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Roofing Systems and their Performance Requirements

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A roof is an integral assembly of a building envelope. The building envelope also includes other assemblies, such as walls, windows and the basement. Each assembly has its unique functions and performance requirements. All of them are designed to separate the controlled indoor environment from the outdoor environment. This paper presents some basic principles of roofing systems and components. The various types of roofing systems commonly used in North America and their performance requirements are systematically documented. To design better roofs, three key performance elements, namely, wind effects, rainwater management and moisture control need to be taken into account. Furthermore, thermal considerations for roofs are also summarized. Lastly, new requirements from the 1995 National Building Code are highlighted throughout the document.

The outdoor environment comprises several phenomena. They include:

- wind;
- rain/snow;
- temperature;
- solar radiation;
- earthquake; and,
- noise.

These may act either independently or combined, for example, wind-driven rain. Their intensity depends on the geographical location of their occurrence and the seasonal conditions. A designer has to select and design the roofing system to withstand these driving forces associated with the phenomena. All of the driving forces mentioned are dynamic in nature.

TYPES OF ROOFS

In North America, a roof can be classified in several ways. Based on its shape, it can be a flat roof or gable roof; or based on the material used, a metal roof and membrane roof. A roof can be named based on the building it surmounts, i.e., residential roof or industrial roof. Nevertheless, in this paper the system is defined by the location of the roofing membrane: (a) conventional and (b) protected membrane roof systems.

Conventional Roofing System

In the conventional roofing system, the membrane is at the top where it experiences such environmental forces as wind and temperature.

Protected Membrane Roof Systems

In a Protected Membrane Roof (PMR) system (also known as upside down roof or inverted roof or insulated roof membrane or IRMA), the membrane is covered by the insulation. The membrane is thus *protected* from environmental elements such as wind, rain, UV and temperature extremes.

ROOFING COMPONENTS, FUNCTIONS AND REQUIREMENTS

Components

Most roofing systems have five components:

1. deck;
2. barrier;
3. insulation;
4. membrane;
5. attachment systems.

It should be noted that some include *interior finishes* (below the deck) as a roofing component. Numerous combinations of roofing systems are available based on the component selection. The following is a partial list of components used in roofing systems.

- **Deck**

  Steel, wood, concrete, fiber and composite boards.

- **Barriers**

  Vapour barrier, air barrier, fire barrier.

- **Insulation**

  Extruded or expanded polystyrene, urethanes, polyisocyanurate, phenolics, glass and mineral fibre.

- **Membrane**

  EPDM, PVC, TPE, TPO, Hypalon, reinforced varieties, neoprene, modified bituminous.

- **Attachment Systems**

  Spot fasteners, bar strap and anchors, adhesive, stone, heavy-weight pavers, light-weight interlocking pavers, ballast, concrete tiles with ship laps.

Functions

Design of a roofing system also involves the selection of compatible components. Component selection plays an integral role in the performance of roofing systems. Each component of a roof has one or more main functions to perform. It's properties must be commensurate with those functions.

Component	Function
Deck	Structural support
Insulation	Thermal control
Barriers	Air and moisture control
Membrane	Waterproofing
Attachment system	Integration

Requirements

The National Building Code of Canada (NBC, 1995) lists the requirements of an environmental separator. A roof, as an integral assembly of the building envelope, should meet certain requirements, among them provision of safety, economy, control over environmental factors, etc.

To achieve safety it must provide:

1. structural strength and rigidity;
2. resistance to initiation and spread of fire; and,
3. control of rain water entry.

To achieve economy it must:

1. be well matched to its purpose;
2. have durable materials and components; and,
3. have reasonable maintenance and operating cost.

To function as a moderator of environment, it must provide control of:

1. heat flow;
2. air flow; and,
3. moisture flow.

Other requirements include control of:

1. odour;
2. light;
3. sound and vibrations; and,
4. solar radiation.

WIND PERFORMANCE

Wind Climate

Wind climate parameters (speed, direction, number of occurrences, etc.) are usually monitored at major airports. Since airports are large open areas without many buildings and other obstructions, the local or surrounding effects are minimal while measurements are taken. Such measured wind speed shows:

1. variations with respect to time in random manner;
2. increases in magnitude with increases of height from the ground level; and,
3. decreases in its randomness (fluctuation) with increases of height from the ground level.

These relationships can be demonstrated by solving the following problem.

Example Problem

"Calculate the mean wind speed and the peak gust speed expected at the top of a building 55 m high located in a downtown location, when the mean speed recorded by an anemometer at 10 m above ground level at the airport is 30 m/s."

Data:

Mean wind speed at anemometer height, $V_a = 30$ m/s

Anemometer height, $Z_a = 10$ m

Building height, $Z_b = 55$ m

Step 1: ***Identity terrain parameters using the following table.***

Parameters	Measured Location (Airport)	Building Location (Downtown Area)
Terrain	Open Country	Urban Exposure
Exponent, a	0.15	0.36
Gradient Height, Z_g	300 m	500 m

Step 2: ***Calculate the gradient wind speed at the airport.***

$$V_g = V_a\left(\frac{Z_g}{Z_a}\right)^a$$

$$= 30\left(\frac{300}{10}\right)^{0.15}$$

$$= \mathbf{50\ m/s}$$

Step 3: ***Calculate the mean wind speed at the building top.***

$$V_{55} = V_g\left(\frac{Z_b}{Z_a}\right)^a$$

$$= 50\left(\frac{55}{500}\right)^{0.36}$$

$$= \mathbf{22.6\ m/s}$$

Step 4: ***Calculate the gradient gust speed at the airport.***

$$G_g = 1.35\ V_g$$

$$= 1.35 \times 50$$

$$= \mathbf{67.5\ m/s}$$

Step 5: ***Calculate the gust speed at the top of the building.***

$$G_{55} = G_g\left(\frac{Z_b}{Z_g}\right)^\beta$$

$$= 67.5\left(\frac{55}{500}\right)^{0.20}$$

$$= \mathbf{43.4\ m/s}$$

Wind Pressure Coefficients

Wind flow around buildings creates two types of pressure components; namely, negative pressure, P_e and positive pressure, P_i. P_e is created by flow separation on the exterior side of the roof. P_i is known as the internal pressure of the building and is generated by the pressure difference induced by the wind and the temperature gradient across the envelope as well as the mechanical ventilation system installed in the building. P_i is especially important for large-span industrial buildings, supermarkets, and similar structures. Since such building envelopes are usually highly wind permeable, the wind-induced internal pressure may sometimes equal the outside negative pressures. The design wind uplift is the vector addition of these pressure components. Wind-induced pressure on a roofing membrane has a static component (mean pressure) and a transient component. The latter varies as a random process. Its dominant frequencies depend on the frequency of the upstream wind and geometry of the building. Thus the wind uplift pressure is time-dependent.

