Chapter 3:

BUILDING SCIENCE

REFERENCES:

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INTRODUCTION:

A building must satisfy several general requirements. It must be:

-safe in respect of structure, fire and health
-economical in initial cost and operating cost -aesthetically pleasing,
-inoffensive to the senses and an aid in sensory tasks.

To achieve safety it must provide:

1. structural strength and rigidity
2. resistance to initiation and spread of fire
3. control of air and water quality and means for waste disposal

To achieve economy it must:

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

To be inoffensive and an aid in sensory tasks it must provide control of:

1. odors
2. light
3. sound vibrations

To function as a moderator of the environment and to satisfy all other requirements, it must provide control of:

1. **heat flow**
2. **air flow**
3. **movement of water as vapour and as liquid**
4. **solar and other radiation**

The environment is always strongly influenced by weather and it becomes vitally important in considering the design and performance of buildings in a cold climate such as ours. The detailed design of buildings in a cold climate is unique and crucial. What may work well in a moderate or warm climate may be dead wrong for ours and may fail. This will greatly affect your research when looking for details or building types for use on a building built in a Canadian climate. When referring to American and British journals, care must be taken in the understanding of the implications of the construction as viewed -- **not all is acceptable in our environment**, and ***to our standards*.**

WEATHER AND CLIMATE:

Temperature, precipitation, wind and sunshine have a direct effect on buildings. A deliberate choice of surroundings may permit us to take advantage of the elements that make the environment more favorable.

Climatic conditions are measured and recorded, the data collected over a period of time provides a statistical record which shows the mean, maximum, minimum and variation of temperature, hours of sunshine, wind, etc. Precipitation records provide an indication of the availability of water; temperature records provide a measure of space heating requirements; rainfall records provide a basis for estimating run-off rates for sizing drains and culverts; wind and snow records provide a basis for estimating winds and snow loads on building structures.

Degree days, which are a measure of yearly heating requirements, are given by the sum of the departures of the daily mean temperature from 18 degrees C for each day on which the temperature falls below that value. The sum total of degree days for a year in a certain location acts as the basis for measuring the amount of heating (or cooling) required for a building. The higher the number of degree days, the more severe the climate.

The Sun:

The sun provides solar radiation and heat for our environment. The earth travels in an elliptical path around the sun, with the sun at one focus of the ellipse so the earth is closest to the sun when at one end of the major axis in December and farthest when at the other in June. The mean distance is 1.496×10^8 km. The intensity of solar radiation which varies inversely as the square of the distance from the source varies by 3.5% about a mean value of 1353 W/m2 at the earth. This has only a small seasonal change with respect to the amount of solar radiation we receive.

The number of hours of sunlight we receive each day is a product of both the incline of the axis of the earth, at 23.5 degrees from the perpendicular, and it position relative to the sun on its yearly rotation. The winter solstice for the northern hemisphere occurs about December 22, as at that time the sun is directly overhead at noon in latitude 23.5 degrees South (the Tropic of Capricorn). The summer solstice occurs about June 22 when the sun is directly overhead at noon at latitude 23.5 degrees North (the Tropic of Cancer). We are located at a latitude of approximately 45 degrees north and hence the sun is never directly overhead. Cognizence of the sun angles is imperative in designing for sun access and penetration into interior spaces. Faces of the building receive differing amounts and quality of light depending on their orientation, time of year and time of day. Building layouts should be programmed to take advantage of solar quality.

The angle at which the sun's rays hit the atmosphere above us (and hence the earth) effect the amount of solar radiation we receive. The length of the atmospheric path is increased when the sun's rays are oblique to the earth's surface. The relationship of the altitude angle, B, of the sun at solar noon measured relative to the tangent plane at the point of observation at latitude, L, and the declination of the sun is shown. The solar declination, δ, is the angle between the earth-sun line and the equatorial plane. It varies throughout the year from +23.5 degrees at the summer solstice to 0 degrees at the equinoxes to -23.5 degrees at the winter solstice.

The altitude angle is given by $\beta = 90^{o} - L$

Beta is important as it tells us at what angle the sun is hitting the 'flat' plane at our location.

