WALLS, WINDOWS AND ROOFS FOR THE CANADIAN CLIMATE

BY

J.K.LATTA

A SUMMARY OF THE CURRENT BASIS FOR SELECTION AND DESIGN

SPECIAL TECHNICAL PUBLICATION NO.1
OF THE
DIVISION OF BUILDING RESEARCH

PRICE $3.00 OTTAWA, OCTOBER 1973 NRCC 13487

FOREWORD

The building designer of the past had to rely on experience or on experiment. When the reasons for the success of past designs were not known it was not possible to identify the significance of departures from them, and thus the new design inevitably became an experiment. It has been necessary, therefore, in establishing a sound basis for rational design, to seek to understand why various arrangements did or did not perform. This has been one of the major tasks of building research institutes in various countries.

The enclosures of buildings merit special attention in every country. They must always be designed with due regard for the materials, the conditions, and the practices of the country, and so can seldom be studied adequately elsewhere. As studies progressed at DBR and at other building research institutes and the essential elements of performance began to be appreciated, it became necessary to emphasize putting the results to work. The Canadian Building Digests and Building Science Seminars were useful in communicating with designers and others, but they were not enough. Something more was needed by way of a thorough but simple treatise relating all the relevant bits of information previously presented in many individual publications. The author, a research officer with the Division, accepted this challenge. He has followed closely the studies and the conclusions arising out of the work of his colleagues in the Division over the years, but the selection and presentation are his, as are the explanations and the examples which are intended to promote the best possible understanding of building enclosure design and performance.

Ottawa
October 1973

N.B. Hutcheon
Director, DBR/NRC

PREFACE

Ever since man ceased to be a cave dweller he has been a builder. In fact, it was his ability to build that enabled him to leave the cave. Slowly, as society evolved towards the present day technological era, the methods and techniques used in building evolved with greater and greater refinement of detail, and the slow tempo of construction in those days allowed time for this process of trial and error.

When one admires an old building that has been standing for centuries, perhaps, one is in fact admiring those forms of construction that were tried and found to be successful. But what of the errors? One cannot help but think that the errors that led to the development of the flying buttresses of the old cathedrals, for example, must have been very costly indeed.

During the last few decades the demand for new buildings has been so great and all costs have been rising so fast that there has been little time for slow and painstaking development of construction methods. In an endeavour to speed the process of building and to cut costs, new materials and methods of assembly have been used without the benefit of long-term performance. The design and construction process has become more fragmented with manufacturers and sub-trades designing and installing a wide variety of components and materials. The buildings themselves have also become more complicated, largely as a result of increasing demands for greater control of interior conditions. Heating, ventilating and electrical systems have also become more elaborate, sometimes as a direct result of the design of the exterior wall. This multiplicity of trades and the desired speed of construction make control of the whole process more difficult and, not infrequently, one trade may be working at odds with another. The installation of one thing may make that of a subsequent one more difficult or necessitate the removal or damage of a previously installed item with the result that the building may not perform as intended.

During the last 15 to 20 years, there has been a growing store of knowledge of the underlying physical phenomena that control the performance of buildings. This is sometimes referred to as "building science". There is, of course, a scientific basis for most of this knowledge but the process of designing and constructing a building is still far from being scientific and might better be described as an art in that many decisions must be made on a subjective or intuitive basis. Much of this information is scattered in various publications and, as far as is known, has never been collected together and presented in one self-contained package.

The purpose of this book then is to present the existing basis for the design of external walls and roofs in so far as they must act to withstand the Canadian climate and contain the desired inside conditions. As knowledge of the subject expands, it is probable that some of the material presented here will have to be modified, restated or enlarged. In a book such as this, one cannot hope to cover all aspects of wall and roof design and many subjects such as structural strength, fire resistance, acoustical properties and aesthetics are not covered. There is scope for many larger, more detailed and all-embracing books on the limited subject matter which has been covered as well as on the many other subjects that have been omitted completely.

It is hoped that the book will be of use to architectural students and others who need to assimilate the basic design principles as rapidily as possible without being overwhelmed with technical or scientific jargon. With this objective, the style of presentation has been kept relatively informal. Possibly the book could be used as the basis of a course of instruction in schools of architecture or building technology. It is also hoped that it may find a place in practicing design offices where the bustle of design and the need to reconcile many conflicting demands may lead to basic principles being violated and where a reasonably concise statement of some of these principles may be of use in straightening things out again.

No claim is made that the principles and theories expounded in this book are all the result of original work by the author. On the contrary, they are largely a consolidation and restatement of the work of many others. Naturally, the principal source of information is the various publications of the Division of Building Research and in particular the Canadian Building Digest series. Additional information has been drawn from other sources outside of DBR. A list of all authors would be excessively long and reference should be made to the bibliographies at the end of each chapter. The use of all information is gratefully acknowledged as are the many pertinent comments and suggestions made by various people within DBR who have reviewed parts or all of the text. Special thanks are due to Mr. George Kuester who prepared many of the special drawings and the architectural details contained in the Appendix.

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CHAPTER I -- THE PROBLEM

WHY DO WE BUILD BUILDINGS?

All over the world new buildings are being built and old ones repaired or demolished to make way for others. In Canada during the late 1960's some $7 to $8 billion, representing about 10 per cent of the gross national product, were spent on this activity each year. Thus it is not unreasonable to ask why do people build buildings? Or, if one wishes to reduce the scale of the question, why does one live in a house?

In the vast majority of cases one builds a building to protect the occupants and contents from inclement weather. It is true that in some cases protection is also needed against animals or insects and against thieves or vandals but in the great majority of cases the initial requirement is for protection from the weather. This protection is given by separating the inside from the uncontrolled conditions outside so that the conditions inside can be modified and controlled to some extent. It is the basic function of the walls, roof and floors of the building to effect this separation.

Since these walls, roof and floors form an enclosure they can conveniently be referred to collectively as the building enclosure. Any fenced area could be called an enclosure but although it has some of the separation characteristics of a building, for normal purposes it cannot reasonably be considered to be one. It is the technical design of a building enclosure in its function as a separator of inside and outside conditions that will be discussed in the following chapters. If this separation is not required, then a building as such is not required, only a structural framework to support the various components in their desired locations.

A complete separation, however, is not always necessary nor even desirable. A greenhouse with an opaque roof would not work very well; lumber stored for air seasoning requires only a roof to keep the rain off and provisions made to ensure a flow of air around and through the pile to carry away the excess moisture. The degree of separation will also vary with the weather, the season of the year and the time of day. Sunlight streaming in through a window can be intolerable at times but on other occasions may be most welcome. Thus the building must not only be an efficient separator but must in some respects be selective in what it excludes and when.

Keeping warm and dry are probably the prime objectives in constructing most buildings. It is clearly impossible to achieve these objectives if the wind is allowed to blow freely through the building. Unless the wind is controlled by the building enclosure it is not possible to control any of the internal conditions satisfactorily except for some partial protection from the sun and rain but even with this partial protection, snow may blow right through. Thus to fulfil its function the building enclosure must control the flow of air. The importance of this fact can hardly be over-stressed for, as we shall see later, failure to control the movement of air through, and within, the thickness of the building enclosure can lead to many serious problems of building deterioration and of failure to perform its intended function satisfactorily. It is probably worthwhile to digress at this point and to anticipate later discussions to point out that the air flows concerned need not be right through the building enclosure but can be within the thickness of the enclosure itself. Furthermore, the forces producing these currents of air are not necessarily those associated with strong winds; convection currents produced by differences in temperature can in many cases be of greater importance.

Even when the wind has been excluded from the building it will still be necessary during most of the year to adjust the internal temperature by means of a heating or cooling system. The size of this system will depend upon the balance between the rate at which heat is generated within the building and gained from external sources such as the sun, and the rate at which it leaks away. If the cost of, and the space occupied by, this system, with all its attendant piping and duct work, and if the cost of operating it are of no consequence, then one can merely provide a big enough system and pump the heat around to maintain the desired internal conditions. Even then control of these conditions would be very difficult because of local cooling or heating effects at various locations. In practice it is highly unlikely that these cost and space requirements can be ignored and so the building enclosure must exercise some control over the flow of heat. Part of this control will be directed toward the control of heat gain from the sun and radiant heat loss to a clear night sky. Of these, heat gain from the sun is probably the more important for, although the primary objective may be to keep warm, we do not want to be too warm.

In addition to the need to control the heat gain from the whole spectrum of solar radiation, specific parts of the spectrum may have to be controlled for other reasons. In particular the effects of ultraviolet radiation on organic materials which either form a part of the building or are stored in it should be considered.

The second main objective in building a building is to keep dry, and this entails a lot more than shedding vertically falling rain off the roof. Rain driven almost horizontally by gale-force winds must also be excluded as must snow which can sometimes drift in through quite small openings if there is a current of air to carry it.

Then there are moisture problems which can originate inside the building because of the water vapour carried in the air. This water vapour will condense on any sufficiently cool surface. The condensed water can then disfigure or damage both the contents of the building and the fabric of the building itself. The condensation will not always occur where it can be seen but may be in the walls or roof. In some cases it will collect in large quantities as frost which will be released as moisture as the temperature rises.

In summary it can be said that a building enclosure is composed of external walls, a roof and those floors, or parts of floors, that are not totally enclosed within the building. The basic function of a building enclosure is to keep the outside out and the inside in, except for those things which we wish to enter or leave the building. These must be controlled so that they enter or leave the building at such points and in such quantity and manner that they neither change the inside conditions too much nor harm the building enclosure in passing through it.

A complete list of all the requirements of the building enclosure would be very long but for our purposes in the discussion that follows they can be limited to the following six:

1. Control of air flow
2. Control of heat flow
3. Control of sunlight and other forms of radiant energy
4. Control over the entry of rain and snow
5. Control of water vapour
6. Satisfactory performance during its service life.

There are many other requirements such as control of fire, control of noise, structural strength, aesthetic qualities, economy of construction, operation and maintenance all of which must be taken into account in the over-all design. It is, however, beyond the scope of this book to cover in detail all of these subjects and so in general they will be excluded from the discussions that follow. This exclusion should not be taken as an indication that they are either not important or that there is a conflict between the solution to wall and roof design to meet the six basic requirements and that required for the control of fire or acoustics, or any of the others. This being so it is preferable to explain the principles underlying good enclosure design without the added complications of these further constraints.

The sixth requirement -- satisfactory performance -- is on the other hand most germane to the theme. It is, in fact, the crux of the matter, for many buildings are built at present in a manner which from time to time causes serious problems in the control of the interior conditions or which lead to rapid deterioration and excessive maintenance costs. The means taken to meet the first five requirements of the building enclosure must be such as will meet the sixth requirement.

In the past, changes in the design of the building enclosure evolved slowly and largely on the basis of trial and error. Today, with new materials and methods of construction available, the tempo of change has increased dramatically. It is no longer adequate to wait for the passage of time to determine the suitability of any design for in the meantime many more buildings will have been built. It is necessary to assess at least in general terms, the probability of the design being satisfactory, before work starts on the site, even if the ultimate test must still be trial by use. However, the dice can be loaded in the designer's favour if certain principles are adhered to throughout both the design and construction of the building.

