducted to study the problem of mold and mildew caused by moisture transfer into walls of concrete masonry unit (CMU) type construction by diffusion and convective transport by air infiltration. This type of construction is common in commercial buildings in the southern United States. The tests were conducted in two phases. Phase 1 evaluated heat and moisture transfer by diffusion. Phase 2 testing involved air infiltration through the test walls. Data were also collected to determine the rate at which the test walls would dry out without infiltration present. Test results indicate that an exterior vapor retarder will reduce the moisture migration into the wall and thereby lower the moisture accumulation due to infiltration when a vapor retarder (such as vinyl wallpaper) is used for the interior surface treatment. Testing also showed that while the exterior wall treatment does have an effect on reducing the total moisture accumulation in the test walls, the interior wall treatment has a much larger impact when infiltration is present. The data support a proposed criterion for the onset of mold and mildew which requires a monthly average surface relative humidity of 80% with temperatures between 32 degree F and105 degree F (0 degree C and 40.6 degree C).

96. Howell, D.G., and W.J. Mayhew. 1987. *Energy Performance of Three Airtight Drywall Approach Houses*. Edmonton, Canada: Alberta Municipals.

The objective of this study was to assess a new construction technique, the Airtight Drywall Approach (ADA), as it was implemented in three test houses, and to compare the performance of these houses against three control houses typical of residential construction techniques in Alberta. The study focused on four aspects of house performance integrity of the air barrier system, energy conservation, ventilation, and indoor air quality, and the development and demonstration of computer-based field monitoring techniques. Data were gathered through continuous computer-based measurements, regular site visits, manual measurements, homeowner interviews, and special site tests. The results of the air-leakage tests indicated that ADA is an effective method of reducing air infiltration in homes. The floor joist sealing technique used in the ADA houses was observed to deteriorate within a year of construction. It is no longer recommended. The monitoring results showed a significant reduction in energy consumption in the homes with energy conservation features. Measurements of air-borne contaminants indicated that the ADA test homes performed similar to other energy-efficient homes monitored across Canada and that pollutant levels were within accepted guidelines.

97. Indoor swimming pools. Humidity Caused Problems and Suggested Solutions. 1989. Ottawa, Canada: National Research Council of Canada. p. 39.

Reports have been received from across Canada on premature deterioration and other problems of indoor swimming pool buildings. This technical paper has been prepared to assist pool managers to solve these problems, which typically include leaking roofs, condensation on inside walls, peeling paint, efflorescence, rusting of metal elements, deterioration of concrete block structures, and high costs for pool heating. An effective insulation and vapor barrier system for a swimming pool roof is described, and the high relative humidity of the typical pool building is discussed as the primary cause of most problems. Proper sealing to cut down air infiltration is recommended, along with proper maintenance and painting. High-energy costs are often due to low insulation values and to excessive ventilation used for decreasing the humidity. By using dehumidifiers capable of heat recovery, and by placing an insulating blanket on the pool after operating hours, it is shown that substantial cost savings are possible.

98. *Indoor Ventilation Requirements for Manufactured Housing*. 1991. U.S. Department of Commerce. National Institute of Standards and Technology. (NISTIR 4574)

99. Ingham, L.A. 1983. *Solar-heated garage/workshop: Final technical report on a Renewables-Conservation Demonstration Program*. Regina, SK (Canada); Saskatchewan Dept. of Energy and Mines; Department of Energy, Mines and Resources, Ottawa, ON (Canada.) 1 Mar (84 p.)

A combination workshop-garage of about 600 ft.^{2} floor area, incorporating a solar heating system, was designed and constructed in Saskatchewan as part of a demonstration project to provide data on solar heating, high insulation levels, building sealing, and related topics. Calculations were made of such factors as available solar energy, heat losses, air infiltration, and performance of vapor barriers and insulation, in order to determine the feasibility of solar heating for the building. The building system was then designed and included a high degree of thermal insulation, multiple glazed windows, and forced cooled solar collector panels on the south and east walls. Construction details are provided of the various components of the building system. Monitoring equipment including temperature recorders and an airflow meter was installed to evaluate the building's performance. Typical solar collector efficiencies were found to range from 19% for the southwest collector to 56% for the southeast collector. For a 1-month test period in February 1982, 57% of the heating load was supplied by the solar heating system and the rest by an electric backup heating system. The actual solar heat collected was 54% of that expected from theoretical calculations. This low percentage is partly due to the inability of the collectors to turn on under low radiation levels, thus reducing the overall average efficiency. Other test results are also presented for such performance indicators as air infiltration, infrared heat loss, cooldown rate, and interior humidity.

100. Jackson, H.A., D.I Masse, and J.A. Munroe. *Air leakage through farm building envelopes in Eastern Ontario*. Ottawa, Canada: Agriculture Canada, Canadian Agricultural Engineering 36 3. July-Sep 1994. p 159-163.

Field study was conducted to measure air leakage in modern farm buildings of typical construction in order to evaluate the performance of their air barriers. A large capacity mobile fan was used to determine air leakage rates for inside-to-outside pressure differences of 10, 20, 40, 50, and 60 Pa. A total of 13 barns were tested including some built by owners and some built by contractors. Air leakage rates of 3 to 12 air changes per hour were measured at 15 Pa. These rates were much higher than those suggested using ASHRAE methodology. There was no apparent difference in air barrier performance according to being owner or contractor built.

101. Karagiozis, Achilles N. and Mikael H. Salonvaara. Hydrothermal Performance of EIFS-Clad walls: Effect of Vapor Diffusion and Air Leakage on the Drying of Construction Moisture. Ottawa, Canada: National Research Council Canada (NRC.)

A study was conducted to investigate the drying performance of a particular barrier exterior insulation and finish system (EIFS) clad wall as a function of vapor diffusion control with a specific air system also showed significant effect. The study was conducted with constant interior temperature and relative humidity. Results show that vapor control strategies are an important parameter dictating the drying performance of the barrier EIFS clad wall. Air leakage through the building walls

102. Katsnelson, Zinoviy, John Proctor, and Brad Wilson. 1995. *Bigger Is Not Better—Sizing Air Conditioners Properly*. Home Energy Magazine, Vol. 12, No. 3, pp. 19–26 (May/June).

103. Katzschner, L. 1997. *Planning Processes with Integrated Evaluation of Climate and Air.* Original Einbindung und Bewertung von Klima und Luft in Plannungsablaeufe. (Kassel Univ. (Gesamthochschule) (Germany). Raumforschung und Raumordnung v 55:1. p 59-68

More and more often, planning requires climate statements, which are suitable to be considered in the weighing of the different factors. The paper makes climate assessment proposals permitting a qualitative and quantitative judgment. Parameters employed are the physiologically equivalent temperature (PET) as well as, increasingly, statements regarding the quality of ventilation. Examples illustrate how space-related planning clues can be derived from climate function maps. The basis for this is climate-geographic surveys (orohydrographic analysis, topographic gradient determination etc.), as well as the analysis of dynamic parameters (air conduction paths and barriers) and thermal parameters (areas warming up excessively, areas of cold and fresh air generation). Linking of these aspects yields a climate function map. It is used to prepare a planning recommendations map, which differentiates and evaluates climate-ecological sensitivities. (Orig.) This issue of the journal is devoted entirely to papers dealing with various aspects of building envelope systems. The following is a list of the feature articles, with the names of authors in parenthesis: 'Building envelope restoration' (P. Wong); 'The case for building envelope repair costs' (T. Woods and B. Boyd); 'Details and execution: the road to quality air barriers' (T. Woods); 'Air barrier performance' (L. Shannon); 'Building envelope viewed as a system' (E.A. Armstrong); 'Sealing exterior insulation and finish system joints' (P. Daechsel); 'The evolution of building science' (B. Burton); 'Separation of environments : air barrier code changes' (B. Partridge).

104. Kim, Andrew K., and Chia Y. Shaw. *Seasonal Variation In Air Tightness Of Two Detached Houses. Measured Air Leakage of Buildings*. Ottawa, Canada: National Research Council; ASTM, Philadelphia, PA. P 17-32 986.

Fan pressurization tests on two unoccupied houses were conducted once every two weeks for a period of a year (May 1982 to July1983) to determine the seasonal variation in air tightness. Both houses are of insulated wood frame construction. House No. 1 was built with more insulation than is required by the local building code, and a polyethylene vapor barrier was applied with special care to improve its air tightness. House No. 2, a less airtight house, was built with various wall construction features and a polyethylene vapor barrier in only two walls. Indoor relative humidity, indoor and outdoor air temperatures, and moisture content of the stud and top plates of the wood framing were measured at the time of air tightness testing to determine whether a correlation exists between these factors and house air tightness.