The Atmosphere:

The atmosphere acts as a storage medium for thermal energy and as an agent in heat exchange at the earth's surface. It can also, by its circulation, transport heat from one region to another. Its greatest influence arises from its ability to intercept, absorb, and redirect incoming solar radiation.

The atmosphere consists of a mixture of gases held by gravitational attraction to the earth. It is compressed under its own weight, and varies in density with altitude and with temperature and water content. The composition by volume of dry air at ground level is 78% nitrogen, 21% oxygen, 0.8% argon, and 0.03% carbon dioxide. The atmosphere contains water vapour in amounts up to 4% by weight. The amount of water in the atmosphere varies with temperature, water existing as a gas, liquid or solid. Water has the ability to absorb solar radiation, hence it is cooler when there is cloud cover as the clouds intercept the heat from solar radiation.

Atmospheric circulation is caused by air currents. Heating of the ground by solar radiation creates rising warm air currents. Cooler air must flow in at ground level as a replacement and must itself be replaced as part of a pattern of circulation. Hence we have winds.

The density of the atmosphere decreases exponentially with altitude. The temperature decreases steadily from ground level to about 10 km up at a rate of 6^{o} C per km, and above this remains fairly constant. The first layer of atmosphere is called the troposphere, the second the stratosphere, the boundary between them is called the tropopause.

SOLAR RADIATION:

Solar radiation is important to consider in the design of buildings as it is possible to receive 'free energy' for heating the internal environment from the sun. Depending on the climate, it is also possible to avoid 'heat gain' if it is not desired.

The intensity of solar radiation outside the earth's atmosphere varies significantly with time of the year as the earth to sun distance changes. The effect of solar radiation on buildings is complex since the rate at which energy is delivered is highly variable with latitude, time of year, time of day, weather, surroundings, orientation of receiving surfaces and transmitting areas, and absorptance and emittance of receiving areas.

Sun Direction:

The sun's position in the sky can be expressed in terms of the solar altitude, β, above the horizontal and the solar azimuth, ϕ, measured from the south. These angles are determined by the local latitude, L, the solar declination δ, , and the apparent solar time (AST). The solar altitude at solar noon is given by:

$$\beta_N = 90^o - L + \phi$$

The solar altitude at other times of the day depends on the hour angle, H, which gives the rotation of the earth in the interval from noon to a particular time. Since the earth rotates 360 degrees in 24 hours, the hour angle changes 0.25 degrees for each minute.

This information is necessary in order to establish the angle of incidence of sunlight for a given surface orientation. It is possible to establish by calculation or by graphical means the shadows cast on surfaces so oriented by various projections such as window reveals, eaves, overhangs, and even adjacent constructions. Overhangs can be used to prevent the sun hitting glazing surfaces in the summer and prevent the gain of heat through solar radiation. If the overhangs are sized right, with the change in sun angle in the winter (it is lower in the sky) the sun's rays may be allowed to strike the glazed area permitting solar heat gain at the time of year it is most desired.

The intensity of the solar radiation varies with the .atmospheric conditions. The sun considered to be at 1.2 times full intensity on clear days, 1.0 times on average cloudless days, and 0.8 times in industrial areas with pollution.

Solar Heat Gain:

Solar radiation of buildings may be incident on opaque surfaces such as roofs or transparent surfaces such as windows. When the receiving surfaces are opaque, the radiation is partially reflected; the remainder is absorbed, producing a rise in the surface temperature. Since the solar radiation is not constant, the temperature and the associated heat flow vary. The thermal storage characteristics as well as the heat transmission properties of the absorbing surfaces become involved in determining the rate at which heat will be delivered through the construction under the combined effects of the solar irradiation of the outer surfaces and the outdoor to indoor temperature difference. For example, when solar radiation hits dark coloured metal surfaces, the material is able to absorb heat very quickly. This heat is also lost quickly when the solar source disappears as the material has a low heat capacity. When solar radiation strikes concrete, the absorbtion rate is slow; however, the heat capacity of the material for thermal storage is high, so the heat remains in the material for reradiation long after the solar source is gone. In the case of windows the transmitted radiation is usually large, the thermal storage of the glass small and usually disregarded.