THE INSIDE CONDITIONS

Having decided that the function of the building enclosure is to protect the inside conditions from the weather outside it is reasonable that the next step should be to determine what we want to protect. That is, what conditions are we going to tolerate inside the building or alternatively what conditions are we going to strive to create and maintain?

Different occupancies can set widely differing conditions inside a building. A cold storage locker will require a temperature of less than 0°F whereas a building for human occupancy will need inside temperatures of around 70°F. For satisfactory use every effort must be made to maintain these conditions. On the other hand some occupancies will create certain conditions that are not really required but can be accepted. Paper making, for example, does not need high temperatures and humidities in the building but the nature of the process and the equipment currently used makes them almost inevitable. In this case the internal conditions do not need to be controlled so closely but can be allowed to fluctuate over a wide range.

A building enclosure will be required to handle the worst conditions without distress and so one must balance the cost and effort required to design and construct such an enclosure against the similar cost and effort required to control the internal conditions more closely. With this in mind let us proceed by reviewing both the effects of some activities on the internal conditions and also the conditions which should be maintained to enable others to be carried on satisfactorily. It is necessary to use the expression "should be maintained" for in all too many instances in the past the limit to the internal conditions has been set by the inability of the building enclosure to maintain the desired conditions satisfactorily.

This review is not intended to be in any way comprehensive and one must turn to other sources for more detailed information. It is however intended to give an over-all picture of the effects and requirements of some types of occupancy so that discussions of satisfactory solutions to the problem of the building enclosure can be set against a reasonably factual background.

Human Beings and Associated Activities

People are warm-blooded animals and must maintain the inner organs of their bodies at a relatively uniform temperature around 98.6°F. Food is used as a fuel which is converted into energy some of which may leave the body in the form of external work. The balance is available to maintain the body temperature. Since the body produces heat continuously it must also lose heat continuously otherwise it will overheat like a car with no water in its radiator. A basic rate of heat production during sleep is about 250 Btu/hr., the heat equivalent of about 75 watts. As the bodily activity increases so does the rate of heat production with approximate values of 400 Btu/hr (120 watts) when awake but sedentary, 650 Btu/hr (190 watts) for light work and 2400 Btu/hr (700 watts) for heavy work.

In addition to the heat produced by persons in a building there is also an associated production of moisture, which is carried in the air in the form of water vapour. In a house with a family of four this has been estimated to be about 12 lb per day. Additional quantities of moisture will be added to the air inside the house by household activities as shown in Table I.1.

These figures show that approximately 15 to 20 lb (1 1/2 to 2 gallons) of moisture per day may be introduced into a house with four occupants under normal living conditions and that this can rise to as much as 40 to 50 lb (4 or 5 gallons) per day on washdays. A gas range in the kitchen will also add moisture to the air from water vapour which is one of the products of combustion when gas is burnt.

Heat and moisture are not the only problems associated with human occupancy; people must also have air to breathe. Fresh dry outdoor air contains about 21 per cent O_2 and 0.03 per cent CO_2 on a volume basis (the remainder being mainly nitrogen). Significant variations in these proportions can render it unfit for human use. For prolonged exposure a minimum concentration of 16 per cent O_2 and a maximum concentration of 0.5 per cent CO_2 (sometimes extended to 1.5 per cent) are commonly accepted standards.

A person, when seated, usually inhales about 18 cu ft of air per hr. The exhaled air contains about 16 per cent O_2 and about 4 per cent CO_2. Thus, if only 18 cu ft per hr of fresh air were provided via a face mask for each person in a continuously occupied space the concentrations of O_2 and CO_2 would approach these levels. If the fresh air is supplied to the room and thoroughly mixed with the room air, each person would ultimately inhale a mixture of half fresh and half room air and the CO_2 level would approach 2 per cent. Exposure for even a short time to a CO_2 level of even 2 per cent would result in a temporary loss of vitality and ability. If, however, ten times this amount of fresh air were provided to the room (180 cu ft per hr or 3 cu ft per minute), the ultimate CO_2 level would be only 1/10th of 4 per cent i.e. 0.4 per cent and the O_2 deficiency would be only 0.5 per cent, instead of 5 per cent. Approximately 3 cfm per person may thus be regarded as the minimum rate of supply of outdoor air, or equivalent, that is required to control, within accepted limits, the concentration of CO_2 arising from respiration of people at rest; only one tenth of this is required to maintain the required levels of O_2. Consumption of O_2 and production of CO_2 increase with activity, and ventilation requirements increase correspondingly. For people who are standing, the values are about 50 per cent higher than for those seated.

People use light to see what they are doing. An illumination of 100 ft-candles provided by recessed fluorescent fixture requires about 0.5 kw of electric power for each 100 sq ft of floor area, most of which sooner or later

TABLE I. 1 MOISTURE PRODUCED BY VARIOUS HOUSEHOLD ACTIVITIES FOR A FAMILY OF FOUR

Activity	Moisture Produced lb
Cooking (3 meals per day)	2
Dishwashing (3 meals per day)	1
Bathing -- Shower	0.5
-- Tub	0.1
Clothes washing (per week)	4
Clothes drying indoors or with unvented dryer (per week)	26
Floor mopping (per 100 sq ft)	3
Occupants (family of four per day)	12

appears as heat within the building.

If these are some of the effects of human beings on the conditions in the building what conditions should we strive to maintain so that people can live and work in them satisfactorily? These will vary with the nature of the activity being carried on; with sedentary occupations an air temperature of 70 to 75°F would be desirable whereas with light activity this range could be reduced by some 5°F. Humidity levels are not so critical. For persons at rest or doing light work they can vary between about 20 per cent and 70 per cent relative humidity provided that the air temperature is less than 78°F.

People themselves are therefore reasonably adaptable but what of the activities they may be doing? The surgeon in the operating theatre may be happy with a considerable variation in conditions but it is essential for considerations of safety that the relative humidity should not drop below 50 per cent. This humidity level is necessary to prevent electrostatic charges building up, with the danger of a spark creating an explosion with flammable anesthetics. The electrostatic charges vary with the relative humidity rising from some base figure at zero R.H. to a maximum which is very often in the range of 20 to 30 per cent R.H. Above this value the surface moisture on the material allows the charge to leak away until it drops to zero at high humidities. The values will of course vary with different materials.

For this same reason of electrostatic charging, textile mills are always run at very high humidity levels. At lower levels the material, which is produced on high speed machines, becomes charged and the various layers cling together making it difficult to handle. Relative humidities of 80 or 90 per cent are often required to overcome this.

An office building may be thought of as occupied predominantly by people and for the bulk of the space in the building this is true. However many offices are now using machines of one sort or another and some of these, particularly computers, will require special conditions to enable them to operate most satisfactorily. Once again controlled humidities at relatively high levels of 50 per cent or more may be required.

The range within which the relative humidity is controlled can be just as important in some cases as the actual value maintained. Many materials swell and shrink with changes in their moisture content which in turn depends upon the relative humidity of the air around them. If the relative humidity is allowed to fluctuate over a considerable range this continual swelling and shrinking can damage articles made from such materials particularly if different components swell and shrink by different amounts. Thus it happens sometimes that some pieces of wooden furniture loosen at the joints or veneers crack or peel off. Artifacts in art galleries and museums also can suffer damage for the same reason.

As mentioned earlier the paper-making process tends to create high temperatures and humidities in the building even though they are not strictly necessary for the process. During visits to some 30 paper mills during 1960-61, temperature and humidity levels were measured in the machine rooms at various locations. The results of these measurements are given in Table I. 2.

TABLE I. 2. MACHINE ROOM CONDITIONS IN PAPER MILLS

	Location	Temp. °F	R. H. %
Average	Over-all	94	53
	Under roof at wet end	94	53
	Under roof at dry end	98	43
	By wall at wet end	90	67
	By wall at dry end	92	56
Highest temperatures	Under roof, dry end of dryers	133	37
	Under roof, over dryers	114	54
Lowest temperatures	Floor level, opposite breast roll	73	73
	Floor level, opposite reel	73	64
Highest R. H.	Under roof, over headbox	90½	85
	Floor level, at wet end	88	83
Lowest R. H.	In penthouse, over dryers	92	9
	In attic, above complete ceiling	75½	12

Some Non-human Occupancies

Animals

Animals, other than humans have different rates of heat and moisture production and also have different requirements for the conditions inside the building. Dairy cows in stalls in a barn will give off some 3500 Btu/hr/1000 lb body weight when the barn temperature is about 40°F. At the same time they will put 0.9 lb of water/hr/1000 lb body weight into the air. These rates of heat and moisture production can lead to considerable difficulties in selecting a suitable ventilation rate in cold weather. If sufficient air is passed through the building to carry the moisture away the inside temperature will drop below the desired level. The ventilation air can, of course, be heated to overcome this but this is an added expense for the farmer.

The conditions that are considered desirable for various classes of livestock are given in Table I. 3. As would be expected, with the exception of one-week-old chicks, animals can tolerate a much greater variation in temperature than can humans.

Storage of Farm Produce

Fruits and vegetables have their own optimum conditions for storage. In general the temperature should be just above the freezing point of the item being stored which is usually two or three degrees below the freezing point of water. Thus the temperature should be around 30° to 32°F. The relative humidities required are always very high and are usually in the 85 per-cent to 95 per cent range. In addition, apples can be stored in special atmospheres in which the amounts of carbon dioxide and oxygen are controlled.

While in storage, fruits and vegetables give off heat which must be dissipated if the desired storage conditions are not to be exceeded. The amount of heat produced increases with an increase in storage temperature and may be more than doubled when the temperature rises from 32°F to 40°F with possibly even greater increases when the temperature rises to 60°F. For meat storage, temperatures of less than 0°F are required. This produces the unusual situation for a building in that the inside is colder than outside for the major portion of the year.

Further information about the desirable conditions under which animals should be housed, plants grown and crops stored can be obtained from both the Handbook of Fundamentals and the Applications Volume of the American Society of Heating, Refrigerating and Air-Conditioning Engineers and from the Canadian Code for Farm Buildings.

From this brief review of the effects of, and desired conditions for, various occupancies it can be seen that a wide range of temperatures and relative humidities may exist inside buildings. Temperatures can vary from below 0°F to over 100°F and the relative humidity from 20 per cent to 95 per cent. Whether these conditions are specifically created and maintained or are the byproduct of some particular activity the building enclosure must be constructed either to assist in maintaining them

TABLE I.3. RECOMMENDED TEMPERATURE AND HUMIDITY LIMITS FOR CLOSED ANIMAL PRODUCTION BUILDINGS*

Class of Livestock	Inside Temp., °F. Recommended Range **		Inside Relative Humidity, % Recommended Range	
Dairy cattle				
cows	20	75	25	75
calves	50	80	25	75
calves-6wks.	0 (if draft-free)	80		
Beef cattle	0	80	25	75
Sheep and goats	0	80	50	75
Swine				
breeders	45	70	50	75
finishers	60	70	50	75
piglets	70	90	50	75
Poultry				
chicks (1st week)	85	95	50	75
hens	20	85	50	75
turkeys	50	70	50	75
Rabbits	20	85	50	75
Horses	20	85	25	75

Notes

* Sainsbury, D. Animal Health and Housing. Bailliere, Tindall and Cassell, London 1967.