105. Knight, K., and J. Sharp. 1997. Prescriptive Testing of Air Barrier System Performance. Canada.

Provisions of the 1995 National Building Code of Canada regarding air leakage were discussed. The discussion was motivated by the recognition that air leakage is an important contributor both to premature deterioration of the building envelope and space conditioning energy requirements. Air tightness of the existing building stock was compared to the maximum air leakage recommendations of the Code. Problems that may arise in testing and inspection of air tightness of masonry ties were examined and the potential improvement in the air tightness of air barrier membrane systems at masonry ties, resulting from rigorous testing and inspection were evaluated. Quantitative air tightness test results demonstrated that a large difference exists between the air tightness of the existing building stock and recommended maximum leakage rates in the National Building Code. However, laboratory testing of air barrier system components indicate that the Code recommendations are achievable, provided that quality in design detailing, material selection and workmanship are maintained at a high level.

106. Kohonen, R.O. and T. Ojanen. 1995. *Hygrothermal Performance Analysis of Wind Barrier Structures*. Espoo, Finland: VTT Building Technology; ASHRAE transactions, Volume 101, p 595-606 (1517 p.)

Wind barriers are used in structures that have air-permeable thermal insulation materials. Their main function is to prevent the pressure differences from causing airflow-related heat loss through the building envelope. Wind barriers should not contribute to moisture problems in structures by causing condensation or moisture accumulation. This paper presents requirements for the air tightness of wind barriers and results of the hydrothermal analysis of wind barrier structures. The studied wind barrier structures were typical for small houses in Finland--timber-framed structures with lightweight glass wool thermal insulation. The air permeances and the parameter sensitivities were studied numerically both for ideal and non-ideal structures. In ideal structures, the material layers were assumed to be tightly (ideally) connected to each other, but in non-ideal structures. There were air leakage routes (air cracks) at the interphases of thermal insulation and adjacent material layers. The drying of moisture through different wind barriers was analyzed in laboratory experiments under boundary conditions similar to those in practice, e.g., with outdoor temperatures below and above 0 C. The measured moisture flows were compared with those derived from a wet-cup water vapor permeability test. Also, the liquid flow along the interface of the wind barrier and glass wool was studied in full-scale experiments with high moisture loads.

107. Leblanc, R. 1991. Air Tightness Tests on Components Used to Join Different or Similar Materials of the Building Envelope. St. Laurent, Canada: AIR-INS, Inc., September.

A study was conducted to verify the behavior of several connection techniques used between various air barrier elements, where the same connections are exposed simultaneously to extended pressure and temperature differentials reflecting those that may exist in the extreme conditions found in Canada. A total of 24 different sealing materials or assemblies were tested, including acrylic and silicone exterior or interior sealants, mineral wool, adhesive tape, closed-cell backer rods, gaskets, polyethylene, wood-urethane-aluminum, and various combinations of materials. The specimens were exposed to a pressure differential of 150 pascals during a continuous 5-month period, or until air tightness was lost. The test temperature was maintained at -20ºC, 20ºC, or 65ºC, depending on the nature of the system elements and on the position of the air barrier in the wall. It was observed that at -20ºC, no specimen suffered damage causing a decrease in air tightness. At 20ºC, the specimens with opened cell gaskets, sheet-type air barriers, and mineral wool improved their air tightness due to dust accumulation on or within the joints. At 65ºC, the acrylic sealant joints were extensively damaged.

108. Lee, R.K., and A. Ozaki. Efficient and Durable Building Envelopes for Japan - part 2: Wall Assemblies Meeting Regional Classifications for Moisture Control in Japan. Ottawa, Canada: Natural Resources Canada; CANMET Energy Technology Centre.

109. Levy, Emanuel, et al. 1982 Technical Support Documentation for Proposed Modifications to Subpart of the Manufactured Home Construction and Safety Standards. Steven Winter Associates, Inc. New York.

This report provides the technical justification and methodological framework for select areas in Subpart F of the Manufactured Home construction and Safety Standards. It assesses the transmission heat loss coefficients of the thermal envelope criteria and includes documentation to support a proposed modification to the coefficients if an air infiltration barrier is provided. The report proposes an alternate method for calculating heat loss, heat gain, and cooling load calculations based on the procedures outlined in National Fire Protection Association Manual 501BM. It analyzes alternate procedures used in selecting criteria in the absence of specific data for estimating the air infiltration loads for equipment sizing. Scenarios are developed for comparing the change in equipment sizing with the change in home size, location, and air change rate. The analyses performed are intended to ensure that the initial investment is recovered within a 5-year period.

110. Lindley, James A., and Helen A. Lunde. *Wall treatment to reduce moisture problems. Proceedings of the Twenty-Fourth Annual Rocky Mountain*. ND: North Dakota State University: Biomedical Sciences Instrumentation, by ISA, Research.

Moisture penetration into walls becomes a problem as air infiltration is reduced in homes. Retarding vapor flow in retrofit projects was investigated. Wall covering can be used to reduce this problem.

111. Lischkoff, J.K., J.W. Lstiburek. 1984. *Building Science Practice and the Airtight Envelope*. Washington, DC.: American Council for an Energy Efficient Economy.

Optimum thermal performance and durability are major consideration in the design of building envelopes. Airtightness is the means by which these goals may be achieved. However, the builder must be aware that an airtight envelope has a significant impact on indoor air quality and ventilation, interstitial moisture accumulation and interior relative humidities. The builder must therefore provide the following: 1. An air barrier. 2. A controlled ventilation system that dilutes interior relative humidity. 3. A vapor retarder. 4. A "weather barrier" that will prevent the ingress of wind and wind driven rain. 5. A forgiving wall design that allows moisture to get out of the wall once it has gotten in.

112. Loading Door Seals put the Crunch on Energy Loss. 1981. Plant Energy Management United States.

Door seals form an environmental seal between truck and building, helping to prevent the loss of heated or conditioned air and forming a barrier to dust, dirt, fumes and pilferage from the outdoors.

113. Louis, Michael J., and Peter E. Nelson. 1995. *Extraneous Air Leakage from Window Perimeters*. Arlington, MA.: Simpson Gumpertz & Heger Inc., ASTM N 1255, Sep.

The window industry has ratings for air leakage through window assemblies. These tests exclude air leakage from the joint between window and wall assemblies or from the sides of the windows. Such leakage is discounted by present window testing standards and labeled 'extraneous air leakage.' Air leakage to the window perimeter can significantly affect the overall performance of the window/wall assembly. A test methodology is presented for quantifying the portion of air leakage that is not measured by current industry standards, but that nonetheless is real and significant air leakage through some types of installed window assemblies. Design guidelines are proposed to minimize air leakage through the window frame and around the window perimeter. This requires careful selection and detailing of the window and wall system to insure that the air barrier effectively seals to the window frame. These details must be carefully coordinated with the design of the flashing and cavity waterproofing, which have distinct and sometimes conflicting purposes. In three examples, the proper location for air barriers in different types of wall construction is identified along with methods to seal the air barrier to the window.

114. Lovatt, John E. Predicting the Durability of Brick Veneer Walls in Cold Climates. Nepean, Canada: Morrison Hershfield Ltd.

Bricks in brick veneer walls of modern buildings in cold climates are exposed to frequent cycles of freezing and thawing, and may have high moisture content during these cycles. Poor air barriers, humidified buildings, higher insulation levels, and less emphasis on details to guide rainwater away from brick surfaces all contribute to this severe environment. Freezing while wet is a major contributor to spilling and premature failure of bricks. A model has been developed to provide a quantitative estimate of the time to freezing-induced failure of bricks in a veneer wall, given the local climate, the brick characteristics, and building design and operating conditions.

115. *Low energy bermed housing: Carroll residence, Swan River, Manitoba*. 1988. Winnipeg, Canada: Manitoba Ministry of Energy and Mines. p. v.

A house was constructed in Swan River, Manitoba, to determine the cost effectiveness of bermed or semi-underground housing as a means of conserving energy. The unique features of the home were examined in terms of general comfort levels, appearance and general design, space temperatures and heating system operation. On the initial visit, the air leakage rate of the structure was determined using an infiltrometer. The objectives were to provide adequate comfortable living space with short term additional cost but long range economic payback as a result of energy conservation, to make use of electric power as a major energy source with supplementing or complementing solar and wood heat, to make full and efficient use of energy by conservation techniques, including earth berms, maximum insulation, vapor barriers, heat gathering atrium, air circulating ceiling fans and a wood burning heat circulating fireplace or stove, to provide a model and demonstration for contractors and the general public of the advantages of the techniques employed, and to increase public acceptance of underground or semi underground living space. Based on the information provided, the bermed wall construction lends itself well to rural house construction, where land is relatively inexpensive. Within the city, bermed wall construction would likely not prove to be cost effective.