The Solar Heat Gain Factor (SHGF) is the total amount of solar radiation received by a window, measured in Watts per Meter squared (W/m^2) in one day. These figures are found on Stephenson's Tables which list the number of watts received per for January 21 and July 21, by Latitude and by the direction the window faces (north, south, east or west).

When calculating solar heat gain through windows, it must be kept in mind that not all types of glazing transmit 100% of the solar energy available. Many products have been developed to reduce solar transmission. Tinted and reflective glazings reduce solar transmission to as low as 10% depending on the makeup of the coatings and ingredients. These type of products are typically used on commerical construction, not residential. In commercial construction, internal heat loads from people, lights and equipment make cooling a priority at all times of the year. The Shading Coefficient (SC) is a reduction factor whereby the type of glass reduces the amount of heat gain.

The instantaneous heat gain for a window is found by:

Heat Gain = (SC x SHGF) + U(t_i - t_o)

Where U is the coefficient of heat transmission for the glass, and t_o is the outside temperature in Celsius and t_i is the inside temperature. Heat flows naturally from warm areas to cold areas.

For example: Find the daily total of solar heat gain for January 21 on an east wall at a Latitude of 45 degrees, and for a window measuring 1 m x 2 m that is double glazed using regular plate glass. From Stephenson's Table the SHGF daily total for an east facing surface is 1346 W/m2. The SC for the glass is 0.83. The U value of the glass is 3.4 W/(m^2 x ^oC). The outside temperature is considered at a worst case of -20 degrees C, and the inside temperature is +20 degrees C.

Heat gain for 24 hours = 0.83 x 1346 + 3.4(-20 - 20)

= 1117.18 - 136

= 981.18 W/m2 x area of glass

= 981.18 x (1.0 x 2.0)

= 1962.36 Watts per day

For our latitude, the maximum solar heat gain in the winter is achieved with south orientation. The minimum amount of heat gain in the winter is with north orientation, this orientation usually results in direct heat loss only.

During the summer the maximum heat gain is by east and west orientations as the sun angle is lowest in the morning and afternoon, allowing penetration into the building. These orientations are the most difficult to control as well through shading.

Control of Solar Radiation through Shading:

In order to control sun penetration to the interior of buildings it is important to provide exterior shading as a part of the architectural envelope design. Such shading devices can be attached to the building or can be achieved by the articulation and disposition of the building floors to create overhangs.

Each orientation of the building requires a different approach to the design of shading. The **north** elevation essentially does not require shading because, for our latitude, except in the summer months in the early morning and late evening, no sun penetration occurs. At this time of day the sun angle is so low that horizontal projections would be useless as shading devices. It is best to limit as much as possible fenestration on the north elevation as there will be very little solar heat gain and much direct heat loss from this side.

The **south** elevation allows for the easiest control of solar energy. Shading devices are normally designed as horizontal projections above the windows -- the length of the projection is determined as a geometric function of the height of the window and the angle of elevation of the sun at solar noon. Such shading devices can be designed to completely eliminate sun penetration in the summer and allow for complete sun penetration during the winter when such is desired.

The **east** and **west** elevations are both difficult to shade "architecturally". The sun angles in the morning and afternoon are low enough to preclude shading using overhangs. The morning sun is normally cooler and less offensive than the heat and glare of the late afternoon sun. Shading needs to be provided in the way of landscaping and foliage. Deciduous trees are effective as they block the sun in the summer when it is not desired and allow sun penetration during the winter. Fences work to block the sun and view at all times of the year and so are not so climatically responsive. Vines on more transparent "fence like" elements are effective as they too bear leaves to shade in the summer, and keep their leaves until later in the fall when sun is again desired. Vines are often used as well on south facing elevations on trellises to achieve seasonal variation in the opaqueness of the overhangs.

Mass Thermal Storage:

Buildings using heavy construction such as brick masonry, concrete block or cast in place concrete are ideal for storing free solar energy. Solar radiation which reaches the interior of the building can be stored in the mass of the building envelope. This works best if these buildings are insulated on the outside as the insulation on the outside of the building retards the flow of heat back out of the building.