** Lower temperatures may be tolerated but usually results in increased feed consumption. At temperatures below 32°F freezing of services must be prevented.

or to tolerate them; but in either case it must do so without suffering any damage.

Finally the reader must be cautioned that while a pound of air at a high temperature contains more heat than that pound at a low temperature it does not necessarily follow that a high relative humidity indicates more moisture in the air than a low one. For example, air at 70°F and 30 per cent R.H. will contain more moisture than air at 0°F and 100 per cent R.H. This subject will however be explored more thoroughly in the section dealing with psychrometry and will not be pursued further here.

THE OUTSIDE CONDITIONS

Having decided upon the conditions which must either be tolerated or maintained inside a building the next step in the design sequence is to find out what the outside conditions are likely to be. Unless the building is in outer space, submerged below water or buried underground these conditions will be set by the weather conditions at the site. All buildings which are not raised above ground on columns do in fact have part of the building enclosure on or below ground so the weather is not the only factor that must be considered. Nevertheless it is the predominant one and it is as well to examine it with a reasonable degree of care.

The weather has been defined as "state of the atmosphere at a definite time and place with respect to heat or cold, wetness or dryness, calm or storm, clearness or cloudiness." According to this definition, the clear atmospheric conditions which permit the sun to shine through are considered as part of the weather, but the sunshine itself is not. The sun, however, cannot be ignored and its effects on a building must be taken into account. Thus the outside conditions will be set by the weather, the sun, and the soil conditions under the ground floor slab or outside the basement walls and floor.

The Weather

Let us take the definition of the weather and look at each of its characteristics in turn.

Temperature - Air

The first of these is "heat or cold" which would normally be termed the temperature and since we are dealing with the atmosphere this means the air temperature. For design

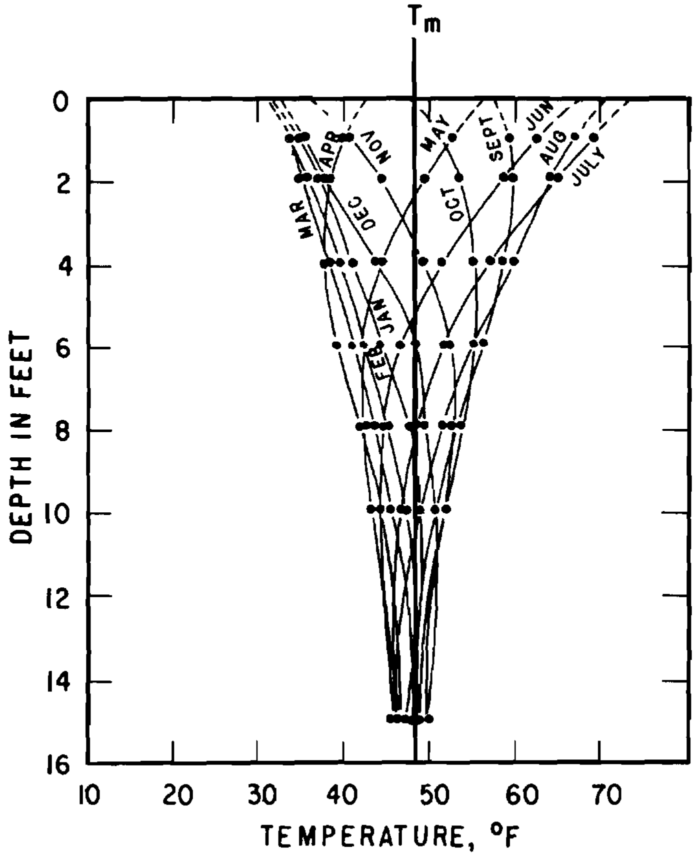


Fig. 1.1 Monthly average ground temperatures measured in clay soil under natural surface cover at Ottawa between May 1954 and April 1955.

purposes, values must be selected which will give the limits to a range of temperature within which the building will be expected to perform satisfactorily. A limiting low value for winter conditions is required and a corresponding high value for summer. Should the temperature vary outside this range some distress both to the occupants and to the fabric of the building enclosure may occur. If the design value has been well chosen this distress will be minor and of short duration.

The use of the average temperature during one or more months in the winter would not be satisfactory as a winter design temperature since the outside temperature wouldbe below the average about half the time during the period considered. The lowest temperature ever recorded is also unsatisfactory for it is usually too severe. In most cases there is no need to design a building so that the inside temperature will never drop below the design value. The results are not catastrophic if a home or office or shop is uncomfortable for a few hours, or in extreme cases, even for a day or two. With the heating system working to its maximum capacity the inside temperature will drop quite slowly because of the release of heat stored in the fabric and contents of the building.

This suggests basing the outside design temperature on the average of the temperatures for the coldest day in each year, or on the tenth or fifteenth coldest hour in an average winter month. The choice depends to some extent on the records that are available and on the techniques to be employed in the analysis.

In Canada the hourly temperature readings in January for ten years have been sorted by machine for a number of stations and tables have been drawn up showing the number of hours at each temperature for each station. From the 7440 hourly temperature readings a "1 per cent design temperature" can be selected such that 1 per cent of the readings lie at or below this value. This means that on the average in January seven or eight hours out of the total of 744 would have temperatures at or below the 1 per cent design value. Temperatures selected in this way agree reasonably well with the design temperatures arrived at by experience in many localities in Canada and the United States. For dwellings, this value is probably unnecessarily low and the corresponding $2\frac{1}{2}$ per cent design temperature is a more reasonable value for general use. This means that in an average January there would be 18 or 19 hours with outdoor temperatures at or below the design temperature. If these hours are distributed over a few nights they will result at worst in a few hours slightly below 70°F within the building, most likely in the early morning.

The problem of keeping a building comfortably cool in summer is similar but, at least in Canada, is less critical. Outside air temperatures rarely reach 100°F. This is only twenty five degrees above the arbitrary comfort temperature of 75°F. Summer design temperatures can be obtained in exactly the same way as winter design temperatures. In Canada the hourly temperatures in July are generally used, as July is the warmest month in most parts of the country.

Temperature-Outside Basements

Below grade the situation is modified considerably by the mass of soil which is interposed between the wall and the outside air. Heat flow from the basement is still ultimately to the air but the thermal capacity of the soil, which is much greater than that of a wall above grade, modifies the effect of the air temperature to a significant degree.

On a terrain devoid of structures the ground surface temperature varies cyclically with the annual weather cycle. The variation is almost sinusoidal and is reflected below grade with an amplitude that decreases with increasing depth until, at about 30 to 50 ft, the temperature remains essentially constant throughout the year at a value called the mean annual ground temperature, T_m. If the surface variation has an amplitude, A, then the maximum and minimum surface temperatures will be

$$T = T_m \pm A\ (°F)$$

Values of T_m and A will vary with geographic locations and surface cover.

Because of the thermal diffusivity of the soil, variations in subsoil temperature lag more and more in time behind surface temperatures as depth increases. At depths of 10 to 15 ft this time lag can generally be measured in months. Figure I. 1 shows values that illustrate the time lag involved. Thermal diffusivity is a measure of the rate at which a change in temperature will spread through a body. It is proportional to conductivity and inversely proportional to the volumetric heat capacity.

The construction of a building with a heated basement establishes a new temperature regime in the surrounding soil which varies with the annual periodic fluctuation in ground surface temperature. The new temperature regime can be determined by combining three separate temperature effects. The first and basic temperature component is the mean annual ground temperature, T_m, at the site of building. The second temperature component is that resulting from placing in the soil at temperature T_m a heated basement at temperature T_i. The

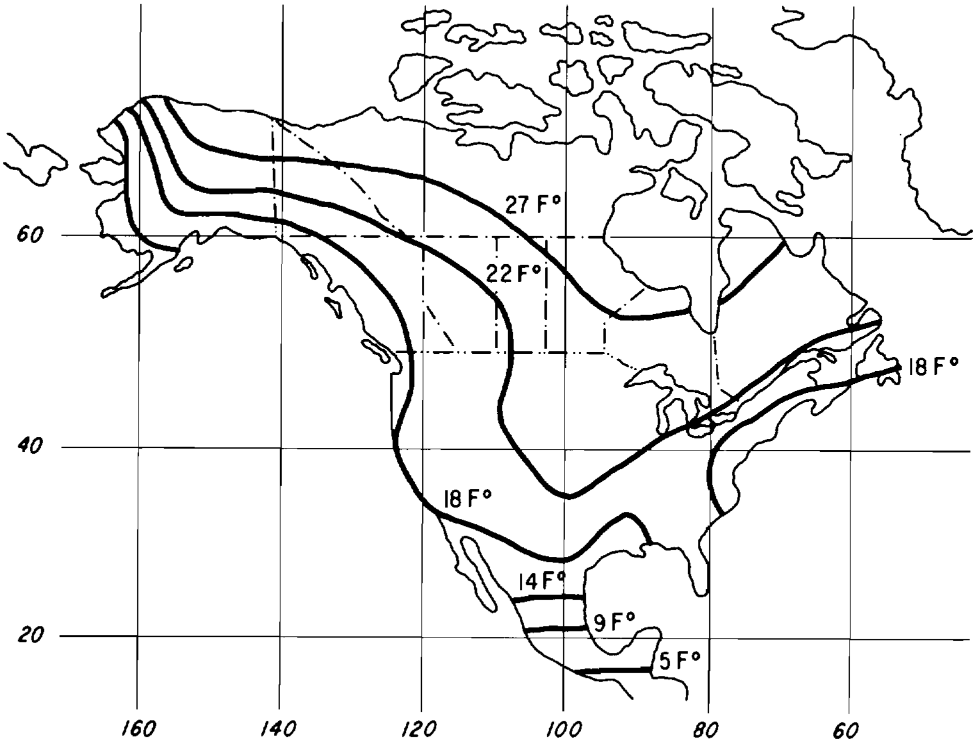


Fig. 1.2 Ground temperature variation 10 cm below the surface. Lines of equal amplitude.

third temperature component is the influence of the fluctuations in ground surface temperature due to climatic conditions and for the purpose of calculating the maximum heat loss from the basement, the condition of interest is $T_m - A$.

Information about T_m is not readily available for many locations in Canada, but as it is related to the mean annual air temperature, T_a, which is always slightly colder than T_m, a suitable external design air temperature will be given by subtracting the amplitude of ground surface temperature variation, A, from T_a, i.e. $T_a - A$. This substitution will probably be satisfactory for practical purposes when one considers the many variables involved, e.g. the presence or absence of snow cover, radiant heat exchange at the ground surface, and the limited knowledge of precise values of both T_m and A.

Table I.4 gives values of T_m, A, and T_a under natural snow conditions for various locations in Canada and can be used in conjunction with the map given in Figure I.2 to estimate additional values of A. This map is part of one prepared by Jen-Hu Chang giving annual range in ground temperature at a depth of 10 cm (4 in.). It may be seen that, in Canada, values of A lie within a range of 10°F. Values of the mean annual air temperature, T_a, can be obtained from local meteorological records.