116. *Low energy bermed housing: Shoal Lake, Manitoba*. 1983. Winnipeg Canada: Manitoba Dept. of Energy and Mines; Conservation and Renewable Energy Branch. p. 51.

A low energy house with earth berms was constructed in Manitoba. The unique features of this home are earth sheltering over the majority of exterior walls, all windows triple glazed and with southern exposure, insulation values far exceeding current standards, entrances protected from direct exposure to the outdoors, well sealed air/vapor barrier, heat retaining atrium, and built-in provision for an active solar system. During a site visit, an air leakage test was performed using an infiltrometer and results are shown in an appendix. The major objectives of the builder were to provide adequate comfortable living space with short term additional cost but long range economic payback as a result of energy conservation using appropriate construction methods to achieve this, to use electric power as a major energy source with supplementing or complementing solar and wood heat, to increase public acceptance of underground or semi-underground accommodation by demonstrating that comfortable conditions can be achieved, to utilize pressure treated wood for the construction of underground earth retaining walls, and to attract greater public attention to the need for alternate energy sources and to the new or revised technologies to be considered in building and construction. It is unfortunate that one of the objectives, to use a pressure treatment wood underground wall, was not met. In future home building, this technique should still be carefully considered in terms of life cycle cost compared to conventional concrete basements. It is felt that the listed objectives will be fulfilled, assuming the public and other builders are made aware of the project.

117. Lstiburek, J.W., and A.F. Rudd. *Vented and Sealed Attics in Hot Climates*. Cocoa, FL: Florida Solar Energy Center.

Sealed attic construction, by excluding vents to the exterior, can be a good way to exclude moisture-laden outside air from attics and may offer a more easily constructed alternative for air leakage control at the top of residential buildings. However, the space conditioning energy use and roof temperature implications of this approach has not been extensively studied. A computer modeling study (Rudd 1996) was performed to determine the effects of sealed residential attics in hot climates on space conditioning energy use and roof temperatures. The one-dimensional, finite element computer model (FSEC 1992) contained an attic model developed and validated by Parker et al.

(1991). Empirical modifications were made to the attic model to provide better alignment with measured ceiling heat flux reductions of ventilated attics with respect to sealed attics for summer peak days from three roof research facilities (Beal et al. 1995; Rose 1996;Fairey 1986). Annual and peak cooing day simulations were made for the Orlando, Florida, and Las Vegas, Nevada, climates, using a 139 m^2 (1500ft^2) slab-on-grade ranch style house with wood frame construction. Results showed that, when compared to typically vented attics with the air distribution ducts present, sealed 'cathedralized' attics (i.e., sealed attic with the air barrier and thermal barrier left bracket insulation right bracket at the sloped roof plane) could be constructed without an associated energy penalty in hot climates.

118. Lux, M., A. Patenaude, and D. Scott. 1988. *Integrating the window with the building envelope: Window Performance and New Technology*. Ottawa, Canada: Proceedings of Building Science Insight '88; National Research Council of Canada. p 47-58 (75 p) August.

Details are provided on the installation of windows in the building envelope, showing how the window and wall elements are joined and operate as a system. Discussion presented in this paper includes the continuity of window-wall elements or providing air barriers, weather protection, and thermal insulation; reducing condensation potential, with the location of the thermal break being the critical factor; tolerance considerations for window-wall junctions, taking into account load transfer, structural support, anchorage systems, and thermal expansion; joint design and sealant selection; and whether or not to test the window system using a mockup.

119. Manning, K. Cellulose Insulation as an Air Barrier. Innovative Housing Grants Program. Edmonton, Canada.

Can-Cell Industries Inc. has been producing loose-fill and spray applied cellulose insulation for over 15 years. Recent research work conducted by the firm has concentrated on development of a technique for spray applying moistened insulation into the exterior wall cavities of houses. The study determined if the wet sprayed cellulose wall insulation system would function satisfactorily without the use of a polyethylene air/vapor barrier, as well as the influence of interior alkyd paint on the vapor diffusion performance of the wall system. Fieldwork involved construction of a conventional duplex housing unit, which was insulated with wet sprayed cellulose in the exterior walls and dry loose-fill cellulose in the attic areas. One half of the unit did not have a polyethylene air/vapor barrier installed. Air leakage and exterior wall moisture levels were monitored for12 months after construction.

120. *Manufactured Housing Walls That Provide Satisfactory Moisture Performance in all Climates* (NISTIR 5558). 1995. U.S. Department of Commerce. National Institute of Standards and Technology.

121. Mayhew, W.J. *Demonstration and Evaluation of Recent Air-Sealing Techniques in Housing*. 1987. Edmonton, Canada: Alberta Municipal Affairs, Innovative Housing Grants Program. September.

The Airtight Drywall Approach (ADA) and the sealed polyethylene approach were developed as two distinct systems for reducing air leakage in housing. Builders have not totally accepted either method but have instead tended to borrow the most practical and cost-effective techniques and materials from each system and combined them into hybrid systems. This project evaluated current air-sealing techniques, developed refinements to some of those techniques and incorporated them into the construction of the Cold Climate Demonstration House (CCDH), a research and demonstration facility in Alberta. By comparing the effectiveness and practical use of different air and vapor retarder materials and techniques, it was found that for the air barrier, ADA materials and techniques were more easily installed. The resulting air seal was more reliable. However, until inspectors accept alkyd or vapor barrier paints as the vapor retarder, polyethylene is recommended. The construction techniques recommended in this report can be installed with a minimum of experience and with minimal involvement of other subtrades. The cost to provide an air/vapor barrier for a 1000 ft^2 bilevel with both levels fully developed (as demonstrated in the CCDH) was approximately $360.

122. McIntyre, E.D., and E.M Sterling. 1986. *Improving Air Quality in Energy Efficient Houses: An architectural. Approach*. Washington, D.C.: American Council for an Energy Efficient Economy.

The authors review two energy efficient town homes designed and constructed in an experiment designed to improve indoor air quality through manipulation of building architecture. Explored within the context of the townhouse project were architectural means of: limiting infiltration of outdoor radon gas; and reducing indoor levels of formaldehyde off-gassed by construction and finishing materials and combustion gases generated by appliances. To reduce indoor concentrations of formaldehyde generated by finishing and construction materials, chemically stable materials were used wherever possible and limited use made of glues, sealants, interior grade plywood and particleboard. Indoor sources of combustion gases were eliminated from both homes by substitution of electric, for gas, appliances. To minimize radon gas infiltration, the houses were constructed on ventilated crawlspaces and an air/vapor barrier installed between the main floors and the crawlspaces. Air quality in the two experimental homes and in two control houses was monitored to evaluate the effectiveness of the designs for improvement of indoor air quality.

123. *Missioning and Monitoring the Building Envelope for Air Leakage*. Ottawa, Canada: Report Canada Mortgage and Housing Corporation; Housing Innovation Division.

Commissioning the air barrier within the building envelope can help control the consequences of damage associated with air leakage. This report provides an approach to air leakage that extends the air barrier commissioning process to the project brief, validation of the design, and progressive certification during and possibly following construction. Their port describes air barrier specifications for the building envelope; the design process for the air barrier along with suggested revisions; air barrier details and specifications; air barrier certification during construction and final commissioning; post commissioning operation monitoring, and repair; and costs. Appendices describe certified air barrier details and the air permeability of construction materials.

124. *MOIST—A PC Program for Predicting Heat and Moisture Transfer in Building Envelopes (Release 3.0)*. 1997. U.S. Department of Commerce. National Institute of Standards and Technology. “NIST Special Publication 917 (software) September.

125. Moisture and Home Energy Conservation, how to Detect, Solve and Avoid Related Problems. 1983. By National Center for Appropriate Technology for DOE. September.

126. Moisture in Houses-Control Technology for Designers and Builders. 1986. Cutter Information Corp. New York, NY.

127. *Moisture problems*. 1987. Ottawa, Canada: Canada Mortgage and Housing Corp., p 48.

A guide is presented for builders to aid in identifying and solving moisture problems in buildings, with discussion of the causes of these problems. Three main approaches are revealed: controlling moisture sources, such as construction materials, ground sources, and occupant-related sources; the air-barrier system, for preventing air infiltration and unwanted condensation inside the building; and the rain-screen principle, which uses a drained and vented cladding to keep rain out of the wall. Specific problems and solutions are detailed according to the particular area of the building: attic, wall cavity, basement, walls, and windows.

128. Moisture Problems in Homes Agricultural Extension Service. 1990. North Carolina State University. October.

129. *Moisture Problems in the Home, the Comfort Zone*. 1996. Alternative Energy Corporation. Spring.