Even buildings which are made of light weight materials such as wood frame or light steel need to have thermal mass provided to enable the storage of heat allowed by large south facing windows. If such is not provided then the gain in free energy provided by large south facing windows in the winter months will be more than offset by the direct nighttime heat loss through the same windows. The provision of thermal mass allows this heat to be stored and slowly released into the interior of the building during the non solar hours. This type of solar storage can be provided by ceramic tile or stone floors with a 25 mm setting bed, if large amounts of concrete or concrete block are not practical.

HEAT LOSS:

The difference in temperature between the air inside the building and the air outside the building causes the heat to try to equalize the heat being transmitted through the wall material to the outside air. Heat flows from hot to cold. The rate of transfer of heat is dependent on the actual difference in temperature from outside to inside (delta T) measured in degrees Celsius, the surface area of the envelope of the building (A) measured in meters squared, and the resistance to heat flow of the wall (R) measured in $m^2 \times {}^{o}C/Watts$. The total heat energy transferred over a period of time can be expressed by:

$$Q = \frac{A \times \text{deltaT} \times t}{R}$$

where Q is the total energy transferred in Watts per hour, and t is the length of time period of time being considered in hours. If the period of time being considered is the entire heating season then the factors T x t can be approximated by

T x t = 24 x total degree days for heating season

Therefore the annual heat loss can be expressed by

$$H_c = \frac{24 \times A \times D}{R}$$

There are two ways to minimize the heat flow through the building envelope, therefore minimizing the heat loss and the amount of heat you have to purchase over the year. These are to maximize the thermal resistance value (R) for the wall (i.e. add more insulation) and minimize the exterior surface area of the building.

The R Value:

The R value is the a term referring to the amount of thermal resistance, or resistance to heat flow of a material. The U value is the conductivity or assistance to heat flow of a material. They are reciprocal values, ie. R = 1/U, and U = 1/R.

There are various ways you will see these values listed in tables. To calculate the thermal resistance (R) of a wall you must sum up the the conductivity values for the wall and then take the reciprocal. The values for materials usually listed in terms of their conductivity. The U value is the conductivity value for an <u>entire building envelope assembly</u>. The k-value is the conductivity for a material for 1 mm of thickness. The C-value is the conductivity of a material for its normal unit thickness.

In addition to thermal characteristics of the materials themselves, both the inside air film and outside air film, and the air space in the wall itself add to the thermal resistance values. These values are always listed in terms of their actual R value as they do not have any conductivity characteristics associated with them. The R value for the interior air film is 0.120, for the exterior air film is 0.030 and for a 25 mm air space is 0.171, (all in m^2 x ^oC/Watts). (For more values refer to the red and white book "Energy Efficiency in Masonry").

It is possible to calculate the temperature differences as you go through the wall using the thermal resistance (R) values. This is important as it is necessary to know what portions of the wall are subject to freezing during the winter as they may tend to deteriorate more rapidly because of moisture present in the construction due to air leakage and vapour diffusion. It is preferable to have the insulation on the exterior of the structural part of the wall as this keeps the structure always warm, not subject to freezing and thawing, and will cut down on its expansion and contraction due to variations in the temperature of the structural materials. Different structural materials expand and contract due to heat and cold at different rates. Metals undergo significant dimensional change due to thermal pressures and should always be kept on the warm side of the insulation. Concrete products, although not subject to extreme dimensional variations, perform better as mass thermal storers when located on the warm side of the insulation.

Thermal Bridges:

Thermal bridges are places in the building envelope where there is no insulation to prevent heat loss. These can result in disasterous effects and should be avoided at all costs, they cannot be tolerated in buildings constructed in our climate. Thermal bridges result in low surface temperatures on the interior of a building causing the adjacent surfaces inside the building to go through freeze thaw cycles that will deteriorate interior surfaces due to the presence of moisture (from cooking, showering, etc.), and will cause tiles to lift, carpet and paint to mould, etc. They are also very hard on heating bills.

One of the largest challenges cold climate architects face in the detailing of buildings is in the elimation and reduction of thermal bridges. It is not easy and often requires an alteration in the conceptual design and material choices in the building.