Rain, Snow and Humidity

From time to time in various countries attempts are made to develop some measure of the intensity of driving rain which has to be resisted by the building enclosure by combining the rate of rainfall with the wind speed at that time. Until such time as rain penetration resistance can be assessed with a greater degree of confidence than it can at present, however, these driving rain indices are of only limited use. They can be used as a basis for selecting a component such as a window following a test as an indication of the degree of care that must be taken in the design and detailing of the building enclosure.

One can determine the heat flow or temperature gradient through the building enclosure by calculation provided reasonably accurate inside and outside temperatures are available. To assess the resistance to rain penetration however, no comparable methods of calculation exist. As will be seen later, the methods used to control rain penetration are more or less the same regardless of the intensity of the rainfall. Some intuitive feeling needs to be developed for the conditions at the extremes of the range of rainfall intensity but little more is needed as far as the design of the building enclosure is concerned. Most buildings are, at some time or another, subjected to reasonably heavy rainfalls accompanied by strong winds and they must exclude the rain at these times just as well as other buildings located where these conditions occur more frequently.

If one could be certain that heavy rains would never occur and that the building would never be subjected to freezing conditions after the envelope has soaked up considerable amounts of water then one could use a somewhat different design. And for some occupancies some degree of rain penetration is acceptable. One automatically accepts this philosophy when one builds a carport rather than a garage; vertically falling rain will be excluded but wind-driven rain will not. The majority of buildings in Canada, however, must be designed with a view to excluding the rain completely.

On the other hand the intensity of rainfall is of great importance in the design of the drainage system and also, in some cases, in the structural design but both of these matters are outside the scope of this book.

The subject of snow is in much the same category. Snow loads are of great importance to the structural designer and he must exercise great care when considering the probability of snow drifting from one part of the structure onto another. The designer of the building enclosure must also consider this matter for in most cases he is the one who will say what shape the over-all structure will take. He will determine the relative size and levels of the various components on the building, what parapets will be built, the size and location of canopies, balconies and sun shades; all of which can influence local snow loads. He should also give thought to the possible effects of wet snow which may cling and build up in some locations. When it melts it may release considerable quantities of water to wet the building enclosure with the danger of subsequent damage on freezing. At the other extreme very fine powder snow can be blown in through quite small openings. Cases are on record of snow being blown into attics in this way and, after melting, damaging the ceiling below. As with rainfall, the designer of the building enclosure seldom needs any exact figures to use in calculations. He should, however, try to develop some sort of intuitive feeling for the behaviour of snow and the way it can drift and accumulate.

Snowflakes of falling snow consist of ice crystals with their well-known complex patterns. Owing to their large ratio of surface area to weight they fall to the ground relatively slowly. Freshly fallen snow is usually very loose and fluffy, with a specific gravity of about 0.05 to 0.1 (1/20th to 1/10th of water). Immediately after landing, however, the snow crystals start to change: the thin, needle-like

TABLE I.4 VALUE OF T_m, A and T_a UNDER NATURAL SNOW CONDITIONS

Place	T_m, °F	A, °F	T_a °F	T_a - A °F
Swift Current, Sask.	44	26	38.5	12.5
Guelph, Ontario	48	22	44.6	22.6
Ottawa, Ontario	48	21	42.0	21.0
Toronto, Ontario	51	23	47.7	24.7
Ste. Anne de la Pocatière, Que.	44	20	39.5	19.5
Fredericton, N.B.	46	22	41.6	19.6
Charlottetown, P.E.I.	45	16	43.1	27.1
St. John's, Nfld.	44	15	40.5	25.1
Saskatoon, Sask.	42	22	35.7	13.7

projections begin to sublime and the crystals gradually become more like small irregularly shaped grains. This results in settlement of the snow and after a few days the specific gravity will usually have increased to about 0.2. This compaction increases further with time and specific gravities of about 0.3 will often have been attained after about a month, even at below-freezing temperatures. Longer periods of warm weather as well as rain falling into the snow (a possibility that must be included in determining design loads) may increase this density even further.

As a simple rule for estimating loads from snow depths the specific gravity can be considered to be about 0.2 to 0.3. In other words, each inch of snow represents a load of about 1 to 1 $\frac{1}{2}$ pounds per square foot, depending mainly on the age of the snow.

The third feature covered by the term "wetness or dryness" is the humidity of the air. Everyone blames the humidity for their discomfort on hot muggy summer days. What is this humidity that is talked about? Suffice it to say for now that the humidity of the air can be taken as a measure of the amount of water vapour in the air. Usually this is not expressed in absolute terms of so many pounds of water vapour per pound of dry air but as a measure of the amount of water vapour in the air relative to the amount the air is capable of carrying at that temperature. Thus we get the relative humidity expressed as a percentage. For example, air at 50 per cent R.H. has half of the amount of water vapour which it is capable of carrying at that temperature.

Thus when dealing with the design of the building enclosure and the associated problems of condensation it is very largely meaningless to give the relative humidity as a percentage without giving the corresponding air temperature. The quantity of water vapour in the air can be expressed directly as the weight of water vapour contained in unit weight of dry air. This is called the humidity ratio or mixing ratio and is usually given in grains of water vapour per pound of dry air. Less direct methods of giving the quantity of water vapour in the air are to give the vapour pressure or the dewpoint temperature. For any given mixture of air and water vapour in the atmosphere the humidity ratio, vapour pressure and dewpoint temperature will remain constant for all air temperatures above the dewpoint temperature. Below that temperature water vapour will condense out of the air and, naturally, the values will change. At Ottawa, for example, the mean monthly relative humidity is at a maximum of 78 per cent in December, dropping slightly (to 75 per cent) in January, and to a minimum of 58 per cent in May, and rising to 66 per cent and 68 per cent in July and August respectively. The humidity ratio, however, is at a minimum of 8 grains/pound of dry air in January and February rising to a maximum of 69 grains/lb in July. Thus we see that although the mean relative humidity may be higher in winter than in summer the quantity of water vapour in the air is less. This very general presentation of relative humidity will be discussed in detail in the Section under "Psychometry" in Chapter III.

Wind

The third aspect of the weather that must be considered is the state of the atmosphere with respect to calm or storm; or, in a word, wind.

Wind usually refers to the movement of air parallel to the earth's surface and for building design purposes we are concerned only with winds in the lowest few hundred feet of the atmosphere. The roughness of the earth's surface,

Fig. 1.3 Hypothetical mean velocity profiles over terrain with three different roughness characteristics for gradient wind of 100 mph

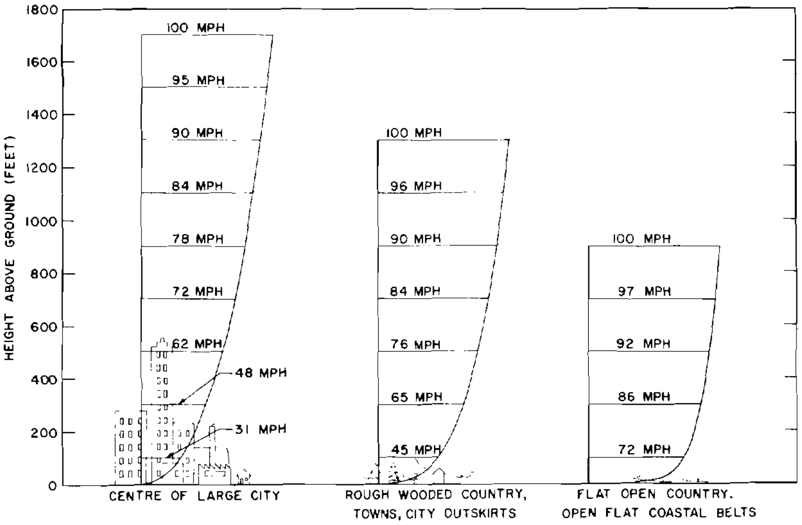
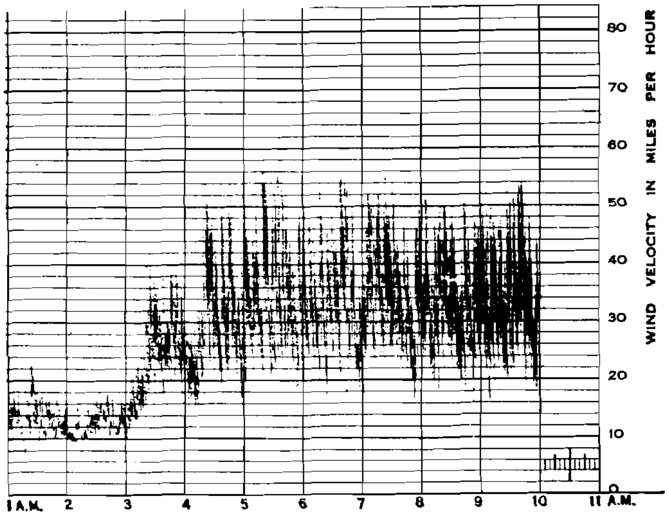


Fig. 1.4 Typical wind speed variation (Courtesy Atmospheric Environment Service, Department of the Environment)



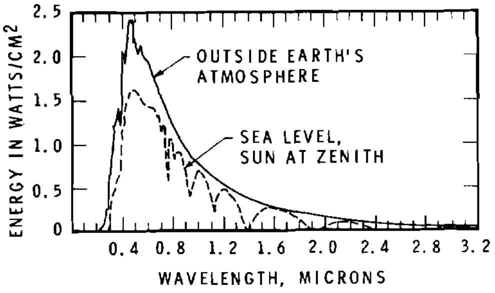


Fig. 1.5 Distribution of solar energy

which causes drag on the wind, converts some of the wind's energy into mechanical turbulence. Thus the wind speed is seldom constant either with height or time nor does it produce anything approaching a uniform pressure over a building. Wind pressures can, for example, change from a positive pressure to a suction in a relatively short distance around a corner, or from one side of a parapet to the other. Nevertheless, despite this complexity in the nature of wind, it is possible to derive a simplified generalized picture of the behaviour of the wind which can be helpful when considering wind action on a building.

Since the turbulence in the air flow is usually generated at the ground surface the wind speed very close to the ground is much less than its speed at higher levels. Turbulence includes vertical as well as horizontal air movement and hence the effect of the surface frictional drag is propagated upwards. The mechanical turbulence and the effect of frictional drag gradually decrease with height and at the "gradient" level (around 1000 to 2000 ft) the frictional effect is negligible.

For strong winds the shape of the vertical profile of the wind speed depends mainly on the degree of roughness of the surface, that is, the over-all turbulence and drag effects of buildings, trees and any other projections that impede the flow of wind at the surface. Turbulence generated by such obstacles may persist downwind for as far as 100 times their height. Three hypothetical velocity profiles are shown in Fig. I.3, where the effect of variable surface roughness on the mean wind speeds is shown for an arbitrarily selected gradient wind of 100 mph.

