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Task 2: Literature Review: Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates

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M.N.A. Saïd

December 2006

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PERD-079 - Engineered Building Envelope Systems to Accommodate High Performance Insulation with Outdoor/Indoor Climate Extremes

Task 2: Literature Review

Building Envelope, Heating, and Ventilating Practices and Technologies for Extreme Climates

M. N. A. Saïd, Ph.D., P.Eng.

Institute for Research in Construction
National Research Council Canada
Ottawa, Ontario, Canada

December 2006

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This report presents a review of literature. The views reported are those expressed in the original documents and do not necessarily reflect the views of the Institute of Research in Construction of the National Research Council Canada.

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List of Acronyms

ach	Air changes per hour
ACHP	Alaska Craftsman Home Program
ASHRAE	American Society of Heating, Refrigeration and Air-Conditioning Engineers
CFCs	Chlorofluorocarbons
cfm	Cubic feet per minute
CHBA	Canadian Home Builders' Association
CMHC	Canada Mortgage and Housing Corporation
EBN	Environmental Building News
EDU	Energy Design Update
EIFS	Exterior Insulated and Finish System
EPDM	Ethylene propylene diene monomer
EPS	Expanded polystyrene
fpm	Feet per minute
HCFCs	Hydrochloro-fluorocarbons
HDD	Heating degree day
HRV	Heat recovery ventilator
HUD	US Department of Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
ICF	Insulating concrete form
L/s	Litres per second
MDO	Medium density overlaid plywood
m/s	Metres per second
NoRTH	Northern Research and Technology
NRC	National Research Council
NWT	Northwest Territories
OSB	Oriented strand board
ppm	Parts per million
PVC	Polyvinyl chloride
RH	Relative humidity

SIP	Structural insulated panel
VDP	Vapour diffusion ports
VOC	Volatile organic compounds

Executive Summary

Canada's regions north of 60 degrees of latitude occupy over 70% of the nation's area, but are populated by less than 1% of the nation's population. Housing designs in Northern Canada are imported from southern regions. As a result, building durability is poor, which affects the quality of the built environment and energy budgets as well as the global environment. The Heat and Moisture Performance of Envelopes group of the Building Envelope and Structure program of the National Research Council of Canada, has started a four-year project to develop durable, energy-efficient wall assemblies that can accommodate the challenges of environmental conditions in Northern Canada as well as along northern coastal regions.

The main objective of Task 2 of the project is to provide a knowledge base for selecting building envelope assemblies to investigate in the analysis tasks of the project. This includes conducting a global literature search to identify technologies, practices, and issues for buildings subjected to extreme environmental conditions. This report documents the findings of the literature review, which includes significant information on practices, issues, and technologies regarding building envelopes, construction, heating, ventilating, indoor air quality, utilities, and socio-housing issues. The literature review also includes example building constructions from the arctic, Antarctica, Scandinavia, the Himalayan region, Japan, as well as indigenous architectures' climate adaptation.

Climate Outdoors
Climate in the arctic and sub-arctic regions varies considerably, particularly, above and below the tree-line regions. Variations include the snow drifting pattern, wind, temperatures, annual amounts of sunshine, and daylight. For example, in the NWT, temperatures range from -45ºC (-49ºF) in winter to 35ºC (95ºF) in summer. Precipitation is mainly in the form of snow with an annual range from 140 mm (5 ½ in.) in Hay River to 425 mm (16 ¾ in.) in Inuvik. High winds and blizzards are common. Daylight, in particular, is extremely variable. It ranges from almost 24 hours of daylight daily in summer with the sun setting just before midnight and rising a few hours later, to very little daylight in winter. In Alaska, low temperatures can range from -57ºC (-70ºF) for weeks in interior areas to -34ºC (-30ºF) in south central and western areas and last for extended periods. Wind speeds in excess of 200 km/h (125 mph) are common.

The maritime climate, dominated by ocean influences, is humid and temperate. Precipitation occurs in all seasons, and might change by the hour. The weather could come from any orientation. Summers are cool and short. Winters are mild and short with some frost but not continuous snow. Spring and fall are extended in length. There are small differences between monthly mean temperatures.

Climate Indoors
As an example, indoor air temperatures in NWT homes averaged from 21ºC to 28ºC (70ºF to 82ºF), RH ranged from 9% to 46%, with an average of 25%, and air change rates varied from 0.042 ach to 2.2 ach. A 20% RH indoors is considered optimum during an

arctic winter. Occupants' discomfort might increase at a RH less than 20%. RH above 20% could lead to condensation.

Selecting Building Envelope Assemblies for Northern Canada

Criteria are based on the following challenges for building construction in Northern Canada.

- **Harsh environmental conditions:** Prevalent low temperatures, wind, and snow drifting conditions exist during the long winters. This leads to large temperature differentials between indoors and outdoors. Extremely variable daylight conditions range from a few hours a day in winter to constant bright sunshine in summer. Snow drifting patterns, winds, temperatures, and the annual amount of sunshine vary throughout the region.

- **Lifestyle**: The North features a wide range of cultures and lifestyles, some of which can generate considerable moisture indoors.

- **A short construction season:** Measured in weeks, the season is characterized by high transportation costs and difficulties due to the landscape and remoteness of the region. The availability of skilled labour and equipment, and the high energy costs are also problems.

Current Wall Systems - Northern Canada

Wood frame systems are common in Northern Canada. These systems use 38 x 139 mm (nominal 2 x 6) timber framing; mineral wool or fibreglass batt insulation in stud spaces; air, vapour, and weather barriers; and plywood or oriented strand board (OSB) sheathing. Semi-rigid insulation might be used over vertical strapping. Galvanized steel siding is common. In some regions, structural panel siding of engineered wood strands replaces sheathing and is nailed directly to the studs. Structural insulated panel systems (SIPs) have also performed well in northern Canada.

Specific design strategies are required for each locale in Northern Canada, because of the variation in environmental conditions. Foundations and envelopes that are wind and snowdrift resistant are design essentials north of 60 degrees. Buildings incorporate expansion joints to compensate for structural movement due to large temperature variations from winter to summer. Walls, floors, and ceilings are insulated and windows are triple-glazed sealed units with low-e coating and insulated preferred frames are PVC, vinyl, or fibre reinforced plastic.

Roof

Avoid stepped roofs, offsets, nooks, or parapet walls to prevent accumulation of snowdrifts. Use a sloping roof section to connect two roof levels. Metal roofing has performed satisfactorily. Skylights are not recommended unless they are designed to control condensation. Preferred minimal eave projections range from 200 to 600 mm (8

to 24 in.) in areas below the tree line and from 100 to 200 mm (4 to 8 in.) in areas above the tree line. Below the tree line, ventilated roof systems perform well. Above the tree line, roof venting is problematic. It is difficult to avoid snow infiltration through vents. Incorporate drains for melted snow.

Foundations
Incorporate strategies to minimize the impact of the building on the thermal equilibrium of the permafrost and reduce snowdrift accumulation. A common strategy is elevating the building about 0.9 to 1.2 m (3 to 4 ft.) above the ground. A Swedish study concluded that a 1.8 m (6 ft.) elevation worked well in Antarctica.

Daylight Extremes
In winter, harness any daylight available through large windows, clerestory windows, and strategically placed skylights. In summer, latticed window screens are used to block the sun's rays. Window shading devices are optimized using solar angle calculations, to block excessive daylight and solar heat gain of the summer high sun and maximize the entry of the low winter sun.

Construction
Considerations are given to the availability of labour and equipment as well as the speed of construction.

Wall Systems to Consider

Northern regions: General considerations for building envelope assemblies include super-insulated (based on a target annual energy budget according to the regions' climate and challenges), airtight, and breathable assembly. The availability of material, construction equipment, and labour as well as construction methods that encourage local participation are additional considerations.

- **Double stud walls** consist of a load-bearing wall and a lighter non-load bearing wall supporting exterior siding or interior drywall. Additional insulation is added in the space between the two walls. Wall thickness depends on the insulation level to be determined with energy optimization analysis based on a target energy budget. Variations in the double stud walls approach include the double 38 x 89 mm (nominal 2 x 4) stud walls system and standoff walls in which one wall is constructed with truss studs designed to accommodate the required insulation. The wall placement is offset relative to the interior stud wall (38 x 64 or 38 x 89 mm / 2 x 3 or 2 x 4 framing) to cover the edge of the floor slab to minimize its thermal bridging.

- **Structural insulated panels** are factory manufactured with a polystyrene, polyurethane, or glass fibre insulating core sandwiched between wood panel sheathing, waferboard, or drywall. May include stiffeners for more panel rigidity. Panels could be installed over timber frame of wall or roof systems as sheathing.

- **Concrete wall systems** use insulating concrete forms that provide the formwork for the concrete, insulation, and sheathing.

Coastal northern regions: For the high-moisture climate in coastal northern regions, key criteria for building envelope assemblies include the ability to handle as well as withstand wetting spells with little impact on the assembly durability. Examples include thermally upgraded rain screen systems consisting of a 38 x 139 mm (2 x 6) stud wall with blown-in insulation in the stud spaces, exterior breathable insulating sheathing board, a vented air space, and cladding.

Concepts to consider from:

- **The advanced wood framing technology:** To conserve timber materials, use 38 x 89 mm (2 x 4) lumber for cripples and jack studs, 38 x 89 mm (2 x 4) lumber for the bottom and top plates, and drywall clips at the corners to eliminate three-stud corners.

- **Indigenous adaptation principles:**
  - Wind-shedding characteristics of the dome architectural form of the igloo reduce erosion of envelope surfaces, accumulation of snowdrifts, and heat loss.
  - **Damp maritime climate conditions:** Use masonry walls or stucco over earthen or adobe walls. For wood, apply protective paint. In northern coastal areas, use large windows to harvest daylight to compensate for overcast skies. Incorporate windows in all directions to provide daylight and summer ventilation. Use window shutters or storm windows to protect against storms and winter cold.
  - **Integrate heating and cooling comfort appliances with building design.**

- **Passive house standards:**
  - Determine the wall insulation level, hence the wall thickness, based on an energy optimization analysis for a target energy budget. As a guide, the European *passivhaus* construction guidelines specify heating energy budgets in the range 10 to 20 kWh/m² for Central Europe.

    Comparison of RSI (R) for Super-Insulated Building Envelopes and Current Practice in Northern Canada

	Super-Insulated Envelopes	Northern Canada Current Practice
Walls	7.0 to 10.6 (40 to 60)	5.0 (28)
Roof	10.6 to 14.1 (60 to 80)	7.0 to 7.7 (40 to 44)
Floor	5.3 to 10.6 (30 to 60)	5.4 to 9 (31 to 51)

  - Use a two-layer insulation approach to reduce thermal bridging.
  - Use two layers of drywall in the interior face of walls for storing heat.
  - Avoid penetrating the building envelope to reduce energy losses as well as not to weaken moisture control barriers. Avoid installing electric boxes or wiring in the exterior walls. For outdoor lights, use wireless battery-operated fixtures in shallow surface-mounted boxes.
  - Consider a south-facing single plane style for the roof.

1. Introduction

Background

Canada's regions north of 60 degrees of latitude occupy over 70% of the nation's area, but is home to less than 1% of the nation's population. Attention has focused on energy efficiency in northern housing designs, with little attention to the suitability of the house to the northern life style. In his textbook introduction, Strub (1996) pointed out that poor building durability in the arctic and antarctic regions is due to the lack of home-grown design and the local construction industry. Polar regions imported copies of building designs from the mid-latitude regions (40 to 60 degrees of latitude). Imported designs solved some problems but created others. When buildings do not fit the need of the occupants, they are poorly cared for and the buildings' service life is shortened considerably. Some buildings lost their service life in the first five years with moisture as the prime factor. Poor durability of building envelopes affects the quality of the indoor environment and the buildings' energy budget which, in turn, has a negative impact on the global environment.

Several challenges face building construction in the north of 60 regions.

- **Harsh environmental conditions:** Low temperatures, wind, and snow drifting prevail during long winters. Large temperature differentials occur between indoors and outdoors. Extremely variable daylight conditions range from a few hours a day in winter to constant bright sunshine in summer. Snow drifting patterns, wind, temperatures, and annual amounts of sunshine vary throughout the region.

- **Lifestyle**: The North features a wide range of cultures and lifestyles, some of which can generate considerable moisture indoors.

- **Building construction season:** Measured in weeks, the season is characterized by high costs of energy and transporting building materials due to the landscape and remoteness of the region. The availability of skilled labour and equipment is a problem.

The Heat and Moisture Performance of Envelopes group of the Building Envelope and Structure program, of the National Research Council (NRC), has started a four-year research project to develop durable, energy-efficient wall assemblies that can accommodate the challenges of environmental conditions in Canada's northern regions as well as northern coastal regions. The main objective of Task 2 of the project is to provide a knowledge base for selecting building envelope assemblies to investigate in the analysis tasks. The approach of Task 2 includes conducting a global literature search to identify technologies, practices, and issues for buildings subjected to extreme environmental conditions.

The literature search resulted in over 100 documents. This report identifies the finding of the literature review, which includes significant information on practices, issues, and technologies regarding building envelopes, construction, heating, ventilating, indoor air quality, utilities, and socio-housing issues. The literature review also includes examples of building construction from the arctic, Antarctica, Scandinavia, the Himalayan region of India, Japan, as well as indigenous architectures' climate adaptation. The report is organized according to building envelope technologies; heating, ventilation, and energy technologies; and socio-economic issues.

Materials: Temperature and Moisture Effects

Moisture issues range from some surface condensation on windows to severe cases that result in decay of the structure. Between these extremes, moisture issues could manifest as stains, peeling paint, leaks, or mould growth on the interior finish. Hutcheon (1960), Wilson (1960), and Hansen (1984) emphasized that winter condensation is probably the most common moisture-related problem affecting houses in Canada. Hutcheon explained that low outdoor temperatures in winter give rise to condensation on and in walls and windows, and tend to produce low relative humidity indoors. Even moderate humidity inside buildings can produce wetting by condensation on and in the building envelope components, because of the large temperature gradients within the building envelope in a Canadian winter.

Hutcheon and Handegord (1989) discussed the effect of temperature on building materials. The influence of temperature on building materials depends on the rate of change in temperature, material properties, and the material's moisture content. For dry homogeneous building materials, slow changes in temperature have little effect. Rapid temperature changes resulting in internal temperature gradients could produce stresses and strains, because of thermal expansion and contraction and, in extreme cases, could lead to fracture of the material if it is restrained. The breakage of window glass due to cooling at the edges is an example of this case. Plastic materials, however, do not fail when restrained, because they have low moduli of elasticity.

For porous materials, the degree of moisture saturation at the time of freezing is a critical factor. Freeze–thaw cycling combined with high moisture levels greatly increases the risk of frost damage to porous materials, such as masonry. For example, the risk of frost damage is high when the masonry moisture content is more than 75% by pore volume. The risk of frost damage also depends on the rate of freezing and on the pore structure of the material. Rapid freezing that does not allow for moisture redistribution within the material could lead to crack development and spalling.

Corrosion, a chemical reaction, of metal materials also depends on the temperature. In the cold climate, the influence of temperature is in producing wetting conditions. Corrosion of metals depends on the length of time the material is exposed to high humidity over 80%. Corrosion could take place at a lower humidity if salt is present.

Moisture Issues: Wood Frame Construction
Canada Mortgage and Housing Corporation (1993) summarized moisture issues in Canadian wood frame house construction from 1975 to 1991.

- Construction practices in Canada's southern regions may lead to serious moisture problems when used in Canada's northern and coastal regions.
- High indoor humidity usually characterizes moisture-troubled houses.
- High indoor humidity is usually a result of a reduction in natural ventilation rates when flues are reduced or eliminated.
- Certain insulation practices that involve low permeability insulation sheathing can reduce the drying potential of wood frame walls.
- Material properties and the moisture-driving forces and transport mechanisms in wood frame walls are complex making it difficult to assess.

Canada Mortgage and Housing Corporation (CMHC, 1993) also summarized research needed for unresolved moisture issues in wood frame construction in Atlantic Canada. Research is needed to identify improvements to current practices for the application of low permeance insulating sheathing, and an examination of current sheathing system practices with regard to preventing air leakage into and out of insulation systems.

Moisture Issues in Northern Alberta
The Alberta Housing Division investigated the cause and solution strategies for condensation problems in rural northern Alberta homes (Lee, 1991). Many houses affected by moisture damage were built in the early 1980s. Condensation damage ranged from stains and mould growth, to deterioration of the building envelope. Some of the moisture-damaged homes were selected for monitoring of indoor temperature and humidity over the heating season of 1988-1989.

Moisture Condensation Causes
A combination of factors led to excessive condensation on wall surfaces and within the building envelope, which caused surface damage, rot, mould growth, and general building decay. There were several contributing factors.

- **Lifestyle of occupants:** This is the largest source of moisture (game preparation, boiling-based cooking style, washing and hanging clothes to dry, firewood storage, etc.). Moisture is often brought into the house by tracking in snow and water. An enclosed porch at the house entrance helps minimize this factor.

- **Building construction:** Southern home designs were adopted in the north without alteration. This resulted in a poorly insulated building envelope. Condensation occurred in the attic space, because of indoor air leaking through the attic hatch.

- **Heating and ventilation:** Wood-burning appliances are the most common. Heat distribution from such appliances is limited to the appliance location as it relies on radiation and natural convection currents to disperse. Also, the operation of the wood

stove is usually intermittent to conserve timber. Limited air circulation caused high humidity in bedrooms, bathrooms, and the kitchen particularly in room corners.

Moisture Mitigation Strategies

Criteria for the selection of mitigation strategies included those that did not require a lifestyle change of occupants, were relatively maintenance free, and economical. The following three mitigation strategies were installed and monitored. The three strategies lowered indoor humidity, but with various operation concerns.

- **Increase outdoor air intake of forced air furnaces:** In this strategy, furnace modifications to increase the outdoor air intake compromised the performance of the furnace.
- **Increase the stack effect induced air pressures for wood stove heated homes:** This strategy was too inconsistent, because of the effect of uncontrolled factors, such as wind and outdoor temperature conditions.
- **Install a make-up air unit with preheat and a variable flow rate, which supplies air directly to the living area:** This strategy (after working out some operation problems — noise, insufficient preheating capacity, and inadequate airflow rates) was found to be the most effective method to reduce indoor humidity and minimize condensation and resultant building envelope damage. The make-up air also improved indoor air quality and safeguarded against chimney back drafts. For a household of nine occupants, the cost of operation (fan and electric preheat) in 1991 was $15 per month.

Moisture Conditions in Buildings in Fairbanks, Alaska

Adkins (1996) discussed moisture conditions and the difficulties in controlling indoor relative humidity (RH) within recommended standards in the range of 25% to 60% in residential and commercial buildings in Fairbanks, Alaska. Difficulties included the dryness of ventilation air especially after cold outdoor air is heated to room temperatures and the poor design and construction of the vapour and thermal control of building envelopes. Standards requirements vary.

- **American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) standards:** 7 litres/second (L/s) (15 cubic feet/minute or cfm) per person.
- **The Uniform Building Code for Dwellings:** 7 L/s (15 cfm) per person, 2 air changes per hour (ach), or operable windows with openings of not less than 1/10 of floor area.
- **Alaska Craftsman Home Program (ACHP) ventilation standard:** 1/3 ach.

Adkins presented RH samples in buildings in and near Fairbanks. In residential buildings, humidity levels were much higher and mould problems more frequent than in commercial buildings. Average RH in 31 residential buildings was 37.4% and the range was 19% to 60%. The houses with RH in the range 19% to about 30% did not have condensation or mould problems: houses with RH of 36% to 60% had severe problems. In 23 commercial buildings, average RH was 13.5% and the range was 6% to 29% except in the University

of Alaska museum where RH was 45%. Adkins suggested 30% RH in buildings in Fairbanks was reasonable and achievable in residential buildings. In commercial buildings, 30% RH could be achieved by separating the construction process of the vapour and insulation from interference by the structure, electrical, mechanical, and finish materials.

Moisture Control: Northern Regions

Three types of barriers are needed in building envelopes in the north (CMHC, 1994-1):

- a wind or weather barrier on the outside of the envelope to protect the envelope from blowing snow and rain;
- an air barrier system to prevent exfiltration of indoor air through the envelope; and
- a vapour barrier, on the warm side of the envelope, to prevent water vapour from entering the envelope.

One material may serve as an air and vapour barrier provided it is located on the warm side of the envelope.

Impact of Improper Selection and Placement of the Vapour Barrier, Arctic
Carlson (1996) demonstrated how improper selection and placement of the insulation, the vapour barrier, and the lack of venting of wall assemblies could lead to building envelope deterioration due to condensation that usually becomes apparent five to ten years later. Moisture diffusion through the inner layer of the building envelope might condense near impermeable outer layers and freeze as the temperature drops below the dew point and freezing. Moisture accumulation and frost buildup will be much greater in northern climates, such as Alaska and Minnesota.

The examples included a retrofit of an impermeable exterior insulated and finish system (EIFS), which was applied on the exterior of an insulated wall in a building in Fairbanks, Alaska. A polyethylene vapour barrier was placed on the warm side next to the interior gypsum board, but because of imperfections, water vapour diffused into the wall, condensed, and froze near the inner face of the EIFS panel. As a result, the panel's fasteners corroded and the frost buildup caused some panels to protrude from the wall. Carlson attributed this damage to a lack of venting of the EIFS panels. Venting would allow excess moisture to drain or evaporate.

Carlson (1996) also presented a spreadsheet tool to assist designers and builders in the selection and placement of the vapour barrier, insulation, and venting in the building envelope assembly. The spreadsheet calculates dew point temperatures in insulated building envelope assemblies. As an example, Carlson used the spreadsheet to investigate moisture deterioration of a Fairbanks, Alaska, building. Carlson made the following recommendations.

- A dew point analysis should be conducted for each building envelope assembly based on local climate conditions. The calculations are particularly important for EIFS and other insulated assemblies retrofitted over insulated steel or wood framing.

- Thermal and vapour properties of building materials should be placed side by side in the same table.
- Insulated impervious building envelope assemblies should include adequate drainage and venting to foster evaporation and drainage of condensate should it occur.

Are Vapour Barriers Necessary in Norway?

Thue et al. (1996) discussed whether a vapour barrier is necessary for wood frame walls and ceilings in cold climate regions. Noting that the function of the vapour barrier is to minimize the diffusion of indoor water vapour into the wall/ceiling assembly (or outdoor water vapour in hot humid climate regions), some believe the so-called "breathing constructions" (i.e., wall assemblies with vapour-permeable components) have as good a moisture performance and contribute to better indoor air quality. Thue et al. argued that there are no general design recommendations regarding the requirements for vapour barriers in wood frame construction. For example, what limits of water vapour resistance are recommended for barriers on the cold and the warm sides of the insulation? Norwegian houses without a vapour barrier did not suffer moisture damage when the wall assembly was airtight [Comment: this is probably because the wall finish, e.g., a painted gypsum board performed the function of the vapour barrier, and indoor air leakage was minimized by the airtight assembly.] In Norway, a typical wood frame wall assembly consists of (inside to outside) the gypsum board or wood paneling wall finish; 0.15 mm (6 mil) poly vapour barrier or equivalent, placed on the warm side of insulation; 150 mm minimum thermal insulation (rock wool, glass wool, or loose fill cellulose fibres) in the stud space; a wind barrier (building paper, fibreboard, or gypsum board), and the ventilated exterior wood paneling. (Thue et al. noted that plywood sheathing, commonly used in North America, is not used in Norway.)

Because of the limited results of only two laboratory tests, Thue et al. (1996) could not provide a firm answer to the question of whether a vapour barrier is necessary for wood frame walls and ceilings in cold climate regions. The authors made the following conclusions.

- A wood frame building envelope with a 0.15 mm (6 mil) polyethylene vapour barrier on the warm side of the insulation could be considered "moisture safe" if it has no air leakage.
- The tests indicated that two parameters have to be considered in wood frame construction in cold climates: the vapour diffusion resistance (or vapour permeability) at the warm side of the insulation, and the ratio between vapour diffusion resistances at warm and cold sides (the vapour resistance ratio).

The values of these two parameters depend on the thermal resistance of the wall. Higher insulation levels would emphasize the requirements for a vapour barrier as potential condensation increases in the wall as the temperature decreases in the components on the cold side of the wall. A high vapour resistance ratio might compensate for a low vapour diffusion resistance on the warm side. Thue et al. presented the following design rules, but with caution because of the limited results.

Let Z_w is warm side vapour resistance, and
Z_c is cold side vapour resistance

$Z_w < 7500$ m^2 h Pa/g	use $Z_w/Z_c > 50$
$7500 < Z_w < 10\,000$ m^2 h Pa/g	use $Z_w/Z_c > 25$
$Z_w > 10\,000$ m^2 h Pa/g	use $Z_w/Z_c > 10$

No Vapour Barrier Case: Sweden

Levin and Gudmundsson (2000) conducted in situ measurements of the moisture content and temperature in walls, roofs, and floors in three houses in which the vapour barrier was replaced by more diffusive open materials. The objective of the measurements was to evaluate how this vapour barrier replacement might affect the risk of condensation in the building envelope. Their study was motivated by a tendency to replace the traditional polyethylene vapour barrier with more diffusive open materials, such as polypropylene fabric, due to a concern for the environment. The measurements were taken at the outermost part of the insulation layer of the building envelope assembly, every three weeks over a two-year period. Indoor temperature and relative humidity were continuously monitored. The in situ measurements were used to develop a one-dimensional transient moisture diffusion computation model to predict the moisture performance of building envelopes for various indoor moisture loads.

Measurements indicated that, for low indoor moisture loads, there was no immediate risk of moisture damage. Computations with indoor moisture loads of 2 and 4 g-vapour/m^3-air and the climate of Stockholm, Sweden, showed that moisture would condense in the wall assembly [see note in the box]. Also the risk of mould growth in the building envelope was feasible, because of prolonged periods of high relative humidity conditions that coincided with favourable mould growth temperatures. Similar computations of the pile-type foundation system showed that the risk for condensation is also high for moderate indoor moisture loads.

[Comment: The following table puts in perspective the moisture load values, 2 and 4 g_v/m^3 dry air, used by the authors. The values correspond to a quite dry environment indoors (10% RH at 22ºC/72ºF and 20% RH at 24ºC/75ºF).]

T (ºC)	RH (%)	w (g_v/m^3air)
24	50	11.4
	30	6.5
	20	4.4
22	10	1.9

Where w is humidity ratio g_v/m^3 dry air
Subscript v: vapour.

Levin and Gudmundsson concluded that the building envelope construction that replaces the traditional polyethylene vapour barrier with more diffusive materials, such as polypropylene fabric, is not recommended.

Wall with Satisfactory Moisture Performance for All Climates in United States

Burch et al. (1995) computed moisture performance of a wall assembly using 1995 construction practices in prefabricated housing, and two proposed alternative wall designs (Figure 1) for both hot and humid, and cold climates. They used a one-

dimensional computer model (MOIST), which could only provide approximate average moisture performance for actual three-dimensional physical conditions. The authors noted that, during winter, more moisture might accumulate in the walls of prefabricated houses than those built on site, because they are fabricated tighter and thus have lower air infiltration rates and thus lower potential drying out of the wall. Table 1 compares the assemblies of prefabricated walls and the proposed walls.

Table 1. Assemblies of Prefabricated Walls: 1995 Practice and Proposed Walls by Burch et al.