Definition of Pressure Coefficient

Building Codes of Practice and Wind Standards provide the values of wind pressure in terms of pressure coefficients. These coefficients are obtained by normalizing the measured pressure at a location with respect to the dynamic pressure at roof height. A significant advantage of presenting the coefficients in this manner is that the obtained non-dimensional pressure coefficients are independent of wind speed; and thus, they can be used directly during envelope design. The coefficients are defined as:

$$\check{C}_p = \frac{\check{P}}{q_H}; \ \hat{C}_p = \frac{\hat{P}}{q_H}; \ \bar{C}_p = \frac{\bar{P}}{q_H}; \ \bar{\bar{C}}_p = \frac{\bar{\bar{P}}}{q_H}$$

where:

$\check{C}_p$ = the maximum instantaneous pressure coefficient measured over the sampling period

$\hat{C}_p$ = the minimum instantaneous pressure coefficient measured over the sampling period

$\bar{C}_p$ = the time-averaged mean pressure coefficient

$\bar{\bar{C}}_p$ = the root-mean-square (RMS) pressure coefficient; and

q_H $= \frac{1}{2}\rho V H_H^2$, the dynamic pressure associated with the mean velocity at roof height.

The mean value gives an indication of the static wind load that can be expected. The $\check{C}_p$ or $\hat{C}_p$ is the measure of storm pressure or maximum suction on the envelope. It is a measure mostly needed for the design of cladding elements. The RMS value is a measure of fluctuation in the pressure signal. Large deviations from the mean value give a higher RMS value.

North-American Approval Test Methods

At present, in North America, there are two test methods being used for approval testing of mechanically attached roof systems. They are the Factory Mutual (FM) 4470 and the Underwriters Laboratory (UL) 580 procedures.

Factory Mutual (FM) 4470 - uplift pressure test

The pressure is supplied through positive air pressure to the bottom of the roof panel using an air compressor. The initial test pressure is 30 psf (1.4 kPa) and maintained for 1 minute. The pressure is then increased by 15 psf (0.7 kPa) each successive minute until failure with the test panel occurs. The scope of FM 4470 is to designate an I-60 or I-90 windstorm classification to the roof assembly tested. ("I" indicates that the assembly has passed other FM tests related to fire, hail, leakage, corrosion and foot traffic.) To obtain approval for a Factory Mutual I roof cover, the test assembly must withstand certain pressure levels for 1 minute. For example, to obtain an I-90 classification, the test assembly must resist 90 psf (4.2 kPa) for 1 minute. Similarly, for an I-60 classification, a pressure of 60 psf (2.8 kPa) is applied for 1 minute.

Underwriters Laboratories (UL) Procedure 580 test method

The UL load cycle is given in the table below.

Rating	Test Phase	Time Duration, Minutes	Negative Pressure, psf (kPa)	Positive Pressure, psf (kPa)
UL 15	1	5	9.4 (0.45)	0.0 (0.00)
	2	5	9.4 (0.45)	5.2 (0.25)
	3	60	5.7-16.2 (0.27-0.78)	5.2 (0.25)
	4	5	14.6 (0.70)	0.0 (0.00)
	5	5	14.6 (0.70)	8.3 (0.40)
UL 30	1	5	16.2 (0.79)	0.0 (0.00)
	2	5	16.2 (0.79)	13.8 (0.66)
	3	60	8.1-27.7 (0.39-1.33)	13.8 (0.66)
	4	5	24.2 (1.16)	0.0 (0.00)
	5	5	24.2 (1.16)	20.8 (1.00)
UL 60	1	5	32.3 (1.55)	0.0 (0.00)
	2	5	32.3 (1.55)	27.7 (1.33)
	3	60	16.2-55.4 (0.79-2.66)	27.7 (1.33)
	4	5	40.4 (1.94)	0.0 (0.00)
	5	5	40.4 (1.94)	34.6 (1.66)
UL 90	1	5	48.5 (2.33)	0.0 (0.00)
	2	5	48.5 (2.33)	41.5 (1.99)
	3	60	24.2-48.5 (1.16-2.33)	41.5 (1.99)
	4	5	56.5 (2.71)	0.0 (0.00)
	5	5	56.5 (2.71)	48.5 (2.33)

In a vacuum chamber, steady and oscillating negative pressures are applied to the top of the assembly, while the bottom chamber applies steady positive pressures to the underside. The positive and negative pressures are applied at values and time durations as shown in the above table. The UL 580 designation classifications are: UL - 15, UL - 30, UL - 60 and UL - 90. The testing period is 80 minutes divided into five phases. Let us consider the UL - 90 load cycle. First phase applies 48.5 psf (2330 Pa) negative pressure for 5 minutes, whereas in the second phase 41.5 psf (1990 Pa) positive pressure is added from the bottom of the roof assembly. During the third phase, an oscillating pressure, 24.2 psf to 48.5 psf (1160 Pa to 2330 Pa) is applied at a frequency of 10 second per cycles for 60 minutes. In the fourth phase, 56.5 psf (2710 Pa) negative pressure is applied for 5 minutes, with positive pressure equal to zero and to end the testing, 56.5 psf (2710 Pa) negative pressure and 48.5 psf (2330 Pa) positive pressures are applied for 5 minutes. If the assembly surpasses this loading cycle, then the assembly is designated as UL-90. Similar arguments applies to Class 30 and 60 rating.