130. Moisture, Ventilation and Thermal Performance Investigation of Manufactured Housing Weatherization Retrofits. 1996. Final Report prepared for BPA by New Horizon Technologies, Inc December.

131. Monitoring and Investigation of a Multi-Suite Residential Complex in Whitehorse, Yukon, from 1988 to 1992. 1993. Edmonton, AB: Howell Mayhew Engineering, Inc., March.

Closeleigh Manor is a three-story 30-suite apartment building in Whitehorse, Yukon Territory. The building is the first of its kind to be constructed to the equivalence of the R-2000 performance standard developed for houses. Energy efficient features incorporated into the Manor include increased wall and ceiling insulation levels, upgraded windows, a vapor diffusion retarder, and a ventilation system with heat recovery. To evaluate the performance of the Manor and to analyze the applicability of R-2000 standards to apartment buildings of this type, a study was initiated in 1988. A computer monitoring system was installed to gather data on building performance and a series of ventilation-related manual measurements was conducted to gather detailed information on the air distribution system and the indoor environment. A detailed analysis of the computerized and manually measured data was conducted in areas including the building envelope, the heat recovery system, the space heating and hot water system, and the ventilation air distribution system. The results showed that the main factors impacting on the building's heating requirement were the ventilation rate, the envelope air leakage, the overall heat recovery effectiveness, and the windows. The effect of these factors on the building's energy performance was studied using a calibrated energy analysis model. The building's current energy requirements are 1,075 GJ/y; if the same building was constructed today but incorporating recent technological advances, it would be possible to attain an annual space heating and ventilation load as low as 574 GJ.

132. Moss, Lincoln. 1999. *Designing and Building Dry Buildings.* Modular Building Institute, July: 5-9.

133. Moyer, N.A., and J.J. Tooley . *Air Handler Fan: A Driving Force for Air Infiltration*. Orlando, FL: Home Energy; Natural Florida Retrofit. Nov-Dec.

This article describes problems in the weatherization of houses. Tests show that not only leaky ducts affect air pressure differences and infiltration rates in homes, but that four other factors can be involved: duct system design, resident interaction with the system, house tightness, and cleanliness of the blower, filter and evaporator coil. The authors tested and inspected 371 homes for pressure problems and found problems in every one, with variable losses. The authors offer the following solutions: the air barrier must be air-impermeable, able to resist the highest air pressure load, be continuous, and durable. These same criteria must apply to the duct system as well, in order to insure optimal energy efficiency.

134. National Institute of Standards and Technology. 1995. Manufactured Housing Walls That Provide Satisfactory Moisture Performance in all Climates. NISTR 5558, January.

135. Nelson, G.D. and G.A. Tsongas. 1991. *Field Test for Correlation of Air Leakage and High Moisture Content Sites in Tightly Built Walls*. Atlanta, GA.: ASHRAE Transactions part 1. Published by ASHRAE, p 1-8.

In a recent field study of 86 new energy-efficient homes with relatively airtight construction in the Pacific Northwest, walls were opened up and unacceptably high wood sheathing moisture contents were measured in numerous wall cavities. A separate field investigation, described here, was undertaken at one home in an effort to determine the cause. The moisture content of the wall sheathing was measured from the outside of the wall, both high and low, in every stud cavity of two walls (120 locations). Three locations were found with more than 40% moisture content, four locations with between 30% and 40%, and eleven locations with between 20% and 30%. Because evidence suggested that the source of the winter moisture buildup in the wood sheathing was moist indoor air migrating out through penetrations in the polyethylene air/vapor barrier, infrared thermography was used during house pressurization and depressurization to locate air-leak sites and paths. Numerous air leaks were observed both on the inside and outside of the exterior walls even though the house was found to be very airtight (1.2 ach at 50 Pa). Many of the leaks resulted from improper sealing or poor workmanship and could have been avoided. What is most important is that a

definite correlation was found between the locations of many of the major air leaks and the locations of sheathing with high moisture content. In almost every one of the 18 places where the sheathing moisture content was more than 20%, there was a noticeable air leak in the wall cavity. Thus, the air leaks on the interior portion of the walls introduced moisture into the tightly built wall cavities that could not dry out during the winter. Some suggestions. Is made to help minimize the effects of air leakage and keep tightly built wall cavities dry. A number of recommendations for further study also are presented.

136. Nielsen, S.E. *Insulating the Old House: a Handbook for the Owner*. 1977. Portland, ME: Greater Portland Landmarks, Inc. p. 47.

The special considerations required in the insulation of old houses are reviewed. The condition of the existing heating system is cited as the primary consideration in an analysis of the heating requirements of an old house; necessary repair or replacement is considered a priority. Identification of the areas of heat loss in the house is considered the next step in the thermal analysis. The primary areas are the attic/ceiling area, walls, basement/floor area, and direct window and infiltration losses. An analysis of heat losses after the installation of fiberglass insulation in the walls and ceiling and the addition of storm doors and windows in two types of houses with full basements indicated that the largest percentage of heat loss occurred through the windows and doors because no weather stripping was installed. This area of heat loss and infiltration is identified as a problem especially peculiar to old houses that often have a large proportion of structural openings. Moisture condensation leading to dry rot in the house structure is a primary consideration when insulating an old house. Changing some habits is a primary consideration when insulating an old house. Changing some habits of the occupants within the house can reduce the addition of water vapor to the air. Standing puddles in the basement, cooking, houseplants, humidifiers, and drying laundry and wood inside can contribute to interior moisture and should be reduced or modified. The installation of a vapor barrier when insulating the old house is considered a critical factor in reducing condensation problems, vapor barriers may be readily installed with the insulation in attics, basements and crawl spaces but side walls may require alternate procedures to create vapor barriers such as the application of aluminum paints, glossy oil-based paints, or vinyl wallpaper to interior walls.

137. Nisson, J. D., 1998. *Radiant Barriers, Air Barriers, and Vapor Barriers*. Energy Design Update. Arlington, MA: Cutter Information Corp.

138. The Northwest Wall Moisture Study 1990: A Field Study of Excess Moisture in Walls and Moisture Problems and Damage in New Northwest Homes., Residential Construction Demonstration Project. Bonneville Power Administration, March. (Have requested a copy of this report)

139. Oak Ridge National Laboratory. 1996. Building Technology Center. Moisture Control in Walls, Version 1.0. (software)

140. Onysko, D.M. 1994. *Wall moisture research in Canada*. Ottawa, Canada: Centre for Mineral and Energy Technology; Efficiency and Alternative Energy Technology Branch. p 109-122, (269 p)

Most concerns about durability of housing construction relate to moisture transport, with the primary concerns being air leakage and vapor diffusion. A review is presented of construction practices that affect wall performance and their durability. Several construction practices cause difficulties with moisture, including use of green or wet wood, field application of vapor barrier or wraps, and construction during winter. Significant excursions have been found in building lumber moisture levels throughout Canada. Excessive moisture in studs can cause drywall cracking or nail popping when the lumber dries. Field studies on the drying of wall systems are described, and it is shown that shrinkage can induce nail popping, leading to creation of air-leakage pathways, wall bowing, etc. Radically different air permeability can be achieved depending on negative or positive pressurization if the air barrier does not have sufficient restraint within the wall.

141. *Passive Solar Home for Northern Climate*. 1977. Alternative Sources Energy, United States. p 5-11. April.

After three years of work, an energy efficient solar home was built utilizing passive systems. The house is oriented towards the south and is protected on the north side by trees. The house is about 1600 sq. ft. and the first floor is partially underground. Eight inches of urea formaldehyde foam was used in the ceiling for an R-value of 38.8, with six inches in the south wall (R-29), and 3.5 in the side walls (R-17). A vapor barrier was applied to all sides of the house. The basement was insulated with 12 in. block insulation and waterproofed. The insulation is protected above ground by a stucco finish. The first floor is four feet underground and the earth is bermed on four sides. Because of a high water table, the area includes an extensive tile drainage system. Westherstripping and caulking help eliminate air infiltration. On the south side of the house the window area is approximately 172 sq. ft. on the upper floor and 70 sq. ft. on the lower floor. Insulated shades were used on the large south facing windows. A Riteway wood stove with a 5.8 cubic foot firebox is also utilized. The house has one central register. The house temperature varies 10-15^{0}F with the heat flow. Hot water is provided by a standard gas hot water heater. A greenhouse is attached to the south side of the house. Electricity is provided by a wind generator with a standby gas driven engine. The house also includes a smaller version of the Clivus Mulstrum compostable toilet. Blueprints are available by writing the Colyers.