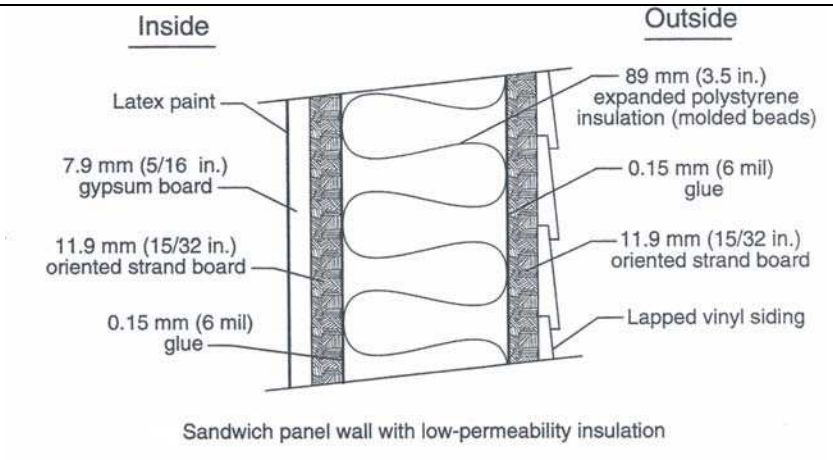
1995 Practice Wall Assembly	Proposed Wall # 1 (Variable-permeance-claddings wall)	Proposed Wall # 2 (Sandwich panel wall with low-permeability insulation)
Latex paint, vinyl wallpaper, or kraft paper	Latex paint	Latex paint
7.9 mm (5/16 in.) gypsum board	7.9 mm (5/16 in.) gypsum board	7.9 mm (5/16 in.) gypsum board
	12.7 mm (½ in.) exterior grade plywood	11.9 mm (5/32 in.) OSB
89 mm (3.5 in.) glass fibre insulation	89 mm (3.5 in.) glass fibre insulation	89 mm (3.5 in.) expanded polystyrene insulation (molded beads)
12.7 mm (½ in.) fibreboard sheathing	12.7 mm (½ in.) exterior grade plywood	11.9 mm (5/32 in) OSB
Aluminum siding	Latex paint	Lapped vinyl siding

Vapour Retarder Requirement

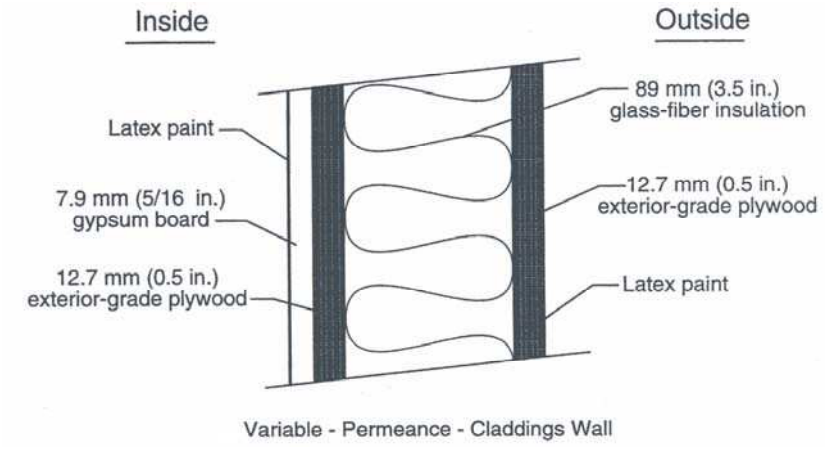
The 1993 Manufactured Home Construction and Safety Standards from the US Department of Housing and Urban Development (HUD) include the following moisture control practice rules for prefabricated homes.

1. Install an interior vapour retarder with a permeance of 57 ng/s m^2 Pa (1 perm) or less, or
2. use permeable sheathing and siding that has a combined permeance higher than 290 ng/s m^2 Pa (5 perm), or
3. provide an outdoor ventilated cavity between the siding and wall insulation.

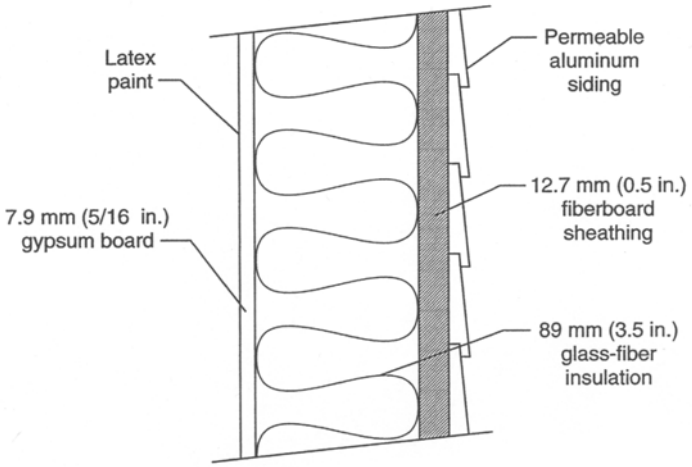
An interior vapour retarder is not required in prefabricated homes when one of the first two options is used. Burch et al. (1995) decided not to consider the third moisture control option, because literature showed that a ventilated cavity might provide poor moisture performance in both hot and humid, and cold climates. The authors considered the combined permeance of the fibreboard sheathing and the aluminum siding to be considerably greater than the 5 perm required by option 2 of the HUD standards. Therefore, the HUD standards do not require this wall to have an interior vapour barrier.



c) Proposed Wall # 2



b) Proposed Wall # 1



a) 1995 Current Practice

Figure 1. Assemblies of Prefabricated Walls: 1995 Practice and Proposed Walls by Burch et al. (Source: Burch et al. 1995, Figures 1 and 5).

Burch et al. (1995) called Wall # 1 the "variable-permeance-claddings wall," because the moisture behaviour of the plywood varies with ambient relative humidity. When the relative humidity is below 50%, the plywood behaves as a vapour retarder. When the moisture content of the plywood approaches saturation, it becomes very permeable.

Computations showed that, for Madison, Wisconsin, a manufactured wall assembly, built to 1995 standards without an interior vapour retarder and permeable sheathing, may not provide satisfactory moisture performance in a cold climate. The same wall but with an interior vapour retarder (vinyl wallpaper, latex paint, or kraft paper) showed acceptable performance in a cold climate such as in Madison, but as expected, performed poorly in a hot and humid climate, such as in Miami, Florida. The proposed wall assemblies with the "variable-permeance-claddings wall" and "sandwich panel wall with low-permeability insulation" both exhibited satisfactory moisture performance in both the cold and the hot and humid climates, even with moderately severe indoor conditions. The proposed walls also performed satisfactorily in a mixed climate, such as in Little Rock, Arkansas. Burch et al. concluded that the proposed wall assemblies would provide satisfactory moisture performance in all climatic regions of the United States.

Moisture Control: Coastal Regions

In coastal regions, deflecting or shedding rainwater off the façade is the first line of defence against rainwater entry into building envelopes. As a second defence, draining wet spells back to the outdoors reduces the length of time a material is exposed to water and thus lessens potential damage to the wall. As a secondary barrier, a weather barrier is used to block rainwater entry into the inner wall assembly while allowing for breathability of the wall to facilitate drying.

Weather Barrier

Canada Mortgage and Housing Corporation (2004) summarized a study that examined the effect of various factors on the performance of various weather barrier materials. These factors included the type of substrate, outdoor weathering, various extractives and surfactants, and fastener penetration. The study concluded that the weather barrier performed well when the wall assembly included a drainage cavity between the weather barrier and the cladding. The drainage cavity prevents water contact to the weather barrier on both sides, because when this occurred water was observed to travel through the weather barrier. [Comment: probably by the capillary action.] Aging, weathering, or mechanical stretching did not affect the weather barrier's pore size. The barrier did not function under some combination of weathering in the presence of wood extracts and other solutes as significant water was observed to pass through the weather barrier.

Drying the Wall Assembly

Joy et al. (1948) observed that ventilation of a wall cavity was effective in controlling condensation in certain cases, particularly when air movement in the cavity was not impeded. The use of vapour diffusion ports (VDPs) is a drying strategy that has been used in the lower mainland of British Columbia (CMHC, 2002-1). The concept involves creating one or two holes 75 mm (3 in.) diameter in the sheathing at the top and bottom of stud spaces. These holes allow vapour in the stud space to dry to the outdoors.

Canada Mortgage and Housing Corporation (2002-1) described the laboratory assessment of a VDP drying strategy. The tests involved six wall panels. Each was 1200 x 2400 mm (4 x 8 ft.); 38 x 89 mm (nominal 2 x 4) J-grade lodgepole pine was used for the wall framing. (Lodgepole pine is a British Columbia native that was used by Native people to build tepees and lodges.) Two types of sheathing were used, oriented strand board (OSB) and Canadian softwood plywood (both were 12.5 mm (about ½ in.)). The walls were fully clad with stucco and insulated with RSI-2.5 (R-14) insulation in the stud spaces. Five wall panels had 19 mm (¾ in.) air cavities, and one had a 10 mm (about 3/8 in.) cavity. The study concluded that panels with VDPs dried faster than those without. Vapour diffusion ports can substantially enhance the drying of OSB-sheathed panels. Panels with VDPs had a substantially higher percentage of moisture loss, higher effective permeance, and lower percent moisture content in the sheathing and framing than in the same panels without VDPs. For the plywood-sheathed panels, VDPs had no substantial impact on the drying rate.

A study by Sherwood (1983) found that vent strips at the top of a wall with high R-value (RSI-4 (R-23)) and low-permeance sheathing resulted in increased air leakage with no benefit in moisture control.

2. Building Envelope Technologies

This section reviews literature on building envelope technologies and practices for extreme climates.

Canadian Technology

This section briefly reviews wall technologies that are considered a reference for thermal performance, air tightness, and construction quality.

The Canadian Home Builders' Association (CHBA, 2001) recommended that the selection of a wall system needs to be based on local climate and seismic conditions, the level of thermal performance required, market acceptance of the system, and material and skilled labour availability. In general, a properly constructed wall that is durable, structurally sound, and resistant to heat, air, and moisture flows would contain the following components:

- an external skin or cladding;
- a weather barrier;
- structural components (framing, sheathing, etc.);
- insulation;
- an air barrier;
- a vapour barrier; and
- an interior skin or finish.

Advanced Framing Technology

The Canadian Home Builders' Association (CHBA, 2001) encouraged the use of "advanced framing," which requires consideration of alternative materials and methods that provide economical and durable construction techniques. Conventional wood frame construction wastes considerable material and labour. Drywall problems are often caused by the differential shrinkage of pieces of lumber nailed together. Features of advanced wood framing include the following elements.

- Space studs 600 mm (24 in.), which saves lumber and allows for more insulation.
- If cripples and jack studs are needed, they only have to be 38 x 89 mm (2 x 4).
- Reduce the size of the bottom and top plate for material reduction. For 38 x 139 mm (nominal 2 x 6) construction, a 38 x 89 mm (2 x 4) bottom plate under a 38 x 139 mm (2 x 6) stud that is cantilevered out 50 mm (2 in.) is acceptable.
- Eliminate wall panel sheathing; instead use a 19 mm by x (nominal 1 by x) material or a T-shaped metal to brace the wall diagonally.
- Use drywall clips at corners to eliminate three-stud corners.

Upgraded Thermal & Air Tightness Wall Systems

The Canadian Home Builders' Association (2001) described wall systems with upgraded thermal performance and strategies to ensure air tightness as well as moisture performance as compared to conventional 38 x 139 mm (2 x 6) framing constructions. Similar wall systems are described in the builders' reference manual prepared by the Alaska Craftsman Home Program (ACHP, 1995):

- single stud walls with exterior insulating sheathing;
- single stud walls with interior strapping;
- double stud walls;
- standoff walls;
- rigid insulating core panel walls;
- stress-skin panels; and

concrete wall construction.

Single Stud Walls with Exterior Insulating Sheathing

A rigid or semi-rigid insulating sheathing board is added on the exterior (Figure 1), with a membrane or rigid air barrier system. A balloon-framing method could be used to reduce thermal bridging. For a 38 x 139 mm (2 x 6) framing, minor modifications to standard construction practices would include the following.

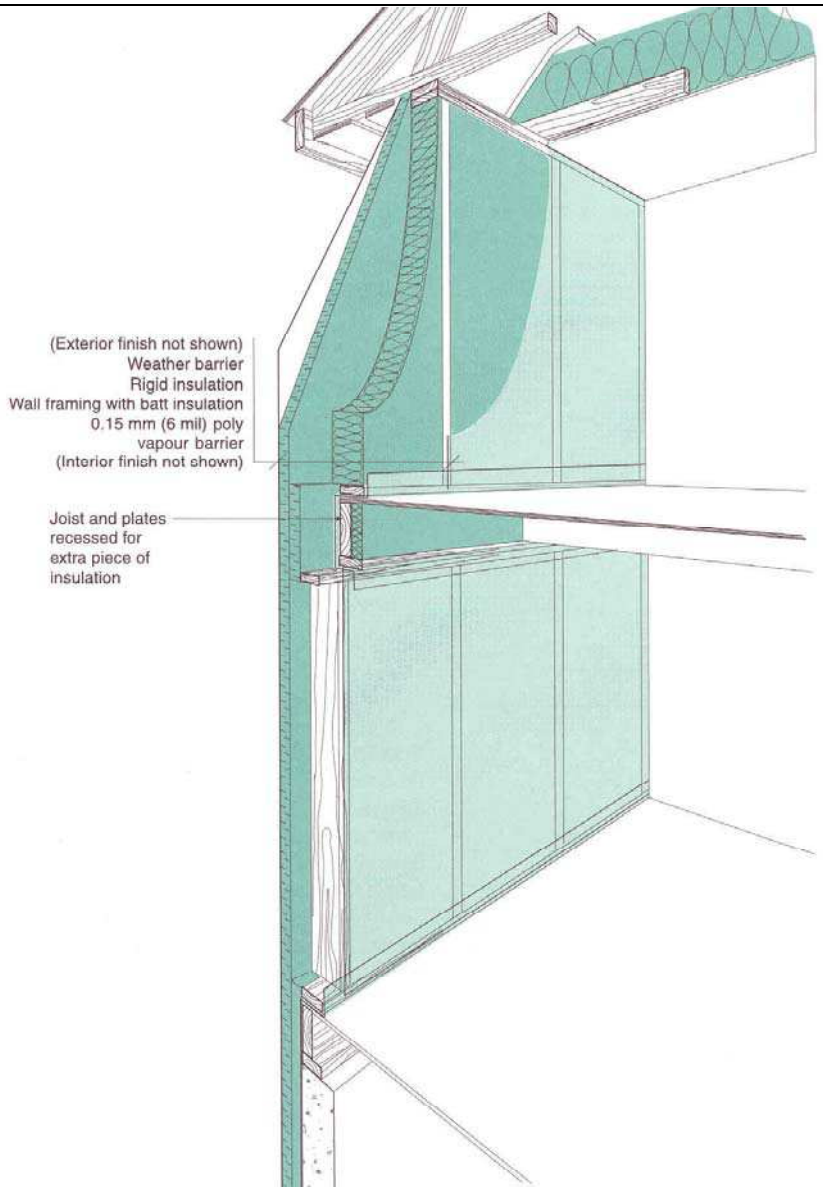
- Space studs on 600 mm (24 in.) on centres.

- Replace structural sheathing with diagonal wood or metal bracing and insulating sheathing, except where structure sheathing is required.

- Recess header joists to allow for higher insulation level at the joists.

- Install continuous vapour and air barriers.

- Upgrade insulation between the studs. Spray-type insulations provide a uniform insulation level and reduce air leakage. High-density spray-type insulations may provide higher thermal resistance per unit thickness than batt-type insulation.



Single stud wall with exterior insulating sheathing
(Source: CHBA (2001: 189, Fig. 11.9).

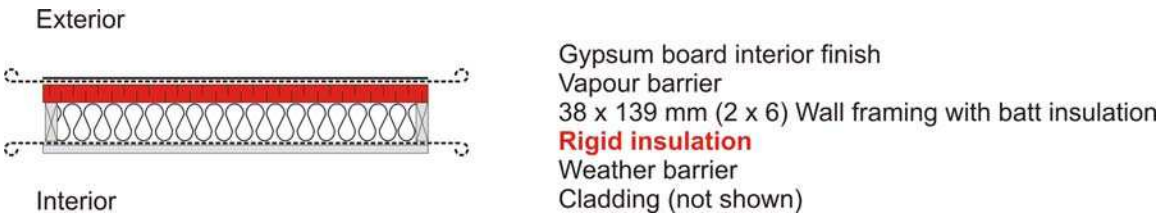


Figure 2. Thermally Upgraded Single Stud Wall

Source: CHBA (2001).

Single Stud Walls with Interior Strapping
First, 38 x 38 mm (nominal 2 x 2) or 38 x 64 mm (nominal 2 x 3) strapping is installed, usually horizontally on the interior of the stud walls. Either membrane or rigid air barrier system can be used. When polyethylene is used as a vapour and air barrier, it is usually placed on the inside face of the studs before the strapping. This approach has advantages: in addition to the RSI-3.5 (R-20) insulation in the 38 x 139 mm (2 x 6) main wall, RSI 1.4 (R-8) batt-insulation can be added in the 38 x 64 mm (nominal 2 x 3) strapped space, which would also reduce thermal bridging.

Double Stud Walls
This system (Figure 2) consists of a load-bearing structural wall constructed with conventional framing techniques, a lighter non-load-bearing wall that supports exterior siding or interior drywall, and either a membrane or rigid air barrier system. The wall thickness depends on the required R-value.

Insulation options include batt insulation. The centre cavity between the two walls, generally 89 or 139 mm (3½ or 5½ in.), will fit RSI-2.1 or RSI-3.5 (R-12 or R-20) insulation batts that are installed horizontally; batts are then installed vertically between the studs. Spray-in-place insulation can also be used. This includes foam, loose fill fibre, or cellulose insulation.

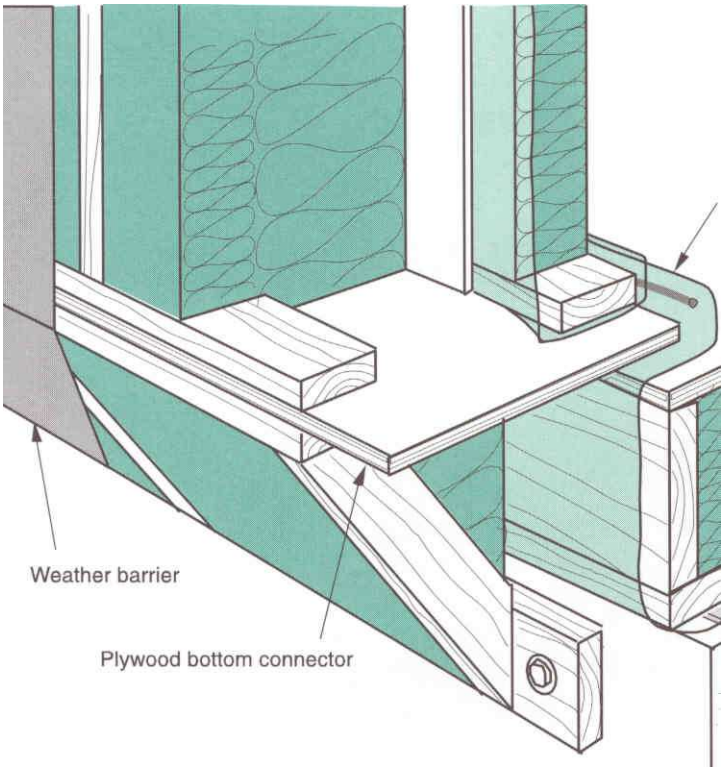
A double stud wall system provides for a flexible wall thickness to accommodate a high level of insulation, ensures a continuous air barrier throughout the building envelope, as it would not be penetrated by electrical or plumbing systems, allows for the use of smaller dimensional lumber, and reduces thermal bridging. However, a double stud wall system means higher labour and material costs. Platform framing techniques may also not be suitable for erecting the exterior wall. Two examples of a double stud wall system (Saskatoon House and Hanover House) are reviewed later in this section.

Standoff Walls
This system, as illustrated in Figure 3, is a variation of the double stud wall system. It consists of:

- a load-bearing interior wall constructed with conventional stud framing techniques (smaller dimension lumber can be used);
- sheathing on the interior of the stud wall;
- a non-load-bearing truss-stud exterior wall either site-fabricated or factory manufactured, designed to accommodate required insulation, is placed offset relative to the interior stud wall to cover the edge of the floor slab to minimize its thermal bridging; and
- either a membrane or rigid air barrier system. If polyethylene is used, it should be installed over the sheathing ensuring that there is sufficient insulation to the exterior to maintain it above the dew point temperature.

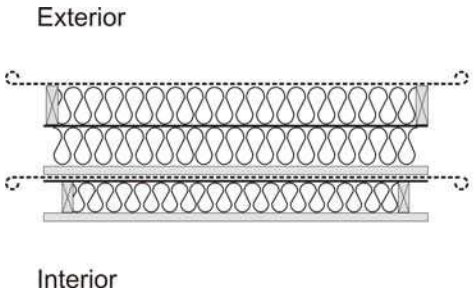
A standoff wall system can accommodate a high insulation level, ensures good air barrier continuity with minimum seams and penetrations, allows for the use of smaller

dimensional lumber and uses conventional stud framing techniques. However, in the truss stud wall, differential shrinkage between inner and outer truss members and the header joist can cause deformation and crack development in the interior finish material (e.g., drywall). An example (Illinois House) of a wall system using engineered floor I-beam as studs is reviewed later in this section.



Foundation wall/floor/wall junction of a double stud walls system.

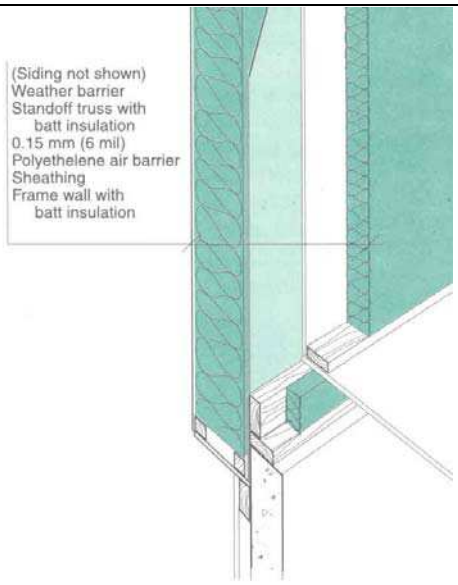
(Source: CHBA (2001: 197, Fig. 11.18).



Interior finish
38 x 64 mm (2 x 3) Structural wall with batt insulation
Air barrier
Sheathing
Batt insulation in cavity
38 x 89 mm (2 x 4) Framing with batt insulation
Weather barrier
Exterior finish (not shown)

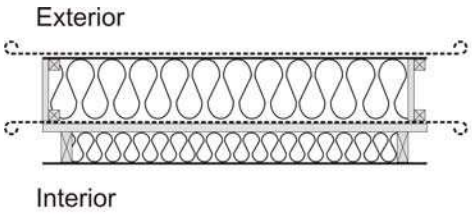
Figure 3. Double Stud Walls Assembly

Source: CHBA (2001).



Standoff wall system

Source: CHBA (2001: 202, Fig. 11.22).



Interior finish (not shown)
38 x 64 mm (2 x 3) Structural wall with batt insulation
Sheathing
Poly air vapour barrier
Standoff truss wall with batt insulation
Weather barrier
Exterior finish (not shown)

Figure 4. Standoff Wall System

Source: CHBA (2001).

Rigid Insulating Core Panel Walls

These systems use foam-insulated, factory-manufactured panels with locking details at the edges to ensure tight fit of joints. Various manufacturing methods are used to build the framing into the foam panel.

Advantages of rigid insulating core panel walls include uniform insulation, good air barrier continuity when joints are well sealed, reduced thermal bridging, and lower installation labour as the studs and insulation are erected together. Manufacturers can also reduce costs by recycling scraps. However, thermal bridging may occur through top and bottom plates, and the system requires accurate drawings and dimensions.

Structural Insulated Panel Systems

Also known as SIPs, these systems are stress-skin panels consisting of polystyrene, polyurethane, or glass fibre insulating cores sandwiched between skins of wood, wood panel sheathing, waferboard, or drywall. The panels come in a wide range of configurations depending on the insulating core, skin type, and the addition of stiffeners

for rigidity, and can be used as sheathing over a wall or roof or as the entire envelope of the house including structural elements.

Advantages of SIP panels include their uniform insulation, they provide a good air barrier continuity when joints are well sealed. The panels also save construction time. However, thermal bridging may occur through the top and bottom plates and vertical stiffeners if used, and the panels require accurate drawings and dimensions. The literature on SIPs and their application in Northern Canada is reviewed later in this section.

Concrete Wall Construction
These systems use insulating concrete forms (ICFs), which provide the formwork for the concrete, insulation, and sheathing in a single system. An ICF system saves construction time by combining the construction of the framing, insulation, sheathing, and air barrier elements into one step. This results in a good R-value and minimum thermal bridging. Little specialized labour or special tools are required, the forming material is lightweight, and there is less construction waste. However, changes are difficult to make on site once concrete has been poured, and the initial cost is high.

Best Practices in Wood Frame Envelopes
The Best Practice Guide - Wood-Frame Envelopes from CMHC (1999-1) addresses principles, practical features, and detailed considerations of constructing wood frame building envelopes across Canada, except along coastal British Columbia. Another best practices guide (CMHC, 2001) addresses wood frame envelopes in the high moisture climate of coastal British Columbia. The best practice guide (CMHC, 1999-1) provides details of three samples of wood frame wall assemblies.

Wall Assembly A: Common Basic Stud Wall
The wall assembly from exterior-to-interior consists of:

- brick veneer cladding, attached with galvanized brick ties nailed into the stud;
- an air space, 38 mm (1½ in.);
- 15 lb perforated asphalt building paper moisture or weather barrier;
- OSB sheathing, 11 mm (7/16 in.);
- wood studs, 38 x 139 mm (2 x 6) at 400 mm (16 in.) or 600 mm (24 in.) on centre;
- batt insulation or blown insulation in the stud spaces, RSI-3.5 (R-20);
- polyethylene air/vapour barrier, 0.15 mm (6 mil); and
- gypsum board, 12.7 mm (½ in.).

The foundation from exterior-to-interior consists of:

- a rigid mineral fibre drainage layer;
- damp proofing to grade: building paper, polyethylene, or asphalt impregnated building paper;
- a poured concrete foundation wall, 200 mm (8 in.);
- polyethylene moisture barrier, 0.15 mm (6 mil), perforated above grade;
- wood studs, 38 x 89 mm (2 x 4) at 600 mm (24 in.) on centre;
- batt insulation, RSI-2.11 (R-12);

- polyethylene air/vapour barrier, 0.05 mm (2 mil); and
- gypsum board, 12.7 mm (½ in.).

Disadvantage:

- Thermal bridging through the studs reduces the wall's thermal performance.

Wall Assembly B: Exterior Insulation System with Airtight Drywall
The wall assembly from the exterior to interior consists of:

- horizontal wood siding;
- vertical 19 x 64 mm (1 x 3) wood strapping;
- 38 mm (1 ½ in.) semi-rigid glass fibre insulation sheathing (RSI-1.18 (R-8)) with spun-bonded polyolefin laminated to the insulation face to function as a moisture barrier and the joints taped;
- 38 x 139 mm (2 x 6) wood studs at 400 mm (16 in.) or 600 mm (24 in.) on centre;
- RSI-3.5 (R-20) batt insulation, or blown insulation in the stud spaces;
- 12.7 mm (½ in.) gypsum board, functioning as an air barrier (airtight drywall approach); and
- vapour barrier, usually paint.

The foundation from exterior-to-interior consists of:

- a rigid mineral fibre drainage layer;
- damp proofing to grade;
- 200 mm (8 in.) poured concrete foundation wall;
- 0.15 mm (6 mil) polyethylene moisture barrier perforated above grade;
- 38 x 89 mm (2 x 4) wood studs at 600 mm (24 in.) on centre;
- RSI-2.11 (R-12) batt insulation;
- 12.7 mm (½ in.) gypsum board; and
- a vapour barrier, usually paint. An insulation-filled polyethylene pillow friction-fit between the joists can also be used.

Advantages:

- Compared to Assembly A, thermal performance is enhanced by increasing the insulation level and reducing thermal bridging at the studs.

- The glass fibre sheathing is highly permeable to water vapour and helps dry out the wall assembly.

Disadvantages:

- Air barrier gaskets need to be installed during framing.

Wall Assembly C: Exterior Airtight Sheathing Element System
The Canada Mortgage and Housing Corporation (1999-1) noted that this system has been used in a limited number of research buildings. The system shows promise for ease of construction and air-barrier performance. The guide proposes the system as an alternative approach to the common wood frame construction approaches.

The wall assembly from exterior to interior consists of:

- stucco finish cladding;
- self-furring lath;
- 15 lb. perforated asphalt building paper moisture barrier;
- sheathing consisting of two layers of 12.7 mm (½ in.) fibreboard sheathing with a spun-bonded polyolefin sheathing membrane (Tyvek®) sandwiched in between (also functions as air barrier);
- 38 x 139 mm (2 x 6) wood studs at 400 mm (16 in.) or 600 mm (24 in.) on centre;
- RSI-3.5 (R-20) batt insulation, or blown insulation in the stud spaces;
- 0.15 mm (6 mil) polyethylene vapour barrier; and
- 12.7 mm (½ in.) gypsum board.