Calculation of Heat Loss:

Heat loss is a measure of the conductivity of the wall as a measure of its area. It is necessary for an architect to be able to do these calculations so to be able to size a furnace or check the capacity of an existing furnace when putting an addition on a house. Computer programs are available to assist with these calculations. Hand calculations are useful in a pinch and to provide an understanding of the implications of construction and material changes. To do such a calculation there are several simple steps: (make a table)

1. list all the materials which make up the wall, including outside and inside air films and air spaces

2. write down the conductivity (C) values down beside the material, or if they are not listed, take the k value and multiply by the thickness of the material in mm. This is the C value.

3. in the next column write down the R values. These are calculated by taking 1/C.

4. sum up all the R values. This gives you a resistance measure in m^2 x ^oC/Watts

5. calculate the U value (overall heat conductivity value for the entire wall assembly) by taking $1/R_{total}$.

6. the heat loss is equal to the (U value) x (the difference in temperature from inside to outside as an absolute value) x (the area of the material)

7. you now have the heat loss for that wall area of the building in terms of Watts per hour.

For example: for a brick veneer wall with 150 mm wood studbackup, inside temperature 23^o C, outside temperature -20^o C

Material	*Conductance*	*Resistance*
Outside air	34.00	0.030
100 mm face brick	13.00	0.077
25 mm air space	4.80	0.208
38 mm polystyrene	0.76	1.316
building paper	95.00	0.010
13 mm plywood sheathing	8.85	0.113
150 mm fibreglass batt	0.30	3.333
0.15 mm vapour barrier	0.00	0.000
13 mm gypsum board	12.50	0.080
inside air	8.30	0.120

Total Resistance 5.286 m^2 x $^oC/W$

$U = 1/R = 1/5.286 = 0.189\ W/(m^2\ x\ ^oC)$

$q = U\ x\ (t_i - t_o)\ x\ A = 0.189\ x\ (23 - (-20))\ x\ m^2$

$q = 8.13\ W/m^2$

where q is the flow of heat per hour.

AIR LEAKAGE:

The leakage of air out of the building contributes to the heat loss in a building. Air has moisture in it the amount which is measured by the relative humidity of the air. This contributes to the deterioration of the building envelope as this moisture when it escapes the building due to differential pressure will 'get caught' in the building materials it is trying to pass through and condense, freeze, and thaw, and freeze ...

The first principle that must be understood is that air is pressurized, via a relation to the atmospheric pressure and the amount of moisture in the air. The warmer the air is, the higher the pressure it has as a gas. If high pressure air is adjacent to low pressure air, it tries to dissipate, moving to the low pressure area to equalize the pressures. The air inside a building in the winter is hotter than outside, therefore the tendency is for the air to try to pass through the envelope of the building to equalize the air pressure. The reverse is true for an air conditioned interior in the summer.

There are two means that air 'leaks' out of a building and many means of preventing this air leakage. The first type of air leakage is through the cracks in the building, around windows and doors, through electrical outlets, etc. These can be solved by careful caulking, sealing and detailing of these areas. Weatherstripping can be installed around doors. Changes in the National Building Code around 1985 required the installation of an Air Barrier in the building envelope as a means to seal the building from air leakage.

The second means of air leakage is through vapour diffusion. This is where the air vapour travels through the wall materials. Materials each have a unique degree of permeability.

This is related to the porousity of the material and its physical structure. Vapour diffusion is normally prevented by the installation of a Vapour Barrier in the wall, floor or ceiling. Polyethylene films are installed on the warm side of the construction (in our cold climate on the inside of the building just beneath the drywall) in a continuous mode to retard the flow of vapour through the wall. This will not completely stop vapour diffusion, but will greatly reduce damage to to moisture escaping into the exterior envelope.

The vapour resistance for the same wall as the thermal resistance was calculated for earlier is calculated as follows. The exterior temperature is -20^{o} C with a relative humidity level of 15% resulting in an exterior vapour pressure of 15.48 Pascals. The interior temperature is +23^{o} C with a relative humidity of 40% resulting in an interior vapour pressure of 1123.6 Pascals. The higher pressure will flow to the lower pressure (inside to outside) (like air escaping from a tiny hole in a balloon...).