142. Pazia, A. 1997. The Dual Challenge of Air Leakage and Thermal Efficiency. Canada v 39:2. p 46-47, Mar.- Apr.

The use of sprayed polyurethane foam (SPF) in building envelopes was discussed. SPFs are different from other insulating materials in that they provide a gap free, air tight, monolithic envelope of low permeability, closed cell, moisture resistant insulation that adheres to all surfaces. Specifically, SPF is an effective air barrier, it eliminates convective airflow through and around the insulation, controls moisture transfer and condensation, minimizes thermal bridging, and is less costly than conventional systems.

143. Persily, A. K. *Development of Thermal Envelope Design Guidelines for Federal Office Buildings.* Gaithersburg, MD: National Institute of Standards and Technology (NEL); Center for Building Technology

Office building envelopes are generally successful in meeting a range of structural, aesthetic and thermal requirements. However, poor thermal envelope performance will occur when there are discontinuities in the envelope insulation and air barrier systems, such as thermal bridges and air leakage sites. These discontinuities result from designs that do not adequately account for heat, air and moisture transmission, with many thermal defects being associated with inappropriate or inadequate detailing of the connections of envelope components. Despite the existence of these thermal envelope performance problems, information is available to design and construct envelopes that do perform well. In order to close the gap between available knowledge and current practice, the Public Buildings Service of the General Services Administration has entered into an interagency agreement with the Center for Building Technology of the to transfer the knowledge on thermal envelope design and performance from the building research, design and construction communities into a form that will be used by building design professionals. The report describes the NIST/GSA envelope design guidelines development at the end of the first year of effort on the project.

144. Persily, A. K. Envelope Design Guidelines for Federal Office Buildings: Thermal Integrity and Air tightness. Gaithersburg, MD: National Institute of Standards and Technology (BFRL.)

Office building envelopes are generally successful in meeting a range of structural, aesthetic and thermal requirements. However, poor thermal envelope performance does occur due to the existence of defects in the envelope insulation, air barrier and vapor retarder systems. These defects result from designs that do not adequately account for heat, air and moisture transmission, with many being associated with inappropriate or inadequate detailing of the connections of envelope components. Other defects result from designs that appear adequate but cannot be constructed in the field or will

not maintain adequate performance over time. Despite the existence of these thermal envelope performance problems, information to design and construct envelops that do perform well. In order to bridge the gap between available knowledge and current practice, NIST has developed thermal envelope design guidelines for federal office buildings for the General Services Administration. The goal of this project is to transfer the knowledge on thermal envelope design and performance from the building research, design and construction communities into a form that will be used by building design professionals. These guidelines are organized by envelope construction system and contain practical information in the avoidance of thermal performance problems such as thermal bridging, insulation system defects, moisture migration, and envelope air leakage.

145. Proskiw, G. 1992. *EMR Federal Panel on Energy Research and Development*. Winnipeg, Canada: Unies Ltd., Sponsoring Organization: PERD, (Ottawa, Canada); Department of Energy, Mines and Resources, (Ottawa, Canada.) May.

A three year field study of 20 energy efficient houses and four conventional dwellings was conducted to evaluate the performance of their building envelope systems. Ten of the houses were built with polyethylene air barriers and 14 using the airtight drywall approach (ADA). All were newly built and used dry wood for framing members, i.e. with wood moisture content (WMC) below 19%. Building envelope performance was evaluated by developing a comprehensive monitoring program that included measurements of wall, attic and floor joist WMC levels, detailed thermographic examinations and regular airtightness testing. Over 13,000 WMC measurements were performed, 1013 thermographic images recorded and 167 airtightness tests conducted. Both the energy efficient and conventional building envelope systems performed satisfactory manner although fewer problems were found in the energy efficient houses. Lower mean WMC levels were measured in the walls and attics and fewer WMC excursions above 19% were recorded. The energy efficient houses also displayed fewer thermographic anomalies, particularly those of a severe nature. The energy efficient houses were found to be more airtight. No evidence of envelope degradation was found in the energy efficient houses. Both the polyethylene air barriers and the ADA system demonstrated predominately stable WMC levels, thermographic characteristics and airtightness. The building envelopes constructed using polyethylene barriers generally performed in a superior fashion to those that used ADA, although both systems provided satisfactory performance. WMC levels were slightly lower in the polyethylene houses as were the number of thermographic faults, particularly those of a severe nature.

146. Proskiw, G. 1992. Field Performance of Energy-Efficient Residential Building Envelope Systems. Winnipeg, Canada: Unies Ltd., May.

The air tightness of 24 new houses was measured on a regular basis over periods up to three years to evaluate the structures' air barrier systems and to study the possibility of air barrier degradation, as would be indicated by an increase in the measured leakage rate. Ten of the houses were built with the polyethylene air barrier system and 14 using an early version of the Airtight Drywall Approach (ADA). The 24 project houses were architecturally similar and of approximately equal size and general layout. The airtightness of the polyethylene air barrier houses was found to remain stable over their respective monitoring periods. It was concluded that no evidence could be found to indicate polyethylene is unsuited for use as an air barrier material in residential construction. Although 2 of the 10 houses demonstrated possible, albeit slight, evidence of airtightness degradation, the magnitude of these changes was small and judged not to be of practical significance. All but one of the polyethylene houses met the airtightness requirements of the R-2000 program at the end of their monitoring periods. The project houses with the lowest measured leakage rates were those built with the double wall system and polyethylene barriers. The study also found that the airtightness of the 14 ADA houses remained stable during the monitoring period and it was concluded that no evidence could be found to indicate that the ADA system is unsuited for use in residential construction. Although 6 of the 15 houses displayed possible, but also slight, evidence of airtightness degradation,

the magnitude of the changes was small and not of practical significance. All 14 houses met the airtightness requirements of the R-2000 program at the end of their respective monitoring periods.

147. Proskiw, Gary. *Measured air tightness of 24 detached houses over periods of up to three years*. Winnipeg, Canada: Proskiw Engineering Ltd.; Proceedings of the Conference on Airflow Performance of Building Envelopes, Components and Systems.

A total of 24 new houses were subjected to regular airtightness tests over a period of three years to evaluate their air barrier systems and to search for evidence, air barrier degradation. Ten of the houses were constructed with polyethylene air barriers while the remaining fourteen used an early version of the Airtight Drywall Approach (ADA). The houses were not only architecturally similar, of equal size and general layout, but were also exposed to similar terrain shielding. The results of the three-year study were generally good.

148. Proskiw, G. 1996. *Measured Variation of House Airtightness Over a Three-Year Period*. Ottawa, Canada: Department of Energy, Mines and Resources. p 217-222

Airtightness tests were performed on 24 modern project houses in Winnipeg, Manitoba. The objective of the study was to search for evidence of air barrier degradation and to comment upon the suitability of various air barrier systems for residential construction. Airtightness refers to the building envelope's ability to resist air infiltration and exfiltration created by pressure differential across joints, holes and other openings in the exterior shell. Air barrier deterioration was considered to be a degradation in airtightness. Three analysis methods were used to evaluate the changes, but no single method provided a definitive statement on whether the airtightness was Degrading with time. Both polyethylene and ADA air barrier systems met the airtightness requirements of the R-2000 program.

149. Proskiw, G. 1997. *Variations in Air Tightness of Houses Constructed with Polyethylene and ADA Air Barrier Systems over a three-year period*. Winnipeg, Canada: Proskiw Engineering Ltd., Journal of Thermal Insulation and Building Envelopes p 278-296, April.

Air tightness describes the ability of the building envelope to resist air leakage through unintentional joints, holes and cracks in the exterior shell. A project was undertaken to monitor the air tightness of a group of twenty-four new houses built with two different types of barrier systems namely polyethylene and Airtight Drywall Approach (ADA) over a multi-year frame in search for evidence of air barrier degradation. It is found that the air tightness of the polyethylene and ADA air barrier houses remained stable over their respective monitoring periods and met the air tightness requirements of the R-2000 program. This concludes that no evidence could be found to indicate that this air barrier system is unsuitable for use in residential constructions.

150. Quirouette, R.L. 1989. The Air Barrier Defined, An air barrier for the building envelope: Proceedings of building science insight '86. Saskatoon, Canada: National Research Council of Canada. P. 1-5 (30 p).

Many building performance problems, including high heating costs and poor temperature control in occupied spaces, can be traced to air leakage through the building envelope. Many of these problems result from the building designer's poor understanding of the principles involved. The principles of vapor barriers and air barriers are explained and performance requirements are illustrated by means of case studies. The mechanisms of air leakage are reviewed under three categories: stack effect, wind pressures, and fan pressurization from the ventilation system. Air barrier requirements include continuity throughout the entire building envelope, structural integrity, air impermeability, and durability. Attention to these requirements at the design and construction stages will help to avoid such problems as interior condensation, decoupling of barriers from inside the walls, leakage during heavy storms, and freezing of the moisture contained in infiltrated air with subsequent melting and penetration of the melt water into occupied spaces.