The foundation from exterior-to-interior consists of:

- a moulded plastic drainage layer;
- damp proofing to grade;
- 200 mm (8 in.) poured concrete foundation wall, functioning as an air barrier;
- 15 lb. non-perforated asphalt building paper moisture barrier;
- 38 x 89 mm (2 x 4) wood studs at 600 mm (24 in.) on centre;
- RSI-2.11 (R-12) batt insulation;
- 0.05 mm (2 mil) polyethylene vapour barrier; and
- 12.7 mm (½ in.) gypsum board.

Advantages:

- This approach ensures continuity of the air barrier by locating it in the outside assembly. This approach also makes it suitable for the retrofit of existing structures.

- No special details are required for electric wiring, partitions, etc.

- The fibreboard sheathing is high water vapour permeable compared to plywood, OSB, foamed plastic, and laminated polyethylene-laminated fibreboard.

Disadvantages:

- This approach requires more labour and materials than assemblies A and B.

Building Envelopes: Northern Canada

Strub (1996) wrote a textbook, *Bare Poles: Building Design for High Latitude*, that provides strategies for designing buildings in Canada's northern regions. The textbook addresses the social and physical mix of peoples, terrain, climate, and building elements, and the constraints for high latitude regions. The book also includes climate charts for northern cities (e.g., Baker Lake, Broughton Island, Cambridge Bay, Fort Liard, Fort Simpson, Grise Fiord, Inuvik, Iqaluit, Rosulte, Yellowknife, and Whitehorse) as well as cities in southern regions for comparison (e.g., Edmonton, Halifax, Montréal, Regina, Sudbury, Toronto, Vancouver, and Winnipeg).

The web site of the Northern Research and Technology in Housing (NoRTH) <www.north-rthn.org> provides a centralized source of knowledge on housing construction in the northern regions. Topics address everything from building envelope components and mechanical systems to community issues and planning. The NoRTH is an association of northern and remote organizations that includes CMHC and the Alaska Housing Finance Corporation. The web site includes CMHC northern housing-related documents as well as case studies of the performance of super-insulated houses in northern communities.

CMHC's North Series

Canada Mortgage and Housing Corporation published a series of publications called the North Series (CMHC, 2001-2003), which includes eight publications that deal with both technical and socio-economic issues related to building technologies and practices for the climate conditions in Canada's northern regions. The series presents example technologies for the north, including the application of structural insulated panels, wastewater reclamation and co-generation demonstration projects, roof and foundation systems, integrated heating and domestic hot water, and guidance for building healthy housing in the north. The North Series complements the more in-depth North Research Reports by CMHC.

- *North Series # 1 Building with Structural Panels Repulse Bay* presents the performance of an application of SIPs in the northern community of Repulse Bay, Nunavut, as compared to the wood frame construction normally used in northern communities. The common wood frame construction uses dimensional lumber for structure, plywood or OSB for sheathing, and fibreglass batts for insulation. The SIP wall construction is described in detail below.

- *North Series # 2 On-Site Wastewater Reclamation Systems for the North* discusses the challenges of wastewater disposal and describes an environmentally friendly on-site wastewater technology for the north.

- *North Series #* 3 *Snowshoe Inn, Fort Providence Co-Generation Model* describes a co-generation demonstration project in Fort Providence, Yellowknife. The project combined heat and electric power generation for the community, and helped conserve energy resources.

- *North Series # 4 Residential Foundation Systems for Permafrost Regions* discusses the advantages, disadvantages, and anticipated life span and life cycle costs of various foundation options for northern climate conditions. Decision flow diagrams aid in the selection of the appropriate type of foundation depending on soil conditions and the availability of appropriate equipment and skilled labour. Foundation systems are described below.

- *North Series # 5 Eagle Lake Healthy House* provides guidance for building healthy housing in the north, and describes a house demonstration project in Eagle Lake First Nations, Northern Ontario. The house is described below.

- *North Series # 6 Arctic Hot Roof Design* presents an arctic roof design that can withstand northern environmental conditions, where there is little annual precipitation and prevalent blowing snow conditions in long winters. The arctic hot roof system has been used successfully in the north in houses and large buildings for about 15 years. Roof systems are described below.

- *North Series # 8 How to Prevent Plumbing and Heating Vent Stack Freeze-Up* presents strategies for preventing the freeze-up of plumbing and heating vent stacks. This is discussed in more detail in the next section.

- *North Series # 9 Fancoil Integrated Combination Heat and Domestic Hot Water Systems* describes the integration of the traditional two separate systems for space heating and domestic hot water into one energy-efficient system. This is discussed in more detail in the next section.

Building Envelope Examples, Northern Canada

The wood frame building envelope system is common in northern Canada. The wall assembly includes 38 x 139 mm (2 x 6) lumber for structure, plywood or OSB for sheathing, and mineral wool or fibreglass batt for insulation in the stud space as well as semi-rigid insulation over the wood strapping. An air barrier membrane is applied on the cold side of the insulation and a vapour barrier membrane is applied on the warm side of the insulation. Galvanized steel siding is common. In some areas, structural panel siding of engineered wood strands replaces sheathing and is nailed directly to the studs. The panels are prefinished and treated to resist moisture and fungal rot.

Wood Frame Assembly

The following are two examples of wood frame construction common in Northern Canada.

Nunavik, Quebec example: Angers (1999) described the wood frame construction used in Nunavik, an area consisting of one third of the Province of Quebec. To put it in perspective, Nunavik is the same size as all of France, and 1.5 time bigger than Japan.

- **Climate:** The Arctic climate in Nunavik is characterized by a long eight months of winter and temperatures that can reach -40ºC (-40ºF). Ground is permanently frozen (permafrost).

- **Transportation challenges:** Prefabricated construction materials are transported by boat from Montréal, which takes about seven days. Extra care is needed, because there is no port infrastructure in Nunavik.

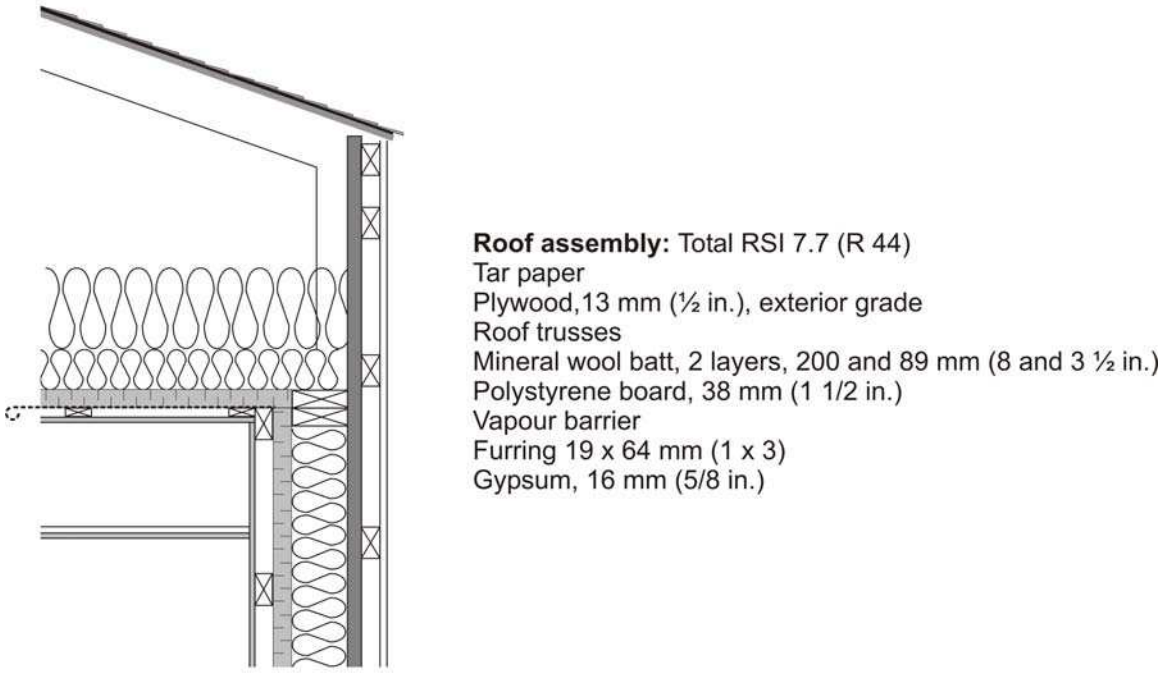


Figure 5. Ceiling Assembly, Nunavik, Quebec

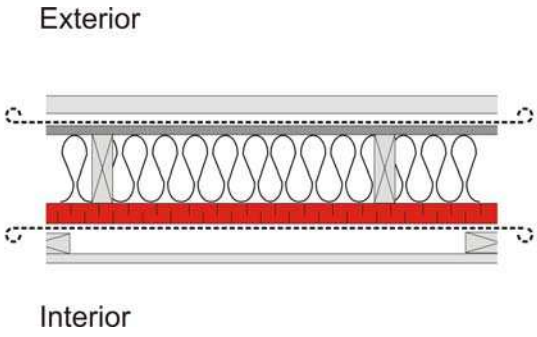
Source: Angers (1999).

- **Foundation:** Buildings are elevated on steel frames equipped with adjustable jacks. Elevating the building minimizes effects on the permafrost instability and reduces snowdrift accumulation near the building. Vegetation is also left intact under the compacted backfill, which helps to stabilize the terrain.

- **Wind and snow drifting:** Buildings are designed without eves and the roof slope is moderate (one in three) to prevent vibration during storms and excessive snow accumulation.

- **Roof:** The thermal resistance of the roof (Figure 4) is RSI-7.7 (R-44) as compared to RSI-7.1 (R-40) in southern Quebec.

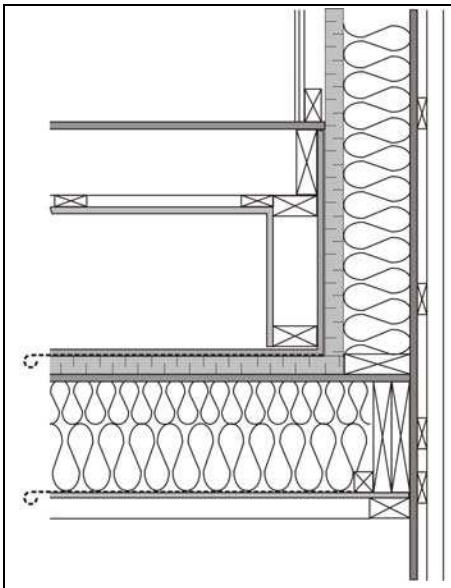
- **Exterior walls:** The thermal resistance of walls is RSI-4.9 (R-28) compared to RSI-4.5 (R-26) in southern Quebec. Figure 5 shows the assembly of exterior walls.



Galvanized steel siding
Furring - 19 x 64 mm (1 x 3)
Air barrier
Plywood - 9 mm
Studs - 38 x 140 mm (2 x 6)
Insulation wool - 38 mm
Vapour barrier
Furring - 38 x 64 mm (2 x 3)
Fireproof gypsum (16 mm)

Figure 6. Wall Assembly, Nunavik, Quebec

Source: Angers (1999).



Floor assembly: RSI-6.7 (R-38), double floor system
Aluminized gypsum, 13 mm (1/2 in.)
Vapour barrier
Polystyrene insulation, 38 mm (1 1/2 in.)
Plywood, 9 mm (3/8 in.)
Joists, 38 x 235 mm (2 x 10)
Mineral wool batt, 2 layers, 89 and 152 mm (3.5 and 6 in.)
Air barrier
Plywood, 19 mm (3/4 in.)
Furring on all joints 19 x 64 mm (1 x 3)

Figure 7. Floor Assembly, Nunavik, Quebec

Source: Angers (1999).

- **Floor:** The floor (Figure 6) is a double system, which creates a service chase for the air ducts of an oil heating system. The thermal resistance of the double floor system is RSI-6.7 (R-38) for public buildings or RSI-5.4 (R-31) for houses. In southern Quebec, RSI-4.7 (R-27) is required for floors.

- **Windows:** Triple-glazed windows provide thermal resistance of RSI-0.5 (R-3) as compared to double-glazed windows in southern Quebec. Window openings are reduced to a minimum.

- **Plumbing system:** To solve condensation problems, plumbing is insulated and, depending on the building's heating system, a glycol or warm air is used to heat pipes.

- **Porch:** Houses include an unheated, insulated porch at the main entrance to act as an air lock to keep cold air out when the door is opened, and also to minimize condensation.

Angers (1999) noted that a new approach is being tried in which building modules are prefabricated in a factory in southern Quebec and transported on barges to the north. The goal is to reduce completion costs on site.

Nunavut Example: A building envelope assembly adopted by Nunavut Housing Corporation (2005) consists of the following. A similar assembly is described in the builders' manual prepared by the ACHP (1995).

- **Exterior wall assembly:**
  - total RSI-5.1 (R-29), from exterior to interior;
  - prefinished structural panel siding[i];
  - air barrier; a complete house rap system;
  - wood studs, 38 x 140 mm (2 x 6) at 600 mm (24 in.) on centre;
  - mineral wool batt, 140 mm (5½ in.), RSI-3.9 (R-22);
  - poly vapour barrier, 6 mil[ii];
  - strapping 38 x 38 mm (2 x 2) at 600 mm (24 in.) on centre;
  - semi-rigid insulation, 38 mm (1½ in.) RSI-1.2 (R-7); and
  - gypsum board, 12.7 mm (½ in.), abuse resistant, painted.

- **Roof assembly:** Total RSI-7.7 (R-44), from exterior to interior;
  - metal roof;
  - strapping 19 x 64 mm (1 x 3) at 600 mm (24 in.) on centre;
  - air barrier;
  - plywood sheathing, 9.5 mm (3/8 in.);
  - joists;
  - mineral wool batt two layers, 150 mm (6 in.) RSI-3.9 (R-22) (fills void completely);
  - plywood sheathing, 12.7 mm (½ in), 3 mm (1/8 in.) gap at joints;
  - vapour barrier; and
  - gypsum board, 12.7 mm (½ in), abuse resistant, painted.

- **Floor insulated assembly:** Total RSI-9 (R-51), from interior to exterior:
  - vinyl tile;
  - underlay (6 mm (¼ in)) over 16 mm (5/8 in.) tongue and groove plywood (glue and screw/nail to floor joists);
  - floor joists;
  - mineral wool insulation, two layers 150 mm (6 in.), RSI-3.9 (R-22) (fill void completely);
  - strapping 38 x 38 mm (2 x 2) perpendicular to the floor joists;

- semi-rigid insulation, 38 mm (1½ in.), RSI-1.2 (R-7);
- air barrier;
- OSB, 9.5 mm (3/8 in.) plus 19 x 89 mm (1 x 4) battens at unsupported edges; and
- plywood sheathing.

The floor is elevated 910 mm (3 ft.) above the ground to reduce snowdrift accumulation. This space is also used to accommodate some utilities, such as fuel and sewage tanks.

Structural Insulated Panel System (SIPs)
SIPs are innovative building envelope systems, which are gaining wide acceptance particularly in sustainable construction, because they improve energy performance of building envelopes and reduce timber use, thus conserving natural resources.

These prefabricated wall panels consist of a wood framing system, typically spaced 1220 mm (48 in.) on centre and expanded polystyrene (EPS) insulation faced with OSB on both sides. The technology is not new. It was first used in residential construction in 1952 in Midland, Michigan in which foam-core SIP panels were used for exterior walls, interior partitions, and roofs (CMHC 2001-2003, North Series # 1).

Advantages: Whalen (2004), a manufacturer of SIPs, concluded that SIP and ICF (insulating concrete form) systems are viable for constructing energy-efficient building envelope assemblies compared to the common wood framing system with 400 mm or 600 mm (16 in. or 24 in.) on-centre studs. Advantages of the SIP and ICF systems include the following.

- There is a considerable reduction in thermal bridges through the wall.

- Savings are realized in timber use.

- There are favourable hygrothermal properties of EPS insulation used in the SIP and ICF systems. The closed-cell structure of EPS insulation provides high resistance to moisture absorption and stable R-value that does not decrease with the dissipation of the blowing agent. The EPS insulation is non-toxic and inert, and is environmentally friendly, because it is free of CFCs (chlorofluorocarbons), HCFCs (hydrochloro-fluorocarbons), and formaldehyde.

Repulse Bay Example: The CMHC's North Series # 1 (CMHC, 2001-2003) presented the field evaluation of a SIP system in Repulse Bay as an alternative wall system to commonly used wood frame construction that uses dimensional lumber, plywood or OSB, and fibreglass batt insulation. The Repulse Bay project demonstrated that:

- There is little difference in the cost of materials including freight between the SIP house and a comparable wood frame house. The cost of the SIP house was 2.4% higher.

- The SIP house required 264 hours of labour (about 45% less) compared to 480 hours for the wood frame house to make the building completely weather tight, such that construction work could proceed from the interior. Less outdoor construction time is important for the narrow window of favourable weather in northern regions.

- Semi-skilled labourers readily acquired the skills needed to build with SIPs. The workers received two days of training by a factory representative, who then left.

Post-occupancy inspections after the first year indicated that, unlike in the wood frame houses, there was no usual nail pops or drywall cracks. Structural movement was small. A fan door test showed the SIP house had 0.49 air changes per hour (ach) at 50 Pa (compared to 1.5 ach for a conventional R-2000-based house). For a 13-month period, the SIP house used 25% less heating fuel than similar-sized homes in Repulse Bay.

Similar to Whalen (2004), the North Series # 1 concluded that the Repulse Bay demonstration house indicated that SIP systems are suitable for northern house construction.

- The SIP system reduces structural framing, therefore reducing the potential for thermal bridging and also saves wood.

- On-site waste is greatly reduced, because SIP panels are precut to various sizes and shapes in the factory.

- The panels do not rot, shrink, swell, split, or warp to the extent that dimensional lumber does.

- The weight of SIP panels is about 35% less than the same size wood frame wall, floor, or roof assembly of the same R-value. The weight ratio of wood frame to SIPs increases as the insulation ratio increases.

- Panel construction using SIPS is faster than wood frame construction.

Example of unfavourable performance: In Juneau, Alaska, over 60 roofs five to six years old built with SIPs showed moisture problems, rotted, and required complete replacement (Andrews, 2001). The failures were thought to be due to a combination of wind-driven rain around plumbing stacks, water vapour diffusion through the roof assembly, and movement of warm moist indoor air within panel joints. There were no flaws in the SIP panels themselves. Poor workmanship (installation techniques and inexperienced installers) was the cause of the roofs' deterioration. Poor workmanship examples included joints that were not sealed well; custom foam wedges to be installed at ridges between SIPs were missing or substituted with scrap foam. There was not enough or missing adhesive; critical components, such as a vapour barrier, were missing; and OSB spline connectors were missing.

Investigators noted that the SIP is a good product, but needs to be properly installed. The detailing associated with SIPs must be installed right particularly in a climate like Juneau, Alaska with 90 inches (2300 mm) of annual rain and 9000 heating degree F days.

Thermal performance in laboratory studies: Laboratory tests suggested that a 100 mm (4 in.) thick SIP wall rated RSI-2.6 (R-15) outperformed a 150 mm (6 in.) thick wood frame wall insulated with fibreglass and rated RSI-3.3 (R-19) (EDU, 2001). The results were based on whole-wall R-value, which is considered to be more representative to field performance than the wall's rated value. The whole-wall R-value accounts for the thermal losses associated with framing (studs, headers, plates, etc.), which account for about 15% to 25% of the wall area. Thermal bridging accounts for about 13% loss in the whole-wall R-value of a 150 mm (6 in.) thick SIP wall compared to about 28% loss in the whole-wall R-value of a 150 mm (6 in.) thick wood frame wall. Table 2 compares the whole-wall R-value for a SIP wall and two wood frame walls.

Table 2. Rated and Whole-Wall RSI (R) Values of SIP and Wood Frame Walls

Wall Type	Rated	Whole Wall
100 mm (4 in.) thick SIP wall	2.6 (15)	2.5 (14)
38 x 139 mm (2 x 6) wood stud, fibreglass	3.3 (19)	2.4 (13.7)
38 x 89 mm (2 x 4) wood stud, fibreglass	1.9 (11)	1.7 (9.8)

Source: EDU (2001).

Based on whole-wall R-values, the R-value for a 100 mm (4 in.) thick SIP wall (R-14) is slightly higher than R-value (R-13.7) for a 38 x 139 mm (2 x 6) wood stud with fibreglass insulation. The study results suggest that upgrading to 100 mm (4 in.) thick SIP walls would be economically better than upgrading wall framing from 38 x 89 mm (2 x 4) construction to 38 x 139 mm (2 x 6).

Energy Efficient Houses, Northern Canada

Keewatin District Energy Efficient Housing Project
Seven high energy-efficient houses were built in Keewatin District, Northwest Territories, in 1980 and 1981 (CMHC, 1994-2). Design heat loss was 14% less than conventional housing, and air tightness was twice that of conventional construction. The ceiling, floor, and walls were heavily insulated: ceiling RSI-10.5 (R-60), floor RSI-8.8 (R-50), and walls RSI-7 (R-40). Thick walls, 27.9 cm (11 in.) were designed to accommodate the insulation. The thick walls also facilitated the construction of rigid and airtight joints at the floor and the ceiling. The foundation is a continuous-span laminated beam system that rests on a gravel pad. Several lessons were learned from the Keewatin District project.

- Inefficiencies in the space heating system detracted from the projected performance.

- The attached sunspace did not provide the expected benefits; overheating in summer and serving only as a windbreak in winter.

- Full height wall/roof trusses proved to be difficult to construct in northern conditions.

- Floor plans need to be developed in consultation with the intended occupants.

Hay River Energy-Efficient Housing Project
Five energy-efficient prefabricated houses were constructed in 1988 in Hay River, Northwest Territories (CMHC, 1994-3). Houses 1 and 3 are each 118.5 m^2 (1275 sq. ft.), and the remaining three are 129.6 m^2 (1395 sq. ft.) each. The houses were constructed close to R-2000 standards and monitored for one year. There was an unheated crawl space under the house as well as an unheated air lock entry.

- **Floor:** Insulated to a total of RSI-7 (R-40) of batt insulation. The floor assembly was constructed of 16 mm (5/8 in.) tongue and groove plywood that was glued at the seams to function as a vapour barrier. A 9.5 mm (3/8 in.) particleboard was glued to the plywood.

- **Walls:** Wall insulation, total RSI-4.9 (R-28), consisted of RSI-3.5 (R-20) batts and 38 mm (1 ½ in.) styrofoam.

- **Ceiling:** High-heel roof trusses were used that accommodate three layers of batt insulation for a total of RSI-10.5 (R-60).

- **Windows:** Double-glazed low-e windows were installed.

- **Doors:** Insulated metal doors with RSI-2.6 (R-15) were used.

- **Energy performance:** Energy consumption was 25% to 30% higher than predicted. The reasons noted included high indoor air temperatures averaging from 21ºC to 28ºC (70ºF to 82ºF), high air change rates up to 1.8 ach at 50 Pa, and high occupancy.

Design Considerations and Strategies

Building Practices for Northern Facilities
The publication, *Good Building Practice for Northern Facilities* (NWT, 2000) presents design considerations and guidelines for performance, materials, and construction methods for buildings and facilities. The technical guidelines are based on the proven successful performance of materials and construction methods in the northern climate. The guidelines are provided where more stringent requirements than the National Building Code and local municipal requirements are needed. The guidelines incorporate observations from builders, designers, operators, and users. The following review of the 2000 edition focuses on the additional requirements to the 1995 National Building Code.

- **Climate:** Conditions vary within the NWT, particularly, above and below the tree-line regions. Variations include the snow drifting pattern, wind, temperatures, and

annual amounts of sunshine. Temperatures: range from -45ºC (-49ºF) in winter to 35ºC (95ºF) in summer. Wind pressure hourly values range from 0.30 to 0.8 kPa. The climate is generally dry and precipitation is mainly in the form of snow. Annual precipitation ranges from 140 mm (5 ½ in.) in Hay River to 425 mm (16 ¾ in.) in Inuvik.

- **Building Envelope:** Thermal resistance varies from RSI-4.9 (R-28) for walls to RSI 7.0 (R-40) for the roof and floor. Moisture sources include snow, rain, ground moisture, and condensation. Air and moisture control requirements include the application of the 1995 National Building Code Part 5 (5.5, 5.6.1, 5.8). In addition, means of venting and draining the envelope to the exterior are required and the rain screen principle, as per *Canadian Building Digest* number 40 (Garden, 1963) needs to be applied.

  Multiple vapour barriers are to be avoided; low permeance material in the low vapour pressure side of the insulation must allow vapour to egress to the exterior. Unheated spaces should be avoided, particularly concealed spaces on the warm side of the vapour barrier. These should be heated to keep surface temperatures above the dew point.

  Air leakage control required the application of the 1995 National Building Code parts 5.4 and 9.25. Air barrier requirements are as per 1995 Part 4.1.8. of the National Building Code. Sealants must be serviceable to -50ºC (-58ºF). Maximum air leakage rates at 75 Pa (0.3 in. water) are as recommended by the 1995 National Building Code:
  - 0.15 litre/sec/m^2 (0.03 cfm/ft^2), typically for buildings with low occupant load or a dehumidifier;
  - 0.10 litre/sec/m^2 (0.02 cfm/ft^2), typically for schools, health centres, libraries, offices; and
  - 0.05 litre/sec/m^2 (0.01 cfm/ft^2), typically for residential, group homes, long-term care facilities.

- **Floors:** For elevated floors, common in northern buildings, apply building envelope requirements for air, water, and vapour control, including moisture drainage, ventilation, sealants, etc. Elevated floors have a potential for air leakage, snow infiltration, and water vapour diffusion. Basements or concrete foundations are possible in few locations and for certain uses. For permafrost sites:
  - Thermal breaks should be provided between foundations and bearing stratum to minimize heat loss from the building to frozen soils.
  - Artificial cooling of the ground can be used to maintain foundation-bearing capacity.

- **Roofs:** Apply building envelope requirements for air, water, and vapour control. Locating the structure inside the air/vapour barrier is recommended. For large buildings, this is cost effective, because condensation within a roof assembly has damaged roofs across the NWT. For small buildings in locations below the tree line, locating the air/vapour barrier on the interior of the roof framing is recommended. In

this case, a means of venting the roof space that minimizes snow infiltration is recommended.

Stepped roofs and offsets are to be avoided to prevent the accumulation of snow drifting that may cause excessive roof loading and wetting of walls and roof joints. If two roof levels are required, a sloping roof section should connect them. Parapet walls are to be avoided, because a parapet adds to snow drifting accumulation on the roof.

A ventilated roof system performs satisfactorily in locations below the tree line. Venting roof assemblies is problematic for locations above the tree line. It is difficult to avoid snow infiltration through vents. Wetting of the insulation and roof assembly occurs when conditions allow snow to melt. Drains should be used to drain melted snow.

Minimum eave projections are 100 to 200 mm (4 to 8 in.) in regions above the tree line, and 200 to 600 mm (8 to 24 in.) in regions below the tree line. Eavestroughs are to be avoided. Ice buildup makes them ineffective and causes damage during spring melt.

Skylights are not recommended unless shown to provide significant benefits and are provided with a means to control condensation. Clerestory windows are alternatives to skylights, but design should ensure they are clear of snow accumulation.

- **Doors and windows:** Door issues include heat loss, an RSI usually less than 1.8 (R less than 10.2) and air leakage at door edges. Here, the weather seal loses its flexibility in extreme cold, and doors are difficult to close properly due to the lack of alignment of the door and frame as a result of higher than normal use or structural strain on the walls caused by impact damage or foundation movement.

  Doors should be insulated metal, with a minimum RSI-1.3 (R-7.4). A vestibule between outer and inner doors is more practical than a storm door and saves energy. Vestibules also help keep warm interior air indoors. A storm door is considered impractical, because leaking warm air from the inner door could cause frost on the colder storm door, affecting the weather seal. Residential grade storm doors also wear out quickly from heavy use.

  Window recommendations include double or triple glazed sealed units with low-e coating. Insulated frame PVC, vinyl, or fibre reinforced plastic frames are preferred, because they are easy to maintain and no potential for damage by condensation. Metal windows with thermal break frames or wood windows are acceptable. The interior of the window frame should be on the warm side of the insulation. Wide interior window ledges should be avoided, because they reduce airflow over the glass, which could allow condensation or frost buildup on the window. Also, the window frame should straddle the plane of the air/vapour barrier.