With lighter winds the thermal stability of air has a considerable effect on the intensity of turbulence. Cold surface air tends to damp out mechanical turbulence; heated surface air tends to rise and to increase turbulence. When the wind is strong, the air near the surface becomes thoroughly mixed and the thermal stability becomes neutral. Under these conditions temperature differences are such that they neither damp out nor increase the mechanical turbulence caused by surface roughness.

The velocity profile describes only one aspect of the wind at the lower levels. Superimposed on the mean speed are gusts and lulls, which are deviations above and below the mean. These gusts have a random distribution over a wide range of frequencies and amplitudes, both in time and space. Figure I.4. shows clearly the unsteady nature of wind speed measured by an anemometer. Gusts are frequently the result of the introduction of fast moving parcels of air from higher levels into slower moving strata of air. This mixing or turbulence is produced by surface roughness and thermal instability.

Large-scale topographical features are not included in the surface roughness mentioned above. They influence the flow, however, and should be given special consideration in design. For instance, wind is usually much stronger over the brow of hill or ridge because the flow lines converge over the obstructing feature and to pass the same quantity of air a higher speed is required. A similar effect can be produced by a large city which forces the air flow upward leading to increased wind speeds at higher levels. Valleys and city streets with tall buildings on each side often have a strong funnelling effect that increases the wind speed along the axis of the valley or street.

Solar Radiation

The final aspect of the weather given in Webster's definition is "clearness or cloudiness." This characteristic is, by itself, of little concern to the designers of buildings and it need be considered only in so far as it affects the exchange of radiant energy with the sun or a clear night sky. Thus, under the present heading of the outside conditions, only a brief description of the characteristics of solar radiation need be given.

Because of the high temperature of the sun solar radiation is essentially short-wave radiation extending, in outer space, over a spectrum of from about 0.1 microns to over 4 microns. This range can conveniently be divided into ultra-violet (UV) radiation below 0.4 microns, a visible range between about 0.4 and 0.77 microns and infrared above 0.77 microns. These divisions are not clear-cut but merge into each other; the limits of visible light, for example, will vary with the individual.

Not all of this solar radiation is received at the surface of the earth since much of it is absorbed or dispersed by the earth's atmosphere. This effect is at a minimum when the sun is directly overhead and increases as the elevation of the sun above the horizon decreases. Figure I.5. compares the distribution of energy in the solar spectrum above the earth's atmosphere with that received at sea level with the sun directly overhead.

The peak in energy is not so concentrated in the blue range of the spectrum but is spread more towards the yellow-green in the visible region, and infrared radiation is reduced owing to absorption by water vapour and oxygen. Finally, and of greatest importance, only near-UV is received at ground level. The absorption of the other UV radiation is caused by ozone in the upper atmosphere. Reduction in energy received at the surface is still greater when the sun, because of time of day or year or latitude, is not at its zenith. At lower angles, radiation has to travel farther through air and consequently more energy is absorbed. In addition, at lower sun angles the shorter wavelengths are more scattered, so that only about half the UV comes in a straight line from the sun.

The importance of absorption of middle UV is related to one of the characteristics of radiation: the shorter the wavelength, the higher the energy content. Fortunately, the proportion of shorter radiation is small. At noon in the summer UV provides 5 to 7 per cent of the total energy, and biologically active UV (less than 0.32 microns) about 1 per cent. These proportions decrease before and after noon and in winter because of the geometric effects already mentioned. For example, at 40° north latitude the four winter months, November to February, supply only about one-ninth of the biological UV provided by the months from May to August. In addition, clouds and smoke reduce total radiation and the intensity of UV. If it were not for these various factors, no organic polymer (including man) would have any exterior durability.

The energy that is incident on a unit area of a particular surface depends upon the intensity of the sun's rays and the angle at which they strike the surface. The maximum intensity for a horizontal surface occurs at noon at the time of the summer solstice for all latitudes outside the tropics. For example, the maximum insolation on one square foot of horizontal surface is 93 watts at Ottawa (latitude 45°N) and 88 watts at Winnipeg (latitude 50°N). At the winter solstice the corresponding figures for noon on a clear day are 39 watts and 29 watts respectively. (Multiply watts by 3.4 to obtain Btu/hr.)

The radiation that falls on vertical surfaces is, however, often of more importance in building design (because of windows) than the radiation on a horizontal surface. The orientation of a wall is an additional variable. A wall facing south at Ottawa receives a daily maximum of 45 watts/ sq ft at noon on 22 June or thereabouts; but at the equinox the daily maximum has increased to 65 watts/sq ft; and the yearly maximum may be as high as 100 watts/ sq ft in winter if there is snow on the ground to reflect some sunshine onto the wall. East and west facing walls, on the other hand, receive their maximum irradiation in the morning and afternoon, respectively, when the sun's rays are more nearly perpendicular to the wall surface. The annual maximum for east and west-facing surfaces at Ottawa is about 75 watts/sq ft and occurs approximately 4 hours before and after noon respectively (as indicated by a sun dial). The magnitude of the daily maximum changes very little between midsummer and the equinox, so that the value of 75 watts/sq ft is representative of the daily maximum insolation on east and west facades during the period from April to October.

Other Factors

Although the weather is the predominant component of the external conditions it would be wrong to leave the impression that it is the only one. In any basement, or even with a slab on grade, the conditions immediately outside the wall are set by the conditions in the soil. Thus one has to consider the moisture content of the soil and, if need be, provide suitable drainage to carry excess moisture away. The soil will also act to modify the temperature regime outside the basement wall and its effect should be taken into account. Thus the soil forms part of the system which separates the inside conditions from the outside ones and can be manipulated in the same way as the components of a wall above grade so as to give the required separation in the most satisfactory way. Other characteristics of the soil may also have to be taken into account. For example if it is sulphate bearing, special precautions must be taken with the portions of the building in contact with it to prevent the concrete from being damaged.

Although the "state of the atmosphere" is given as one definition of the weather, nothing is mentioned in Webster's definition about any pollutants in the atmosphere unless water is considered to be a pollutant. Nowadays there is, unfortunately, far too much pollution in the air. Although the subject is receiving a lot of attention in various quarters, it is doubtful if we will ever achieve the happy state of completely pollution-free air in our cities. Consideration must thus be given to the effects of dirt in the air which can disfigure an otherwise beautiful building and which can also assist in creating conditions which promote corrosion of metals and damage to the surface of stonework. Gases, such as sulphur dioxide, in the air are also potentially harmful to buildings by combining with water to form sulphurous acid. Corrosion will then be greatly accelerated. Salt spray from the sea is another potential trouble maker. When the salt is absorbed in different amounts in adjacent areas of concrete accelerated corrosion of the reinforcing bars can result.

Noise can also reach such proportions as to be considered a pollutant. Supersonic booms are not yet a widespread phenomenon but they are only one source of noise pollution; heavy aircraft taking off from an airport are a serious noise problem. Heavy ground traffic or industrial noise can also require special design of the building enclosure either to exclude it or to contain it.

Thus there are many factors about the two sets of conditions inside and outside a building that must be considered when designing a building enclosure whose function it is to separate the two. Nevertheless it is the purpose of this book to deal with this problem without digressing to any great extent into areas dealing with problems caused by such pollutants. Unless the basic problem of separating two air masses at differing temperature and humidity conditions is solved satisfactorily, attempts to deal with these other problems are akin to Nero's fiddling while Rome burned.

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CHAPTER II -- BUILDING MATERIALS

From time to time in the popular press, and elsewhere, accounts are given about new and wonderful building materials which it is claimed will solve, or almost solve, all our building problems. Very often such accounts are of small-scale pilot projects or are projections into the future and usually little or nothing more is heard about them. There are good reasons for this.

In the first place the new materials, very often plastics of one form or another, are usually considerably more expensive than conventional materials. Volume production and improved production techniques would, undoubtedly, reduce the cost but the basic raw materials are more expensive than the stone, sand, cement and water that make up concrete, for example. The manufacturer of plastics may have dreams of extruding houses at the end of his production line and chopping them off like so many sausages. But when he wakes up and goes to work the next morning he usually ends up extruding some eaves-troughing, for here he has a component which can be produced reasonably competitively and which does have some advantages over the more conventional galvanized steel or aluminum eavestroughs. Thus relatively unconventional materials do have a place in building construction but, since buildings are required now, we cannot sit back and wait for the perfect material to be produced but must go ahead and use the normal materials at hand.

In the second place conventional materials, when used properly, are not really so bad. It is natural for an architect or builder who has had a bad experience with a particular material to say that he will never use that material again. That, after all, is called learning by experience. The trouble is that experiences often appear to contradict each other and a material that failed on one building performs quite satisfactorily on another. Thus, as experience grows, one decides that the material that failed did so because of the particular manner in which it was used and one modifies one's blanket condemnation of the material to say that one won't use that material in that manner again. This is an important step forward but unfortunately it does not take one very far for one cannot create all possible situations for the use of all materials to see how they will react.

Thus the only practical solution to the use of building materials is to gain an understanding of how various conditions and changes in conditions affect them and then to use them in such a way that they are not subjected to situations they cannot tolerate.

There are several factors which, either singly or in combination, affect the behaviour of building materials but the three principal ones that must be considered are water, temperature and ultra-violet radiation. Of these three water is probably the most important. There are other factors but in the absence of water they normally are harmless. Thus if one can control the water one will have gone a long way towards making a durable building.

THE NATURE OF MATERIALS

Before examining the effects of these three factors it is desirable to take a brief look at the nature of materials since this will help us to understand why materials behave as they do.

The basic chemical building units are the atoms bonded together by chemical reaction to form molecules. The molecules in turn are bound together to form crystals or particles which are the micro-units of the materials which we know. The molecules also form liquids and gases, in which case there are no micro-units.

A solid can be formed from the micro-units in two ways. If it is formed by a molten mass solidifying and forming crystal grains we have a structure in which the boundaries of the micro-units come into direct contact with no space between them. There are therefore no internal pores in this type of material, examples of which are metals and some igneous rocks formed at high temperatures and pressures. With other materials the micro-units are not moulded to fit together in this manner and come together only at certain points, in which case there are internal spaces or pores which connect together and with the outside. Many building materials, such as most rocks, brick, and concrete, fall into this class of porous materials.

Consider now such a material made up of uniform spheres. Even when they are packed together as closely as possible there will still be a pore volume equal to about 28 per cent of the total volume. Since in actual materials the micro-units are not uniform spheres but vary greatly building materials will have a great range of pore sizes and shapes and as a result will vary greatly in their characteristics. Some have an irregular pore structure giving them more or less isotropic characteristics because the random selection of micro-units and their arrangement will, in the total, be the same in any direction. Others, such as wood, have micro-units of a regular shape and uniform arrangement. The wood cells are in the form of tubes which are bonded together along their length by the cementing action of the lignin. Thus wood has non-isotropic characteristics with high strength and low shrinkage in the direction of the wood fibres and lower strength and high shrinkage across the fibres. A glass fibre fishing rod is man's copy of the wood composite.

A further feature of the model of uniform spheres is that the spheres have only point contacts. Thus if they are connected together at these points the strength of the system would not reflect much of the strength in each sphere, or micro-unit. The total bond area of this assemblage would be less than 5 per cent of the total cross-sectional area. We can now begin to see why such porous materials may be much weaker in tension then in compression.