151. Quirouette, Richard L. 1983. Moisture Sources in Houses, Building Science Insight, Humidity, Condensation and Ventilation in Houses Series. National Research Council of Canada.

152. Reed, R.T. 1980. *Passive Solar Home*. Houston, TX: Doyle Stuckey Homes; US Department of Energy Passive and Hybrid Solar Energy Program update meeting.

The objective of the work reported is to design and construct a single-family dwelling of average size and cost in the Houston marketplace and to incorporate in it all of the most cost effective passive solar concepts using state of the art technology and commonly available materials. Because of the intense heat and high humidity of the area, the house is designed to provide a sufficient barrier to air infiltration and heat gain and to maintain good air circulation. There is plenty of shading. Thermal mass is used to store cold or heat, depending on the season. Use is made of the thermal break concept, the intent of which is to break the conduction of heat cycle. (LEW)

153. Remmele, Thomas E. 1999. *Flashing: The Plain Solution to Leaky Walls*. Building Standards November-December.

154. Research and Development Highlights from Canada Mortgage and Housing Corporation: Structural Requirements for Air Barriers. 1995. Journal of Thermal Insulation and Building Envelopes, p 102-117. Oct.

The Canada Mortgage and Housing Corporation conducted a study in the requirements for the structural design of the components within a building envelope providing air brightness, called air barriers. The results of the study will be useful in the development of the National Building Code of Canada design guidelines requiring the provision of an effective barrier to air exfiltration and infiltration.

155. Rose, William B. 1995. *The History of Attic Ventilation Regulation and Research*. Thermal Performance of the Exterior Envelopes of Buildings VI Conference and Proceedings (ASHRAE), December: 125-134.

156. Rose, William B., and Anton TenWolde. 1999. *Issues related the Venting of Attics and Cathedral Ceilings*. ASHRAE Transactions 1999, 105(Pt.1): 1-7.

157. Rose, William B. 1997. *Moisture Control in the Modern Building Envelope*. APT Bulletin Envelope, 28(4): 13-20.

158. Rose, W.B. 1994. A Review of the Regulatory and Technical Literature Related to Crawl Space Moisture Control. ASHRAE Transaction Volume 100 Part 1

159. Rose, William B. and David J. McCaa, Ph.D. 1998. *Temperature and Moisture Performance of Wall Assemblies with Fiberglass and Cellulose Insulation*. Thermal Performance of the Exterior Envelopes of Buildings VII, December: 133-144.

160. Rousseau, J. 1999. *Creating Effective Air Barriers: Materials and Techniques*. Ottawa, Canada: Canada Mortgage and Housing Corp.; Canadian Housing Experience '99.

The National Research Council of Canada (NRC) considered the question of maximum acceptable air flow in a review of existing research on air leakage. The standards reviewed included one developed by the American Architectural Manufacturers Association which lacked lower the acceptable factor of leakage by two and recognized that acceptance of a level would depend on the relative humidity inside a building. Canada Central Mortgage and Housing Corp. revisited the question in a more scientific and specific way. Further factors considered were: climate, interior relative humidity and construction materials. A computer program designed to take these variables into account determines maximum leakage levels for a variety of wall assemblies and climates.

161. Rousseau, Madeleine Z. 1985. *Sources of Moisture and its Migration Through the Building Enclosure*. Ottawa, Canada: National Research Council of Canada; Division of Building Research.

Moisture problems are related to three conditions: the indoor temperature and humidity, the outside climate, and the design and construction of the building envelope. In order to get an adequate moisture balance in the building, three factors can be adjusted. Moisture sources can be reduced or eliminated in some cases, ventilation can be increased, and the building can be designed and built to control built-in moisture flows through the envelope. In order to control the concealed condensation problems, there must be vapor and air barriers in the enclosure. To control air leakage, the air pressure difference must be resisted, and to this end, a continuous juxtaposition of building materials capable of withstanding the air pressure difference is required.

162. Scharmann, L. Energy Efficiency for Architectural Drafting Instructors. Lincoln, NE: Nebraska Energy Office.

This curriculum guide contains five units that were designed to be in corporate into an existing program of Architectural Drafting. Energy Conservation Awareness presents an overview of residential energy use and audit procedures. Residential Energy Consumption provides information on space heating, ventilating, air conditioning, hot water heating, lighting, and appliances. Design Considerations for Residential Energy Efficiency deals with site orientation, building type, room arrangement, location of openings, and building codes. Residential Construction Practices and Materials include building and insulating materials, construction methods, infiltration, vapor barriers, and moisture control. Energy Saving Devices and Methods covers familiarization with ventilation, lighting, solar systems, stoves and fireplaces, wind generators, heat sinks, and moveable insulation, without mechanical ventilation, 0.2 to 0.5 ach, and yet indoor concentrations.

163. Shakun, W. 1992. The Causes and Control of Mold and Mildew in Hot and Humid Climates. ASHRAE transactions 1992, 1282-1291 (1371).

A study was conducted to determine the cause of interior moisture damage at selected Florida hotel-motel sites generally identified by (1) peeling of the vinyl wall-covering material; (2) high moisture content in the gypsum board, resulting in crumbling or material structural failure; (3) fungal growth with a red, yellow, or black stain; (4) paint delamination; (5) cold, clammy, uncomfortable rooms; and/or (6) surface mildew on some interior furnishings. The primary cause of the condensation problems is a direct result of warm, humid outdoor air infiltrating into the wall cavities followed by condensation of the water vapor. Since the hotel-motel sites are in the region of high relative humidity and corresponding high temperatures during a major portion of the year, air conditioning of the occupancy space is a necessity. With vinyl wall-covering material in the guest rooms acting as a vapor retarder, moisture is trapped inside the wall cavities, resulting in concealed condensation when the wall temperature is below the dew-point temperature. Moisture migrates from a place of high vapor concentration to a place of lower vapor concentration by two methods--diffusion through materials and by airflow carrying moisture with it. The moisture flowing as a result of diffusion is a function of the difference in vapor pressure between the two sides of the supporting walls, the permeability of the construction materials used in the structure, and the exposed surface area. The amount of moisture accumulating as a result of air infiltration is a function of the mass flow rate, the humidity ratio difference between the flow stream and the interior space. In general, air infiltration will have a greater effect on the deterioration of the interior materials than vapor diffusion.

164. Sherman, M.H. 1990. Reduction of the Effective Leakage Areas of Single-Section HUD-Code Manufactured Homes due to Air Infiltration Barriers. Atlanta, GA: ASHRAE transactions.

This paper addresses the effective leakage area (ELA) reduction in single-section HUD-code manufactured homes due to the application of an air infiltration barrier (AIB). The data used for the analysis were generated over a period of three seasons, through hourly measurements of air infiltration, temperature, and wind speed, at a site with two HUD-code homes, one sheathed with an AIB and the other one caulked. The effective leakage areas are calculated using a model that correlates the air infiltration rate in residences to weather variables, the effective leakage area of the house, and coefficients that are determined by construction and terrain characteristics. Two sets of ELA calculations are performed for both AIB and caulked homes. In the first one, the model has the site-built housing coefficients presented in the ASHRAE Handbook of Fundamentals. In the second one, the construction coefficients in the model are modified to account for the particular construction characteristics of single-section HUD-code manufactured homes. The magnitude of the ELAs is discussed and recommendations are made for the value of the ELA reduction attributable to an AIB

165. Sherwood, Gerald E. *Condensation Potential in High Thermal Performance Wall, Hot, Humid Summer Climate*. US Department of Agriculture – Forest Products Laboratory Research Paper 455.

To observe actual moisture patterns and the potential for condensation Due to long periods of air conditioning in a hot, humid climate, a test Structure was constructed near Gulfport, Mississippi, for exposure of eight types of insulated wall panels at controlled indoor conditions and typical outdoor weather conditions. Panels were instrumented with moisture sensors and tested without (Phase 1) and with (Phase 2) penetrations (electrical outlets) in the indoor surface. There was no sustained condensation in any of the walls during either winter season. One type of high thermal performance wall had sustained condensation during both summers, but the wall dried out as the weather became cooler, and moisture content off ramming never exceeded 17 percent. Low-permeance sheathing appeared to provide resistance to the buildup of moisture during summer in walls with high overall 'R' values. Penetrating the walls with electrical out lets resulted in slightly higher moisture levels in all of the walls throughout the year. This paper should be useful to building designers, builders, and building code officials in establishing vapor retarder requirements for walls.