- **Siding:** Materials should be durable, lightweight, and easily installed and removed with locally available trades. Materials considered to satisfy these requirements include plywood, exterior grade particle and oriented strand boards battened at the joints, and corrosion-protected ribbed sheet metal. Preservative-treated materials should be used only where continually high humidity is anticipated.

  Materials that are not recommended include metal siding, which is susceptible to damage from impact and cannot easily be repaired locally. In addition, aluminum siding is subject to large thermal expansion and contraction, and rippling. Vinyl siding expansion and contraction cause warping. Vinyl becomes very brittle in cold temperatures and is easily damaged on impact. Stucco is easily damaged on impact and repair materials are unavailable. Medium density overlaid plywood (MDO) is difficult to repair. Without back priming and edge sealing, the MDO's kraft paper surface is subject to delaminating and peeling at the edges.

- **Roofing materials:** Asphalt shingles are recommended in locations below the tree line, where the roof slope is 4 in 12 or greater, or 2.5 in 12 for fully tabbed shingles. Asphalt shingles are readily available, less expensive, and represent a lower fire hazard than wood shingles. The two-ply, torched-on modified bitumen membrane performs well under sub-zero temperatures, and repairs are relatively simple to perform. Metal roofing also performs well.

  Asphalt shingles are not recommended in locations above the tree line, because it is usually very windy and shingles could be blown off and are difficult to replace. Loose-laid rubber roofing (EPDM or ethylene propylene diene monomer) could allow moisture to travel between the membrane and the backing, making it difficult to trace leaks.

Northern Architectural Design Strategies

The following strategies are practiced by northern architects in adapting to the extreme climate, variable light conditions, and indigenous culture in northern Canada.

Diakun (1997) presented the work of a northern architect, Gino Pin, and provided examples of Pin's architectural strategies in response to the cultural needs of the First Nations and the harsh climate in northern Canada. Architectural design factors discussed include the following.

- **Harsh climate and daylight extremes:** Daylight, in Yellowknife, ranges from five dim grey hours in winter to constant bright sunshine in summer, when the sky may become red at dusk but never dark.

- **The indigenous culture of the First Nations.**

- **The natural environment of pristine land, wildlife, and northern lights:** For example, trees can take years to reach a significant size, because of the short annual growing season.

- **High energy and transportation costs.**

Architectural design strategies to address indigenous culture and the natural environment included the following.

- **Integrate a building with the natural surroundings to connect people to the land:** This approach is especially meaningful to First Nations occupants. This strategy includes using materials that merge with the landscape in colour and texture. For example, cast zinc panels textured similar to the rocky surrounding were used in a building in Yellowknife, because zinc weathers to a grey patina that matches the shades of the adjacent granite outcropping.

- **Incorporate traditional symbols and materials in the design:** For example, moose antlers were used for door pulls and bearskin was used for rugs.

- **Embrace an extensive consultation process with the First Nation:** For example, in the design of a seniors' housing complex in the Northwest Territories, the consultation process with the elders in the community was weekly and for a full year. The resulting design included clusters of rooms modelled on traditional family groupings, and separate smoke houses for treating meat, in the traditional way, on the ground.

- **Select a construction method that encourages local participation:** Native communities prefer log construction to the standard light wood framing, because log construction is viewed as culturally meaningful, reminiscent of life in the bush. Log construction has a long history among the First Nations, which they adopted from the early Europeans traders.

- **Use indigenous plants for landscaping:** These plants survive with little maintenance. Examples include fireweed and birch trees.

Architectural design strategies to address daylight extremes.

- **In winter, it is desirable to harness any daylight available:** Architectural strategies include clerestory windows and strategically placed skylights to allow natural light to penetrate into the central spaces of the building. A sequence of aligned glazed walls provide multiple layers of transparency throughout the interior space. This strategy allowed for light penetration into the interior space as well as for occupants to enjoy sight lines and view colours.

- **In summer, latticed window screens block sun rays:** The continual oblique rays fade exterior colours and cause glare and rapid heat buildup indoors.

Architectural design to address extreme climates included specific strategies for each locale in the Canadian north, because moisture conditions, extreme temperature differences, snow drifting, and permafrost vary considerably from east to west and from

south to north across the arctic. Pin's strategy is to work with the climatic conditions, rather than against them.

- **Snowdrifts:** The building is elevated above the snow surface. A series of portaled foundation walls channel blowing snow under the building and away from the building entrance on the leeward side. This strategy is based on experience and an understanding of snow drifting patterns in Northern Canada.

- **Ventilation:** Portholes are used to provide cross ventilation and enhance air movements in summer and winter without freeze up, jamming, or causing gusts.

Jen (2005) described another example of a northern architectural response to the extreme climate, daylight conditions, and the culture of the First Nations in Yukon. Daylight, in particular, is extremely variable. It ranges from almost 24 hours of daylight daily in summer with the sun setting just before midnight and rising a few hours later, to very little daylight in winter. In response to such challenges, the use of southern exposure benefits is optimized.

- Large windows with triple-pane, low-e glazing, and vinyl frames were used. Jen (2005) noted that vinyl-framed windows are economical, perform better than aluminum, wood, or steel in the extreme cold climate, and are manufactured locally.

- Shading devices made of 38 x 139 mm (2 x 6) cedar slats were used above the windows. The scale and spacing of the slats were determined using solar angle calculations. The spacing on the lower portion of the shading device was made much denser to block the excessive daylight and solar heat gain of the high summer sun while maximizing entry of low winter sun into the interior of the house.

Indigenous culture needs included round forms, the use of wood, striking colours and, most importantly, a strong connection to the land. The architectural response included:

- incorporating large (244 x 81 cm/96 x 32 in.) windows to link the house to its site;
- wood shading devices and exposed wood structural elements for colour warmness; and

corrugated galvanized siding cladding for colours and textures.

Foundation Design Considerations

Soil condition is an important consideration, because ground movements can cause cracks in walls, distortion in windows, doors, and floors, separated walls and floors, and damage to plumbing. This is particularly significant in the permafrost regions that underlie all of the Northwest Territories, Yukon, Nunavut, and portions of the provinces particularly Manitoba and Quebec.

Permafrost Characteristics and Challenges

Strub (1996) defined permafrost as the ground whose temperature remains consistently below the freezing point of water. The term "permafrost" describes the soil thermal regime, and not the soil type or the amount of water or ice in the ground. At high latitudes

as well as at high altitudes, where the mean annual temperature is below freezing, the ground temperature near the surface portion of the Earth's crust remains near or below the water freezing point indefinitely. The ground is perennially frozen to depths sometimes exceeding a thousand metres. A thin surface layer is thawed each summer by the around-the-clock sunshine.

Johnston (1965) described the characteristics of permafrost and its problems related to foundation design in Canada's permafrost region. Similar to Strub (1996), Johnston defined the term permafrost as the thermal condition of earth materials under which their temperature remains below 0ºC (32ºF) continuously for a number of years. Earth material includes sand, gravel, silt, peat, refuse piles, or bedrock. In far northern areas, permafrost existed for a long time in equilibrium with the climate, and possibly goes back to the cold period, the Pleistocene Era.

In Canada, most continuous permafrost is located beyond the tree line. Within the tree line, the permafrost may be a discontinuous island of perennially frozen ground surrounded by ground that freezes to a shallow depth in winter only to thaw again in the spring. The environment easily affects discontinuous permafrost islands. Two hot summers in a row or human-induced changes to the insulating properties of the ground surface are sufficient to change the dimension of the permafrost island. The delicate sensitivity of discontinuous permafrost to the environment is a critical consideration for the design of buildings foundations in Northern Canada.

Ground temperatures never exceed 0ºC. Fluctuations in air temperature produce corresponding fluctuations in ground temperature. The magnitude of the fluctuations is reduced with increased depth, because of the effect of snow and moss surface cover as well as the thermal characteristics of the soil. A time lag is introduced as the depth increases. Fluctuations become imperceptible at the level called "zero annual amplitude," that is, between 6 and 15 m (20 and 50 ft.) depth. Below the zero annual amplitude depth, ground temperatures change only in response to long-term climate changes extending over centuries.

The challenges associated with building in a permafrost environment include the following.

- **Freeze-thaw cycle:** The active layer consists of frost-susceptible soil and is saturated with moisture, because the permafrost is relatively impermeable. (Water cannot percolate through frozen soil.) The active layer freezes and thaws annually. As water in soil freezes, it expands, which increases the volume of the soil–water mixture. As ice in the soil thaws, the mixture volume shrinks. The heaving and settling caused by the changes in soil volume due to the freeze–thaw cycle could damage foundations and buildings.

- **Permafrost's delicate thermal equilibrium:** Permafrost is sensitive to thermal changes. Therefore, it is important that all construction operations not disturb the environment or the existing insulating properties of the ground surface at the site, which might affect the delicate thermal equilibrium of the permafrost.

- **Soil characteristics:** Frozen soil provides excellent bearing for a structure. When soil, usually fine-grained, thaws, it turns into slurry with little strength. This can lead to large movement, and the structure might fail.

Foundations

Johnston (1965) presented four approaches for foundation design in a permafrost environment. The results of site investigation will indicate the design approach and the construction technique to be used.

- **Conventional design and construction methods - I:** Permafrost conditions can be neglected when the site is well-drained granular soils or solid rock, because they contain little or no ice.

- **Conventional design and construction methods – II:** If it is not possible to preserve the frozen conditions, two approaches are possible: in areas where ground temperatures are close to 0ºC (32ºF), thaw and then consolidate the soil prior to construction, or remove the soil and replace it with compacted, well drained, non-frost-susceptible material.

- **Pile foundations:** Pile foundations in drilled holes to 4.6 to 9 m (15 to 30 ft.) depth could be used when the permafrost conditions can be preserved and thus could be used to support a structure. Ventilation or insulation can be used to preserve permafrost. Ventilation is commonly used with heated buildings. The structure is raised above the ground surface to permit air circulation beneath to minimize or prevent heat flow to the ground.

- **Flexible foundations:** In areas with anticipated settlement, flexible foundations can be used, which can be adjusted to eliminate structural deformation as differential settlement occurs. To ensure stability of the structure, special settlement joints could be incorporated, which permit individual sections of the building to move without causing deformations in adjacent sections.

Screw Piles Foundation, Permafrost, Alaska

Johnston et al. (1999) discussed the versatility and effectiveness of screw piling for building foundations in soils with inadequate bearing capacities for conventional concrete footings. Screw pile foundations are effective for supporting construction on low-bearing capacity materials, such as the peat and saturated marine silt deposit soil in Juneau, Alaska, that has inadequate bearing capacities.

The screw piling foundation method involves the use of a power head and pile driver to penetrate the permafrost active layer and insert bearings in the inactive layer. The screw piles consist of a plate or plates, formed into the shape of a helix or screw thread attached to a central shaft. Advantages of the screw piling method include the absence of impact and vibrations that may be harmful to adjacent buildings, as compared to driving wood or steel piles into the soil. Screw pilings are also quickly and easily installed at a lower cost than traditional methods.

Foundation construction in the permafrost regions in the arctic and antarctic are described later in this section. Other relevant Canadian building digests include the following.

- CBD-26 describes the physical processes involved in ground freezing and frost heaving (Penner, 1962).

- CBD-61 describes methods to avoid or alleviate problems resulting from differential heaving of freezing ground (Brown, 1965).

- CBD-81, with emphasis on large buildings, presents a selection of the type foundations best suited for a particular site (Legget and Crawford, 1966).

- CBD-128 deals with the mechanism of frost heave and adfreezing of foundations (Penner and Burn, 1970).

- CBD-182 explains causes of frost action and its construction problems, and presents solutions to control frost action (Burn, 1976).

North Series # 4 (CMHC 2001-2003) explains how to choose a foundation system, which could withstand northern climate conditions. North Series # 4 discusses the advantages, disadvantages, and anticipated life span and life-cycle costs of various foundation options. Decision flow diagrams are provided for selection of the appropriate type of foundation depending on soil conditions and availability of appropriate equipment and skilled labour. Foundation systems discussed include the surface foundation, pile foundation, rigid foundation, shallow foundation, and basement systems.

- **Surface foundation systems:** These systems are intended for home constructions that could tolerate a reasonable degree of movement. They are particularly attractive for ice-rich permafrost where more permanent foundation systems are not feasible. The foundation is elevated above the ground, about 0.7 to 1 m (28 to 39 in.) to ensure any heat from the building does not thaw the ground and also to minimize snow drifting. In addition to the slab insulation, the permafrost might be further protected using a heat pump with an in-ground heat exchanger (ground-source heat pump).

  Surface foundation systems include a timber pad and wedges, timber pad and screw jacks, pad and post, insulated slab on grade, and timber sills systems, which can be constructed on site. Pads and posts are generally constructed of pressure-treated timber but could be made from a combination of timber, concrete, and steel. They also require periodic leveling to adjust to differential settlement and heave.

- **Pile foundation systems:** These systems include driven piles, sand slurry or adfreeze piles, modified sand slurry piles, grouted piles, and end-bearing piles. Timber and steel are most commonly used in pilings. Steel piles perform well in frozen ground. Timber, if not pressure treated, might experience decay.

- **Rigid foundation systems:** In these systems, the structure and the foundation act as a single unit. The structure is allowed to tilt rather than deform, which results in less

damage to the structure. Adjustable plates can remedy tilting. Rigid foundation systems include space-frame and torque tube systems. The space-frame foundation is the only rigid foundation system in widespread use at the time of the preparation of the North Series # 4. It can tolerate ground movement, and therefore little site preparation is required, such as leveling or the addition of a gravel layer.

- **Shallow foundation systems:** Similar to surface foundation systems, the shallow system must be elevated above the ground to ensure any heat from the building does not thaw the ground. Shallow foundation systems include the buried pier foundation (called Greenland foundation), footings in fill, and footings on rock systems. In the Greenland foundation, a common system, pits for the foundation are dug until permafrost is reached. Footings and piers, or posts and pads are installed, which project about 1 m (39 in.) above the ground. To protect the footings from thawing, rigid insulation is placed on the ground surface with a 300 to 450 mm (12 to 18 in.) layer of gravel above it. Footings on rock systems are suitable where bedrock is exposed or shallow. The footings are tied into the rock with grouted dowels for good support.

- **Basement systems:** Basements are not generally used in permafrost areas, because of the excavating cost and the need to protect the ground from thawing.

Foundations Repair, Arctic

Bickley (1999) described the repair of reinforced concrete pier foundations damaged by sulphate attack (called thaumasite formation) in Resolute, Cornwallis Island, about 75 degrees north latitude. Winter temperatures could reach a low of -49ºC. In a brief period during summer, the surface layer of the permafrost thaws during the day. The reinforced concrete pier foundations of two buildings were severely damaged by thaumasite formation within two years of construction. Repairs to the piers supporting one building were successfully made by excavating to below the permanent frost line and all deteriorated concrete removed. Each pier was then jacked up with steel tube fabricated in two halves with a grout inlet at the bottom and an outlet at the top. Silica-fume grout (pre-bagged and requiring only the addition of water) was injected into the column. The soil was backfilled to the original ground level. The repaired piers were protected from further sulphate attack as they were in permanently frozen ground. The quality control procedures and test results are reported.

Roof Design Considerations

Allaire (1998) discussed roof design, and system selection and installation guidelines for cold climate environments. Considerations included structural (expansion joints and added snow loads) and hygrothermal (vapour and air barrier, drainage, and insulation requirements).

Structural Considerations

- Structural movement is created by expansion and contraction of materials due to temperature variations, -29ºC (-20ºF) in winter to 38ºC (100ºF) in summer. This requires integrating expansion joints, which will depend on temperature variations and the type of materials used. Movement will be less in conventionally insulated flat

roof assemblies, because the roof deck is located below the insulation. The location and size of the structural expansion joints are usually based on experience, as there are no rules in most building codes. Other design factors may provide a logical location for the expansion joints, such as where a low roof area meets a high roof area.

- Significant snow load is another important consideration in Northern Canada.

Hygrothermal Considerations

- **Vapour and air barriers:** Canadian designers tend to specify the use of a vapour retarder more often, using the rule "when in doubt, specify one" (Allaire, 1998). This is because when outdoor temperature is -20ºC, the high vapour pressure indoors drives moisture through the roof/wall assembly toward the lower vapour pressure outdoors. Potential condensation may occur at the membrane level when it is located toward the exterior cold side. A vapour retarder in the insulation's warm side of the roof/wall assembly will prevent potential condensation.
- **Insulation:** In cold climate design, it is desirable to control heat loss more than heat gain, because cold conditions prevail for more months throughout the year. The required R-value depends on code requirements, building use, and the location and type of building. Allaire (1998) grouped insulating materials into three groups:
  - low R-value materials: fibreboard and perlite;
  - medium R-value materials: fibreglass, mineral wool, and expanded polystyrene; and
  - high R-value materials: extruded polystyrene and polyisocyanurate. Phenolic foams are no longer used, because of moisture problems associated with the corrosion of steel decks.

  A two-layer insulation system is preferred, because this allows insulation joints to be staggered and minimizes the thermal bridging potential of fasteners of the base layer.

Roof Drainage Considerations

Interior drainage is often preferred in a cold climate, as water in drainpipes will not freeze. In areas with high indoor humidity, Allaire (1998) recommended insulating the pipes to avoid the condensation potential.

Roof Venting

In the north, roof systems that rely on venting to purge moisture seldom vent moisture before it condenses into frost. The imperfect poly-vapour barrier membrane permits moisture-laden indoor air to escape into the attic space. Condensate decreases insulation effectiveness and damages walls and ceiling finishes. Also, in the spring, melted accumulated snow may leak indoors and into walls.

The Cold and Hot Roof Systems

Seifert (nd) discussed the heat, air, and moisture control of the two basic types of roof designs commonly used in Alaska: the cold and hot roof systems. The main difference

between the hot and the cold roof systems is that the cold roof has a ventilated attic above the insulation, while the hot roof does not have ventilation.

The Arctic Hot Roof System
North Series # 6 (CMHC, 2001-2003) presents the arctic hot roof design that can withstand northern environmental conditions characterized with little annual precipitation and prevalent blowing snow conditions in long winters. The system has been used successfully in Northern Canada in houses and larger buildings for about 15 years. A similar roof system approach is well liked in Europe, because it allows the use of the attic as a living space.

The arctic hot roof system is an inverted roof system approach consisting of the following elements.

- A roof deck provides continuous rigid support for the air/vapour barrier membrane.

- A continuous membrane functions as an air/vapour barrier, on the warm side of the insulation, but still on the outside of the roof structure and decking. A single-ply, torched-on modified bitumen membrane is recommended, because it remains flexible at low temperatures down to -40ºC (-40ºF).

- Two layers of rigid insulation that are resistant to moisture are installed (over the membrane) at right angles to each other to reduce thermal breaks and penetration of the membrane.

- The roof cover serves as ultraviolet protection and sheds moisture.

- Controlled venting along the roof membrane allows any moisture (from rain and melting snow) that infiltrates the insulation to drain out of the roof assembly along the membrane.

The hot roof design was based on the sod roof design that has been used in Northern European countries since the 1960s as a solution to continuing problems of roof membrane failure in conventional roof systems. The sod roof consists of birch bark placed on the timber frame structure of the roof. The birch bark provides a shingled drainage surface or some other moisture barrier. An earth-sod cover, as insulation, is placed over the shingles.

The hot roof system differs from the inverted roof system by one fundamental factor. The hot roof system includes an additional water-shedding weather barrier above the insulation, which was added in response to the North's high winds and blowing snow. The inverted roof system allows moisture to seep down to the level of the membrane, which is the only moisture barrier in the system.

Advantages of the hot roof system include the following.

- The roofing membrane, air/vapour barrier, is protected against mechanical damage and from the stress of temperature extremes and potential condensation. The insulation layer maintains the membrane at a constant temperature that is higher than the dew point temperature throughout the year. The membrane is also protected from ultraviolet radiation, thus enhancing the membrane's durability.

- Insulation is at a reduced risk of trapping infiltrated moisture, because of the controlled venting.

- Insulation is easily accessible, which makes it easy to replace or increase as energy costs rise.

Disadvantages of the hot roof system include the following.

- Insulation can be exposed to water from rain and melting snow. This limits the number of insulation materials that can be used.

- Heat can be lost at the membrane level, because of moisture drainage.

Building Envelopes: Humid Climates

The literature search yielded few results on building envelope practices in humid coastal climate probably due to a lack of key words. Canada Mortgage and Housing Corporation has several publications addressing moisture issues and control strategies for wood frame building envelopes in the high moisture environment of the coastal areas of British Columbia (1990-1,-2, 1991-1,-2, 1998-1,-2, 1999-2,-3, 2001, 2002-1,-2, 2003-1, 2004). Some of these publications address moisture issues of the recent leaky condominium problem in British Columbia.

Lessons from the Building Envelope Failures, Coastal British Columbia
Canada Mortgage and Housing Corporation (1998-2) summarized the results of a survey of building envelope failures along coastal British Columbia. Large numbers of low-rise multi-unit wood frame residential buildings, built between 1988 and 1994, experienced envelope performance problems that included water penetration, damage to cladding systems, and rotting and decay of wood components. The cladding included stucco, wood, and vinyl wall types. The wall assembly included various combinations of building paper, OSB, plywood, and house wraps.

The primary source of problem moisture was water entering the building envelope at interface details between envelope components or at penetrations, such as details at windows, decks, and balconies. For windows, water penetrated through the window frame joints and through the interface between the window and the adjacent wall assembly. For balconies, the cause was improper installation of waterproof membranes. Observed issues with problem envelopes as compared to non-problem envelopes included the following.

- The wind exposure of the non-problem envelopes was generally lower than that of the problem envelopes.

- The absence of overhangs above walls in problem envelopes contributed to moisture damage.

- The non-problem envelopes had fewer architectural features and details had flashing.

- All cladding types experienced performance problems, although more problems were reported on stucco walls.

Key lessons from these failures included the following.

- The coastal climate requires greater attention to moisture management strategies: deflection of façade moisture, drainage, and drying potential. Rain screen wall assemblies have demonstrated acceptable wall moisture performance.

- It is essential to provide key details and improve their documentation (e.g., guidance documents, larger-scale, project-specific information, and mock-ups).

- There needs to be better communication between designers and trade personnel.

The *Best Practice Guide: Wood-Frame Envelopes in the Coastal Climate of British Columbia* (CMHC, 2001) is a resource on moisture management principles and practices for wood frame construction in coastal climates characterized by a high frequency of wind-driven rain. The guide addresses building science principles, behaviour and limitations of wood materials, prevention of wood decay, controlling moisture sources, and application of the rain screen principle to cladding. It also provides detailed drawings showing moisture, air, and thermal control approaches for wood frame construction with an emphasis on the intersection of building envelope components.

Indigenous Architecture

Cook (1996, Section 1.3, p. 279) defined indigenous architecture as sensitive to local variants, such as a microclimate. Cook stated that it is "the human constructive parallel to the Darwinian evolution of environmental fitness in the biological world." The design prepares for anticipated climate extremes. Every design aspect and each element of the building contribute to the net environment of the living space.

As an indicator of climate adaptation, Cook reviewed the climate and examined examples of indigenous architecture responses for the arctic, sub-arctic, and the maritime climates. The arctic was defined as the areas north of the Arctic Circle (66º 33` north latitude), while the sub-arctic includes areas south of the Arctic Circle. The arctic and sub-arctic consist of four distinct biological regions or biomes:

- the uninhabitable frozen polar area and the glaciers that cover all of Greenland except its coast;

- the coasts and islands with their marine climates;
- the treeless tundra with its continuous permafrost (10% of the world's land); and
- the taiga, the largely coniferous boreal forest that covers more than half of Canada, most of Alaska, and much of Scandinavia and Siberia.

Arctic Indigenous Architecture

Cook (1996) described the arctic climate as a frigid high latitude desert, scarce vegetation, and strong swings of daily and seasonal air temperature. Annually, the arctic can receive more direct sunlight than the equator, but much of the incoming solar energy is taken by outgoing radiation, because of reflection from snow, clear air, and low aerosols and water vapour content. Winters are long, cold, and dry. A typical winter-day temperature ranges between -23ºC and -34ºC (-9ºF and -29ºF). Summers (July and early August) are short and cool.

Cook noted that most climates have unpredictable extreme moments that defy concepts of passive architectural intervention and are sources of occasional discomfort. That is, there is no such thing as an extreme climate per se; each climate has its share of extreme conditions that are outside the design conditions. Climates can be considered extreme on a relative basis. For everyone except Inuit, the arctic and sub-arctic represent one of the most extreme climates for humans. General design conditions for most regions can be established, but still each region will experience times when the conditions will exceed the design conditions. Cook examined the Inuit snow igloo and Sami hut of northern Scandinavia and Russia to demonstrate the indigenous architectural responses to the arctic environment.

The Arctic Igloo

The Inuit snow igloo is a complex high-performance system of construction and operation in which every aspect and each element contributes to the net environment of the living space. The igloo is a wind-shedding aerodynamic architectural form in a flat landscape, where wind and snow drifting are prime environmental factors. The igloo's semi-spherical form reduces erosion of the building surfaces and controls deposit and drifting of wind-blown snow. A windbreak snow wall is usually built to protect the windward side from erosion. The igloo's design also reduces conduction and convection heat transfer from the igloo's envelope surface.

The igloo's thermal performance could provide a temperature differential, indoor to outdoor, of 40ºC (72ºF). This is achieved by controlled entry that consists of a cluster of modules (used for storage) that provide a climatic transition from outdoors to an indoor living module. Also, oil lamps contribute to space heating; a ventilation hole and the entry door provide ventilation. For structure reasons, the mean radiant temperature of the ice surface needs to be kept near freezing.

The Sami Hut

The Sami hut is another example of an indigenous architectural response to the arctic environment in northern Sweden, Norway, Finland, and Russia. The hut is a conical-shaped building designed for the arctic climate (see Figure 8).



Figure 8. A Sami Family and Hut around 1900
Source: < http://en.wikipedia.org/wiki/Sami_people > (accessed December 7, 2006).

The architectural climate adaptation features of the Sami hut include the following.

- Curved rafters support a continuous all-roof enclosure built with layers of logs, bark, peat, and turf.
- The ground is insulated with a thick layer of spruce boughs or birch twigs and covered with reindeer skins.
- The central fire pit with its ring of hearthstones and the suspended hot metal pot provide a radiant heat source.
- Cracks in the plank door provide ventilation air.
- Smoke and ice fog, from cooking and breathing, fill the top part of the hut. This induces cold air movement close to the ground. The smoke also helps control seasonal flying insects.

In comparing the Sami hut to the snow igloo:

- The Sami hut's fuel consumption is much greater and less effective than the igloo.
- Tending the fire in the Sami hut is a continuous physical activity, while the igloo encourages rest by its horizontal accommodation and low burning lamps.
- The igloo maintains a much finer restraint and balance of combustion and ventilation air resulting in a more stable interior environment.

Maritime Climate Indigenous Architecture

Cook (1996) described the maritime climate zone as the mid-latitude (between 40º and 60º latitudes, both north and south) coastal regions of the globe dominated by ocean influences. The maritime climate is humid and temperate. Precipitation occurs in all seasons (no dry season), and might change by the hour. The weather could come from any orientation. Summers are cool and short. Winters are mild and short with some frost but not continuous snow. Spring and fall are extended in length. There are small differences between monthly mean temperatures. In Canada, the Atlantic Provinces and the West Coast have typical maritime climates. Similarly, the northwest, northeast, and mid-Atlantic coasts of the United States, the coasts of Chile and New Zealand, the southeast coast of Australia, and most of Japan are maritime climate regions. Most maritime climates, except Western and Central Europe, are restricted by coastal mountain ranges, which limit the spread of wind and climate conditions inland.

Cook noted that architectural responses to a maritime climate are always sensitive to dampness, but architectural responses to changeable temperate maritime climates are not consistent.

The Cape Cod House or Cottage of New England

The Cape Cod house (also called colonial, hall and parlour, or early American) is an example of an architectural response to the climatic changeability of the maritimes. The Cape Cod is an old UK house type that was adopted and modified for the more rigorous and unpredictable maritime climate with warmer summers, colder winters, and more wind throughout the year. The Atlantic Ocean dominates the climate in New England and is known to be more extreme than in the United Kingdom in terms of changeability. Cook (1996) reviewed the evolution of the Cape Cod through the time from a two-room house to the current large colonial house. Today, Cape Cod style is chosen for taste and not for its bioclimatic benefits. The Cape Cod type is also common in the Atlantic Provinces.