NRC's Approach

In 1994, the Institute for Research in Construction, National Research Council of Canada (IRC/NRC) initiated a project, "*Dynamic Evaluation of Roof Attachment Systems*," to evaluate mechanically-attached roof systems under dynamic loading. Test procedures and numerical models are being developed to evaluate their performance. The analyses and the test results will be combined to produce a design manual for the roofing industry. The experimental project includes laboratory tests to evaluate materials, systems performance, and wind tunnel unsteady-load measurements. The numerical modeling involves the development of a Finite Element Method (FEM) structural model and a CFD wind-loading model.

In 1995, a consortium, ***Special Interest Group for Dynamic Evaluation of Roofing Systems* - (*SIGDERS*)** was formed. SIGDERS has two objectives:

1. develop, design and test procedures to evaluate and certify roofing systems under dynamic loads; and,
2. carry out generic and pre-competitive research for the benefit of roofing industry.

SIGDERS consists of a wide range of clients concerned about roofs, including manufacturers (Canadian General Tower Ltd./Prospex Roofing Products Ltd., Carlisle SynTec Systems, Cemfort Inc., Firestone Building Products Co., JPS Elastomerics Corp. - Construction Products Group, Soprema Canada, Vicwest Steel), building owners (Department of National Defense, Public Works and Government Services Canada), managers and architects (Canada Post Corporation). Also involved are two associations: the Canadian Roofing Contractors' Association (CRCA), and its American counterpart, the National Roofing Contractors' Association (NRCA).

The following progress has been made on this on-going project:

- State-of-the-art reports for laboratory and numerical procedures for the roofing system evaluation were prepared. This systematic review summarizes the findings of past research activities along with their limitations. As well, it recommends future research areas in dynamic testing of both the driving forces and roofing system response.
- A unique North-American roofing facility for the dynamic evaluation of the roofing systems has been designed, fabricated and commissioned. It is about 10 m long, 3 m wide and 3 m high (35 feet by 10 feet by 10 feet) and can simulate wind pressures of up to 9 kPa (200 psf) and about 5 Hz wind gusts.
- Two series of wind tunnel experiments were carried out using full-scale roof section of 3 m by 3 m (10 feet by 10 feet) in the NRC's 9 m by 9 m (30-by-30 foot) wind tunnel. This provided a unique database containing values for unsteady wind loads on roofs. The first series utilized a PVC roofing system. Department of National Defense partially funded the experimental studies. An EPDM roofing system was used for the second wind-tunnel study. SIGDERS funded the second series of wind tunnel test.

- A wind load cycle is being developed representing the dynamic wind-induced effects on roof attachments. Experimental investigations, using these load cycles, were started on single-ply, mechanically-attached PVC systems on a roofing facility.

RAIN WATER MANAGEMENT

A three-fold matrix approach is needed for successful water management on roofs:

1. Durable roof membrane;
2. Properly installed flashing;
3. Well designed drainage.

Flashing

A flashing is a roofing element used to prevent water from penetrating the exterior surface of a roof or to intercept and lead water out of it. Flashing diverts the water to the membrane. The membrane then carries it to the roof drains. Typically, flashing intercepts water flowing down parapets, down walls of higher adjacent construction and down roof penetrations. There are four locations where a flashing is needed:

1. Terminations;
2. Junctions;
3. Projections; and,
4. Joints.

In any flashing detail, there are up to three different flashing components:

1. Base flashing;
2. Counter-flashing; and,
3. Cap flashing

Base flashing

Base flashing is an extension of the roofing membrane or a different material that is bonded to the roof to form a waterproof joint. It extends upward along the vertical surface to divert water onto the membrane. If the roof terminates in a parapet or cant, the base flashing should pass over the top of that construction and be secured to the outside, for example, with a nailing strip. This minimizes the likelihood of water leaking behind it and into the roof. Liquid-applied material may not be suitable for flashing since it cannot be carried over a parapet or across a roof-wall joint. The base flashing should reach a higher level than that reached by water on the roof. In some situations, water may have to be temporarily stored on the roof. This may occur during heavy rainfalls, where the drain size is inadequate, where local building regulations require controlled flow drains, or where ice and snow restrict drainage.

Counter-flashing

Counter-flashing is used, in some situations, to carry water onto the base flashing and the membrane. This may be the case where a wall rises above a roof and masonry or concrete wall cladding is carried down to the roof surface. It covers the vertical face of the base flashing. It provides protection for the base flashing and may serve to shed water. Where required, the counter-flashing is secured to the parapet or wall cladding. Counter-flashing may not be required where modified bitumen or single-ply membranes are used for the base flashing. If not required, it should not be used, since it will cover defects and hinder maintenance. Thermal expansion coefficients between the flashing and the cladding may cause differential movements between these two components. In most cases, these stresses will break the seal.

Cap flashing

Cap flashings are horizontal coverings for parapets and expansion joints. Cap flashing should be sloped toward the roof and secured to allow differential movement. Failure to provide for adequate flashing height at the design stage may result in serious problems that cannot be corrected subsequently. For example, if access is provided from a traffic deck or lounge roof deck to an adjacent inside space on the same level, the entry must be flashed high enough to prevent water from flowing over the top of the base flashing and into the building. Good flashing practice should be given preference over ease of access between the interior of the building and the roof deck.

Design considerations

Many factors affect the performance of the flashing system. Design drawings for several common applications are available from the CRCA and NRCA manuals.

Drainage

Draining methods

Flashing will divert the falling water and the membrane is a waterproof element. Only drains that are properly designed and maintained will keep water off the roof. Good drainage, i.e., sufficient slope and an adequate number of drains, properly located, can be obtained either through interior or peripheral drainage systems. In an interior drainage system, rainwater flows from elevated areas to the drain, arrangements are needed to take the rainwater through the building interior. They can be located along building columns. In a peripheral drainage system, rainwater flows from elevated surface to the building outside and drains through scuppers.