166. Smith, C. J. M. 1974. *Cladding*. Cold Formed Steel, Short Course, University of Waterloo, Ontario, October 1973 (p 77-86). Published by Univ. of Waterloo Press, Solid Mechanical Division, Ontario, Canada.

An analysis of the significant trends in the design requirements for the cladding of high rise buildings brings out an apparent contradiction - on the one hand a requirement for a flexible skin able to cope with dimensional variations due to thermal differentials and the greater movement and distortion due to ever increasing heights, and on the other hand, a requirement for the virtual elimination of air infiltration and exfiltration through the cladding or outer skin of the building. The design criteria for the cladding of the Commerce Court West Tower in Toronto contained both of these requirements and this building is used as an example to discuss the technological basis for the requirements and also how these requirements have been met by the design of the cladding. The cladding construction, working from the outside of the spandrel in, consists of an exterior " weather " surface of 1/8 inch stainless steel, an air space which is sufficiently ventilated to the exterior to allow for the equalization of air pressures on both sides of the stainless steel spandrel, insulation, 20 gauge galvanized steel forming the " structural "air vapor barrier and the fireproofing.

167. *Structural Requirements for Air Barriers*. 1991. Ottawa, Canada: Canada Mortgage and Housing Corp., August.

Canada's national building code requires buildings to be provided with an effective barrier to air exfiltration and infiltration. A study was undertaken on the requirements for structural design of air barriers. Information is presented to indicate the types of loads that must be considered in structural design of air barriers and the process of structural design required in order to ensure that an air barrier will be able to resist loads imposed during its functional life. A summary is given of what is known about the magnitude and frequency of air pressure loading on air barriers arising from mechanical pressurization, wind, and stack effect. Building code provisions for these types of loads are reviewed and their applicability to air barrier design is discussed. Differences between compartmented and non-compartmented rainscreen walls and the resulting loads on air barriers are examined. The differences between load-carrying mechanisms of flexible and rigid air barrier materials are noted. Air barrier systems employing materials such as gypsum board, polyethylene, rigid insulation, and membranes are assessed. Structural design philosophies such as limit states design are discussed for their relevance to air barrier design guidelines. The structural review of air barrier systems is illustrated with examples. Limitations in the current database of structural information on air barrier materials is also discussed and recommendations are provided for structural data necessary for structural design of air barriers.

168. *Study of the Rain Screen Concept Applied to Cladding Systems on Wood Frame Walls*. Ottawa, Canada: Morrison Hershfield Ltd, and Canada Mortgage and Housing Corporation; Project Implementation Division.

The rain screen wall system consists of an exterior cladding, drained and vented to the outside, a cavity behind the cladding, an inner plane called the air barrier system, and a set of compartment seals limiting the cavity to a modest size. This study examines the performance characteristics of air onscreen cladding on a wood frame wall. A laboratory investigation was conducted of brick veneer, stucco, and vinyl exterior cladding systems in which sample walls were subjected to simulated wind-driven rain in an environmental chamber and the amount of water passing through the veneers was determined gravimetrically. The second part of the study investigated the compartmentalization requirement of the cavities behind the cladding and was done through the use of a full-scale construction model installed in a wind tunnel. The third part developed a simulation model to predict the pressure equalization performance of various types of exterior cladding and wall systems. Parameters included the vent areas required, air leakage areas, volume of the cavity, and stiffness or rigidity of the air barrier and the cladding elements.

169. *Super Insulation: Alternative for the '80s*. 1982 (United States). REC Magazine. Volume 29:4

Super insulation is defined as: (1) Wall R values of 40 or more; (2) Ceiling R values of 50 or more; (3) Minimal air infiltration; (4) Use of effective vapor barriers; and (5) Use of air-to-air heat exchangers. Annual heating and cooling expenses for a super-insulated test house in the Minneapolis area are less than one-third of those in conventional house construction. (JMT)

170. Swinton, M.C., M.A. Tremayne, and D.W. Webster. 1983. Modeling of Residential Air Change Heat Loss in the CMHC-2 Program. Ottawa, Canada: Canada Mortgage and Housing Corp. p. 44. July.

The Canada Mortgage and Housing Corporation-2 (CMHC-2) residential energy analysis and cost-optimization model ranks energy conservation options for individual house components on the basis of cost-benefit merit of each option. A means of relating cost to benefit has been developed for conservation measures involving the airtightness of components. The resulting air change model, developed jointly by CMHC and Canada Consultants Limited, was presented in this report. The model was intended to assist in the design and choice of air barrier cost/benefit basis. The focus of this report was the algorithm developed for estimating air leakage through cracks and unintentional openings, since this phenomenon is a strong function of construction technique and quality of workmanship. The method consisted of relating cracks and openings associated with all of the major house components, and their design detail and construction quality. A sensitivity analysis was undertaken using the model to illustrate its use and to assess its credibility in a preliminary fashion. The study concludes that the presented method can be used with a measure of confidence for evaluating air tightening options in new construction and air leakage performance for existing structures, since it was derived to fit field test data, using conventional engineering judgment.

171. Tamblyn, T. 1994. *Energy efficiency in the Canadian Multi-Residential Sector*. Ottawa, Canada: Natural Resources Canada; Canada Mortgage and Housing Corp., p 231-243. (428 p.)

Energy efficiency of Canadian multi-residential buildings has not kept pace with energy efficiency improvements in other building sectors. In the multi-residential sector, energy efficiency considerations are usually subordinate to a dedication to reduced first cost. The energy use of a typical 100-unit apartment building in Toronto is reviewed, and strategies for energy efficiency improvement are outlined. These strategies include heat recovery from ventilation air, better design and construction of air infiltration barriers, increasing the levels of insulation, using higher-efficiency windows, better insulation of hot water tanks and piping, use of high efficiency boilers and motors, and using more efficient lighting and cooking technologies. The result of the application of all available efficiency improvements will be a reduction of the energy utilization index from 52.8 $kWh/m^2/y$ to ca 26.8 $kWh/m^2/y$.

172. Tang Lee Environmental Design. 1984. *Condensation in Manufactured Housing*. Alberta, Canada: The University of Calgary.

173. TenWolde, Anton, et al. 1993. *Air Flows and Moisture Conditions in Walls of Manufactured Homes*. U.S. Department of Agriculture, Forest Service Forest Products Laboratory Washington, D.C.

174. TenWolde, Anton. 1993. Ventilation, Humidity and Condensation in Manufactured Houses During Winter. U.S. Department of Agriculture, Forest Service Forest Products Laboratory Washington, D.C.

175. TenWolde, Anton 1993. *Ventilation, Humidity, and Condensation in Manufactured Homes During Winter*. Forestry Products Laboratory, U.S Dept. of Agriculture and Forestry Service, prepared for U.S. Dept. HUD. March.

176. *Testing of air barrier systems for wood frame walls*. 1988. Saskatoon, Canada: National Research Council of Canada; Institute for Research in Construction. (94 p.) June.

Air leakage in a building can be controlled by an air barrier system, i.e., a continuous plane of air tightness designed and constructed into the building envelope. This plane of air tightness may be achieved with a single strong airtight material or a combination of materials. In either case, the assembly must be structurally capable of withstanding the air pressure load exerted on the building envelope. The objective of this project was to measure the air leakage and structural performance of air barrier systems intended for use in wood frame walls. Measurements were performed using a test apparatus and procedure both of which were developed at Institute of Research in Construction (IRC). Ten specimens were tested - nine constructed with wood studs and one constructed with steel studs. All test specimens, save one, were constructed at IRC using methods approved by the Canadian Mortgage and Housing Corporation. The manufacturer prefabricated the final specimen. For eight of the ten specimens tested pressure differences measured indicated laminar flow. This indicates these specimens are leaking through porous materials or very tight joints. Two specimens exhibited turbulent flow indicative of a combination of flow regimes. Eight specimens passed all steps of the negative pressure difference structural test. Two were too leaky to test. Seven specimens failed the positive pressure difference test, mostly at fasteners. Most specimens would have passed with modified fasteners.

177. Thomas, Howard L. 1995. *Uses of Technical Nonwovens in Building Construction.* International Textile Bulletin - Nonwovens Industrial Textiles v, 41 n 1 1st Quarter 3 pp.

Current trends in the US building construction industry imply that the specialty textile products market will continue to increase faster than the housing industry itself. Nonwoven fabrics provide high strength at light weight, some degree of permeability, an affinity for other materials, isotropic features, flexibility at different temperatures, resistance to degradation, and low cost. Thus the volume of nonwoven use has grown due to their popularity with builders. The wide acceptance of spun bonded house wrap relapsing tarpaper is one good example of their increase.