Initially, the Cape Cod was a compact one-storey, cubical form with a timber-framed exterior. There was a large central fireplace and a large thermal mass masonry chimney. The cubical form is said to be thermally efficient. The house faced south regardless of the road direction. Thermal gains were not the reason for this orientation; people wanted to face the rarely seen sun. South was also the usual direction of fair and fine weather.

The Cape Cod's building envelope adaptation included the following.

- Building for foul weather was addressed in all directions, because climate is similar in all exposures.

- Masonry walls, stucco, or lime washes over earthen or adobe walls are responses to damp conditions. For wood, protective paint is applied. The local presence of rot-resistant timbers, such as red cedar on the west coast of Canada, was used to support the exposed wood structures.

- Clapboards, shingles, and plank frames were other adaptations to make the building envelope more rigid and climate responsive. Exterior non-structural weatherboards were used over the traditional English heavy timber mortises and tenon frame.

- Sheathing, as a substrate for the weather skin (the cladding), was used for walls and the roof to form structural integrity and allow the use of lighter timber frame.

- There are no overhangs or porches because, in a changeable climate, they might keep sun and daylight away from windows.

- Small-paned windows faced all directions to provide daylight and summer ventilation. Window shutters protected against storms and winter cold. However, at high latitudes such as in Scandinavia, large windows for daylight are an architectural compensation for overcast skies.

The Hungarian House

The Hungarian village house combines social custom, indigenous materials, and acclimatization to a maritime climate from the north and west. Initially, it was mostly small with one all-purpose room for sleeping and social use, and cooking in a hearth and oven. Later on, the house evolved to include three rooms in a row. The kitchen function moved to the middle room and provided heating to the other two rooms.

The bioclimatic features of the Hungarian house include adobe walls, a thatch roof, and a hearth with heavy mass. The house was partially sunk into the earth; thus the earth embraced the structure and the earth-shaped interior provided a thermal mass that was warmed by an open hearth. The north wall had no openings to guard against the cold winter northern winds. The south wall was open, which evolved to include a continuous porch. The smoke from the chimneyless kitchen (to avoid taxes) was vented through the attic. This helped preserve the roof thatch and food stored in the attic, such as sausages.

Sustainability Concepts in Indigenous Architecture

Indigenous design by definition is based on local materials, is restricted by local resources, and is developed through consistent human engagement. Sustainability concepts in indigenous architecture could be an answer for today's building issues.

- **Use local materials:** Advantages of local materials include resilience to local climate, low costs of origin, and low transportation cost. They require little processing, and local workman know how to handle them. For example, cedar shingles and redwood lumber are resilient materials in their native temperate and damp climates but deteriorate quickly in a desert climate.

- **Design for microclimate:** The reliable performance of indigenous architecture is a result of a conscious design for both indoor and outdoor microclimates.

- **Integrate comfort sources:** Construction strategies of indigenous architecture always include the integration of strategic sources for relief from climatic stress, which is considered as an extension of the architecture both thermally and aesthetically. For

example, in cold climates, the comfort source is an open flame from a burning fuel, while in hot climates; the comfort source is an overhead fan.

Global Practices in Building Envelopes

Arctic and Antarctic Regions

Permafrost Considerations

Meckler (1991) examined design considerations for buildings and underground services for permafrost regions in the arctic. Design considerations include air infiltration and condensation effects on structures. Meckler argued that approaches used in the design and repair of buildings, underground utilities, and engineered facilities in the arctic differ considerably from those used in temperate regions. Design techniques employed in temperate regions are not suitable and often present major construction problems in the permafrost region. The design of buildings and underground services in arctic regions requires knowledge unique to the arctic climate. Knowledge includes heating and ventilating, piping distribution, fire, and life safety systems positioned within the building envelope or served by underground services.

Foundation Design Considerations

Foundations in permafrost present unique construction problems, because of the properties of the permafrost, such as ice content, thermal sensitivity, and imperviousness to water movement. In ice-rich soil, ice creeping below foundations is another difficulty for foundations resting on permafrost. Thus, foundation construction requires careful evaluation of the soil compaction, material confinement, grading, and other conditions under which the permafrost soil materials will continue to exist in the thawed or frozen state. For unheated structures, it is advisable to retain the permafrost in its frozen state using one of the following methods.

- Provide a ventilated air space that can maintain a temperature between the building and the ground at or near the ambient outdoor air temperature.

- Use a mechanical refrigeration system to maintain frozen conditions in the soil.

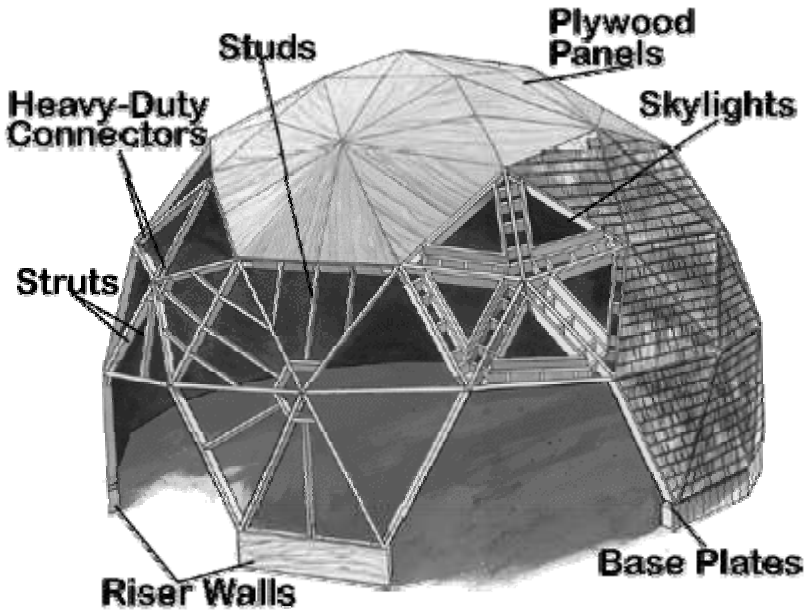
- Use a heat pipe, embedded in the permafrost, which operates in the winter when air temperatures are below ground temperatures.

Building Envelope Considerations

In addition to insulation in ceilings, walls, and floors, proper placement of a vapour barrier is important. Building envelopes should also be tightly sealed to prevent infiltration of blowing snow, because snow infiltrating through small holes or cracks can overwhelm the structure and damage the insulation and building interior when it melts.

Dome Shell Structures

The efficient use of structural materials, speed of construction, thermal efficiency, and structural stability make dome structures attractive for a number of applications.[iii] Figure 9 shows an example of a dome building.



An Example of a Dome Anatomy (Source: http://www.domehome.com/productinfo.html)



Figure 9. An Example of a Dome Building and Anatomy
Source: <www.domehome.com/> (Accessed November 23, 2006)

Globally, domes constructed with air-form techniques have been used for utility, educational, religious, and residential structures for many years. Quimby (1998) proposed the use of air-formed concrete dome shells in the arctic and sub-arctic regions where unique design, construction, and operational challenges exist. Quimby believed dome structures hold promise in arctic and sub-arctic regions. The author noted the following requirements for the ideal cold region structures.

- Satisfy the functional requirements of occupants.
- Use a minimum of materials to construct.
- Require a minimum amount of labour to construct.
- Insulate appropriately to minimize energy costs.
- Be maintenance free.

Quimby (1998) described the construction of a dome building in cold regions and demonstrated how dome buildings could meet the challenges presented by the northern climate. The dome structure, constructed in 1993, was a 24.4 m (80 ft.) diameter church centre in Soldotna, Alaska. Design criteria included snow loads of 1.9 kPa (40 psf) and wind speeds of 161 k/hr (100 mph.). The thickness of the concrete shell was 76 mm (3 in.) and 152 mm (6 in.) at the supporting beam interface. The shell thickness was controlled by the need for concrete to cover the reinforcing steel. The shell contained 62 m^3 (81 cu. yd.) of a special mix concrete (with high cement content and small aggregates) and about 7200 kg (16 000 lbs) of reinforcing steel. The fabric form used in the construction of the dome was Hypalon®, which has excellent ultraviolet resistance, and might remain in place after construction to become the roofing membrane for the dome or may be removed and cleaned for reuse as a form.

The builder was a local general contractor experienced in the use of polyurethane foam. The builder brought in outside experts to train his crew. Volunteer labour was used wherever possible. Once the dome fabric form was stretched over the foundation and inflated, successive thin layers of polyurethane foam (to a total thickness of 76 mm/3 in.) were applied to the inside of the fabric form. Light gauge metal plates with attached wires were embedded in the foam. The protruded wires were used for attaching the reinforcing steel of the structure. Once the steel was in place, the concrete was sprayed in successive thin layers (about 20 mm (3/4 in.) thick; each layer was applied before the previous layer was completely cured. This step required experienced operators and special spray and pumping equipment. The time required to construct the dome was 13 days from ground breaking. Quimby noted that using an experienced crew could have reduced construction time by two days. The building was heated by a gas-fired forced air system.

The building dome shell has performed well over five winters. During this period, the dome experienced moderate wind and seismic events without any sign of distress.

Quimby (1998) compared the energy use of the building to a typical two-storey Alaskan residence that encloses a volume of 968 m^3 (the volume of the dome building was 2211 m^3), has RSI-3.3 (R-19) walls and RSI-7.9 (R-45) ceiling, and is heated by a hot water baseboard system. The energy use for the dome building per unit volume of enclosed area was about 88% of that required by the residential building during the same period.

Air-formed concrete dome shells offer several advantages for cold region applications:

- the efficient use of materials;
- the speed of construction;
- the limited amount of work to be performed outdoors (Once the dome fabric is inflated, all work moved indoors.);
- the ability of the dome shape to shed snow (Virtually no snow accumulated on the Alaskan dome, because of the low surface friction of the form fabric and also the result of wind scour. Snow is generally windswept from the surface with some snow drifting on the windward side of the building.);
- the absence of ice damming, which eliminates the maintenance and safety problems associated with it;
- the structure's extraordinary strength and low stresses; and
- its thermal efficiency and lower air infiltration rates. Compared to other types of construction of similar size, computations indicated that dome buildings require the lowest heating load. For a 21ºC (70ºF) interior temperature, -23ºC (-9ºF) exterior temperature, the heating demand of a dome with 75 mm (3 in.) polyurethane insulation (RSI-3 to 3.6/R-17 to 20)[iv] is reported to be 75% of that of a comparable frame construction building with RSI-3.3 (R-19) walls and RSI-6.7 (R-38) ceilings.

Dome structure disadvantages include instability, known as snap through buckling. This is often a concern of large domes. In smaller domes, the need to wait for curing of successive layers of concrete might cause down time. This is not a problem in large domes, because the first sprayed concrete has time to set before the entire layer is completed.

Swedish Research Station, Antarctica

The Swedish Research Station (called the Wasa Research Station) was constructed in the summer of 1988-89. Haugun (1991) presented the design and construction of the station, as well as its monitoring program and results. The station is located at S 74º 35' and W 11º 13', at about 450 m (1476 ft.) above sea level, and 100 m (328 ft.) below the Basen summit. The Station consists of two buildings. A utility building is made of three steel containers that are joined together. This building is about 25 m^2 (269 sq. ft.) and contains the generator, repair shop, and storage. The main building, about 117 m^2 (1259 sq. ft.) provides shelter to 12 people and is equipped with comfort amenities.

Facility Construction

The main building was constructed with the same technology common to houses in Northern Scandinavia. The structure consisted of prefabricated wood panels and steel beams. Two factors determined the selection of the building envelope system: transportation issues limited the weight of each building element to 450 kg (992 lbs) and

time limitations existed for the building construction. The outer shell (walls, roof, and floor) had to be completed in three days.

The Building Envelope

The building's largest structural elements, the roof and floor, measured 7.5 x 1.2 x 0.3 m (24.6 x 3.9 x 1 ft.) each. The wall elements measured 2.4 x 1.2 x 0.3 m (7.9 x 3.9 x 1 ft.) and consisted of two sheets of 12 mm (1/2 in.) plywood, which sandwiched a 5 cm (2 in.) air space and a 25 cm (9.8 in.) thick layer of mineral wool insulation. The roof panels were covered with asphalt shingles. To minimize lift forces during high wind speeds, the roof was constructed with as small an inclination as possible. A slope of two degrees was used to avoid accumulation of snow melt. Haugun (1991) noted that, in the roof design, they did not consider rainfall, but in 1989-1990, there was rainfall on two occasions. As a result, a greater roof slope, about five degrees, would be better for rainwater run-off. Also, instead of the asphalt shingles roofing, a watertight roofing membrane, and sealing all joints would be sufficient.

Blowing Snow and Wind

The Swedish Research Station facility was built to withstand high wind speeds and heavy snow drifts. The facility building was elevated 1.5 to 2 m (4.9 to 6.6 ft) above the ground level. Haugun noted that elevating the building above the ground by 1.8 m (6 ft.) worked well in avoiding excessive snow accumulation around the building. Wind flow under the building kept the building's immediate area clear of snow. The building affected the snow accumulation around the site to a distance of 150 m (492 ft.).

The facility was exposed to a wind/snow storm during the antarctic 1989 winter season. The only damage to the building was some asphalt shingles were blown off the roof. Haugun noted that this was because the shingles were only fastened with tacks. A communication antenna was destroyed, and the telephone and telex machines experienced electrical damage. Data loggers also behaved irregularly. The loggers operated independently of each other and sampled data up to 50 times a day as compared to their normal setup of eight times a day. Haugun thought this irregular behaviour might be caused by static electricity, which could be developed during a snowstorm. Recorded wind speeds at the site were up to 50 m/s (180 km/hr/112 mile/hr) for long periods and the minimum temperature measured -33ºC (-27ºF).

Ventilation

Blowing snow is known to infiltrate through very small openings or cracks. Thus, air slots were used for ventilation air intake, which included a rock wool insulation layer to filter infiltrated blowing snow. The ventilation air supply duct was placed in the wall exterior layer (between the façade and the insulted section) then through the outer layer of the roof where a supply fan delivered the preheated air to the space. The preheating increased the temperature of the ventilation air by up to 40ºC (72ºF). Haugun pointed out that solar panels mounted on the façade could provide efficient heating of the main building during the high solar period.

Energy Consumption
The average diesel fuel consumption of the power supply generators was about 100 litres (26 gallons) per day. Future development included the use of solar and wind energy for the power supply.

Building Monitoring
The main building was instrumented with sensors for measuring humidity, temperature, moisture in walls, and displacement at various representative locations. The objective of the instrumentation was to better understand the effect of the climate on the building and the climatological strains and stresses to which the various materials are exposed. There was a concern that building envelope components might suffer a considerable decrease in moisture content in the spring when the sun starts to heat the building. Measured data will be used in designing solar and wind energy for heating and power supply. Selection of the instrumentation system was based on two criteria: very low electricity consumption and whether it could operate in temperatures as low as -55ºC (-67ºF).

Four data loggers were used to ensure the reliability of the monitoring program. The loggers were set to collect data eight times per day. Haugun (1991) presented an example of measured temperature distribution in a wall section during a sunny day in January 1990. The outdoor air temperature varied from -10ºC (14ºF) in early morning to about 5ºC (41ºF) in the evening. The indoor air temperature varied between 21ºC to 24ºC (70ºF to 75ºF). Temperature of the air in the wall cavity between the façade and the insulted section followed outdoor air temperature variation but with about a two hour lag. In about half a day, the cavity air temperature increased by about 40ºC (72ºF) from –5ºC (23ºF) in the morning to about 34ºC (93ºF) in the evening. The variation in the temperature of the wall insulation was much less. It ranged from about 14ºC to 22ºC (57ºF to 72ºF).

The US Amundsen-Scott South Pole Station
Ferraro (1999) discussed the design concept and the problems with on-surface structures of the US Amundsen-Scott South Pole station. The station is located inland, on the interior plateau that consists of a permanent ice shelf. The ice shelf is characterized by an annual snow accumulation of about 50 cm to 150 cm (20 in. to 60 in.) depending on the inland location, gale-force winds that are common 180 days a year, and seaward drift of the ice shelf of about 1000 m (3281 ft.) per year (Brooks, 2000).

The facilities were initially built in 1957 on the snow surface inland. The station was annually covered with snow up to 8 m (26 ft.) above the roofs. This necessitated extensive snow maintenance at the beginning of each summer season. Snow that had not been removed led to structural deterioration problems in the timber panelized components. The facilities were rebuilt in 1975 using corrugated steel arches, a 51 m (165 ft.) diameter aluminum geodesic dome, and a balloon inflation tower. The arch structures acted as a protective shell over the utility facilities. The dome sheltered the staff living, labs, and office spaces. The expected life cycle of the 1975 facilities was 15 to 20 years. The buildings were still built on the snow surface and needed snow removal. As a solution, the new facilities scheduled for completion in 2007 were elevated above the snow surface using a pier foundation.

Pier Foundation System
Brooks (2000) discussed the rationale for the pier foundation for the above-surface facilities. Environmental conditions in Antarctica's non-coastal locations pose significant challenges, and traditional construction methods of cold regions are not adequate to cope with them. The main challenge is the annual snow accumulation. With no frost cycle, snow accumulation eventually buries structures built on the surface. Snow drifts, created by high winds, speed up the burial process. To overcome this environmental difficulty, the pier foundation is used and buildings are initially constructed 3 to 5 m (10 to 16 ft.) above the snow surface, often incorporating a means of periodically raising the building to remain above the snow accumulation.

Pier foundations also help in controlling snow drifting. The elevated structure allowed wind to channel below the structure, which effectively swept the snow away, eliminating the problem. Haugun (1991) reported a similar finding. Elevating the building above the ground by about 1.8 m (6 ft.) worked well in avoiding excessive snow accumulation around the building. Wind flow under the building kept the immediate area of the building clear of snow. Brooks (2000) also reviewed various pier foundations and structure-jacking methods for other above-surface stations built on the interior ice shelf plateau in Antarctica.

Station Construction
The US South Pole station consists of a row of 13 modular buildings elevated 3 m (10 ft.) above the surface on scaffold piping. Based on the results of wind-tunnel testing, the row of buildings was oriented at right angles to the prevailing wind and connected by a single walk covered by semicircular corrugated galvanized steel siding on the windward side. The visual effect is that of a C-shaped structure, rounded on the windward side and squared on the leeward side.

Construction Challenges
Marty (1999, 2000, 2004) and Rand and Brier (2000) discussed the construction of the station that replaced the 1975 facility. The construction started in 1997 with a planned completion in 2007. When completed, the elevated facility will include new remote facilities, a communications centre, garages, and shops. The design concept of the 1975 as well as the 1957 facility was based on placing buildings within steel arches that could withstand burial and also within a dome structure. The concept of the new facility was based on a balance of below-surface and elevated structures. The existing steel arches are to be used for utilities and storage. The unique complexities and challenges of construction particular to this antarctic location included the following.

- Shortness of breath and headaches caused by altitude are common. The station is situated at 2852 m (9355 ft.) above sea level. In addition, barometric pressure fluctuations create equivalent altitudes of 3424 m (11 235 ft.). Clothing weight limits dexterity and work efficiency. The average weight of clothing is about 16 kg (35 lbs). Climate conditions include a mean temperature of -49ºC (-56ºF) in summer and -62ºC (-80ºF) in winter. Wind chill can lower average temperatures to -57ºC (-70ºF) in summer and -73ºC (-100ºF) in winter.

- The construction time window is limited in summer to about 110 days from November 1 to February 15, during which there are 24 hours of sunlight and the warmest yearly temperatures. Careful sequencing of summer work is crucial for the success of the following winter work. During the winter months, February 16 to November 1, construction work is performed from inside the structure, because of the extreme temperatures and continual darkness (four months of total darkness).

- Material transport and storage is a problem.

Snow Drifting

Several publications (Waechter and Williams, 1999; Delpech et al., 1998; Kwok et al., 1992, 1993), addressed snow drifting around Antarctic buildings. Waechter and Williams (1999) presented design guidance for snow drifting for the new US station. They discussed the various design recommendations resulting from various analysis techniques, which included three-dimensional computational fluid dynamics, water plume snow simulation (using sand and water to reproduce snowdrifts), and wind-tunnel testing. Analysis included the effect of different building shapes and features on snowdrift deposition patterns. Recommended snowdrift design guidance included three suggestions.

- Elevate buildings sufficiently above the snow surface.

- Orient a row of linked buildings perpendicular to the prevailing winds.

- Understand that snow drifting will invariably occur; therefore, sensitive activities should be located away from the snow deposition area.

Delpech et al. (1998) used real snow in a climatic wind tunnel to investigate wind-induced snow drifting around the Concordia station in Antarctica, which consisted of two cylindrical buildings connected by a gangway. Each building is three floors high, 17 m (56 ft.) in diameter, and is elevated on six piles with hydraulic jacks for height adjustment. To alleviate the snowdrift hazard around the buildings, they investigated various types of attachments to the buildings that would accelerate the airflow under and between the two cylindrical buildings. Accelerating the airflow reduces snow deposition and blows the snow away from the building to the leeward direction. Attachments investigated included:

- a horizontal rounded streamlining edge at the bottom of the building on the windward side, which accelerates the airflow under the building;
- guide vane walls fitted on each side of the cylindrical buildings from the floor to the ground surface; and
- an optional attachment to the gangway between the two buildings made of vertical rounded walls, which speeds up the airflow between the two buildings.

Delpech et al. (1998) concluded that the most effective configuration was the long guide vane on each side of the buildings.

Kwok et al. (1992, 1993) also used wind-tunnel and field measurements to investigate snow drifting around antarctic buildings, both on-ground and above-ground construction. Their objective was to formulate design guidelines for buildings in Antarctica. They investigated the effects of the model geometry and the angle of wind incidence on snowdrift formation. Their finding included the following.

- **For a single on-surface building:** Snow drifting was attached to the leeward side of the building. By elevating the building, snow drifting can by considerably reduced and formed well clear of the building. The wind load and vibration of elevated buildings should be considered in the structural design of the building, particularly in the design of foundations.

- **For grouped on-surface buildings:** A large snowdrift formed at the leeward side of the last building in a row of buildings and was attached to the leeward wall. Significant snowdrift also formed between buildings and was attached to the neighbouring walls. Grouped above-surface buildings created larger snowdrifts than grouped on-surface buildings. However, the snowdrifts for the above-surface grouped buildings were not attached to the leeward wall, as was the case for the grouped on-surface buildings. Also, smaller snowdrifts formed between and underneath grouped above-surface buildings.

Windows Performance

Dutta (1999) evaluated the performance of four prototype windows at extremely low-temperature environments similar to the condition at the location of the US South Pole Station. The study objective was to identify whether the window performance degrades with progressive thermal cycling over time. The interior of the building was maintained at a temperature of 24ºC (75ºF) . The outside temperature varied from -70ºC (-94ºF) to -5ºC (23ºF) on a sunny day. The windows were exposed to a large temperature differential up to 94ºC (169ºF), which led to differential expansion and contraction of the windows' materials. The differential movement might produce unacceptably high stresses leading to either the failure of components or degradation of their performance over time.

Measured R-values ranged from R-2.5 to R-10 (RSI-0.44 to RSI-1.8). Dutta used measured transient temperature data to calculate R-values; therefore, Dutta noted that these R-values are for comparison only, and couldn't be compared to the manufacturers' values that are based on steady state conditions. One of the four windows performed best in terms of endurance and R-value that ranged from R-5 to R-10 (RSI-0.9 to RSI-1.8). The change in glazing surface temperature was small (1ºC to 5ºC/2ºF to 9ºF) with the large change of ambient temperature from the warm to cold cycles of 24ºC (75ºF) to -70ºC (-94ºF).

Structural Materials Performance, Antarctica and Indian Himalayas

Pathak (1996) reviewed a number of construction materials used successfully in the extreme cold environmental conditions of Antarctica and the Indian Himalayas. These included a special frost-resistant concrete mixture, new aluminum alloys, sandwich composite panels, sealing compound, and a fire retardant material.

Frost-Resistant Concrete Mixture
Pathak (1996) noted that freezing fresh concrete greatly affects its strength. Concrete exposure to a cold environment induces thermal cracking. Frozen concrete is strong, but because the strength is due to ice cementing, the strength vanishes as the concrete thaws. As a solution, he recommended using heating, thermal protection, and special frost-resistant concrete mixtures and mortars. Admixtures commonly used in cold regions (such as air entraining agents, accelerators, plasticizers, and antifreeze) improve the workability, curing properties, or freeze–thaw resistance. Calcium chloride is the most commonly used accelerator, which provides rapid strength and reduces the time needed for protection. Pathak described a hydraulic binder that is primarily binder slurry, which is poured over the compacted aggregate in a special manner. The hydraulic binder was used in the foundations of the Indian antarctic station. Pathak also recommended that foundations should be placed as far as possible below the active layer of the permafrost and should avoid drainage channels.

New Aluminum Alloys
Pathak (1996) noted that the properties of aluminum alloys in general are favourable for cold climate applications. Aluminum's mechanical properties improve slightly with decreasing temperature. Aluminum has good corrosion resistance strength, good weld-ability, and a low weight/strength ratio. Two aluminum alloys, RDE-32 and RDE-40, were developed and were used in the construction of a 20 x 20 m (66 x 66 ft.) helipad at Antarctica that was constructed of aluminum planks with an insulated underside.

Sandwich Composite Panels
These panels, made of plywood on both sides with core insulation between them, were used in the construction of modular structures (living accommodation, kitchen, etc.) in both Antarctica and the Indian Himalayas. At Antarctica, timber frame was used and the panel thickness was 124 mm/4 7/8 in. (12 mm/1/2 in. thick marine plywood on each side and 100 mm/4 in. core polyurethane foam insulation). Outdoor temperature was as low as -45ºC (-49ºF), and the inside temperature was maintained in the range of 15ºC to 20ºC (59ºF to 68ºF). Pathak noted that the floor needed additional insulation, because temperatures varied from -4ºC (25ºF) at the floor to 15ºC (59ºF) at the ceiling. At the Indian Himalayas site, aluminum portals were used and the panel thickness was 86 mm/3 3/8 in. (3 mm/1/8 in. of fire retardant grade fibre-reinforced polymer on both sides and 80 mm/3 1/8 in. phenolic core batt insulation).

Sealing Compound
Silicon gel-sealing compound worked well in joints between panels, columns, walls, etc. at Antarctica and in the Indian Himalayas. But a better sealing compound is needed to withstand blizzard conditions.

Fire Retardant Material
Gypsum board was found to be an effective fire retardant material in interior wall and ceiling surfaces. For cladding, plastisol coated gypsum sheets were used.

Composite-Wrapped Concrete Column
Karbhari and Eckel (1994), similar to Pathak (1996), noted that degradation of mechanical properties of concrete materials exposed to sub-zero temperatures is a problem in regions, such as the arctic. As a solution, Karbhari and Eckel proposed the use of composite materials. Composites are attractive for cold region applications due to their high strength-to-weight and stiffness-to-weight ratios. They are lightweight (and hence easily assembled), and are resistant to the environment.

Karbhari and Eckel investigated the effects of cold temperature, -18ºC (0ºF) (60 days conditioning), on the strengthening efficiency of three different composite-wrapped concrete columns. The composites tested were glass fibres, carbon fibres, and aramid fibres (Kevlar 29®). They also discussed the differences in the failure mode of the entire structural element, the composite wrapped column. They concluded:

- For both glass and carbon fibre reinforced composite wraps, the compressive strength and rigidity increased as the temperature decreased.

- A carbon fibre jacket appeared to be the best in terms of structural performance, but its failure mode was catastrophic. The failure mode for glass fibre was better as a more benign mode of gradual failure.

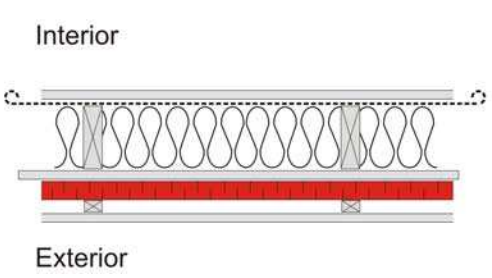
- The use of carbon glass hybrids would provide the optimum combination.

Neale and Labossière (1998) studied the effectiveness of using fibre-reinforced composites for structural rehabilitation and strengthening in a severe cold climate. The authors reviewed field applications in Quebec involving structural elements, such as exterior building columns, columns of a highway overpass, partially submerged bridge piers, and beam and column elements of a major parking garage structure.