Deck sloping

Sloping is crucial for successful drainage. The preferred method for achieving adequate slope is to have the slope built into the roof structure by using, for example, cambered roof decks or steel trusses with slope designed into them. Provisions for structural slopes must be made when the building is designed. A more general criterion for adequate slope is that it should be unbroken and have no area where ponding is likely to occur. This means that the drain must be at a low point in the roof and the roof must slope smoothly toward it.

Insulation sloping

If the deck is not sloped, tapered insulation may be used to provide a slope. This can work, but it is a poor alternative to a deck built with an appropriate slope. To achieve the purpose of insulation sloping, three factors are important:

- insulation securement;
- insulation efficiency; and,
- the ability of the roof, flashing, and access doors to accommodate the additional height.

Thick insulation may make securing a membrane difficult. In some cases, a mechanical fastener would have to be more than 150 mm long to pass through the insulation. It would act as a cantilevered beam when resisting wind uplift on the membrane. Using non-uniform thickness is also an inefficient way to insulate a roof. The area near the drain is under-insulated, whereas the area away from the drain is over-insulated. The effect on heat flow is less than if the same amount of insulation is uniformly distributed, where the insulation is thin, the deck becomes cold in winter and condensation is more likely to occur.

NBC Requirement

The National Building Code of Canada tabulates the rainfall intensity for different locations in Canada. In the NBC (1995), these values represent the 1 day rainfall amounts. The 24-hour rainfall values were based on measurements of the annual maximum 1 day rainfalls for 2051 stations with a 10 year or longer record. These are one-in-30 year values. This representation is new compared to the NBC (1990) in which rates were provided for 15-minute rainfalls and they were one-in-10 year values.

MOISTURE CONTROL

Moisture Entry Through Air-Leakage

Most water vapour migrates into roofing components because of air-leakage. Controlling air-leakage is a continuing challenge for the envelope designer in so far as an optimal balance between the indoor air quality and the energy consumption has to be struck. There are three main factors causing the building air-leakage:

1. Wind induced pressure difference across the envelope;
2. Stack effect due to temperature difference across the envelope;
3. Pressure difference generated due to building ventilation process.

The resultant of this process is infiltration from the building bottom and ex-filtration through the top. From the point of view of moisture control, this relates to air containing moisture entering through the lower floor levels of a building and being transported upward toward the roofing system. This is called air-borne moisture and it can cause condensation on the roofing components. Air can move through cracks and openings even with small pressure differences. Electrical outlets, pluming stacks, and deck overlaps are some typical air leakage paths.

Functions and Properties of Air Barriers

Controlling air movements is critical in roofing design. Recently, NRC developed a technical guide, *"Air barrier systems for exterior walls of low buildings"*. It defines the air barrier system as "*the assembly installed to provide a continuous barrier to the movement of air.*" This section presents the functions of air barriers and identifies the possibility of roofing components that act as air barriers.

Air barrier

The function of the air barrier in a roofing system is to minimize air leakage through the roof. This reduces energy losses and minimizes condensation resulting from the transfer of air-borne moisture from inside the building into the roof assembly. In contrast to wall assemblies, most of the time, there is no single component that takes the responsibility of an air barrier. Equally, the air barrier concept is not well understood by the roofing community. A number of roof components may act as the air barrier, e.g., the deck, membrane and support boards. Components are also combined to act as an air barrier assembly. Selection also varies with types of roofing, namely, conventional system or protected membrane system.

Roof deck as an air barrier

Airtight roof decks could function as air barriers in addition to fulfilling their structural requirements. Typically, concrete decks with proper air seals at movement joints can act as an air barrier in a roof assembly. Plywood and Oriented Strand Board (OSB) decks may take the role of air barrier for architectural metal roofs with proper joint air seals.

Membrane as an air barrier

In certain situations, the roof membrane performs as the air barrier, in addition to its primary function of keeping the water out of the roof. This is not only widely encountered in the conventional roof assemblies, where the vapour barrier is not airtight, but also where the vapour barriers are loose-laid. In some mechanically fastened, single-ply roofing assemblies the vapour barrier material, such as polyethylene, does not seal around the fasteners. This approach can lead to problems. Wind flow over the roof creates membrane ballooning. During this process, air from the building interior can be easily drawn into the roof assembly. This is more pronounced in mechanically-fastened single-ply roofing systems. In the case of protected membrane roofs, the roof membrane, adhered to the deck, functions better as an air barrier than in the case of the conventional roofing system assembly.

NBC Requirement

NBC (1995) {section 5.4, air leakage, and section 9.25, heat transfer, air leakage and condensation control} stipulate the air barrier requirements. An air barrier system's air leakage characteristic should not be greater than 0.02 $L/(s\ m^2)$ measured at an air pressure difference of 75 Pa. To be effective, the air barrier must be impermeable to air flow and continuous even at joints and junctions. An air barrier system and its components will be subjected to wind loads and must therefore either have the strength and rigidity to resist these wind loads totally or be supported by and secured to a structural element that has the required strength and rigidity. For a deflection requirement, 1.5 of design wind loads should be considered.

Functions and Properties of Vapour Barrier

Vapour barrier function

A vapour barrier is defined as a building envelope element that limits diffusion of moisture into an assembly. Diffusion is water vapour migration in a material. Its rate depends on two factors:

- water vapour pressure difference across the roof assembly;
- resistance of materials along the migration path.

Some materials have more resistance than others. Placing a high-resistance material in a roof assembly will help control moisture migration.