Element	**Thickness**	**Vapour Resistance**
Face brick	100 mm	0.023
Polystyrene	38	0.017
Building Paper		0.00056
Plywood sheathing	13	0.05
Fibreglass batt	150	0.00088
Polyethylene VB	0.15	0.3
Gypsum board	13	0.00046
2 coats latex paint		0.0043

Total Vapour Resistance = 0.3962 Pascals x seconds x m^2 /ng

The higher the value the more resistance to vapour diffusion through the wall material. Permeance is the value which tells how easily the flow occurs and is calculated by taking the reciprocal of the resistance. Permeance is calculated as the number of nanograms (billionths of a gram) that flow through a material per second per square metre of material per pascal of air pressure.

Permeance = 1/0.3962 = 2.52 ng/(s x m^2 x Pa)

Mass flow rate of water
=(Permeance) x (no. of hours) x (difference in inside and outside air pressures)

Mass flow rate = 2.52 x 1 x (1123.6 - 15.48)
= 2,796.87 ng/s x m^2

24 hour flow = 24 x 3,600 x (2,796.87) x 10^{-9}
= 0.242 g/m^2

Therefore over a 24 hour period 0.242 grams of water flow through each square metre of wall. This is a good wall as far as vapour diffusion is concerned. Walls with no vapour retarder will allow significantly more water vapour through and cause much destruction. For this reason it is essential to put a vapour retarder underneath the concrete floors in basements. There is a lot of moisture in the earth below and it will tend to penetrate into the basement and make it unduly damp.

Dew Point:

The calculations of permeability of a wall to vapour are also used to plot the varying air vapour pressures within the wall assembly, as numerical values. This, in combination with the calculations of the varying temperature in the wall from the thermal resistance values are used in order to see where the dewpoint occurs within the wall. The dewpoint is the temperature at which air becomes saturated with water vapour and below which moisture is likely to condense; this varies with the amount of moisture contained in the air (relative humidity), ie. the warm moist air from inside the building, travelling through the wall is cooled to a point where the water contained in the air as vapour is condensed and subject to freezing.

Even if the condensation is not cooled to the point of freezing, damage occurs when this condensation gathers in the insulation as it greatly reduces any resistance to heat flow. Soggy batt insulation can even act as a heat conductor.

The Psychometric Chart is used to quickly determine where the dewpoint occurs. To calculate the dew point for a certain air mixture at a certain temperature and relative humidity using the psychometric chart you.

1. read across the bottom the dry bulb temperature, ie. 21^{o} C

2. read up that line vertically and find its point of intersection with the relative humidity line (dark lines curving upward to the right), for example 50 % RH.

3. the point of intersection of those two lines is called the state point. Now read horizontally across the chart to the left and find the wet bulb or saturation temperature, for this case it is 10^{o} C. These values are on the uppermost curving humidity line.

This tells you that when the interior air at 21^{o} C at 50% RH travels out through the wall, when it is cooled down to 10^{o} C, will form condensation.

WIND ON BUILDINGS:

Wind exerts an influence on buildings and their operation through the pressures generated by the flow of air over them. The resulting forces are often important determinants of the structural loads that the building and its parts must withstand. The pressures caused by wind can also lead to air leakage, which is a major consideration in heating and cooling and in the movement of dust and smoke. Wind direction must be taken into account when designing window locations for natural ventilation. Wind can cause a breeze to enter a room if the opening is on the windward side of the building, and may suck air out of the building if on the leeward side as this is an area of negative pressure.

To assist in natural ventilation and cooling, it is important to design for cross ventilation in residential buildings. This entails windows with significant operable portions located in such a manner as to encourage air flow in and out of the rooms -- taking advantage of natural air flow and prevailing wind patterns. Rooms with windows on only one side tend to encourage stagnant air and deter natural cooling. This situation can be improved by positioning windows at high and low levels to increase the air flow caused by stack effect (i.e. hot air rises). Better are windows located on adjacent walls or best, opposing walls. High level windows are essential in the summer to exhaust the hot air that collects in ceiling spaces and draw in cooler air adjacent to the building.