Scandinavian Region
Steel Construction
Aromma (1999) and Sandberg and Nieminen (1997) studied the hygrothermal performance of a full-scale wall assembly using laboratory testing, three-dimensional computations, and field measurements to demonstrate the performance and suitability of using perforated-web light-gauge steel (1.2 to 1.5 mm/0.05 to 0.06 in. thick) structures for houses in the cold climate of Finland. The perforated web of the steel improved the thermal performance of the steel structure by providing a thermal break, which reduced thermal bridging along the web by 70% to 80%.

Four buildings, three row houses, and an apartment building were built in 1996 to demonstrate the suitability of steel structures for Finnish buildings. The houses were built using steel as load-bearing materials in walls and roof trusses. The houses also included stiffening insulated wall panels, prefabricated bathroom modules, and so-called new "snap-on" roofing panels (Aromma, 1999). One of the row houses was designed as an energy-efficient house with targeted heating energy consumption of 50% of that of a reference house built according to the Finnish building code.

The energy-efficient house included additional insulation in the walls, roof, and floor. It also included more efficient windows, a floor heating system, heat recovery ventilation, and had better air tightness construction. The house was constructed on site using precut materials. Figure 10, shows a schematic of the wall assembly.



From interior to exterior
Gypsum board, 13 mm (1/2 in.)
Polyethylene sheet 0.2 mm (8 mil)
Stud space with mineral wool 175 mm (6 7/8 in.)
Gypsum board 9 mm (3/8 in.)
Exterior insulation board 45 mm (1 3/4 in.)
Strapping
Ventilated air space
Cladding

Figure 10. Wall Assembly of the Finnish Energy-Efficient House

Source: Aromma (1999).

The wall assembly of the reference, so-called, normal house was the same as the energy-efficient house except it did not include the exterior insulation board layer. The house was constructed using large panel wall systems, regular windows, and radiator heating. Thermal insulation was according to Finnish building code as listed in Table 3.

Table 3. R-Values, Finnish Building Code for Detached Houses

Component	U (W/m^2 K)	RSI (m^2 K/W)	R (h ft^2 F/Btu)
Wall	0.28	3.6	20
Floor	0.36	2.8	16
Roof	0.22	4.5	26
Window	2.1	0.5	3
Door	0.7	1.4	8

Note:
R-values are calculated from U-values listed by Sandberg and Nieminen (1997).

Moisture performance: Laboratory and field measurements showed that there is no risk of moisture condensation due to indoor air infiltration into the structure if the vapour/air barrier is installed properly. In the energy-efficient house, some wall materials got wet during construction as a result of a heavy snowfall. Inspection the following spring indicated that the moisture in the wall had dried out. This suggested that the wall was able to dry to the outdoors. Temperatures of wall surfaces were sufficiently high to prevent condensation. The authors noted that relative humidity in Finnish houses is usually between 20% and 40% and occasionally up to 60% in winter.

Environmental impact: In terms of energy consumption and CO_2 emissions associated with material manufacturing and transport, the environmental impact of a light-gauge-steel building envelope is similar to timber and brick systems. But, the energy

consumption and CO_2 emissions associated with electricity and heating of the house over its service life are much greater than the energy consumption and CO_2 emissions related to the manufacturing and transport of building materials. Therefore, in this regard, the authors argued that, a light-gauge steel building envelope system possibly reduces the environmental impact due to the operation of the building. Computed heating energy consumption of the energy-efficient steel frame house was 40% to 50% lower than the energy consumption of a house constructed according to the Finnish building code standards.

Aromma (1999) and Sandberg and Nieminen (1997) concluded that using perforated-web, light-gauge steel did not increase the energy consumption of buildings, and allowed for possibly reducing the environmental impact due to the operation of the building. A perforated web light-gauge steel building envelope would provide energy-efficient and environmentally friendly building envelopes for the cold climate of Finland. The extra insulation layer on the outside of the steel stud wall solves the thermal bridging deficiency of the steel.

Japan

Yoshino (1991) discussed design strategies for houses in the cold-climate regions in Japan (Hokkaido District and the northern area of the Tohoku District). Yoshino also reviewed climatic characteristics, thermal performance of the building envelope, heating and ventilating equipment, energy consumption, and cold weather-related house problems. The cold-climate regions in Japan are characterized by 3000ºC to 4500ºC days (heating-degree-days base 18ºC), which is comparable to the southern regions in Canada. The average outdoor temperature in January is –5ºC (23ºF). The seasonal northwest wind, laden with moisture, is intercepted by mountain ranges and bring heavy snow to the region along the Sea of Japan. Dry air then passes over the mountain and results in clear, sunny weather in areas along the Pacific Ocean. The summer is hot and humid where the mean outdoor temperature is 24ºC (75ºF), and the mean relative humidity is 80%. Thus, Yoshino recommended that the summer climate should also be taken into consideration when designing houses in such cold climate regions along the Pacific Ocean.

The average floor area of houses in Japan's cold regions ranged from 118 m^2 (1274 sq. ft.) to 150 m^2 (1616 sq. ft.). The space heating equipment used in most houses is a large kerosene space heater with a chimney for exhaust. The thermal insulation level varied between cold regions. Table 4 lists the R-value range of insulation used in the so-called standard Japanese houses.

Double-pane windows with an air space more than 10 mm (3/8 in.) are used in most houses. Single-glazed windows are common in some regions. Plastic and aluminum sashes are used in 45% of the houses. The air tightness of the building envelope, expressed in terms of the equivalent leakage area per floor area, ranged from 0.27 to 20 cm^2/m^2 (0.003% to 0.2% of floor area). The lower air-tightness value, 0.27 cm^2/m^2, is comparable to the Canadian R-2000 house standards.

Table 4. Range of R-Values of Insulation Used in Houses in Japan's Cold Regions

	Equivalent Thickness of Fibreglass cm (inches)	Approximate RSI-Value (R-value)
Roof	5 to 30 (2 to 12)	2 to 7 (8 to 50)
Wall	5 to 10 (2 to 4)	2 to 7 (8 to 17)
Floor	5 to 15 (2 to 6)	2 to 7 (8 to 25)

Notes:
R-values are calculated based on fibreglass thickness reported by Yoshino (1991).
The R-value of fiberglass is taken as RSI-0.7 per 25 mm/R-4.2 per inch).

Yoshino (1991) reviewed house problems in the cold climate regions in Japan. Yoshino noted that as houses became more insulated and airtight, many problems arose.

Indoor air pollution increased in terms of CO_2 concentration, which was more than 1000 ppm in many houses and more than 3000 ppm in some areas. CO_2 concentration was particularly high in houses with unvented portable kerosene heaters.

A back flow in the chimney of the space heater was caused by negative internal pressure (-30 Pa) that is a result of using a large capacity fan (125 L/s (265 cfm) or more) for kitchen exhaust. Large capacity fans are mandated by the building code when natural gas is used for cooking. Yoshino noted that the chimney back-flow problem has become a health concern.

Moisture condenses in unheated rooms due to low air infiltration and the fact that only the living room was heated in many houses.

As a solution, Yoshino suggested the following design strategies and provided examples.

The heating and ventilation equipment and type of cooking appliance should be selected according to the air tightness level of a house.

- The building code needs to specify lower ventilation rates (suggested 92 L/s (195 cfm)) when electric appliances are used for cooking.

- Kitchen ventilation should be independent of other ventilated zones, because the required ventilation air volume is large. Kitchen fan operation affects comfort in the living room and the bedrooms.

Zero-Energy Sustainable Houses

This section reviews a group of homes loosely called zero-energy homes. These homes actually have very low energy consumption; they are super-insulated, airtight, and include green features that minimize the impact of the house construction and operation on the environment.

The Eagle Lake Healthy House
The Eagle Lake healthy house (CMHC 2001-2003, North Series # 5) was built for the Eagle Lake First Nation in Northern Ontario in 1997 as a demonstration project for

healthy, sustainable, durable, and affordable housings. The house is a 107 m^2 (1152 sq. ft.) bungalow. The approaches for the design, materials, and construction method were discussed and agreed to by the First Nations Tribal Council.

The building envelope: In the exterior walls, I-beam trusses were used to accommodate additional fibreglass insulation to a total of R-50 (RSI-8.8). Fibre cement board siding, a composite material of cement and wood fibres, finished the outside. The fire resistance property of the fibre cement siding lowers the threat from forest fires that are common in the region. Two layers of drywall were used in the interior face of the walls to act as a heat sink for storing heat.

The triple-glazed, low-e casement windows can be opened to provide cross-ventilation in summer. Fixed, sealed window units were also used.

The attic was insulated with R-60 (RSI-10.6) blown-in-place fibreglass. Metal roofing was used for durability.

For the foundation, insulated concrete slab was used. Three layers of 600 mm (24 in.) styrofoam insulation (a total of about R-30 (RSI-5.3)) were placed below and around the concrete slab.

Power and utilities: An integrated combined heating and utilities module, EcoNomad® was used to provide heat, power, drinkable water, and wastewater sufficient for a family of five. EcoNomad is operated by a small 6 kW diesel generator, which co-generates electricity, space heating, and domestic hot water. The system uses 20 to105 ampere-hour sealed batteries configured in a 48-volt system. Photovoltaic panels and a wind generator provide backup power to the batteries. Four photovoltaic panels, each provide 75 watts at peak and produce up to 1/3 kWh of electricity. A wind generator, mounted on the roof, produces 550 to 600 watts of electricity.

The concrete slab was heated by a hot-water radiant floor heating system, which allows for a low temperature setting indoors. The concrete slab and the double layer of gypsum walls provide thermal storage for the house.

Ventilation was provided by a balanced HRV system.

Healthy features: Low VOC paint was used on the walls. Cabinets were made of boards that combine straw fibres and non-toxic resins. The radiant floor heating does not stir up dust compared to forced air systems. A balanced HRV continually provides fresh air and removes stale, moisture-laden air. Closets did not have conventional doors to allow for air movement to help preventing condensation and mould growth.

Environmental efficiency features: The EcoNomad utility unit uses a small diesel engine generator that achieves over 90% fuel efficiency by producing electricity as well as reclaiming heat simultaneously. Wastewater is reclaimed and treated for use in toilets.

This reduces water consumption by up to 30% and reduces the septic field area. The latter reduces the construction cost and the environmental impact of a large septic bed.

The sun and wind provide 20% of the energy requirement, which reduces consumption of non-renewable resources. Large windows in the south-facing walls increase the potential of solar gain. Stored heat in the concrete slab and the double layers of drywall provide a natural heat source. Also 300 x 300 mm (12 x 12 in.) ceramic tile flooring, in addition to providing durability and low maintenance, helps with thermal energy storage.

The fibre cement siding is more durable than typical wood fibre or vinyl siding.

Special faucets, the toilet, shower, and washing machine use less water than conventional ones.

Affordability features: With overall energy savings up to 40% and a reduced upfront cost for connecting the house to conventional utilities, costs were down.

The Saskatoon Super-Insulated House

Dumont (2000) described his family super-insulated, two-storey, four bedrooms, 245 m^2 (2640 sq. ft.) house (excluding basement), built in 1992 in Saskatoon, Saskatchewan (52° north latitude). The house was described as the best insulated in the world with the lowest heat loss coefficient per square metre of floor area of any house anywhere. Dumont built the house as a model for energy efficiency and sustainable construction that minimizes energy use, uses renewable energy sources and recycled materials, and generally minimizes the impact of the house construction and operation on the environment.

Dumont argued that using extra insulation is a simple, effective way to reduce energy consumption and thus reduce fossil fuel consumption. Because insulation has no moving parts; it will last indefinitely provided it is protected from the elements with proper vapour and weather barriers.

In a Saskatoon climate is characterized by an average temperature in January of -18°C (0°F), annual heating degree days of 10 900 (base 65°F), 2400 hours of bright sunshine each year, and a winter design temperature of -34°C (-30°F).

The energy efficiency features included the following.

> The building envelope included extra insulation compared to the conventional RSI-3.5 (R-20) value. Blown-in cellulose insulation was used because of its green characteristics. The attic has RSI-14.1 (R-80), the walls (including basement walls) RSI-10.6 (R-60), and the basement floor RSI-6.2 (R-35).

The wall assembly included double 38 x 89 mm (2 x 4) stud walls (400 mm/16 in. total wall thickness) to accommodate extra insulation. 6-mil poly air and vapour barrier placed on the warm side of the insulation. Blown-in cellulose insulation in the stud space. The double wall thickness with high-density cellulose insulation increased the wall mass, which increased the thermal mass of the wall and reduced noise transmission.

Triple-glazed windows (about RSI-0.9 (R-5)) with two low-e coatings, argon gas fill, low conductivity spacer bars, and wood frames were used.

The injected cellulose insulation made the building envelope more airtight as compared to using fibreglass insulation. Additional measures ensured good air tightness of the building envelope. All joints in the air/vapour barrier were carefully sealed with acoustical sealant; the rim joists were wrapped with Tyvek® that was sealed to the poly. The blower door test result for the house was 0.47 ach at 50 Pa. The Canadian R-2000 standard is 1.5 ach at 50 Pa.

Indoor air quality features included the following.

A balanced heat recovery ventilator (HRV) included a high-efficiency double-core plate air-to-air heat exchanger. The HRV unit was run continuously at 100 CFM (47 litres per second) to ensure a high indoor air quality.

Dry basement systems prevent mould and mildew growth. Installing exterior perimeter water drainage and proofing, and insulating the floor slab (RSI-6.2 (R-35)) accomplished this.

Particleboard, OSB, wall-to-wall carpets, and vinyl flooring were avoided to avoid off gassing of volatile organic compounds (VOC). Douglas fir plywood for the sub-floor, solid hemlock fir joists, and prefinished solid oak strip and ceramic tiles were used for flooring. Kitchen cabinets and vanities were birch plywood and solid oak. Low-VOC paints were used.

Green features included the following.

Scrap gypsum was added to the interior walls to cut down on landfill waste and provide additional thermal mass, which helped moderate the temperature swing in the house caused by solar gain. In summer, the flywheel effect of the walls' thermal mass kept the home cooler during the heat of the day and warmer during the night and early morning hours.

No air conditioning was needed, because of the fenestration design and overhangs on all the south windows that limit overheating during the summer period. Also, efficient appliances were used to reduce internal heat gains. Compact fluorescent and T8 lamps were used for lighting. Shiny reflectors were used over the kitchen light to enhance lighting quality.

Decorative shutters on the smaller north-facing windows gave the appearance of larger windows without the heat loss and poor solar performance that accompanies large north windows during the coldest part of the winter.

The house was oriented so windows faced south for passive solar gain. An active solar hot water system with 15.6 m^2 (168 sq. ft.) of selective-surface liquid solar panels had a low-cost wood-framed, EPDM -lined tank, which holds about 5300 litres (1400 US gallons) of water. This large water tank improves the year-round efficiency of the solar collection. The hot water in the tank is used to heat the domestic hot water and also heats the house. This operates via a water-to-air heat exchanger within the forced air furnace, which uses a brushless direct current fan motor. The fan provides about 800 cfm (376

L/s) of airflow using 110 watts of fan power. Additional heat is available through five electric baseboard heaters located around the house

> Water efficiency measures included low-flow showerheads, a variable-water-level clothes washer, and low-flow toilets. For landscaping, drought-resistant vegetation replaced a conventional lawn at the front. Collected rain and snowmelt run-off from the roof to use for irrigation.
>
> Recycled lumber was used in the construction with polyethylene lumber on the front and back stairs. The polyethylene lumber was manufactured from recycled plastic waste.
>
> To assist with ongoing recycling, a special chute under the kitchen sink directs metal and plastic cans and bottles to a large container in a closet in the basement. The container could hold about six month's supply of cans and bottles. The cans and bottles are then taken to the recycling depot. A composting container made of recycled polyethylene was conveniently located near the garage and used year round.

Features that reduced the embodied energy of the structure construction considerably included using cedar shake rather than an asphalt shingle roof, wood flooring rather than synthetic wall-to-wall carpets, preserved wood instead of concrete basement walls and floor, and cellulose insulation that is much less energy intensive than fibreglass.

Lessons learned in building an energy-efficient home included the following.

> The incremental costs for the energy efficiency and water efficiency measures, in 1992, amounted to about C$13,000 and the annual energy and water savings amounted to about C$800, giving a payback period of about 16 years, or an annual return of about 6.2% after taxes. Over the seven years (1993-1999), the total energy consumption averaged 15 300 kWh per year, or 46.9 kWh/m^2 per year (14 900 Btu/sq. ft. per year). The average energy use in Saskatchewan is 300 kWh/m^2 (95 000 Btu/sq. ft.).
>
> A low energy house does not cost much more than a conventional one. For a well-insulated house, the space-heating source can be centralized and there is no need to place a heating source under each window. This reduces the cost of the distribution duct system of warm-air heating systems. A rectangular two-story house is a lot easier to heat than a sprawling rancher. Good indoor air quality in a new home could easily be achieved by avoiding use of polluting materials, such as carpeting and particleboard.
>
> Dumont (2000) concluded that if a similar house is built in a milder climate, such as that in a coastal city like Seattle, it would probably be a zero-energy, space-heating house.

The Alberta Sustainable Home

The Alberta Sustainable home (Rieger and Byrne, 1996) is a three-bedroom, 170 m^2 (1820 sq. ft) house and office located in Calgary, Alberta. The climate is described as cold, dry, and sunny. It has 9620 annual heating-degree-days base 65ºF (5345 heating-degree-days base 18ºC). The building is designed to be environmentally responsible (independent of sewer, electric, and water systems), healthy, energy efficient, and affordable (same price as a comparable conventional home). The designer and builder have lived and worked in the building since April 1994.

The building envelope is airtight and super-insulated (RSI-8.8 (R 50) in walls and RSI-13 (R-74) in the roof, both insulated with blown-in cellulose). Rigid foam was used under the concrete slab-on-grade and was extended 1200 mm (4 ft) horizontally outside the perimeter (Note: R-value not listed).

The so-called "Eco-Studs" were used, which is a double-stud wall framing system consisting of a 38 x 89 mm (2 x 4) interior load bearing stud connected to an outer 38 x 64 mm (2 x 3) stud at the bottom, middle, and top using the left-over cutoffs lumber. The Eco-Studs are manufactured as one stud for fast installation with any width possible to accommodate the required insulation. Fiberboard that contains 23% recycled newspaper was used for the wall sheathing and acrylic stucco was used for the cladding.

The windows, rated RSI-3 (R-17) at the centre of the glass, included five glazing (two glass and three heat mirror films), Krypton gas fills, and warm edge insulating spacers.

The primary energy is Solar power both active and passive techniques. Active solar technology included grid-connected photovoltaic solar modules that produce about 2000 kWh per year. The passive solar techniques included a solar box cooker and thermal mass application (dark stucco façade, dark interior floor tiles, heavy brick fireplace, etc.) to store solar heat to provide space heating and hot water.

A ground source heat pump provides space heating. A multipurpose wood-fired fireplace is a backup heater. It has two combustion chambers with an external air supply. The primary chamber provides space heating and hot water (with heat exchanger coils) as well as is used as a stove. The secondary chamber is used as a baking oven. [Note: The multipurpose masonry fireplace is an old method that was commonly used in the early American Cape Cod house and in the Hungarian village house.]

The domestic hot water system consists of a horizontal 360 liters (80 gallons) tank containing three heat exchanger coils. The first coil brings heat from the fireplace, the second brings heat from a solar panel on the roof, and the third provides hot water for a radiant floor heating system.

A heat recovery ventilator (HRV) provides ventilation air that is preheated by heat exchangers on the dryer exhaust and the gray-water outlet. A solar hood collector on the south façade also preheats the ventilation air.

Healthy features included: A seven-filter air cleaner for dust, smoke, and pollen was installed at the HRV outlet. Natural nontoxic materials and finishes were used such as concrete without chemical additive, caulk and adhesives with low VOC or solvents, and cabinets made of formaldehyde-free particleboard. Flax linoleum, cork, and pine were used for flooring.

Green features included: Using natural furnishings and building materials made from renewable resources, salvaged items, and materials with low embodied energy; and using

several water conservation technologies that included a composting toilet, ultra low-flush toilet that uses 0.6 liter (1 pint) per flush, low-flow showerheads, and faucet aerators. These technologies helped keep the use of city water to 2 cubic meters (440 gallons) per month. Also a rainwater collection system is used to collect water from the roof. Sewage treatment will be handled on-site in the future, with gray-water to be used for the landscape.

A green illumination technology, the SunPipe (also called daylight pipe or solar tube), provides daylight for the hallway, bathroom, and north bedrooms. Compared to other daylighting technologies, the SunPipe uses a minimum glass surface area for reduced winter heat loss and minimal invasion of the thermal envelope. The ancient Egyptian utilized the SunPipe method.

The Passivhaus - Europe

More than 5000 super-insulated, low-energy houses have been built in Europe (Feist, 2005). These houses were built according to a construction concept known as the passive house (*passivhaus* in German). The concept was developed at the Passivhaus Institut Darmstadt in Darmstadt, Germany, established in 1996 as an independent private research institution with a focus on research and development of highly efficient energy buildings and systems. The Wikipedia (nd.) web site describes the development of the concept, design, and construction of the passive house. From 1997 to 2002, the European Commission funded the development of the Passive House Energy Standard as a leading standard for energy-efficient design and construction (EDU, 2004-1).

The term *passivhaus* does not necessarily refer to a passive solar energy house type as known in North America. The term refers to a house that could maintain comfortable indoor environment without active heating and cooling systems. Passive houses are airtight, super-insulated, and have a specified maximum annual energy consumption depending on the climate. The Passivhaus Institute defines the passive house as a building in which a comfortable interior climate can be maintained without active heating and cooling systems; the house heats and cools itself, hence passive (Feist, 2005, What is a Passive House?). For the European climate, passive construction requires an annual heating budget of less than 15 kWh/m² (4,755 Btu/sq. ft.). Also, combined annual energy use of a house for heating, domestic hot water, and electricity is not to exceed 120 kWh/m² (38,000 Btu/sq. ft.). Table 5 lists the passive house standard for the Central Europe climate.

The passive house concept is a comprehensive approach to cost-efficient, high quality, healthy, and sustainable construction. Occupants of passive houses indicated significant reduction in energy costs as well as increased comfort of the built environment. Energy saved on heating is 80% compared to conventional standards. The energy requirement for heating is in the range 10 kWh/m² to 20 kWh/m² (3.2 to 6.4 Btu/sq. ft.) depending on climate. Passive houses achieve low energy consumption by superior design and highly efficient components with respect to:

Table 5. Passive House Standard for Low-Energy Houses for the Central Europe Climate

Maximum annual heating requirement	15 kWh/m² (4,755 Btu/sq. ft.)
Maximum combined annual energy use for heating, domestic hot water, and electricity	120 kWh/m² (38,000 Btu/sq. ft.)
Maximum heating load	10W/m² (3.2 Btu/sq. ft.)
Minimum R-value for walls and roof	RSI-6.7 (R-38)
Air tightness standard	Maximum 0.6 ach @ 50 Pa
Minimum window R-value	RSI-1.2 (R-7)
Typical glazing	Triple-pane, gas-filled, with 2 low-e coatings
Minimum HRV efficiency	80%
Blower door testing	Required for every house

Source: EDU (2004-1).

insulation;
- avoiding thermal bridges;
- air tightness;
- ventilation with heat recovery;
- windows (area and orientation) are optimized for passive solar gain;
- heating technology; and

design based on optimal interaction of all components.

Thousands of super-insulated homes have been built in the United States (EDU, 2004-2). The building envelope, energy, and sustainable features of two houses are reviewed below.

The Hanover House

The Hanover House (EBN, 1998) is an advanced super-insulated, low-energy house in Hanover, New Hampshire. It was built in 1994 according to passive house standards (Feist, 2005). The house is wood-framed, two-story, 175 m^2 (1887 sq. ft.) (exclusive of basement) with an attached garage. The *Environmental Business News* (EBN, 1998) noted that the Hanover House has about the lowest energy consumption of any house in the United States. It won an ASHRAE technology award in January 2000.

Super-Insulated Envelope: Double 38 x 89 mm (2 x 4) walls insulated with 290 mm (11 1⁄2 in.) of dense-pack cellulose provide RSI-7 (R-40). The ceiling is insulated with RSI-10.6 (R-60) blown cellulose. Band joists were insulated with RSI-7 (R-40) rigid foam and fibreglass, and the basement walls were insulated on the interior with RSI-1.9 (R-11) fibreglass.

Windows and Doors: High-performance windows and doors were site-glazed with the top-performing glazing. The windows have insulated-fibreglass frames with centre-of-glass R-values ranging from RSI-1.2 to RSI-1.6 (R-6.7 to R-9). The windows have deep wells for better light distribution into the house. Three quarters of the window area were placed on the south side for passive solar gain. In northern New England, the south-

facing windows could result in overheating in late March or September when the sun is relatively low in the sky and outside air temperature is higher than about 21°C (70°F). To address the overheating issue, few windows are opened. Opening windows at night keeps the house cool in summer.

Airtight Construction: Air sealing was a high priority. A polyethylene membrane served as both an air barrier and vapour retarder on the walls and ceilings. Foam-in-place polyurethane was used at all penetrations, and sealant was used at framing connections. Neoprene boots sealed plumbing stacks. The envelope measured air tightness was 0.37 ach at 50 Pa or 65 L/s (137 cfm) at 50 Pa.

Ventilation: A central HRV supplies fresh air into the return air ductwork.

Heating System: A drain-back active solar system heats the house. This includes a 33 m^2 (360 sq. ft.) collector built on site and a 4500 litres (1200 gallon) storage tank. A 52-gallon electric water heater is used for backup heat and domestic hot water. A water-to-air heat exchanger in the forced-warm-air delivery system extracts heat from the storage tank of the solar system to heat the house. When there isn't enough heat in the storage tank, the electric water heater (with a 5 kW element) takes over. The electric water heater was metered separately to collect data on the energy consumption of each energy source.

Lighting and Appliance Efficiency
The use of compact fluorescent lighting, halogen lighting on dimmers, and the selection of efficient appliances helped reduce the energy load on the house.

Sustainable Features included:

- **Grey water separation:** The house was plumbed so grey water (wastewater from showers, bathroom sink, and washing machines) could be collected separately if regulations change. Regulations at the time of the house construction (1994) did not permit grey water treatment by individuals.

- **Efficient use of environmental resources:** Very little lumber from large-diameter trees was used. Trusses and I-joists were used for framing members larger than 38 x 89 mm (2 x 4). Oriented strand board was used for sheathing and sub-floors.

- **Built for durability:** The house was constructed to be very durable through careful selection of materials and attention to moisture and airflow in the home.

Indoor Air Quality Features included

a continuous supply of fresh air;
- the use of low- or zero-formaldehyde wood composites;
- flooring of hardwood, tile, or natural linoleum instead of carpeting or vinyl, and counters of granite rather than laminate;
- only water-based finishes used to avoid the generation of VOCs;
- no combustion of wood or fossil fuels on the site; and

an installed passive radon stack. An in-line fan could be added should high radon levels ever be found.

Energy Performance
During the first three years of operation (1994-1997), total annual energy consumption for the house ranged from 4255 kWh to 5556 kWh (see Table 6), and the total annual electricity consumption (backup heating and domestic hot water) ranged from about 1200 kWh to 2243 kWh (see Table 6). *Environmental Building News* (EBN, 1998) reported that the house designer believed weather variability was the reason for the high electricity consumption in the second year, which was double the consumption in the first year of operation. After a three- to four-day cold weather and cloudy period the thermal storage was used up, and each day could add as much as 100 kWh to the annual energy consumption.

Table 6. The Hanover House, Measured Annual Energy Performance during the Heating Season

	1994-1995	1995-1996	1996-1997
Heating degree days (ºF) base 65ºF	7029	7826	7344
Heating degree days (ºC) base 18.3ºC	3905	4348	4080
Electricity use – backup heating and domestic hot water (kWh)	1197	2243	2178
Total electric consumption (kWh)	4255	5541	5556

Source: EBN (1998).
Note:
Heating-degree-day information is for the September through April heating season.

Comfort
Occupants were very satisfied with the house and the quality of the indoor environment. Indoor air temperatures stay uniform throughout the house including by the windows that provide substantial daylight.

Room for Improvement
The house designer identified a number of opportunities for greater energy savings that could reduce annual energy use by as much as 25%, or 1150 kWh to 1450 kWh. Energy savings opportunities include the following.