Vapour barrier properties

Vapour barriers are intended to limit moisture diffusion. Therefore, the main property requirement of a vapour barrier is low water vapour permeance. Water vapour permeance is defined as "*the time of water vapour transmission through a unit area of flat materials or construction induced by a unit vapour pressure difference between two specified surfaces, under specified temperature and humidity conditions*". According to the Part 9, section 9.25.4.2 of the NBC, vapour barriers shall have an initial permeance not greater than 45 $ng/Pa{\cdot}s{\cdot}m^2$, where: 1 ng (nanogram) = 10^{-9} grams; Pa = Pascal; s = second; m = metre. Some typical vapour barrier materials and their permeances are listed in the following table:

Vapour Permeance Values of Common Roofing Materials[1]

Material	Thickness or Weight	Permeance, ($ng/Pa \cdot s \cdot m^2$)	Type
Common vapour barrier materials			
aluminum foil	0.03 mm (1 mil)	0	I
	0.01 mm (0.35 mil)	2.9	I
polyethylene	0.15 mm (6 mil)	3.4	I
	0.10 mm (4 mil)	4.6	I
	0.05 mm (2 mil)	9.1	I
asphalt kraft paper facing		17	II
unplasticized poly(vinyl chloride)	0.05 mm (2 mil)	39	II
polyester	0.03 mm (1 mil)	42	II
Paint and wallpaper			
asphalt paint on plywood	2 coats	23	II
aluminum paint	2 coats	17-29	II
latex VDR paint	1 coat	26	II
oil-based paint on plaster	2 coats	91-172	—
Insulation materials			
extruded polystyrene	25 mm (1 in.)	23-92	—
polyurethane	25 mm (1 in.)	69	—
expanded polystyrene	25 mm (1 in.)	115-333	—
rock wool	100 mm (4 in.)	1666	—
cellulose fibre	100 mm (4 in.)	1666	—
glass fibre wool	100 mm (4 in.)	1666	—
Other building materials			
glazed tile masonry	100 mm (4 in.)	6-9	I
asbestos-cement board with oil paint	3 mm (1/8 in.)	17-29	II
board (wood)	19 mm (3/4 in.)	17-232	II
poured-in-place concrete	200 mm	23	II
CDX plywood	6.4 mm (1/4 in.)	40	II
concrete block	200 mm (8 in.)	137	—
tar paper	6.8 kg (15 lb.)	230	—
hardboard (standard)	3 mm (1/8 in.)	630	—
plaster on metal lath	19 mm (3/4 in.)	860	—
spun-bonded polypropylene		884	—
insulating board	12.7 mm (1/2 in.)	1150-2875	—
builder's sheathing paper		1170	—
gypsum drywall		2860	—

[1] *Note: Values from the details for air barrier systems for houses. Ontario New Home Warranty Program, North York, 1993.*

In practice, vapour barriers are classified as Type I, Type II or Type III. For example, a 6 mil thick polyethylene sheet qualifies as a Type I vapour barrier.

The ASTM E96 procedure is used to measure water vapour transmission properties. However, this procedure applies to measurements for two RH conditions. The dry- and wet-cup method corresponds to 25% and 75% mean RH, respectively. A recent study at NRC found that this information is not enough to describe the behavior of materials and components through the entire range of RH. Currently a logical extension of the E96 standard is being proposed by NRC which will cover the measurement procedure over a range of mean RH values.

THERMAL CONSIDERATION

Roofing system durability or service life depends greatly on the resistance of the system to thermal effects. Thermal performance of a roofing system, in turn, depends on the insulation. Therefore, the preliminary requirement of insulation is to control the heat loss and heat gain through the roofing system. Secondly, the insulation should also maintain the temperature of the vapour barrier and the components below the vapour barrier above dew point temperature. In other words, the secondary requirement of insulation is to minimize condensation on the roof surface.

Heat Transfer

There are three ways in which heat flow occurs through a roofing system: conduction, convention and radiation.

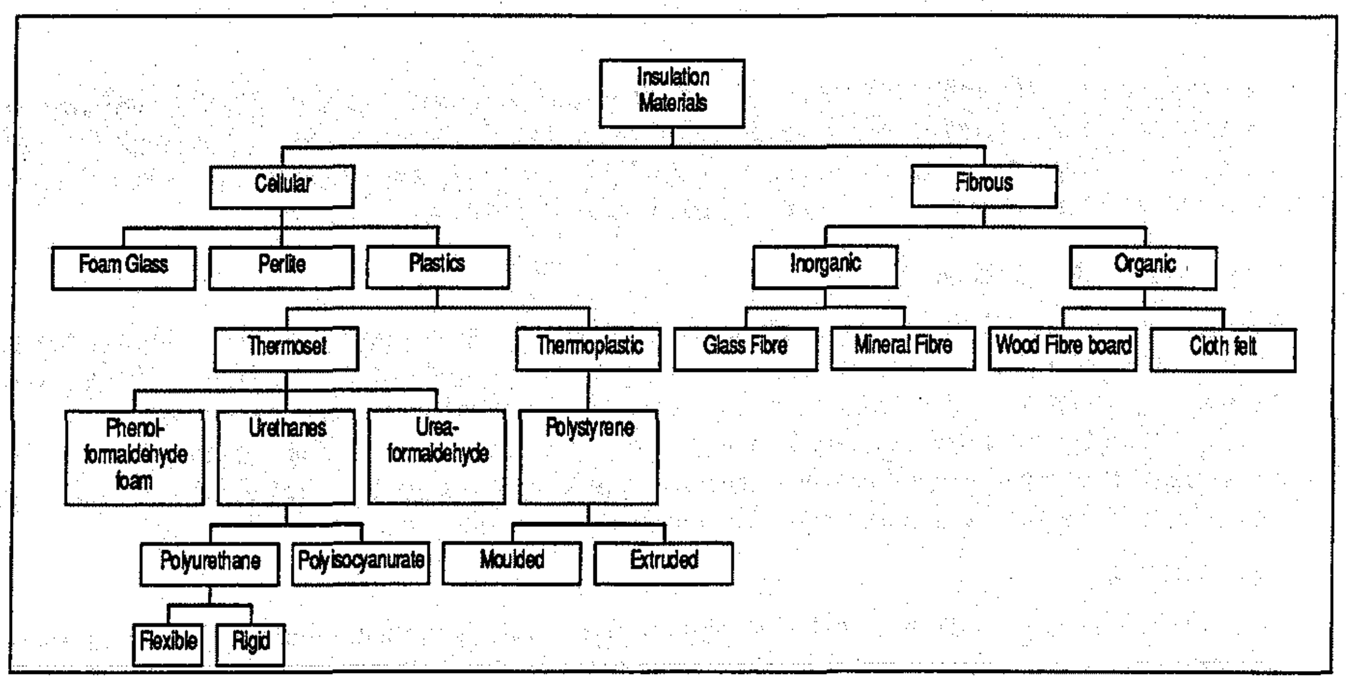
Conduction is the transfer of heat through direct contact of molecules. For example, if a metal deck is used to separate the hot and cold environment, then hot molecules will conduct heat to cold molecule. This process continues until molecules reach equilibrium status. Adding another component, e.g., membrane, will start the process again.