178. Tsongas, G. A. 1991. *Field Study of Indoor Moisture Problems and Damage in New Pacific Northwest Homes.* Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.,

The interior living spaces and the ventilation systems of 86 newly constructed houses in the Pacific Northwest were inspected to determine if building them to energy-efficient standards with more insulation (at least R-19 (R-3.3) in walls) and relatively airtight with an air-vapor retarder causes indoor moisture problems or damage. The test houses were located in three climatic regions: 50 in the

metropolitan Seattle-Olympia area, 16 on the rainy Washington coast, and 20 in the cold Montana region. Numerous moisture-related problems were observed within the homes, primarily because of inadequate moisture control and consequent high indoor relative humidities. One-third of these new homes had mold and mildew on indoor surfaces such as walls, one-third had mold and mildew on window frames and/or sills, almost three-quarters had condensation on window glass and frames, and one-quarter had window sill damage as a result of the window condensation. A majority of the ventilation systems, including spot exhaust fans and air-to-air heat exchangers (AAHX), were not working as well as expected or were not being used by the occupants. Overall, for a variety of reasons, there was no AAHX ventilation in about one-third of the homes, no kitchen ventilation in almost two-thirds of the homes, and no bathroom ventilation in about half of the homes. All of these ventilation system problems resulted in inadequate removal of excess moisture. The findings of the study dramatically point out the need for better indoor moisture control in these and probably other new homes. For future tightly built homes, moisture control must have a much higher priority in their design, construction, inspection, and ongoing operation. Specific recommendations are made to improve indoor moisture control through better ventilation, including automatic control, and dehumidification.

179. Tsongas, George. 1995. *Moisture and Mobile Home Weatherization*. Home Energy Magazine. July/August.

180. U.S. Department of Commerce. 1996. National Institute of Standards and Technology: Mathematical Analysis of Practices to Control Moisture in the Roof Cavities in Manufactured Homes (NISTIR 5880).

181. Uvslokk, S. 1983. *Field Verification of the Air Infiltration Model Used in the Computer Program Encore*.

182. *Ventilating your Home*. 1988. Edmonton, Canada: Alberta Energy; Energy Conservation Branch. p. 20.

This booklet is intended to help the homeowner identify and remedy possible problems with air quality and ventilation. Recent efforts to conserve energy have led many homeowners to reduce air leakage by installing vapor barriers, sealing and weather-stripping, or other techniques. This has led, in many cases to humidity and indoor air pollution problems, which are identified and explained. Solutions for controlling indoor air quality include proper selection of building materials, proper venting and operation of appliances such as furnaces and stoves, and reduced use of pollution-causing products. Another problem of concern to health is backdrafting of combustion gases, occurring when combustion air in furnaces is not being properly replaced. A number of ways are outlined to identify and solve this problem. Selection of ventilation systems is discussed, with reference to Alberta building codes. Overall design and system characteristics are given for passive, exhaust-only, and heat recovery ventilation systems, and guidelines are presented for selecting and installing heat recovery ventilators.

183. Waldman, Donald J., and Michael L. Zieman. 1984. *Moisture Problems in Mobile Homes*. Prepared for Office of Manufactured Housing and Regulatory Functions. US Dept of HUD. RADCO, July.

184. Woods, T. 1988. *Air leakage control in High-rise Multifamily Buildings*. Mississauga, Ontario Canada: CANAM Air Leakage Control Systems Corporation; Affordable comfort III program. Publisher: Pittsburgh, PA (US) Action-Housing, Inc. p 46 (88 p)

High-rise multifamily buildings have been largely ignored as representing tremendous cost effective, fuel-saving potential by applying appropriate air leakage control measures. This workshop postulates that they are not difficult to deal with and suggests ways and means backed by case studies, which have been monitored. Testing equipment, innovative foams and weatherstripping are demonstrated. Building science and environmental issues also are addressed. As a result of this tutorial, participants

will: (1) Become familiar with the simple, logical and very effective method of assessing, reporting and estimating the air leakage component of the heating and cooling bills of large buildings. This methodology has been evolving in Canada for the last 12 years and is now in widespread use; (2) Be introduced to the latest in window testing equipment, standards, etc.; (3) Learn to love stack effect, the difference between air barrier and a vapor barrier, and how lack of understanding these is steadily wrecking existing and new high-rise buildings.

185. Woods, T. 1997. *High Performance Buildings need High Performance Envelopes*. Energy Manager v 4:6. ISSN: 1198-5070, p 7, 10, Nov.

The significance of the right choice of building envelope in terms of cost savings when retrofitting an apartment or commercial building was discussed. The continuity of an air barrier system was emphasized as being crucial to any energy saving from an envelope upgrade, since air leakage is the single largest source of heat loss (or gain) through the envelopes of nearly all types of buildings. Performance requirements for an air barrier system include continuity, the ability to fasten to supporting structures, ability to resist peak wind loads, sustained stack effect, and pressurization from ventilation equipment, virtual air impermeability, and durability. Worst areas for air leakage in buildings were identified (mechanical penthouses, soffits, parapets, doors, links connecting below grade areas to other buildings, joints between one system and another), and the relative air permeability of various materials ranging from bitumen-based membranes (lowest) to vermiculite and sprayed cellulose insulation (highest) were tabulated.

186. Woods, T. 1998. *Reducing Air Leakage Through the Building Envelope Cuts Energy Demand and Consumption*. Mississauga, Canada: CanAm Building Envelope Specialists, Inc.

The influence of uncontrolled leakage of conditioned air through the building envelope on the cost of operating the building, and the value of air leakage control is discussed. The case for controlling air leakage is made by discussing the results of a detailed before-and-after study of two electrically heated high-rise apartment buildings in Toronto and Ottawa. Peak space heating demand was reduced in the two buildings by 8.5 and 11 per cent per sq m of floor space. 6.5 and 12 per cent per sq m/year after upgrading the building envelope also cut heating energy consumption. The upgrading included windows, exterior doors, and gaps behind baseboards, shafts and several vertical penetrations. Additional tests showed that with due respect to the need for mechanical ventilation, the upgrading produced no negative impact on comfort or air quality in either building. Specifications for air barrier materials, and various air leakage predictive programs such as the modified Public Works Canada EC 128 and the ALCAP (air leakage control assessment procedures) originally developed by Ontario Hydro.

187. Wray, C.P. 1991. *Computer Simulation of the Transport of Soil Gas, Indoor Air, and Atmospheric Air into Subslab Venting Systems*. Winnipeg, Canada: G.K. Yuill and Associates Ltd. August.

The effectiveness of subslab ventilation systems in reducing indoor radon levels, and their potential for creating foundation problems, wasting energy and creating troubling or dangerous indoor depressurization were studied. A computer program was used to simulate the flow of air and radon through a house and the soil surrounding it for fifteen cases. These cases considered different combinations of three radon mitigation systems (subslab depressurization, subslab pressurization, and basement suction), a large and a small separation width between the basement wall and backfill, a soil air barrier at grade level, and two subslab ventilation system flow rates. Of the three systems, subslab depressurization was found to always work best. With a small separation between basement wall and backfill, or with the soil air barrier installed, most air removed came from the basement and not from the soil, so that freezing of soil under footings is unlikely. However, sufficient depressurization occurred that furnace back drafting might occur, or excessive outdoor air might be drawn into the house. Providing combustion air to the furnace, tight basement sealing, and optimization of system flow rate could mitigate this.

188. Zumoberhaus, M. *Concepts for an airtight building envelope in wooden houses,* (Original: Konzepte fuer eine luftdichte Gebaeudehuelle im Holzbau. Eidgenoessische Material pruefungs and Versuchsanstalt fuer Industrie, Bauwesen und Gewerbe, Duebendorf, Switzerland)

An excessive air permeability of the building envelope in many representative wooden buildings was the starting point of a comprehensive investigation funded by a government impulsion program for better wood utilization. It was known that air leaks cause discomforts and uncontrolled heat losses, which can lead to sizeable damages to the buildings due to the condensation of moisture in walls and roof constructions. The project was limited to a period of 3 years and investigated the planning and execution of the building envelope. Various concepts to prevent air leakages and their consequences for materials as well as construction procedures have been evaluated. In a first phase, measurements of the air leakage have been performed on 42 buildings that are mainly wood or wood/brick constructions and some concrete/brickwork houses without wood. To evaluate the long-term effectiveness of air leakage reduction measures and -materials, 9 of these buildings have been checked again after carrying out the upgrading. The measurement of the air permeability was performed by the so-called 'blower door method to provide the n_L value, and was supported by simultaneous infrared thermography to find the major leakage spots. In one building the natural air exchange n_L was also evaluated by means of the tracer gas method (using N_2O) and registering the decline of concentration. The results have shown that low air leakage characteristics can be achieved securely, if a clear concept of an air leakage barrier is carefully executed on the building site