- Use more efficient motors in the solar system pumps and in the fan coil blower. This could save an additional 250 kWh to 300 kWh annually.
- Use more efficient lighting and a super-efficient refrigerator to save another 300 kWh to 400 kWh annually.
- Replace the desktop computer with a laptop in the home office to save another 150 kWh to 200 kWh annually.
- Grey water heat recovery would reduce backup electricity use during the three coldest months by about 200 kWh to 300 kWh annually.

- Standby electricity consumption of the TV, VCR, stereo, microwave oven, answering machine, etc. comes to about 30 watts on a continual basis. If these were on separate switches, more than 250 kWh could be saved annually.

Environmental Building News (EBN, 1998) noted that while the design is the key to this home's low energy consumption; the owners' commitment might also be a factor. Occupant behaviour is known to change energy performance sometimes by a factor of two or more.

The Klingenberg House

The Illinois passive house, the Klingenberg House, was built in 2003 in Urbana, Illinois, according to the *passivhaus* guidelines (EDU, 2004-2). The designer, K. Klingenberg, used a computer model to refine the *passivhaus* specifications developed for the central European climate. The winter design temperature for Urbana, Illinois, -19ºC (-3ºF) is considerably colder than that for Berlin -14ºC (7ºF), Amsterdam -7ºC (20ºF), or Paris -6ºC (22ºF).

Energy budget optimization analysis using computations indicated the need for thick walls and a box shape for the house. The box shape minimizes its surface-to-volume ratio and, therefore, minimizes energy losses from the building envelope. Nooks and objects (such as plumbing stacks and ventilation air ducts) penetrating the building envelope are not desirable, because they contribute to energy losses. The air intake and exhaust ducts were passed to the outdoors through the underground. Table 7 lists the house specifications.

Foundation

Concrete walls 245 mm (9 5/8 in.) thick concrete block walls were insulated on the exterior with 150 mm (6 in.) of expanded polystyrene foam (RSI-4.2 (R-24)). The polystyrene above grade was protected with slate. The concrete-block walls surrounded a concrete slab that was poured over a 355 mm (14 in.) thick layer of expanded polystyrene foam for a total of RSI-10 (R-56), which was built up with of seven layers of 50 mm (2 in.) insulation boards.

Table 7. Specifications of the Klingenberg House

Location	Urbana, Illinois
Floor area	134 m^2 (1450 sq. ft.) including loft
Foundation	Concrete block wall, 245 mm (9 5/8 in.) thick
Foundation insulation	150 mm (6 in.) expanded polystyrene foam, RSI-4.2 (R-24)
Under-slab insulation	355 mm (14 in.) thick layer expanded polystyrene foam, RSI-10 (R-56)
Wall framing	300 mm (12 in.) I-beam
Wall insulation	300 mm (12 in.) blown-in fibreglass plus 100 mm (4 in.) exterior rigid polystyrene foam, RSI-10.6 (R-60)

Roof framing	400 mm (16 in.) I-beam rafters with a vent channel between two layers of exterior sheathing.
Roof insulation	300 mm (12 in.) blown-in fibreglass, RSI-10.6 (R-60)
Air tightness	Not measured
Windows	Triple-pane, argon-filled, low-e glazing, 1 W/(m^2 K) / 0.17 Btu/(h sq. ft. ºF) overall U-factor
Ventilation system	HRV
Heating system	Electric resistance element in the HRV
Domestic hot water system	Instantaneous electric water heater

Source: EDU (2004-2),
Note: SI units are converted from English units given by the author.

Exterior Walls

Structure framing: The thick walls, dictated by energy optimization analysis, were framed with a 300 mm (12 in.) wide I-beams commonly used for floor joists. The manufacturer provided details allowing its floor joists to be used as studs. The use of the I-beams as studs required structural sheathing on both sides. Oriented strand board was used for interior sheathing, which also functioned as a vapour retarder. A 12.7 (½ in.) vapour-permeable structural fibreboard, RSI-0.23 (R-1.28), was used on the exterior. The walls were cladded with cedar bevel siding. The top and bottom wall plates were double 32 mm x 300 mm (1¼ in. x 11 7/8 in.) rim boards of engineered laminated strand lumber.

Insulation: A total of RSI-10.6 (R-60) consisted of 300 mm (12 in.) blown-in fibreglass insulation in the stud space, plus two layers of 50 mm (2 in.) thick exterior rigid polystyrene foam installed over the fibreboard sheathing using vertical strapping screwed through to the studs.

Rain screen: The vertical strapping created a rain screen drainage cavity behind the cedar siding.

Foundation - above grade protection: The walls were extended 64 mm (2 ½ in.) beyond the foundation to shed rain beyond the slate protecting the exterior polystyrene foam of the foundation.

Air/vapour barrier integrity: To maintain the integrity of the air barrier, no electric boxes or wiring were installed in the exterior walls. Receptacle boxes were installed in the floor. For outdoor light, wireless battery-operated fixtures were used, installed in shallow surface-mounted boxes. All panel joints were glued or taped.

Windows: All windows have triple-pane, argon-filled, low-e glazing, and an overall U-factor of 1 W/(m^2 K) / 0.17 Btu/(h sq. ft. ºF). The exterior polystyrene foam partially overlapped the window frames. Exterior jam extensions and wood sills were used to trim the edges of the polystyrene and the rain screen strapping. Most of the windows, a total of 17.7 m^2 (190 sq. ft.) of fixed glazing and casements, were placed on the south-facing wall, protected from summer sun by the roof overhang.

Roof: With a shallow-pitched south-facing single plane framed with 400 mm (16 in.) I-beam rafters, the so-called "cool roof" consisted of two layers of exterior roof sheathing sandwiching a vent channel. The lower layer of sheathing was vapour-permeable structural fibreboard and the upper layer was OSB. The roofing was standing-seam galvanized steel. The roof was insulated with 300 mm (12 in.) blown-in fibreglass with a total of RSI-10.6 (R-60). Future additions might include uni-solar peel-and-stick photovoltaic modules to be installed on the metal roof.

Ventilation: A heat-recovery ventilator with a damper controller allowed the homeowner to select between two possible air intake ducts depending on the outdoor temperature. One air intake duct, an "earth tube," was a 30 m (100 ft.) long polyvinyl chloride (PVC) duct buried in the ground. The HRV controller regulated ventilation air intake as follows.

> For an outdoor temperature of less than 13ºC (55ºF), ventilation air is drawn through the earth tube, where it is heated by the soil.
>
> For an outdoor temperature greater than 13ºC (55ºF), but less than the indoor air temperature, ventilation air is drawn through the conventional outdoor air intake grille.
>
> When the outdoor temperature equals the indoor air temperature, the heat recovery function is bypassed.
>
> For an outdoor temperature greater than the indoor air temperature, ventilation air is drawn through the earth tube, where it is cooled by the relatively cool soil.

Heating*:* A 1000-watt (3141 Btu/h) electric resistance element, installed in the HRV, heated the house.

Table 8 compares R-values and air tightness of the four super-insulated building envelopes:

Table 8. Comparison of R-Values and Air Tightness of Four Super-Insulated Building Envelopes

Component	**Eagle Lake House** (North Series # 5, CMHC, 2001-2003)	**Saskatoon House** (Dumont, 2000)	**Alberta Sustainable Home** (Rieger and Byrne, 1996)	**Hanover House** (EBN, 1998)	**Klingenberg House** (EDU, 2004-2).
Wall framing	I-beam	Double 38 x 89 mm (2 x 4) walls 400 mm (16 in.)	Double 38 x 89 mm (2 x 4) and 38 x 64 mm (2 x 3) stud walls, 325 mm (13 in.)	Double 38 x 89 mm (2 x 4) walls 290 mm (11½ in.)	300 mm (12 in.) I-beam
Wall RSI (R)	8.8 (50)	10.6 (60) blown-in cellulose	8.8 (50) blown-in cellulose	7 (40) blown-in dense pack cellulose	10.6 (60) 300 mm (12 in.) blown-in fibreglass + 100 mm (4 in.) rigid polystyrene
Roof RSI (R)	10.6 (60)	14.1 (80)	13 (74) blown-in cellulose	10.6 (60)	10.6 (60)
Floor RSI (R)	5.3 (30)	6.2 (35)	Not listed, Rigid foam under slab and extends 1200 mm (4 ft) horizontally outside the perimeter		10.0 (56)
Basement walls				1.9 (11) from inside	4.2 (24) from outside
Windows RSI (R)		0.9 (5) triple glazed	3 (17) five glazing (two glass and three heat mirror film)	1.2 to 1.6 (6.7 to 9)	1.26 (7.14) triple glazed
Air tightness (ach at 50 Pa)		0.47	Not listed	0.37	Not measured

Domestic Hot Water: An instantaneous electric water heater supplied hot water.

Energy Budget: The all-electric super-insulated house did not require supplemental heat for most of the year. In January 2004, which included two cloudy weeks and temperatures as low as -23ºC (-10ºF), the total electricity consumption for all household uses including heating was 340 kWh.

Innovative Wall Assemblies

This section reviews innovative wall assemblies for cold climates and a hot, humid climate. Some assemblies reviewed are still in the conceptual state.

Cold Climate

Transparent Insulation Materials

These materials, such as granulated silica aerogel and honeycomb or capillary sheet, are used to fill the space between two layers of glass to enhance the insulation level of windows. Lien et al. (1997) investigated the application of transparent insulation materials in low-energy dwellings in northern regions of Norway. The climate in northern Norway is characterized by four months of dark and the coldest period with little or no solar radiation. Solar energy can, however, be used the rest of the year as heating is needed in the spring and the fall, and sometimes in the summer.

To reduce heat losses during the winter and make use of solar heat in the spring and the fall, the windows should have both high thermal resistance and high transmittance of solar radiation. This is achieved by using transparent insulation materials. Capillary (circular polycarbonate or polymethacrylate or glass tubes) and honeycomb (angular plastic tubes, usually square shape) are among the most promising transparent insulation materials, because of the combination of both high transmittance of solar radiation and good thermal resistance. The capillary structures reduce convection losses, while increasing solar radiation transmission, because all reflections are directed inward through the capillaries. The capillary or honeycomb material is placed perpendicular to the glass of a window or to the absorber of a solar collecting wall. It is possible that most of the building envelope would consist of transparent insulation materials, which Lien et al. (1997) referred to as “daylight walls.”

Calculations indicated about 20% savings in heating and ventilating energy for a two-storey row house, 108 m^2 (1165 sq. ft.) floor areas, with windows and daylight walls with capillary materials of three different thicknesses. The energy savings potential was especially promising for the coldest climate zone in Norway, where the problem of overheating is small and the energy saving potential is good. Table 9 lists the U-values used in Lien et al. (1997).

Transparent insulation materials affect light distribution in the room, depending on the type of material, its thickness, and the sun angle. The capillary material spreads direct daylight in a cone shape and distributes it to certain areas of the floor, walls, and ceiling of a room depending on the incoming angle of incidence. Aesthetics depend on the size of the capillaries and the way the materials are cut. If the capillaries have a 1 mm (0.04

in.) diameter, it appears quite whitish, with no visibility through the material. Lien et al. (1997) concluded that transparent insulation materials are promising when both energy savings and daylight use are considered.

Table 9. U-Values for Windows and Walls with Capillary Transparent Insulation Materials

Component	U ($W/m^2 K$)	RSI ($m^2 K/W$)	R (h sq. ft. F/Btu)
Window			
Treble glazing, one low-e coating	1.6	0.6	4
Double glazing	2.4	0.4	2
Daylight wall			
35 mm (1 3/8 in.) capillary, 2 glass layers	1.7	0.6	3
100 mm (4 in.) capillary, 2 glass layers	1	1.0	6
200 mm (8 in.) capillary, 2 glass layers	0.7	1.4	8

Note:
R-values are converted from U-values given by Lien et al. (1997).

Hybrid Heating/Cooling: Wall System

The hybrid or active wall system (LOWTE, 2001) provides low temperature heating and cooling for building applications where the temperature requirement is about 20°C (68°F), such as a garage or greenhouse, and keeping entrance porch areas ice free. The system uses the so-called double-air-gap wall in which the wall assembly is modified to include two air gaps positioned between two layers in the wall, such as insulation layers. An air circulation fan and water-to-air heat exchanger are located at the bottom of the wall. The downward air stream in the outer gap is heated in the heat exchanger and moves upward in the inner gap where it heats the interior surface of the room. The heat exchanger may use ground source heat, waste heat sources, or a district heating system. Solar heat gains may also be used to raise the temperature of the air stream in the outer air gap. Window units may also have double air gaps, which become a continuation of the two air gaps in the opaque wall section below.

Schmidt and Jóhannesson (2001) demonstrated the use of a computation-based design tool to optimize the design of the double-air-gap wall system. Design parameters included size and placement of the air gaps in the wall assembly. Schmidt and Jóhannesson gave suggestions for the placement of the double air gaps in the wall assembly, which depends on the available heat/cold sources.

Hot Humid Climate

Breathing Wall

Hoyano et al. (1995) and Sugawara and Hoyano (1997 and 1996) proposed the so-called breathing wall for temperate and humid climate regions. The breathing wall is a passive solar design wall that "breathes," such that air and moisture vapour can flow back and forth through it. The breathing wall provides continual natural ventilation to the building as well as sufficient thermal insulation for Tokyo's winter climate. Sugawara and Hoyano (1997) noted that the design and application of the breathing wall differ from the European "dynamic insulation" wall.

The climate in southern Japan is described as temperate and humid, where summers are hot and humid, and winters are cold enough to require heating, but mild. Summer and winter extremes are brief and are separated by a pleasant spring and autumn. Because of the climate, traditional houses in Tokyo have a wide-open corridor (called an *en-gawa*) or a small gardening courtyard (called a *tsubo*), which opens the indoor environment to the outdoor climate. Before air conditioning technology, building design relied on natural cross-ventilation for cooling and controlling indoor moisture. Today, houses are highly insulated, airtight, and rely on heating, ventilation and air conditioning (HVAC) equipment.

A breathing wall consists of a number of aluminum foil sheets with many fine perforations. The foil sheets are sandwiched between plywood sheets. Aluminum foil was chosen because of its low emittance properties. The wall design parameters include:

- the number of aluminum foil sheets;
- the wall thickness; and
- the diameter and spacing of the holes in each foil sheet.

These parameters affect the amount of air and moisture flow rates. Controlling the amount of moisture vapour flowing through the wall prevents condensation within the wall.

Sugawara and Hoyano (1997) graphed the effect of the number of aluminum foil sheets (5 to 25 sheets) and wall thickness 60 to 120 mm (2 3/8 to 4 3/4 in.) on the equivalent thermal transmittance that ranged from 0.04 W/m^2 K (RSI-25 (R-142)) for a 120 mm (4 3/4 in.) wall thick and 23 foil sheets to 0.45 W/m^2 K (RSI-2.2 (R-12.5)) for a 60 mm (2 3/8) wall and six foil sheets. Sugawara and Hoyano, using computations, studied the effect of the breathing wall on the indoor air quality and optimized its design for Tokyo's winter conditions (temperature 0ºC/32ºF, relative humidity 60%, and wind speed 3 m/s (11 km/h)). The resultant wall: 60 mm (2 3/8 in.) thick, contained 11 perforated aluminum foil sheets, with a perforation diameter/spacing of 1/23 mm on the innermost sheet and 0.25/1 mm on the other sheets. This wall provides:

- 0.5 air changes per hour;
- a 4.8 $m^3/h\ m^2$ (3.4 million cfm/ft^2) airflow rate (inward and outward) (Analysis indicated no condensation within the wall with airflow rates up to 7 $m^3/h\ m^2$. (5 million cfm/ft^2)); and

- an equivalent thermal transmittance of 0.34 W/m^2 K (RSI-2.9 (R-17)) with an inward airflow and 0.38 W/m^2 K (RSI-2.6 (R-15)) with an outward airflow.

The evaluation results of a natural ventilation system with a pitched roof based on the breathing wall assembly described above is presented in Sugawara and Hoyano (1996). The natural ventilation system was developed to provide a healthy and comfortable indoor environment for the climate of Tokyo, Japan.

Air-Cooled Walls and Roofs

The concept of this system is based on the air-cooled walls principle described in the textbook by Rogers (1951). Rogers discussed and provided example buildings demonstrating how air-cooled walls and roofs could improve building performance. An air-cooled wall includes an air space in the outer shell between the cladding and the sheathing, which is vented at the bottom and top. Solar heat gain received by the cladding warms the air in the vented cavity. As warm air rises, it draws in cooler air at the bottom vent. The cavity air carries away most of the solar heat, leaving only the radiated component across the vented space to the main mass of the wall.

Rogers used the concept of the tent-fly operation to explain the air-cooling of ventilated roofs. The exposed top deck (flat or sloped) receives the sun heat. Beneath, in the attic or loft, as the air is heated, it seeks to escape out of the roof vents, drawing in cooler air. Rogers noted that a secondary benefit of air-cooled walls and roofs is their ability to remove moisture that might diffuse through the wall during winter. Air-cooled walls require thoughtful design. If the air space is narrow and air movement is slow, frost may fill the space. The vents must be designed to prevent wind-driven snow and rain from entering the wall or roof space. Vent openings that are made large for summer cooling may have shutters that reduce their area for winter moisture removal.

The vented air space concept was used to preheat ventilation air at the Swedish Research Station in Antarctica (Haugun, 1991). The intake air slots included a rock wool layer to filter out infiltrated blowing snow. Ventilation supply air ducts, after leaving the wall air space, passed through the air space in the outer layer of the roof where a supply fan delivered the preheated air to the building. Haugun reported that this approach increased the temperature of the ventilation air by up to 40ºC (72ºF).

The air-cooled roof concept was also used in the Klingenberg's Illinois passive house (EDU, 2004-2). The shallow-pitched, south-facing single plane consisted of two layers of exterior roof sheathing sandwiching a vent channel. The lower layer of sheathing was vapour-permeable structural fibreboard, and the upper layer was OSB

Comments - Innovative Wall Assemblies

Some of the innovative concepts of these walls, or with modifications, could be applied in Northern Canada. The transparent insulation materials could be used to enhance the thermal performance of glazing, provided that economical benefits are demonstrated. The solar heat gain concept of the air-cooled walls and roof could be used in northern Canada in a double stud wall system.

The hybrid heating/cooling wall system concept to use solar heat gain as well as recovered waste heat requires a heat exchanger and an air circulation fan that would require maintenance. The breathing wall concept uses innovative perforated aluminum foil sheets, but their manufacturing and economic benefits still need to be assessed.

3. Heating, Ventilation, and Energy Technologies

Heating and Ventilating

HVAC Design Considerations

Meckler (1991) and Armstrong (1993) discussed design challenges of HVAC in the arctic regions of Alaska and Canada. Armstrong noted that the climate presents environmental challenges that must be recognized and addressed in every HVAC system design. The challenges result from extremes of cold, wind, snow, dry air, solar gain, and extended darkness.

Climate Challenges: Alaska

- Heating degree days range from 6697 heating degree days (base 65°F) in Ketchikan (at 55º 21 N´ latitude) to 20 341 heating degree days (base 65°F) in Barrow (at 71º 18 N´ latitude).

- Snowfall varies greatly in Alaska.

- Temperate coastal communities (e.g., Ketchikan) have an average annual snowfall of 94 cm (37 in.) and little accumulation over a few days.

- South central and northern communities (e.g., Valdez) receive large quantities of snow; an average annual snowfall is 625 cm (246 in.) with a record snowfall in excess of 1524 cm (600 in.). Snow accumulates for most of the winter, and compacts to a depth of about 4 m (12 ft.).

- Low temperatures can range from -57ºC (-70ºF) for weeks in interior areas to -34ºC (-30ºF) in south central and western areas and last for extended periods. Temperatures can reach 35ºC (95ºF) in summer. There is very little temperature swing from night to day during the winter months when there is little or no sun.

- Wind speeds in excess of 200 km/h (125 mph) are common. The coastal areas are subjected to storms with hurricane force winds.

- Summer days are long, particularly north of the Arctic Circle where the sun rises in the early summer and stays until fall. Continuous sunshine poses special challenges in dealing with solar gain that does not subside during the night.

HVAC Design Considerations

Meckler (1991) noted that design considerations for the arctic region differ from temperate climates and require greater attention to condensation on building envelope surfaces and glazing. In some areas, the moisture content of the outdoor air is almost zero for several months of the year, and heating without adequate humidification can result in an unacceptable indoor humidity level. Design of HVAC systems in such regions requires modifications to the common design methods used in temperate climates

(Armstrong, 1993). Meckler (1991) and Armstrong (1993) presented the following general design approaches that address the challenges of the arctic cold climate.

- The HVAC systems must be easily maintained and reliable, because transportation is expensive and sometimes not available due to bad weather.

- It is important to consider local microclimate conditions, because temperatures stay at design conditions for long periods.

- Building penetrations should be kept to a minimum, because of high wind and snow drifting.

- Cooling and ventilating systems must be designed for continuous operation without reducing loads during the night, because solar gains do not subside during the night. Designers should ensure that computerized load analysis programs account for continuous solar gain conditions.

- To avoid condensation and ensure the effectiveness of draft, the heating appliance flue should be routed through an insulated or warm space.

Forced-air heating systems are more common in cold regions, because of their simplicity of installation and maintenance (Meckler, 1991). Space heaters usually lead to severe stratification, because heat distribution is usually by natural convection. Radiant floor or wall panel heating systems may not be suitable when outdoor temperatures fall below -54ºC (-65ºF), because corresponding design floor temperatures may exceed the ASHRAE comfort guidelines of 30ºC (85ºF) or above for light footwear. Occupants must wear heavy footwear, as it is often necessary in cold climates to restrict radiant floor temperatures to about 21ºC (70ºF).

Humidification equipment ranges from self-contained atomizing units placed in the occupied space to pan or steam-grid units placed downstream of the heating unit in the air distribution system. Temperatures of the indoor wall surfaces and glass should be considered in the design of the humidification system to avoid condensation and frost issues.

Ventilation: Design Considerations

Construction details of air intakes and exhausts require particular attention to avoid entrainment of exhaust gasses and to keep out driving snow, which can easily be entrained because, usually, it is light and flaky. In some regions air intakes and exhausts need to be protected from hoarfrost or snow.

Locations to Avoid

Air intakes and outlets should be located high but not through the roof. Roof-mounted inlets and outlets are not desirable, except in areas with little snowfall. Avoid locating inlets on the windward side. The North Series # 8 (CMHC, 2001-2003) presents strategies to prevent plumbing and heating vent stacks from freezing.

Locations that Work Well
For buildings on 1.2 m to 1.8 m (4 to 6 ft.) pile foundations, ventilation opening under the building works well since high wind conditions prevent snow accumulation under the building. Openings under the building also prevent the entry of wind-driven snow.

Openings Design
Air intake opening should be sized for low velocities, about 2.5 m/s (500 fpm). High intake air velocities could entrain snow and rain. The reverse is true for exhaust openings. High exhaust air velocities propel moist air away from the opening before frost can build up.

Ventilation
In cold regions, Meckler (1991) recommended that ventilation air should not be introduced directly into occupied spaces. With hot-air heating systems, ventilation air is either preheated by a heating coil or supplied to the return air plenum. Mixing ventilation air with warmer return air prevents thermal shock to the air heater. In steam or hot-water perimeter heating systems, ventilation air is usually ducted by a separate air distribution system equipped with non-freeze-type, tempering hot water or steam coils. Due to potential freezing conditions, steam and hot-water coils must be equipped with controls to prevent them from freezing. Freeze-up could present a problem in ventilation air supply coil applications where steam is used as the heating medium. Hot water with a dedicated circulating pump is usually preferred.

Challenges include ice buildup on heat exchanger surfaces. Therefore, defrosting of the heat exchanger surface is a critical design consideration. Because of the high cost of electricity, up to $0.5/kWh (1993 rates), Armstrong (1993) recommended analyzing the application of heat-recovery systems in Alaska to determine whether they can provide economical benefits. Those systems that did work well in Alaska included the run-around loop and air-to-air heat exchanger.

Design Example: Alaska
Ninomura and Bhargava (1995) described the design of an HRV in multi-family residences in Kotzebue, Alaska. Kotzebue is located at 67º, just north of the Arctic Circle on the coast of the Arctic Ocean. The climate is characterized by prolonged and severe winter conditions and typical coastal strong wind conditions. The design criteria developed by the US Corps of Engineers identified the following:

- minimum temperature: -47ºC (-52ºF);
- January mean minimum temperature: -27ºC (-17ºF);
- January mean maximum temperature: -17ºC (1ºF);
- summer temperature rarely exceed 13ºC (55ºF);
- heating degree days base 65ºF: 16 500; and
- wind design load: 40 lb/sq. ft. (1.9 kPa)

The building envelope: The exterior walls construction was 38 x 178 (nominal 2 x 8) studs with R-30 (RSI-5.3) insulation, which provided an effective R-value of R-27 (RSI-4.8). A life cycle cost energy analysis indicated that an R-20 (RSI-3.5) would provide the

lowest life cycle cost. The building envelope incorporated a continuous vapour barrier, and the construction was designed to be airtight. A pile foundation elevated the building 600 mm (24 in.) above the ground to keep the underlying permafrost from thawing.

Heating system: The residential units are heated by a hydronic baseboard fin-tube system that uses a central fuel oil boiler.

Ventilation: Heat recovery was incorporated into the design, because of the large temperature differential between indoors and outdoors. An individual HRV was provided for each residential unit. The HRV supplied air, as per ASHRAE Standard 62-1989[v] (ASHRAE, 1989), to centralized occupied areas within each residential unit. The return air grilles were located in the kitchen and bathroom(s). It was an air-to-air plate type heat exchanger with counter-flow airstreams.

HRV defrost: The potential for defrost is present eight months of the year, where the mean monthly temperatures are below -1ºC (30ºF) except for June to September. Defrost was provided by recirculation of the exhaust air stream back through the supply to the heat exchanger. Defrosting by preheating supply air significantly reduces recovered heat benefits. The defrost cycle was designed to be initiated when the outdoor temperature was less than -2ºC (29ºF) and continue until the temperature of the air stream entering the HRV heat exchanger is 1ºC (33ºF). The defrost time was limited to no more than 20% of the operation time at design conditions.

Supply air diffusers: Location and selection of the supply air diffuser were important to avoid dumping cold air into the room. As recommended by the ASHRAE (1992), ceiling diffusers were used for the supply air whenever was practical. Sidewall diffusers were used when it was necessary to accommodate architectural restraints.

Indoor humidity: Outside air at winter design temperature of -39ºC (-38ºF) passes through the HRV and enters the occupied area at a temperature of about 4ºC (40ºF) and a relative humidity of essentially zero. Thus, an excess ventilation rate is not desirable, because it could result in reduced indoor air comfort. Ninomura and Bhargava (1995) commented that, 20% relative humidity is considered optimum during winter for arctic residences. At a relative humidity of less than 20%, occupant's discomfort and complaints might increase. Experience in the arctic showed that a relative humidity above 20% could result in condensation and mould growth.

Energy savings: The fuel costs in Kotzebue, Alaska, in 1993, were $1.6/gal for # 1 fuel oil and $0.1844/kWh for electricity. The net savings were calculated to be $464 per year with a pay-back time of seven years. (The HRV installation cost was $1,500.) Ninomura and Bhargava (1995) concluded that HRVs were an economical way to provide ventilation that complies with ASHRAE Standard 62-1989 and saves on operational costs. The extreme low temperatures of the arctic presented challenges in the incorporation of HRVs in the ventilation design.

District Heating Considerations

Armstrong (1993) recommended the application of district heating, because of its benefits. The layout of most arctic communities places the buildings in close proximity to one another. District heating would facilitate utilization of heat recovery from the electrical generators. The North Series # 3 (CMHC, 2001-2003) described a co-generation demonstration project in Fort Providence, Yellowknife. The co-generation project provided the community with heating and electricity.

Integrated Heat and Domestic Hot Water System:

The North Series # 9 (CMHC, 2001-2003) described an energy-saving solution for space heating and domestic hot water. It recommended replacing older; non-efficient traditionally separate systems for the space heating and domestic hot water by one efficient system, such as a fancoil integrated system. There have been several successful installations of the integrated system in northern communities. Conversion was mostly from an oil-fired furnace and electric hot water tank to an integrated system consisting of an oil-fired hot water tank with a forced air heating distribution system. The hot water tank provides domestic hot water as well as hot water for heating the space supply air (a mixture of recirculated air and ventilation air) in the fancoil unit.