Convection is the transfer of heat by movement of particles. In this process, air particles move from hot surface to a cold surface. It is also called convection current. Air leakage through cracks or unsealed membranes can transmit heat by convection. In a roofing system, heat transfer occurs primarily through conduction and less through convection.

Radiation is a heat transfer process due to waves emitted by bodies. In roofs, a black membrane will typically absorb the heat from sun rays. This is also true in the case of roof skylights. Reflective surfaces, such as an aluminum sheet or coatings, help minimize this process.

Types of Insulation

Many different types of thermal insulating materials are used by the roofing industry. They can be organic, inorganic, metallic or a combination of them. These materials are available as loose fill, blanket, batts, block or slab or board, reflective and foams. Some products are combinations of two or more types of insulation, such as reflective mineral wool blanket insulation. Building Products of Canada provides a classification for the spectrum of common insulation materials shown in the following chart.



Requirement of Insulation

Similar to other roofing components, the requirements of insulation vary with a building's use and location. The *Canadian Coordinating Committee for Thermal Insulation Standards and Quality* (CCCTISQ) commissioned a study to assess the current status of insulation standards for residential applications. The report, *"Study of thermal insulation standards for residential application - G.R Genge"* stipulates the requirements for insulation listed in the following table:

Property	Requirement
Air Leakage Resistance	maximum acceptable air permeance to be part of the air barrier system
Bond Strength	minimum acceptable bond insulation materiel (cohesion and surface adhesion under service loads)
Capillary Action Resistance	maximum allowable capillary potential to avoid damage to insulation and other components and loss of thermal performance
Compatibility	proof of compatibility with common construction solvents which may contact the insulation (such as adhesives, damp-proofing, etch.)
Compressive Strength	minimum acceptable compressive resistance of materials subjected to expected loads (such as slabs, backfill, foot traffic, wind)
Corrosiveness	maximum acceptable potential of insulation to cause corrosion of metal elements (such as studs, fasteners, etc.)
Dimensional Stability	maximum acceptable dimensional change to avoid loss of performance or damage to adjacent materials
Dimensional Tolerance	maximum acceptable variance in product dimensions as manufactured for intended assemblies
Drainage Capability and Flow Rates	Capability of products intended to perform as a drainage layer on foundations to handle water in backfill
Fastener Tear-Out Resistance	tear out resistance of insulation attached by fasteners when subjected to construction and service loads, such as winds, gravity, and etch

Property	Requirement
Flame spread and Smoke Rating	tests for compliance of insulation materials and typical assembly used for compliance with code requirements
Freeze/Thaw Resistance	minimum acceptable resistance to cyclic expansion/contraction forces so as to avoid performance loss or damage
Heat Tolerance:	ability to resist loss of performance and structural integrity over time when in contact with hot ducts, pipes, etc.
Mechanical Damage Resistance and Durability	minimum acceptable resistance to tearing, permanent compression, puncture, etch. typical of construction and service conditions
Ozone Depletion Potential	maximum acceptable ozone depletion potential for the product and its manufacture
Placement of Blown-in Insulation	minimum acceptable standard for blown-in insulation to allow intended level of performance (i.e., no pockets, good distribution, etc.)
Post Expansion Pressures	maximum acceptable post expansion pressure of foams to avoid damage to windows, finishes, framing, etc
Rigidity	minimum acceptable rigidity to allow flat finishes and racking resistance for frames when use in place of sheathing
Settlement Resistance	maximum acceptable sag, consolidation, settlement, etc. that won't lower the thermal performance or leave air gaps
Shear Strength	minimum shear strength based on structural or non-structural use to resist construction and in-service forces.
Thermal Degradation	maximum acceptable loss of thermal resistance of insulation material due to aging over a typical building life
Thermal Oxidation	minimum acceptable resistance to chemical degradation of materials subject to thermal stresses over a typical building life.
Thermal Resistance	minimum acceptable thermal resistance for products or assemblies relative to labeling and intended use
Ultra Violet Radiation Resistance	maximum acceptable loss thermal performance and physical deterioration due to predictable lifetime exposure
Vapour Retarder Classification	minimum acceptable permeance rating according to requirements of potential material location
Volatile Organic Emissions	maximum acceptable levels of various volatile organic emissions with respect to indoor air quality guidelines, both short and long term exposure

In addition to the above, the following are some of the subjective parameters:

- The material shall have sufficient structural integrity to maintain its basic form and structure during normal handling and installation.
- The surface of the insulation shall be free of cracks, lumps, or other defects that may adversely affect its service quality or appearance.
- The insulation shall have no objectionable odour.
- The material shall be reasonably uniform in cell structure.
- Workmanship shall be in accordance with good commercial practice.
- When applied, the insulation shall not present any health hazard to the potential occupants.

- Facings shall be well adhered.
- All material shall be free from foreign matter.
- The material shall be rot proof and mildew and fungus growth resistant.
- The material shall not be corrosive to metals commonly found in building construction.

Additional Requirements for PMR Insulation

In PMR assemblies, the insulation may be exposed to the exterior environmental effects. Besides its preliminary function of controlling heat flow, it must also protect the membrane from such effects as temperature difference, wind uplift, and solar radiation. In many cases, either ballast or pavers are used to hold the insulation against wind uplift. However, securing ballast or pavers against wind is equally critical. Extensive work was done using NRC's wind tunnels on roof models. The results of these tests provided valuable tools to designers for dealing with such wind uplift problems and gravel scouring under the various climatic conditions that prevail in Canada.