An inevitable consequence of a porous microstructure is that the surface exposed to the aggressive action of the environment is the total internal surface represented by the boundaries of the internal spaces, if these are connected to the outside. This allows foreign agents to penetrate right into the "heart" of the material. Because the micro-units are very small in most porous materials, this internal surface area can be very large. In the case of hydrated cement which has a layered or folded sheet structure and has interconnected spaces, the total surface area of 1 pound of material will be about 5.5 acres.

Except for the brief comment about wood, so far, only the normal inorganic building materials have been described. Organic materials have a somewhat different structure since they are composed of what are sometimes described as big molecules. Inorganic materials have molecules made up of perhaps 2 to 50 atoms whereas big molecules can be composed of thousands or even hundreds of thousands of atoms. These atoms are joined together in long chains which may have various offshoots. It is these long molecules that lead to the development of fibrous materials. However, the molecules are never straight but are coiled up in some irregular manner. When the material is stretched the molecules straighten out but when the tensile force is removed they coil up again, somewhat like a child's slinky toy.

If the only force holding these long molecules together was the attraction between the intertwined molecules a relatively small force would cause them to slip one over the other until they became disentangled and the material would break. This is somewhat akin to pulling a piece of spaghetti out of a plateful by pulling slowly on one end. If one stops pulling, the spaghetti stops where it is and does not snap back into the pile. Something else must be done with the long molecules if the material is to have much strength and elasticity. This "something" is a cross-linking between the chain molecules so that they are now bound together by chemical forces. The chains are now tied together and will no longer slip one over the other and so all the chains act together more or less as one gigantic molecule. Each cross link forms a constraint on the molecules, however, and so as the number of cross links increases so will the stiffness of the material.

Following this brief account of the nature of building materials let us now consider the effects of the three principal factors of deterioration: water, temperature and ultra violet radiation.

THE DETERIORATION OF MATERIALS

Water

The molecules forming a micro-unit of a building material are bound together by electromagnetic forces. In the heart of a micro-unit these forces between the molecules are in balance but at the surface there is an imbalance because of the absence of molecules further out. This imbalance results in what is described as interfacial energy. It creates a tension at the surface of the micro-unit; and in a liquid the phenomenon of surface tension. The tension at the surface of a micro-unit places the unit in compression. When a foreign molecule, of water for example, comes near the surface it is subjected to an attractive force due to the imbalance of electromagnetic forces and is adsorbed onto the surface. [This is the action of what are called van der Waal's forces.] When adsorption occurs some balancing of the forces at the surface of the micro-unit may occur leading to a reduction of its surface tension and a relaxation of the micro-unit. Thus an expansion can be a result of adsorption. Furthermore, the presence of

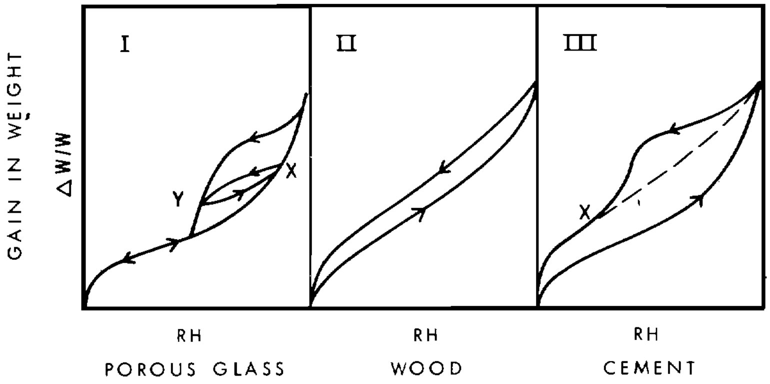

Fig. II.1 Typical adsorption and desorption curves with change in relative humidity at constant temperature water in the spaces between the micro-units may reduce the attractive forces between these units allowing them to move further apart. Thus when water is taken up by a porous material, the material expands. With a non-porous material, such as a metal or a plastic, the outside surface will be wetted by water but since there are no passages to enable the water to get inside the material no expansion will result.

The amount of expansion that takes place will depend upon several factors and will vary from one material to another. For any given piece of material, however, it will be a function of the amount of water adsorbed. This in turn is primarily related to the relative humidity to which the material is exposed. If a completely dry piece of material is exposed to an atmosphere in which the relative humidity is progressively increased the amount of water adsorbed and the resulting expansion can be measured. Likewise the loss of water and shrinkage as the material is dried out again can be measured. Neither on wetting nor on drying is the effect uniform and the wetting, or adsorption, curve usually does not coincide with the drying, or desorption curve. Some typical curves are given in Fig. II. 1.

In building construction the material does not start off bone dry and it is seldom completely saturated. By examining these curves it can be seen that if the changing conditions can be confined to a portion of the curve which is relatively flat the effects of a changing moisture content will be relatively small.

There are some materials that are set in place more or less saturated; cast-in-place concrete, for example. As put in place, concrete is not a rigid material but as the hydration of the cement particles takes place it sets into a rigid mass. As hydration continues the hydration products expand to fill more and more of the voids in the concrete giving increasing strength; hence the necessity for prolonged curing of concrete. The hydration process naturally uses up some of the water but there is always an excess of water available to give workability to the concrete. As this excess water dries out after the curing period certain irreversible processes take place which are thought to be due to the points of contact of the micro-units being dissolved allowing them to be drawn together more closely. This gives the initial drying shrinkage of concrete which is not recovered on subsequent wetting. Superimposed on this drying shrinkage are the expansions and contractions caused by changes of moisture content as described earlier.

A further factor affecting the behaviour of concrete in buildings is the phenomenon of creep. Creep is a gradual and largely irreversible shortening of concrete under a sustained load and is additional to initial shrinkage, moisture expansion and contraction, and elastic deflections. Although it is not fully understood it is believed to be due, in part at least, to the removal of water from between the sheets of calcium silicate crystallite.

These accounts of the behaviour of water in a porous material show that the precise action of water can be quite complicated. At the risk of over simplification, however, they can all be summarized in the statement that adding water to a porous body causes expansion and removing it causes shrinkage.

Before leaving the subject of the effects of water acting by itself there is one further aspect to be considered: the effect of a differential moisture content. Since a porous material will expand on wetting and contract on drying it follows that when different parts of such a material have different moisture contents it will attempt to expand or contract differentially and so be in a state of stress. The greater the difference in moisture content the greater will be the stress. For example, if the surface of a concrete slab is dried out quickly by the sun and a dry wind, it will try to shrink but will be restrained by the inner mass of concrete. If the rate of drying is rapid the surface will be crazed with many small cracks. Similar differential shrinkages lead to the splitting of wood and the warping of other products.

Table II. 1 gives some values for moisture deformations for some building materials together with comparable temperature deformations. The two temperatures ranges of 80°F and 230°F are reasonable values for short-term and seasonal variations for materials on the outside of a building.

Temperature

The effect of temperature variations on building materials is well known and need not be discussed in any detail here. As a material warms up it expands and as it cools off it contracts. The degree of expansion or contraction for each degree of temperature change is called the coefficient of thermal expansion; values for several building materials have been given in Table II. 1. It is obvious that if two parts of a piece of material are at different temperatures a stress will be produced in the material. Similarly if two pieces of material with different coefficients of expansion are bonded together and then subjected to the same change in temperature they will be stressed.

TABLE II-1

TEMPERATURE AND MOISTURE DEFORMATIONS FOR SOME COMMON BUILDING MATERIALS

	Coeff. of Thermal Expansion per deg F	Deformation Due to Temperature Change of 80°F		Deformation Due to Temperature Change of 230°F		Moisture Deformation on Wetting from Dry to Saturated (or Vice Versa)		Modulus of Elasticity E	Failing Stress Comp. or Tension	Deformation Required to Cause Failure	
		Per Cent	In./ 10 ft	Per Cent	In./ 10 ft	Per Cent	In./ 10 ft			Per Cent	In./ 10 ft
Normal Dense Concrete	$6\text{x}10^{-6}$	0.05	0.06	0.14	0.17	0.03	0.04	$2.5\text{x}10^{6}$	2500C 250T	0.10 0.01	0.12 0.01
Brick	$3\text{x}10^{-6}$	0.024	0.03	0.07	0.08	0.007	0.008	$3\text{x}10^{6}$	6000C 500T	0.20 0.016	0.24 0.02
Marble and Dense Limestone	$3\text{x}10^{-6}$	0.024	0.03	0.07	0.08	<.001	--	$10\text{x}10^{6}$	25000C 600T	0.25 0.006	0.30 0.007
Sandstone	$7\text{x}10^{-6}$	0.056	0.07	0.16	0.19	0.07	0.08	$5\text{x}10^{6}$	12000C 400T	0.24 0.008	0.29 0.01
Reinforced Polyester	$10\text{x}10^{-6}$	0.08	0.10	0.23	0.28	<.001	--	$1.5\text{x}10^{6}$	15000T	1.00	1.20
Steel	$7\text{x}10^{-6}$	0.056	0.07	0.16	0.19	none	--	$30\text{x}10^{6}$	40000T (yield point)	0.13	0.15
Copper	$10\text{x}10^{-6}$	0.08	0.10	0.23	0.28	none	--	$17\text{x}10^{6}$	50000T	0.29	0.35
Aluminum	$14\text{x}10^{-6}$	0.11	0.13	0.32	0.38	none	--	$10.3\text{x}10^{6}$	40000T	0.39	0.47

In either case there will be a potential for damage or distortion if the stresses produced are great enough.

A further effect of temperature is the change in viscosity that occurs in liquids and in some organic materials, such as bitumens and sealants. As the material is heated it becomes "thinner" and flows more easily. As it cools it thickens and at a sufficiently low temperature it can be quite brittle. With plastic materials there are usually two critical temperatures that must be considered when choosing a material for a given purpose: the glass transition point and the softening point.

Below the glass transition temperature the forces holding the molecules of a plastic together are the attractive forces between them as is the case with inorganic materials such as steel or concrete. These attractive and repulsive forces act between the molecular blocks of the material and it is the balance of these forces that keeps the molecular blocks in place. If we apply a force and start to stretch the material, this balance must be overcome. The force needed is large but the elongation at break is very small because the attractive force between atoms and molecules decreases rapidly with increase in distance. With steel this condition persists with increase in temperature up to the point where it melts. Most polymers on the other hand have an intermediate rubbery state where the atomic attractive forces are reduced and the elasticity originates from the long chain structure of the molecules and not from the balance of forces. Thus, above the glass transition temperature, we are pulling against the coiling-up tendency of the molecules and not against the atomic attractive forces of the cross links. A much longer elongation before break is obtained with rubbery polymers and, of course, the force needed for deformation is much smaller; that is, the modulus is smaller.

With a further increase in temperature a polymer becomes a viscous liquid which deforms readily under a steadily applied load. Naturally, it is important that materials used in buildings should have a softening temperature higher than any temperature which they will experience in use and it can readily be seen that if this were not so the results would be disastrous. Paints would run down the walls, sealants droop out of joints and plastic light fixtures would distort and fall to pieces. For some applications, such as hot applied bituminous waterproof coatings, the material must be heated to above the softening point before being applied and then cooled once it is in place. The danger here is that if it is heated too much the material will decompose and lose its desirable properties.