There are benefits in a combined heating and domestic hot water system.

- Running one heating appliance instead of two reduces appliance stand-by heat losses.
- The elimination of the electricity-dependent hot water tank results in considerable savings as, in the north, the cost of electricity is considerably higher than the equivalent cost of oil.
- A fancoil combination system could be designed to supply a number of zones with different heating demands.

The oil-fired furnace and electric hot water tank in a six-plex row-housing unit in Whitehorse was converted to a fancoil integrated heat and domestic hot water system in April, 2000. Electric and water costs and weather data were monitored for a year before and after the conversion. For a four-month period (October to January 1999-2000 and again in 2000-2001), the savings were about $83 for electricity and $131 for oil for a total of $213. In terms of kWh, the savings were about 600 kWh for electricity and 3200 equivalent kWh for oil.[vi]

Indoor Air Quality and Health

Mould

Canada Mortgage and Housing Corporation (2003-2) prepared a resource guide for First Nations housing providers on mould issues. The guide provides a compilation of information, programs, products, and services from government agencies and the private sectors on a wide range of information on moisture and related mould problems.

The Eagle Lake Healthy House

The North Series # 5 (CMHC, 2001-2003) provides guidance for constructing healthy and environmentally friendly housing in Northern Canada. The document describes a demonstration project, the Northern Healthy House, built for the Eagle Lake First Nation in Northern Ontario in 1997 as a solution to housing durability, affordability, water quality, and safety. The house construction was described earlier in section " Zero-Energy Sustainable Houses".

Healthy features included: Low VOC paint was used on the walls. Cabinets were made of boards that combine straw fibres and non-toxic resins. The radiant floor heating does not stir up dust compared to forced air systems. A balanced HRV continually provides fresh air and removes stale, moisture-laden air. Closets did not have conventional doors to allow for air movement to help prevent condensation and mould growth.

Indoor Air Quality: Northwest Territories Housing

Canada Mortgage and Housing Corporation (1991-3) reported the results of a survey of indoor air quality (IAQ) in 60 homes in seven communities in the Northwest Territories. The main objective was to identify potential IAQ issues resulting from improved construction techniques of energy-efficient homes. The IAQ testing was conducted during November and March to April. During this period, outdoor air temperatures were in the range –35ºC to –21ºC (-31ºF to -6ºF) and high winds and blizzards were common. The study resulted in the following conclusions. Indoor air temperature was up 28ºC (82ºF).

- **Indoor humidity:** Over a seven-day period, relative humidity ranged from 9% to 46%, with an average of 25%.

- **Air tightness:** Measured air change rates varied from 0.042 ach (quite tight) to 2.2 ach, with about half (35) the houses having air change rates below 0.3 ach. All houses tested in one community were below 0.3 ach. (The 0.3 ach was the required ventilation rate of the 1990 National Building Code.) The houses had operable exhaust fans or passive vents. Measured airflows from a sample of bathroom fans were in the range 5.5 to 14 L/s (12 to 30 cfm). The low fan flows, intermittent usage of fans, and tight building envelope explain the measured low air change rates.

- **Carbon dioxide:** The highest CO_2 level measured indoors was 2000 ppm, which is lower than the 3500 ppm acceptable-long-term-exposure-range of Health Canada. Twenty-five of 54 houses tested included at least one location in the house with CO_2 levels above the 1000 ppm limit specified in ASHRAE Standard 62-1989 (ASHRAE, 1989). The CO_2 level is an indicator of occupancy density, but could also be from sources, such as wood fire stoves.

- **Formaldehyde:** Only four houses showed levels above the target level of 0.05 ppm, but none were above the action level of 0.1 ppm set in the exposure guidelines of Health Canada.

- **Particulates:** the measured level was 167 µg/m^3 (10.4 µlb/ft^3), which is considerably higher than the 40 µg/m^3 (2.5 µlb/ft^3), acceptable long-term exposures level of Health Canada.

- **Radon gas:** Levels were well below the Health Canada guidelines.

- **Microbial:** Tests identified poor indoor quality conditions, but did not indicate any immediate health risk.

Canada Mortgage and Housing Corporation (1991-3) concluded that the low air change rates could be responsible for the decrease in indoor air quality in some homes studied. Alternative ventilation strategies to maintain the air change rate to a minimum level in the houses are needed.

Energy

Energy Solutions: Cold Climate
Nelson and Rantama (1993) reviewed the evolution of low-energy buildings in Finland as driven by its cold climate, lack of energy resources, and environmental considerations. Finland's northern region is characterized by six to seven months of sub-zero temperatures as low as -30ºC (-22ºF). The summer is short with continuous sunlight and temperatures up to 30ºC (86ºF). The authors noted several engineered low-energy solutions that take advantage of Finland's climate conditions.

Building Envelope Solutions
- Use an integrated combination of concrete, steel, and timber. (The authors called it "combined structures.")

- Treat the roof structure as an integral part of the building envelope. This improves energy efficiency, as the roof is the most important component with regard to energy-efficiency solutions.

- Use prefabricated components and modules.

- Target R-values for building envelope components are listed in Table 10.

Table 10. Target R-Values for Low-Energy Houses in Finland

Component	U-Value (W/m^2 K)	R-Value (h ft^2 F/Btu)	RSI-Value (m^2 K/W)
Wall	0.2	28	5.0
Floor	0.15	38	6.7
Window	1	6	1.0

Note:
R-values are converted from U-values listed by Nelson and Rantama (1993).

- **Technologies to facilitate winter construction:** Use protective transparent screens to facilitate heating and maximize the use of day lighting. Movable quilts protect cast concrete, as does the electric heating of concrete and hot casting. Dehumidifiers control moisture during drying. Extensive use of prefabricated concrete units reduces the need for site drying. Flexible central heating systems exist that have been designed for building sites.

- **HVAC:** Integration of the structure and air conditioning promotes energy efficiency as the structure can act as a heat source or sink as well as for distribution, such as through prefabricated concrete hollow-core slabs. Passive control can be achieved through the efficient use of heat gains, night flushing, and evaporative cooling. With zoning and individual controlled operation, HVAC serves only occupied zones. By switching the lights on, occupants activate HVAC for the occupied zone.

  Individual metering of each apartment reduces heating energy and water consumption.

  Use low-temperature radiator heating with thermostat-controlled valves. Local district heating saves energy. Nelson and Rantama (1993) noted that, in Helsinki, the atmospheric sulphur content decreased by 50% since district heating was introduced. About 45% of the building stock in Finland is connected to district heating.

  A balanced mechanical air supply and extraction system with heat recovery saves energy.

- **Lighting**: Use low wattage fluorescent, halogen lamps, and spotlights for local high lighting. In office buildings, after working hours, lights are automatically turned off by the building automation system. Individual lights can be relit manually. In both instances, maximize the use of day lighting.

4. Socio-Economic Issues

The Vegetation Ecosystem

Tundra is a Lapp word that denotes a polar plain (Strub, 1996). Tundra is the dominant vegetation region of northern Canada. Vegetation cover is sparse, next to zero toward the pole but nearly continuous at the southern limit. The number of species in the high latitudes (from 60 to 90 degrees) is smaller than that in lower latitudes. Many of the species have relatives at mid-latitudes (from 30 to 60 degrees).

- The growing season of one to three months is short, and shadows are long, because of the low angle of the sunlight.
- In the "polar desert," as described by Strub (1996), precipitation is scarce and averages about 100 mm (4 in.) annually.
- There is poor precipitation distribution due to snow drifting and poor drainage due to the imperviousness of the permafrost table, which prevents deep root penetration and keeps the shallow active layer cold enough to retard absorption of water by the roots.
- The fine-grained soil in the active layer is unstable due to soil heaving by freeze–thaw cycling.
- There is a high plant mortality rate due to low winter temperatures and the drying caused by the wind. Low temperatures prevent polar flora from contributing oxygen to the atmosphere and absorbing carbon dioxide in significant amounts.
- Long nutrient cycles and high soil acidity, because of the low temperatures, inhibit the decay of plants and animal remains.
- A short supply of the nutrients, particularly nitrogen and phosphorous, in the soil retard the growth of vegetation.
- The ecosystem is very fragile; a decline in one species affects the other species.

Vegetation Adaptation

- Most polar plants hug the ground. Stems and leaves form a canopy that deflects the wind and absorbs sunlight efficiently. Temperatures below the canopy are several degrees higher than the ambient air.
- Dryad flowers, shaped to concentrate sunlight, turn to follow the path of the sun, thereby raising the temperature of their critical parts by several degrees.
- Some plants grow hair as insulation. Others have frost-resistant structures.

The People

Strub (1996) provided a detailed history of the natives of the polar regions as of the ice age. He described the population profile, the people, and their lifestyles and habits. To demonstrate the sparseness of the northern population, he compared the population density of the Northwest Territories to the City of Toronto and Canada:

> The Northwest Territories: 0.019 persons per square km (1 person for 52 sq. km)
> The City of Toronto: 6300 persons per square km
> Canada as a whole: 2.5 persons per square km (6.5 persons per sq. mile)

In the 1950s, The Canadian government obliged the northern populations to live in designated centres — settlements — to facilitate delivery of basic services, such as schools and health care. In Strub's opinion, the Northern regions are mostly undeveloped; they can lack a stable pool of technical skills and are rich in non-renewable resources but unable to exploit them because of high development costs and an inadequate system of highways to ship goods to markets.

Housing

Canada Mortgage and Housing Corporation (2002-3) examined the housing conditions of North American Indian, Métis, and Inuit households. The study included households in urban and rural areas, and on reserves. Three housing standards — adequacy, suitability, and affordability — were used to assess conditions. The dwelling unit is considered "adequate" when its condition does not require major repair, "suitable" when the unit has enough bedrooms, and "affordable" when shelter costs are less than 30% of the before-tax household income. Due to a lack of data, only the adequacy and suitability standards were used to examine housing conditions on reserves.

The study concluded that on reserves, 50% of Native households had housing, which met or exceeded the adequacy and suitability standards. For those households in below-standard housing, most did not meet the adequacy standard.

Lifestyle

Canada Mortgage and Housing Corporation (2003-3) also investigated lifestyle to determine if the domestic activities of Inuit families are compatible with the floor configuration of Euro-Canadian house models currently built in Northern Canada. The study examined the differences in the patterns of domestic activities by Inuit and Euro-Canadian families living in Arviat, Nunavut. The study found that activities of Inuit families differ significantly from those of Euro-Canadian families.

- The cultural values of the Inuit society emphasize the social solidarity and mutual assistance of the extended family. Thus, a collective form of social interaction characterizes the lifestyle of Inuit families. A wide range of activities are

concentrated in a few integrated spaces in the house, such as living rooms and kitchens, which reflects the different cultural values of Inuit with regard to individuality and privacy. The activities of Euro-Canadian families are more widely dispersed throughout the house. The lifestyle of Inuit families needs to be considered in their house designs.

- Houses built over the past 30 years in Northern Canada indicated a trend toward floor plans that are increasingly subdivided with a greater number of smaller rooms. This resulted in limiting visual information and interaction among family members as they spread in the house. The house plans with smaller rooms are not compatible with the lifestyle of the Inuit families as spaces are often too small to accommodate the family's collective activities.

Canada Mortgage and Housing Corporation (2003-3) made several recommendations.

- Construct houses with more open floor plans. Eliminate long central corridors from which rooms are accessed. Instead, smaller rooms (bedrooms, utility rooms, etc.) should open directly onto a single, large space. Integrate the kitchen and living room into a large space, because most family activities take place in the living room and kitchen.

- Include a large enclosed porch as necessitated by hunting and fishing activities.

- Construct single-floor houses, as they are favoured over multi-story houses, because a single floor increases visual interaction. It also would reduce the overheating problem of the second floor in the summer months.

- Include a ventilation system that accommodates the large amounts of condensation released during the preparation of traditional foods.

5. Conclusion

A literature review was conducted to provide a knowledge base for selecting building envelope assemblies to investigate in the analysis tasks. The literature review provided significant information on practices, issues, and technologies regarding building envelopes, construction, heating, ventilating, indoor air quality, utilities, and socio-housing issues. Example building constructions from the arctic, Antarctica, Scandinavia, the Himalaya region, Japan, as well as indigenous architectures' climate adaptation have also been reviewed.

Climate Characteristics

Outdoors: Climate varies within the arctic and sub-arctic regions, particularly, above and below the tree-line regions. Variations include the snow drifting pattern, wind, temperatures, annual amounts of sunshine, and daylight. The arctic climate is described as a frigid high latitude desert, scarce vegetation, and long and dry Winters. For example, in the NWT, temperatures range from -45ºC (-49ºF) in winter to 35ºC (95ºF) in summer. Precipitation is mainly in the form of snow with an annual range from 140 mm (5 ½ in.) in Hay River to 425 mm (16 ¾ in.) in Inuvik. High winds and blizzards are common. Daylight, in particular, is extremely variable. It ranges from almost 24 hours of daylight daily in summer with the sun setting just before midnight and rising a few hours later, to very little daylight in winter. In Alaska, low temperatures can range from -57ºC (-70ºF) for weeks in interior areas to -34ºC (-30ºF) in south central and western areas and last for extended periods. Temperatures can reach 35ºC (95ºF) in summer. Wind speeds in excess of 200 km/h (125 mph) are common.

The maritime climate, dominated by ocean influences, is humid and temperate. Precipitation occurs in all seasons (no dry season), and might change by the hour. The weather could come from any orientation. Summers are cool and short. Winters are mild and short with some frost but not continuous snow. Spring and fall are extended in length. There are small differences between monthly mean temperatures.

Indoors: An indoor RH of 20% is considered optimum during an arctic winter. Occupants' discomfort might increase at a RH less than 20%. RH above 20% could lead to condensation and mould growth. In seven communities in the Northwest Territories, indoor air temperatures averaged from 21ºC to 28ºC (70ºF to 82ºF), RH ranged from 9% to 46%, with an average of 25%, and air change rates varied from 0.042 ach to 2.2 ach (During the measurements, outdoor air temperatures varied from –35ºC to –21ºC (-31ºF to -6ºF), high winds, and blizzards.).

Criteria for Selecting Building Envelope Assemblies for Northern Canada

Harsh Environmental Conditions

Prevalent low temperatures, wind, and snow drifting conditions exist during the long winters. Large temperature differentials occur between indoors and outdoors. Daylight conditions vary from a few hours a day in winter to constant bright sunshine in summer.

Snow drifting patterns, winds, temperatures, and the annual amount of sunshine vary throughout the region.

Lifestyle
Lifestyle: The North features a wide range of cultures and lifestyles, some of which can generate considerable moisture indoors.

Construction Difficulties
A short construction season, material transportation costs and difficulties, the availability of skilled labour and equipment, and energy costs all add to higher housing prices.

Current Practices in Northern Canada

- Wood frame systems consist of 38 x 139 mm (2 x 6) timber frame, mineral wool or fibreglass batt insulation in the stud space; air, vapour, and weather barriers; and plywood or OSB sheathing. Semi-rigid insulation might be used over vertical strapping. Galvanized steel siding is common. In some regions, structural panel siding of engineered wood strands replaces sheathing and is nailed directly to the studs.

- Structural insulated panel systems have performed well in Northern Canada when properly installed. These panels improve the energy performance of building envelopes and reduce timber use. Advantages include the fact that SIPs: do not rot, shrink, swell, split, or warp to the extent that dimensional lumber does. A panel's weight is about 35% less than the same size of wood frame construction. Panel construction is faster than wood-frame construction.

Specific designs strategies are required for each locale in Northern Canada, because of the variation in environmental conditions.

To Address Occupants' Lifestyle
Integrate the design of the building envelope and ventilation system to manage the high moisture indoors. Select a building envelope system that encourages local participation in construction.

To Address Environmental Conditions
Building envelopes and foundations that are wind and snowdrift resistant are design essentials in the regions north of 60. Walls, ceilings, and floors are insulated.

Table 11. Example RSI (R) Values of Building Envelopes, Northern Canada

	Nunavik, Quebec	Nunavut
Walls	5.0 (28)	5.1 (29)
Roof	7.7 (44)	7.7 (44)
Floor	5.4 (31)	9.0 (51)

Sources: Nunavik: Angers (1999); Nunavut Housing Corporation. (2005)

- Incorporate expansion joints to compensate for structural movement due to large temperature variations from winter to summer.

- Install triple-glazing, low-e coating windows with insulated fibre reinforced plastic frames.

- Avoid stepped roofs, offsets, nooks, or parapet walls to prevent the accumulation of snowdrifts. Use a sloping roof section to connect two roof levels. Metal roofing has performed satisfactorily. Skylights are not recommended unless designed to control condensation. Eaves minimum projections are 200 to 600 mm (8 to 24 in.) below the tree line and 100 to 200 mm (4 to 8 in.) above the tree line. Below the tree line, ventilated roof systems perform well. Above the tree line, roof venting is problematic. It is difficult to avoid snow infiltration through vents. Incorporate drains for melted snow.

- Incorporate strategies to minimize the impact of the building on the thermal equilibrium of the permafrost and also to reduce snowdrift accumulation. A common strategy is elevating the building about 0.9 to 1.2 m (3 to 4 ft.) above the ground. A Swedish study concluded that a 1.8 m (6 ft.) elevation worked well in Antarctica.

- In winter, strategies to harness any daylight available include large windows, clerestory windows, and strategically placed skylights to allow natural light to penetrate into living spaces. In summer, latticed window screens block the continual oblique rays. Scale and spacing of the slats of window shading devices may be optimized using solar angle calculations to block excessive daylight and solar heat of the high summer sun while maximizing the entry of low winter sun.

- Considerations are given to the availability of labour and equipment, speed of construction, and methods that encourage local participation.

Heating and Ventilating Strategies

Load estimation computations are modified for northern conditions, as temperatures stay at design conditions for long periods and solar gains do not subside in summer nights. Easily maintained and reliable systems are preferred, because transportation is expensive and sometimes not available in bad weather. Ensure air supply and exhaust openings can withstand wind and snowdrifts.

Ventilation

An indoor relative humidity of 20% is considered optimum during an arctic winter. Occupants' discomfort might increase at a relative humidity of less than 20%. Relative humidity above 20% could lead to condensation and mould growth. Mechanical ventilation is preferred. Defrosting surfaces of the heat exchanger of the HRV is a critical design consideration to minimize ice buildup. Avoid high intake air velocities, because they could entrain snow and rain. The reverse is true for exhaust openings, as high exhaust velocities propel moist air away from the opening before frost buildup.

Thermally Upgraded Wall Systems

This system consists of:

- Single 38 x 139 mm (2 x 6) stud walls have exterior rigid or semi-rigid insulating sheathing board.

- Single stud walls with interior 38 x 38 mm (2 x 2) or 28 x 64 mm (2 x 3) strapping are placed on the interior of the 28 x 139 mm (2 x 6) stud wall. Additional insulation can be added in the strapping space.

- With double 38 x 89 mm (2 x 4) stud walls, a load-bearing wall is combined with a lighter non-load bearing wall that supports exterior siding or interior drywall. Additional insulation is added in the space between the two walls.

- Standoff walls are similar to the double stud walls system, except the exterior wall is constructed, on-site or in factory, using truss-studs designed to accommodate required insulation. The wall placement is offset relative to the interior stud wall (38 x 64 mm or 38 x 89 mm/2 x 3 or 2 x 4 framing) to cover the edge of the floor slab to minimize its thermal bridging.

- With rigid insulating core panel walls, foam insulated factory-manufactured panels are built in wood framing.

- Stress-skin panels have a polystyrene, polyurethane, or glass fibre insulating core sandwiched between wood panel sheathing, waferboard, or drywall.

- Insulating concrete forms provide the form work for the concrete, insulation, and sheathing in a single system.

Super-Insulated Building Envelopes

Table 12 lists the wall framing system, R-values, and air tightness for four super-insulated envelopes. The Hanover and the Illinois houses were built according to the German *passivhaus* construction concept, which is a comprehensive approach to constructing airtight, super-insulated houses with a specified annual energy budget depending on the climate, which is about 20% of the energy budget of a comparable conventional house.

Innovative Wall Assemblies

Reviewed innovative wall assemblies for cold climates and temperate humid climates included transparent insulation materials and hybrid heating/cooling wall systems for cold climate applications; and breathing wall and air-cooled walls and roofs for temperate humid climates. Some of the innovative concepts of these walls could be used in Northern Canada provided economic benefits are demonstrated. Transparent insulation

materials could enhance the thermal performance of glazing. The solar heat gain concept of the air-cooled walls and roof could be used in a double stud walls system. This concept was used to preheat ventilation air in the Swedish Research Station in Antarctica by up to 40ºC (72ºF). The ventilation supply air duct passed through the wall's exterior air layer, then through the air space in the roof where a supply fan delivered the preheated air to the building. The vent openings were designed to protect the cavity from wind-driven snow.

Table 12. R-Values and Air Tightness of Super-Insulated Envelopes

Component	Eagle Lake House	Saskatoon House	Alberta Sustainable Home	Hanover House	Klingenberg House
Wall RSI (R)	8.8 (50)	10.6 (60)	8.8 (50)	7 (40)	10.6 (60)
Roof RSI (R)	10.6 (60)	14.1 (80)	13 (74)	10.6 (60)	10.6 (60)
Floor RSI (R)	5.3 (30)	6.2 (35)	Rigid foam R-Value Not listed		10.0 (56)
Basement walls			N/A	1.9 (11)	4.2 (24)
Windows RSI (R)		0.9 (5) triple glazed	3 (17)	1.2 to 1.6 (6.7 to 9)	1.26 (7.14) triple glazed
Ach at 50 Pa		0.47	not measured	0.37	not measured

Sources: Eagle Lake (North Series # 5, CMHC 2001-2003); Saskatoon House (Dumont, 2000); Alberta Sustainable Home (Rieger and Byrne, 1996), Hanover House (EBN, 1998); Klingenberg House (EDU, 2004-2).

Building Envelope Systems to Consider

General considerations for building envelope assemblies for northern climates include super-insulated, airtight, and breathable assemblies based on a target annual energy budget according to the region's climate and challenges. Additionally, market acceptance of the system and the availability of material, construction equipment, and labour are factors for consideration. Preference would be for construction methods that encourage local participation.

Northern Regions

Wall systems to consider include:

- double stud walls systems, which can be a double 38 x 89 mm (2 x 4) stud walls, and a standoff walls system with I-beam studs (Wall thickness depends on the insulation level to be determined with energy optimization analysis based on a target energy budget.);
- SIP systems; and
- concrete wall construction using ICFs.

Coastal Northern Regions

For high-moisture climates, key criteria for building envelope assemblies are an ability to handle as well as withstand wetting spells with little effect on the assembly durability. Design needs to emphasize deflection, drainage, drying, and durability moisture management strategies. Wall systems to consider include:

- single 38 x 139 mm (2 x 6) stud wall with exterior rigid or semi-rigid breathable insulating sheathing board and blown-in insulation in the stud spaces; and
- single 38 x 139 mm (2 x 6) stud wall with interior 38 x 64 mm (2 x 3) strapping on the interior. Additional batt insulation is placed in the strapping space.

Concepts to Consider from the Advanced Wood Framing Technology

- Use 38 x 89 mm (2 x 4) lumber for cripples and jack studs.

- Use a 38 x 89 mm (2 x 4) lumber for bottom and top plates to reduce material consumption.

- Use drywall clips at the corners to eliminate three-stud corners.

Concepts to Consider from Indigenous Adaptation Principles

- Respect the indigenous appreciation and careful management of local materials and resources.

- Every design aspect and each element of the building contributes to the net environment of the living space.

- The dome architectural form of the igloo sheds wind, which reduces the erosion of envelope surfaces, the accumulation of snowdrifts, and heat flow from the building envelope.

- In the Cape Cod and Hungarian houses, masonry walls or stucco over earthen or adobe walls were used in response to damp conditions. For wood, protective paint was applied. In northern coastal areas, use large windows to harvest daylight to compensate for overcast skies. Windows in all directions provide daylight and summer ventilation. Window shutters or storm windows protect against storms and winter cold.

- Integrate heating and cooling comfort appliances with the building design.

Concepts to Consider from Super-Insulated Envelopes

Building Envelope

- Determine the wall insulation level, hence wall thickness, based on energy optimization analysis using a target energy budget.

- Use two-layer insulation, because it allows insulation joints to be staggered and reduces the thermal bridging potential of fasteners of the base layer.

- Optimize the area and orientation of windows for passive solar gains.
- Use two layers of drywall in the interior face of the wall to function as a heat sink.
- Avoid penetrating the building envelope as this contributes to energy losses and weakens moisture control barriers. To maintain the integrity of the air and vapour barriers, avoid installing electric boxes or wiring in the exterior walls.
- Use I-beam for studs.
- Consider a south-facing single plane style for the roof.

Heating, Ventilation, and Services Considerations

- A solar wall concept preheats ventilation air.
- Use an integrated system for heat and domestic hot water in place of the traditional two separate systems. Consider an instantaneous electric water heater for domestic hot water.
- Co-generation district heating is suitable for close proximity communities.

Appendix A: Literature Search Approach

Objective

Review building/housing issues and building envelope technologies adopted in the extreme climates in Canadian northern and coastal regions as well as elsewhere globally particularly in high latitudes regions such as Norway, Finland, Sweden, Greenland, Russia, and. Northern China.

Extreme climates are defined as:

- extreme cold outdoor climate;
- extreme humid-cold outdoor climate (as in Canadian northern-coastal regions); and
- high indoor humidity and extreme cold outdoors.

Literature Topics

For extreme cold and humid-cold climates, review the global literature on:

- building envelope systems;
- outdoor/indoor environments;
- building technologies; and
- sustainable building envelope examples.

Key words/Combination Keywords
Extreme climate housing/buildings
Extreme climate
Northern housing
Northern construction
Sustainable northern communities

Cold climate buildings durability
Cold climate technology
High latitudes buildings

Humid climate
Humid cold climate
Humid
High humidity buildings
Condensation severe, northern housing
Damp northern buildings rot
Moisture problems northern buildings/housing

Regions:
Housing in Scandinavian countries (Norway, Finland, Sweden)
Greenland
Northern China
Northern Russia

Housing/Buildings Organizations, Agencies, and Colleges in target communities (documents addressing housing issues, durability, moisture, condensation, technologies).

- Housing Authorities in: NWT, Nunavut, Yukon, Nunavik-Quebec, Prince Rupert-British Columbia, Alberta, and Labrador-Newfoundland
  - Yukon Housing Corporation
  - Kativik Municipal Housing Bureau
  - Société d'habitation du Québec, (SHQ)
  - Service Habitation au Nunavik, SHQ
  - Nunavik Housing Department, SHQ
  - NHA housing

- Colleges/Research Institutes:
  - Nunavut Research Institute
  - The college of the North Atlantic
  - Aurora College
  - Aurora Research Institute

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Note: Unless otherwise indicated, all URLs in this report were confirmed in November, 2006.

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Endnotes

[i] The structural panel siding is an engineered wood strands-based product that can be nailed directly to the studs. The manufacturer noted that the panels are "designed to withstand tough environments," and include the following features.

Each strand is coated with an advanced resin providing strength and moisture resistance.

Panels are treated with a zinc-borate-based process to resist fungal decay and termites.

- A resin-saturated, paint-based overlay provides moisture resistance and better paintability.
- Proprietary edge coating protects the panel from the elements.

[ii] The (0.15 mm) (6 mil) poly vapour barrier would also perform as an air barrier on the warm side of the insulation.

[iii] The following are some Internet resources on dome structures.

Domes example buildings: <www.greatbuildings.com/types/elements/domes.html>.
Wood domes examples: <www.greatbuildings.com/buildings/Kresge_Auditorium.html>.
Concrete dome builders: <www.ecobusinesslinks.com/monolithic_concrete_domes.htm>.
The air dome: <www.hssstructures.com/>.
Monolothic dome construction: <www.monolithicdome.com/>.
Academic theses about monolithic domes: www.monolithicdome.com/thedome/theses/>.
Monolithic concrete domes: <http://itotd.com/index.alt?ArticleID=265>.
Geodesic dome homes advanced housing technology: <www.aidomes.com/>.

[iv] R-values are in the range of RSI-1 to RSI-1.2 per 25 mm/R-5.8 to R-6.8 per inch, CMHC (2005).

[v] Current reversion has been given the new designation 62.1-2004 to distinguish it from the ANSI/ASHRAE Standard 62.2-2004 "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings".

[vi] The kWh values are approximate as they were extracted from a graph in The North Series # 9.