Roof drainage is an important part of a PMR system. Water, usually, will not seep into the insulation used on PMRs. Rather, the moisture enters the insulation as vapour. Vapour gradient causes moisture to diffuse into the insulation. As a second line of defense, a designer should also ensure that moisture in the insulation is allowed to escape to the atmosphere through a gravel cover or by providing ventilation space between pavers and PMR insulation. If pavers are placed directly on the insulation, water may be trapped at the surface between insulation and paver. When the sun shines, it heats the paver. If the temperature gradient is reversed, i.e., the temperature at the top surface of the insulation exceeds that of the insulation below it, water vapour will be driven into the insulation and condense there. Pavers should be spaced 10 to 20 mm above the insulation, so that vapour in the insulation and water on top of it can evaporate to the outside.

Evaluation Standards and Test Methods

Several of the above requirements can be evaluated through standard laboratory test procedures. The following tables provide a listing of the Canadian insulation evaluation standards and test methods. However, currently, the *Canadian Coordinating Committee for Thermal Insulation Standards and Quality* (CCCTISQ) is developing recommendations to the Canadian General Standards Board (CGSB) for harmonizing the thermal insulation standards for Canada.

Canadian Standards Association (CSA)

Number	Name
CSA/A101-M1983	Thermal insulation, Mineral Fibre, for Buildings
CAN/CSA-A247-M86	Insulating Fiberboard
CSA/A284-1976	Mineral Aggregate Thermal Roof Insulation
CAN/A451.1-M86	Polystyrene insulation Adhesives

Canadian General Standards Board (CGSB)

Number	Name
CAN/CGSB-51.2-M88	Thermal Insulation, Calcium Silicate for Piping, Machinery and Boilers.
CAN/CGSB-51.5-92	Thermal Insulation, Block or Blanket, Elevated Temperature.
CAN/CGSB-51.9-92	Mineral Fibre Thermal Insulation for Piping and Round Ducting
CAN/CGSB-51.10-92	Mineral Fibre Board Thermal Insulation.
CAN/CGSB-51.11-92	Mineral Fibre Thermal Insulation Blanket
CAN/CGSB-51.12-M86	Cement, Thermal Insulating and Finishing
CAN/CGSB-51.20-M87	Thermal Insulation, Polystyrene, Boards and Pipe Covering
51-GP-21M78	Thermal Insulation, Urethane and Isocyanurate, Unfaced
CAN/CGSB-51.23-92	Spray-Applied Rigid Polyurethane Cellular Plastic thermal insulation
CAN/CGSB-51-92	Thermal insulation, Phenolic, Faced
CAN/CGSB-51.26-M86	Thermal Insulation, Urethane and Isocyanurate, Boards, Faced
51-GP-27M79	Thermal insulation, Polystyrene, loose Fill
51-GP-29Ma	Phenolic Thermal Insulation for Pipes and Ducts
CAN/CGSB-51.31-M84	Thermal Insulation Fibre Board for Above Roof Decks
CGSB-51.32-M77	Sheathing, Membrane, Breather Type
CAN/CGSB-51.33-M89	Vapour Barrier Sheet, Excluding Polyethylene, for Use in Building Construction
CAN/CGSB-51.34-M86	Vapour Barrier, Polyethylene Sheet For Use in Building Construction
CAN/CGSB-51.38-92	Cellular Glass Thermal Insulation
CAN/CGSB-51.39-92	Spray Application of Rigid Polyurethane Cellular Plastic Thermal Insulation for Building Construction.
CAN/CGSB-51.40-M80	Thermal insulation, Flexible, Elastomeric Unicellular, Sheet and Pipe Covering
51-GP-42MP	Handbook on Insulating Homes for Energy Conservation
51-GP-44MP	Manual for: Installers of Cellulose Fiber Blown Loose Fill thermal Insulation
51-GP-45MP	Manual for: Installers of Mineral Fibre Blown Loose Fill Thermal Insulation
51-GP-47MP	Manual for Installation of insulated Cladding Systems
51-GP-51	Polyethylene Sheet for Use in Building Construction
51-GP-52Ma	Vapour Barrier, Jacket and Facing Material for Pipe, Duct and Equipment Thermal Insulation
51-GP-53M	Jacketing, Polyvinyl Chlorine Sheet, for Insulating Pipes, Vessels and Round Ducts
CAN/CGSB-51.60-M90	Cellulose Fibre Fill Thermal Insulation
CAN/CGSB-51.65-M90	Insulating Blankets for Domestic Hot Water Heaters

ASTM Standards and Test Methods

Number	Name
B142	Specification for Copper Sheet, Strip, Plate and Rolled Bars (Discontinued, Replaced by B456-93a, Specification for Electro-deposited Coatings of Copper plus Nickel Plus Chromium and Nickel Plus Chromium) [51.60]
C163.88	Practice for Mixing Insulating Cement Samples [51.60]
C165.92	Test Method for Measuring Compressive Properties of Thermal Insulations [A101, A284, 51.5, 51.31, 51.38]
C166-87 (1992)	Test Method for Covering Capacity and Volume Change Upon Drying of Thermal Insulating Cement[51.12]
C167-90	Test methods for Thickness and Density of Blanket or Batt Thermal Insulations
C177-85	Test Method for Steady-State heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus [A101, A284, 51.2, 51.5, 51.9, 51.1, 51.11, 51.12, 51.20, 51-GP-21M, 51.23, 51.25, 51.26, 51-GP-27M, 51.29, 51.31, 51.38, 51.40, 51.60,]
C203-92	Test Methods for Breaking Load and Flexural Properties of Block-Type Thermal Insulation [A101, A284, 51.5, 51.20, 51-GP-21M, 51.25, 51.26, 51.29, 51.31, 51.38]
C209-92	Test Methods for Cellulose Fiber Insulating Board [A247, A284, 51.31]
C236-89	Test Method for Steady State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box [51.26]
C240-91	Test methods of Testing Cellular Glass Insulation Block [51.38]
C273	Method for Shear Test in Flatwise of Flat Sandwich constructions or Sandwich Cores. [51-GP-21M]
C302-82	Test Method for Density of Performed Pipe-covering-Type Thermal Insulation [51.2, 51.9, 51.29]
C303-90	Test Method for Density of Performed Block-Type thermal Insulation [51.2, 51.5, 51.9, 51.1, 51.38]
C335-89	Test Method for Steady-State Heat Transfer Properties of Horizontal Pipe Insulation [51.2, 51.9, 51.29, 51.40]
C353-90	Test Method for Adhesion of Dried Thermal Insulating or Finishing Cement [51.12]
C354-90	Test Method for Compressive Strength of Thermal Insulating or finishing Cement [51.12]
C355-63	Water Vapour Transmission of Thick Materials (Discontinued, Replaced by E96) [A284, 51-GP-21M, 51.40]
C356-87	Test Method for Linear Shrinkage of Performed High-Temperature thermal insulation Subjected to Soaking Heat [51.2, 51.5, 51.9, 51.1, 51.11, 51.12]
C390-79 (1989)	Criteria for Sampling and Acceptance of Performed thermal Insulation Lots [A284, 51.11, 51.25, 51.31, 51.38]
C405-82 (1992)	Practice for Estimating Consistency of Wet-Mixed Thermal Insulating Cement [51.12]
C411-82 (1992)	Test Method for Hot-Surface performance of High-Temperature Thermal Insulation [51.9, 51.10, 51.11]
C421-88	Test Method for Tumbling Friability of Performed Block-Type thermal Insulation [51.2]
C466-88	Test Method for Breaking Load and Calculated Modulus of Rupture of Performed insulation for Pipes [51.2]
C458-90	Test Method for Organic Fiber Content of Asbestos-Cement Products [51.2]