Ultraviolet Radiation

When a molecule absorbs radiation it is raised to an excited state, usually at one particular atom. It may return to its unexcited or ground state by dissipating the energy by re-radiation of fluorescence, phosphorescence or heat. In such a case the molecule is unaffected. This is what happens with long-wave radiation which is turned into heat. The shorter the wavelength, however, the higher the energy content and if the radiation contains sufficient energy it may cause a chemical reaction at the excited atom leading to deterioration of the material. Many of the polymers used in organic building materials are composed of long-chained molecules with carbon-to-carbon backbones which can be disrupted by radiation within the ultraviolet wavelength range as received at the earth's surface.

Only ultraviolet possesses sufficient energy to break the primary bonds, and the only chemical effect of visible and infrared radiation is to speed up the rate of reactions that may be occurring from other causes. The quantity of heat in solar radiation is not sufficient to raise the temperature to the point where chemical bonds can be broken thermally. Chemical deterioration caused by ultraviolet radiation can take two forms. In the first form the energy starts a process with some materials which is the reverse of the polymerization reaction that originally produced the large molecules. In this case the polymer may be broken in isolated locations - called chain scission - or it may completely revert to small molecules. The latter is the so-called "unzipping" of the polymer which, fortunately, occurs very slowly when radiation is the only factor. In the second form the smaller molecules produced by chain scission, or reactive sites on large molecules, react with other chains. This results in more cross-linking than was originally present so that the material becomes harder and more brittle.

Frost

As water expands on turning to ice, building materials can be damaged if frozen when wet. Actually it is the water that is frozen not the material but it is perhaps a little pedantic to insist on this stricter use of the word. It is also reasonable to expect that if the water can expand freely on turning to ice, it will do no harm. Most of us will have seen examples of a milk bottle, for example, in which the milk has frozen and pushed the cap off. One could argue that pushing the cap off is a form of damage, but in any event, the bottle itself is not damaged.

From our knowledge of the nature of building materials it is clear that if the material is not porous the water will remain on the outside surface where it will do no harm on freezing. It is also reasonably clear that a porous material will come to no harm if the water in its pores can, on freezing, expand into suitable spaces. There is some difference of opinion as to the precise mechanisms involved but for practical purposes the basic requirement is space for expansion.

This requirement will be met if there is very little water in the material, for most of the pores will be empty, and it will not be met if the material is saturated and all the pores are fitted. Somewhere in between these two extremes there must be a changeover point. Since ice occupies about 9 per cent more space than the unfrozen water it is clear that a material which is more than 91 per cent saturated will not have enough space left for expansion. Because of variations in the textures of materials and since the rate of freezing can have an influence a considerably lower moisture content is required to prevent frost damage; perhaps 75 to 80 per cent of saturation. Ideally, suitable expansion spaces should be provided at a suitable spacing throughout the material and this is the basis on which air-entrained concrete works. Here, under optimum conditions, bubbles of about 0.01-in. diameter are spaced about 0.02 in. c.-c. throughout the cement paste. This leads to a total air content in the concrete of some 5 to 7 per cent by volume.

Ice Lensing

In some materials a second type of effect can be produced when the water is frozen, this is the phenomenon of ice lensing which is often referred to as frost heaving since it is more often recognized in soils than in building materials.

When a material is cooled to below the freezing point of water the outer layers of the material reach the freezing point first and then, as more heat is extracted, the freezing plane moves progressively further and further into the material. If the material contains some water some of this will freeze as the freezing plane reaches it. In so doing a moisture gradient is created which tends to draw more water to the freezing plane from deeper in the material. When this happens the new water joins the already frozen water and an ice lens starts to grow. So long as the conditions remain unchanged this lens will continue to grow and the expansion produced can be vastly greater than the 9 per cent increase in volume as water turns to ice. In the laboratory, conditions can be held steady and ice lenses several inches thick can be grown. In practice, however, there is usually some disturbing factor, such as a change in temperature, and so in most cases a multitude of smaller lenses develop. These collectively can produce a heave of several inches in soils. In building materials having some tensile strength the heaving force must first overcome this resisting force before the lens can grow.

There are therefore three conditions which must be satisfied if an ice lens is to be produced:

(i) a freezing plane in the material
(ii) a supply of water
(iii) a fine-grained material that will permit the water to move through it under the moisture gradients created.

Coarse-grained soils, such as coarse sands, gravels and crushed stone will not heave, but fine-grained types, such as fine sands, silts and clay will. Most building materials will not form ice lenses but some mortars, such as those sometimes used as infill between facing stones and a back-up wall, can give trouble leading to the stones being displaced from the building.

Corrosion

Most of the discussion so far has been related to porous building materials; now we must consider metals.

Corrosion processes are usually electrochemical in nature, having the essential features of a battery. Dissimilar metals in the presence of a conducting liquid, known as the electrolyte, develop an electrical potential that causes a current to flow whenever a suitable path is provided. Such electrical potentials may also be developed between two areas of a component made of a single metal as a result of small differences in composition or structure or of differences in the conditions to which the metal surface is exposed. That part of a metal component which becomes the corroding area is called the "anode;" that which acts as the other plate of the battery is called the "cathode" and does not corrode, but is an essential part of the system.

In the corrosion systems commonly involved in buildings there may often be only a single metal involved, with water as the electrolyte. The water is often contaminated with various pollutants such as sulphur dioxide from the air or chlorides which will accelerate the corrosion reaction. There are also instances when water containing dissolved carbon dioxide has caused corrosion of materials, such as copper, which are normally considered corrosion resistant. Soft waters which are slightly acidic (low pH) can also attack copper.

Corrosion may even take place with pure water, if oxygen is present. In such cases, oxygen combines with the hydrogen generated at the cathode, removes it and permits the reaction to continue. Other agents, notably certain bacteria in the soil which remove hydrogen, can also act as depolarizing agents and thus promote the corrosion reaction.

Rotting of Wood

Rotting of wood is probably the first effect that comes to mind when considering the combined effect of water and other agents on organic materials. Wood rots because it is attacked by a fungus under suitable conditions of moisture and temperature. Five conditions must be satisfied for rotting to take place. These are:

1. a suitable food for the fungus (the wood itself)
2. a supply of moisture
3. a supply of oxygen
4. suitable temperature conditions
5. a source of infection.

If any one of these conditions is absent the wood will not rot.

As the wood itself is the food for the fungus it is, obviously, always present where wood is used, although some species are less liable to attack than others. It can be poisoned by suitable wood preservatives but complete penetration of the wood, in most instances, is impossible and any subsequent checking opens up paths for the infection to get at the untreated wood. Also in many instances the effects are only temporary where the wood is exposed to the weather. There is always some moisture in wood in service but the fungal spores do not germinate readily in a wood whose moisture content is below the fibre saturation point. This is reached at about 25 to 30 per cent moisture content although a lower value of about 20 per cent or less is usually needed to be sure that the wood will be immune from attack. Oxygen is always present in building construction except when completely submerged, which explains the good durability of wood under water or below the water table in the ground. Fungus will become dormant at about 40°F but will not be killed by low temperatures. Optimum temperatures for decay are between 65 and 95°F and the fungus will be killed by high temperatures over about 120°F although prolonged exposure to such a temperature would be required. Higher temperatures would kill the fungus more quickly. Finally,

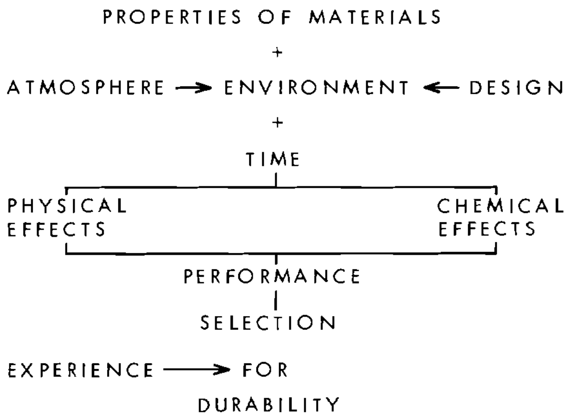

Fig. II.2 Selection of a material for durability since there are so many possible sources of infection it is seldom possible to eliminate them all although removing any decaying wood will reduce the danger to some extent.

Most of the other organic building materials that are composed of long chain molecules are resistant to attack by water alone at normal temperatures. It is possible, however, for radiation to raise the temperature to a point where solution or hydrolysis can occur. Thus, plasticizers for vinyl coatings and plastics may be removed if they are appreciably soluble in water at elevated temperatures. Strength of polyester laminates can also be reduced through attack by water either on the resin itself or on the bond between the resin and the glass fibre. These actions are not so marked as in actual immersion in hot water, but they can contribute to the process of deterioration. When coatings containing drying oils are irradiated by ultraviolet light, both cross-linking and scission of the oil chains occur. The low-molecular fragments from scission could act as plasticizers, but they are removed by water, adding to the brittleness caused by cross-linking. Leaching by water of irradiated lignin is responsible for the greying of exposed wood.

Radiation, Oxygen and Temperature

Ultra-violet radiation is a prime agent in the deterioration of materials by weathering and some of the effects of radiation alone, and of water and radiation combined, have been discussed earlier. A natural weathering combination that has an even greater effect is oxygen and radiation, referred to technically as photo-oxidation. As is often the case these agents together produce an effect greater than the sum of the individual effects. Finally, there is the combination of the three elements: heat, radiation and oxygen. As expected, together they are more damaging than any combination of only two of the factors.

DURABILITY

One might well ask "Is there any such thing as a durable building material?" The answer to this question must be "No, there is not," for durability is not a property of a material but a combination of the physical characteristics of a material and the conditions around it.

To clarify this, let us consider the durability of wood. As already discussed, if any one of the five conditions required for wood to rot is absent it will not rot. Thus if wood is kept dry, for example, it will not rot and will last for centuries. On the other hand in a warm humid atmosphere it can be destroyed in a matter of a few weeks. Is wood, therefore, a durable or a nondurable material? Clearly it is durable in the first example and not in the second, which is what many people have found by experience.

The next question which can reasonably be posed is "How can one determine when the conditions are such as will give the material an adequately long life?" To this there is no easy answer and for most practical cases the balance point between an adequate and an inadequate life cannot be calculated. However, with some knowledge of the effect on various types of building materials of different agents of deterioration, one can make an intelligent assessment of whether the surrounding conditions will be harmful to that material. One also sometimes has the option of loading the dice in favour of good durability without knowing precisely what are the limiting conditions. For example, in the case of wood it is seldom of much concern to the designer to know just how dry it must be, it is usually sufficient to keep it as dry as possible.

All this assumes that the designer can in the first place assess what the conditions will be and in the second that he can do something about them. In some cases, the conditions are fairly obvious; a wooden post standing in water will be durable below water and, except for some checking caused by alternating wetting and drying, will be durable above water but it will rot off at the water line. In other cases, such as in the core of a wall, the conditions are by no means so clearly established. Nevertheless, they can be established and controlled with a reasonable degree of confidence as will be described in later chapters.