Number	Name
C518-91	Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus [A101, A284, 51.2, 51.5, 51.9, 51.11, 51.12, 51.20, 51-GP-21M, 51.23, 51.25, 51.26, 51-GP-27M, 51.29, 51.31, 51.38, 51.40, 51.60]
C534-88	Specification for Performed Flexible Elastomeric Cellular Thermal insulation in Sheet and Tubular form [51.40]
C550-81 (1987)	Practice for Measuring Trueness and Squareness of Rigid Block Thermal Insulation
C533-92	Specification for Mineral Fiber Blanket Thermal Insulation for Commercial and Industrial Applications [51.5, 51.9, 51.10, 51.11, 51.31]
C585-90	Specification for Inner and Outer Diameters of Rigid thermal Insulation for Nominal Sizes of Pipe and Tubing (NPS System)
C726-93	Standard specification Test for Mineral Fiber Roof insulation Board
C728-91	Specification for Perlite Thermal insulation Board [A284]
C739-91	Specification for Cellulosic Fiber (Wood-Base) Loose-Fill thermal Insulation [51.60]
D618	Standard Practice for Conditioning Plastics and Electrical Insulating Materials for Testing [51.20, 51-GP-21M, 51.23, 51-GP-27m, 51.29]
D1037	Standard Test Methods for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials [A284]
D1621	Standard Test Method for Compressive Properties of Rigid Cellular Plastics [51.20, 51-GP-21M, 51.23, 51.25, 51.26, 51.29]
D1622	Standard test Method for Apparent Density of Rigid Cellular Plastics [51.23, 51.29]
D1623	Standard Test Method for Tensile and Tensile Adhesion Properties of Rigid Cellular Plastics [51-GP-21M, 51.23, 51.25, 51.26]
D1667	Specification for Flexible Cellular Materials - Vinyl Chloride Polymers and Copolymers (Closed Cell Sponge)
D2126	Standard Test Method for Response of Rigid Cellular plastics to Thermal and Humid Aging [51.20, 51-GP-21M, 51.23, 51.25, 51.26, 51.29]
D2842	Standard Test Method for Water Absorption of Rigid Cellular Plastics [A284, 51.20, 51-GP-21M, 51.23, 51.26]
D2856	Standard Test Method for Open Cell Content of Rigid Cellular Plastics by the Air Pyconometer [51.23]
D2863-87	Test Method for Measuring the Minimum Oxygen Concentration to Support Candle-Like Combustion of Plastics (Oxygen Index) [51.20, 51-GP-27M]]
E96-93	Test Methods for Water Vapor Transmission of Materials [A101, 51.20, 51.23, 51.25, 51.26, 51.32, 51.33, 51.34, 51.38,51.52]
G1-90	Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens [51.60]
G26-92	Practice for Operating Light—Exposure Apparatus (Xenon Arc Type) With and Without Water for Exposure of Nonmetallic Materials [51.34]

OTHER REQUIREMENTS

Requirement for Snow Loads

Snow accumulations on roofs are usually quantified by gathering field data. Part 4 of the NBC (1995) and its User's guide, Commentary - H provides values for design snow loads for roofs. Roof snow loads mainly depend on four factors:

1. *Basic roof snow load factor*: mainly depends on the ground snow load of the location;
2. *Wind exposure factor*: accounts for the reduction in snow load, if applicable, due to snow drifting caused by wind flow over the roof configuration;
3. *Roof slope factor*: a reduction factor dependent on the roof slope; and,
4. *Accumulation factor*: depends on the roof slope and local climate effects.

Requirement for Fire Resistance

NBC (1995) Part 3.1.14 and 3.1.15 mainly covers fire requirements of roof assemblies. ULC Standard 107, "*Standard method for testing fire resistance of roof coverings materials*" is required by the building code to meet the fire resistance performance. There are three classes for rating roof coverings based on their ability to resist fire:

- **Class A:** for severe fire exposure conditions;
- **Class B**: for moderate fire conditions; and,
- **Class C**: for light fire exposures.

SUMMARY

This paper presented some basic principles of roofing systems and components. Two types of roofs are commonly used in North America, namely, conventional roofing systems and protected membrane systems. These were discussed together with their performances requirements. During the service-life of a roof, several harsh climatic factors with varying degree of effects from environmental forces are encountered. Three key performance elements were addressed, namely, wind effects, rainwater management and moisture control. For these elements, building science principles, application roofing and new requirements from the 1995 National Building Code were discussed. Lastly, North American standards and test methods for roof insulation were also summarized.

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