The process of achieving durability is shown diagramatically in Fig. II. 2 for it starts with the properties of the materials which must be considered in relation to the environment in which they will exist. This environment in turn will be set by the combined effects of the atmospheric conditions and the design of the building in all its details. Time is then a factor for time is necessary for the various physical and chemical changes to take place leading to the performance of the material in the building. From such an assessment the designer will make his selection to obtain durability; but, as always, he must feed into the process at this point the results of his experience.

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CHAPTER III -- PHYSICS

In Chapter I the idea was developed that the basic function of a building is to separate the differing conditions inside and outside the building. It was also shown that this is largely a matter of separating two air masses: the inside one which we wish to control and the outside one which varies according to the weather at the locality. In addition, there are the effects of solar radiation to be contended with.

In Chapter II we saw that this separation must be effected using existing building materials and that the life of these materials is affected for better or for worse by the conditions to which they are subjected. It follows then that to make durable buildings we must see to what extent we can determine the conditions at any point in the fabric of the building enclosure so as to select materials that can accept these conditions. Alternatively, if we want to use a particular type of material for some reason, such as economics or aesthetics, then we must try to modify the conditions so that they are acceptable to that material.

How can we do this? The conditions in the enclosure will be set by an interplay between the inside and outside conditions, and the arrangements and proportions of the various components of the enclosure. In Canada during the winter the outside conditions are often very cold and it follows that if a material is adversely affected by the cold then it should not be used on the outside of a building. It must be brought in out of the cold, assuming, that is, that the inside conditions are warmer than those outside. All of the materials, however, cannot be inside the building; some of them must be on the outside and the various components must somehow be connected. Thus we still have the task of determining, among other things, how cold they may be at some times and how hot at others, and then of selecting a suitable material and fixing it in place in a suitable manner.

The only satisfactory way to tackle this problem is through an understanding of the physics of the situation. With such an understanding it will then be possible to anticipate how the conditions within the thickness of the enclosure will be changed by some modification to the enclosure itself. The three physical phenomena that must be examined to enable us to do this are:

(i) heat and heat flow,
(ii) psychrometry and moisture movement,
(iii) air pressures and air movement.

These are by no means completely independent phenomena but it is convenient to discuss them separately in the first instance.

HEAT

Heat may be defined as "the form of energy that is transferred by virtue of a temperature difference." In winter, when one of the principal functions of a building enclosure for buildings occupied by people is to keep out the cold, we may have quite large temperature differences to deal with. Some knowledge of the behaviour of heat is thus essential if we are to have any hope of designing satisfactory buildings. As a form of energy, heat can be created out of other forms of energy or alternatively it can by transformed into other forms. (This is the first law of thermodynamics.) It is the form of energy which is associated with the perpetual movement of the molecules and temperature is a measure of the vigour of this movement. The flow of heat is always towards the lower temperature and can take place by conduction, convection or radiation.

Conduction

Within a material, be it solid, liquid or gaseous, the molecules in the hotter portions move faster than those in the colder parts. As the molecules collide with each other the faster-moving ones are slowed down and the slower-moving ones speeded up until eventually they are all moving at the same speed. In this way the thermal energy is equalized throughout the material and it is all at the same temperature. If, however, heat is supplied to one part of the material the molecules at that part will be speeded up again after each collision and heat will flow away towards the colder parts. If there is a second location where the heat is extracted, the flow of heat will be from the first location to the second. This is the method of transfer of heat by conduction and in it the molecules need not leave their mean position. It is the only method by which heat can flow through an opaque solid. Heat can also pass from one material to another in this way provided they are in intimate contact.

Convection

Within a fluid, be it liquid or gaseous, heat can be transported by the movement of the fluid from one region to another. This method of heat transfer is called convection and since a mass of the fluid must move there must be a force to cause this movement. When this force is supplied by some mechanism such as a pump or fan the convection is called forced convection. With natural convection the force of gravity produces the necessary movement. The fluid in the hotter parts expands and rises being displaced by the denser colder parts.

Radiation

All objects lose energy continuously by the emission of electro-magnetic radiation and gain energy by absorbing some of the radiation that is incident on them from other objects. This process of energy transfer by radiation can take place without the presence of any material in the space between the radiating and receiving objects. The radiation from the sun reaches the earth through empty space. There is, however, a difference between the radiation received from the sun and that given off by most terrestrial objects. The frequency and wavelength of the radiation is set by the temperature of the body emitting the radiation. The sun is very hot and emits essentially short-wave radiation whereas objects in and surrounding buildings are relatively cool and so emit long-wave radiation. This difference leads to the familiar greenhouse effect since the transmission of radiant energy through a transparent body is dependent upon the wavelength. Short-wave solar radiation is able to pass through the glass and some of it is absorbed by the objects inside, then they, being at a lower temperature, reradiate energy as long-wave radiation which is not able to pass through the glass and so the heat is trapped in the greenhouse. The temperature inside builds up until the heat gained by radiation is balanced by the heat lost by conduction and convection.

A further factor which is of importance when considering the exchange of heat between bodies by radiation is the nature of the surfaces of the bodies. An ideal black body is one which absorbs all the radiant energy which falls on it; none is reflected or transmitted. Actual building materials are not ideal black bodies, not even those that look black, and they absorb only a proportion of the radiant energy, the remainder being either reflected or transmitted. Any given surface will have the same ability to emit as to absorb radiation of the same wavelength. The ratio between the ability of an ideal black body to emit radiation and the ability of a real surface to emit radiation of the same wavelength is called the emissivity (e) of the surface. The value of the emissivity of many surfaces will vary with the wavelength of the radiation and so their ability to absorb short-wave solar radiation may be different from their ability to absorb long-wave terrestrial radiation. Some typical values for both long- and short-wave emissivity/absorptivity are given in Table III-1.

This difference in emissivity between long- and short-wave radiation can be used to advantage on some occasions. Many aircraft have the upper parts of their fuselage painted white and the lower parts are left unpainted. The absorptivity for short-wave radiation of both white painted surfaces and unpainted aluminum are approximately the same thus the top surface will absorb the same amount of heat whether painted or not. However, the emissivity for long-wave radiation of the white surface is nearly four times that of the unpainted surface and so the temperature of the aircraft skin will be less to maintain the necessary balance between the heat absorbed and the heat reradiated. On the underside the aircraft receives long-wave radiation from the ground and here the lower absorptivity of the aluminum reduces the amount of heat picked up.

TEMPERATURE GRADIENTS

The example of the aircraft is of interest but we are not concerned here with the design of aircraft but rather with more mundane types of accommodation. Thus we must develop satisfactory working techniques to handle our day-to-day problems of maintaining the required temperature difference between the inside and outside of the building. At the same time we must also be able to determine the temperature conditions throughout the thickness of the building enclosure; in other words to determine the temperature gradient through the building enclosure.

Since the temperature on the outside of the building will fluctuate widely, the temperature gradient will also fluctuate. The outside temperature varies not only with the season but also with changes in the weather, between day and night and even with clouds which obscure the sun from time to time. The precise determination of a temperature gradient under these widely and rapidly fluctuating conditions is very difficult and is made more so by the heat storage capacity of the various components of the wall which means that they will require time to warm up and cool down. Fortunately, a high degree of accuracy is hardly ever required and satisfactory results can be obtained by quite simple methods, aided at times, it must be admitted, by a little intelligent guesswork. To provide building materials with conditions which they find acceptable we seldom need to know the exact balance point between acceptability and unacceptability, if there is such a point, but we do need to know what will be favourable.

For most practical situations the temperature gradient can be determined assuming steady-state parallel heat flow conditions.

TABLE III-1

RADIATION FACTORS OR EMISSIVITIES

		Fraction of Black Body Radiation at		
	Surface	50-100°F	1000°F	Absorptivity for Solar Radiation
1.	Small hole in an enclosure	.97 - .99	.97 - .99	.97 - .99
2.	Black, nonmetallic surfaces	.90 - .98	.90 - .98	.85 - .98
3.	Red brick and tile, Stone and concrete Rusted iron and dark paints	.85 - .95	.75 - .90	.65 - .80
4.	Yellow and buff building materials	.85 - .95	.70 - .85	.50 - .70
5.	White or light cream surfaces	.85 - .95	.60 - .75	.30 - .50
6.	Glass	.90 - .95		transparent (8% reflected)
7.	Bright aluminum paint	.40 - .60		.30 - .50
8.	Dull brass, copper, aluminum, polished iron	.20 - .30	.30 - .50	.40 - .65
9.	Polished brass, copper	.02 - .05	.05 - .15	.30 - .50
10.	Highly polished tin, aluminum, nickel, chrome	.02 - .04	.05 - .10	.10 - .40

That is fixed inside and outside temperatures are adopted and it is assumed that these conditions have been fixed long enough for all the materials to have reached steady conditions, that is, they are neither warming up nor cooling down. We assume also that the heat flow is straight through the enclosure and is not deflected sideways. Under these conditions all parallel paths through the enclosure have the same conductivity and all the heat that enters the warm side flows through each component in turn and is carried away from the cold side. As with many cases of uniform flow such as this, the rate of flow is directly proportional to the magnitude of the driving force and inversely proportional to the resistance, i.e.,

$$\text{Heat Flow} \propto \frac{\text{Temperature Difference}}{\text{Thermal Resistance}}$$

Thus it follows that the temperature drop through each component of the wall is proportional to its thermal resistance. The driving force is provided by the difference in temperature and the thermal resistance is a property of the materials and of the construction of the component being considered. The next problem therefore is to obtain suitable values for these thermal resistances. To understand how to do this we need to know the meanings of two related terms - thermal conductivity (k) and thermal conductance (C), for the thermal resistance (R) is the reciprocal of the thermal conductance, i.e.,

$$R = \frac{1}{C}.$$

Conductivity and Conductance

Homogeneous Materials

Heat will flow through different materials under the action of conduction alone at different rates and these rates are a function of the nature of the materials. With homogeneous solids, or materials such as lumber, brick and stone which may be considered as homogeneous, thermal conductivity is a measure of this rate of heat flow. The conductivity, or 'k' value, is the number of British thermal units (Btu) of heat that will pass through 1 square foot of material 1 inch thick in one hour under a temperature differential (i.e. driving force) of 1°F; [Btu/(hour) (sq ft) (°F/inch).] Thus the material is subjected to a thermal gradient of 1°F per inch and if this thermal gradient is changed then the rate of heat flow will also change. If the 1°F temperature difference is applied across a 2-in. thickness of material then the thermal gradient becomes 1/2°F per inch and the heat flow is halved. The value obtained in this case is called the thermal conductance of that specific thickness of material. With homogeneous solids the thermal conductance for any thickness can be obtained by dividing the conductivity (k) by the thickness in inches (n), i.e.

$C = \frac{k}{n}$ Btu/(hr) (sq ft) (°F temperature difference), leading to the thermal resistance

$$R = \frac{1}{C} = \frac{n}{k}$$

Nonhomogeneous Materials

Nonhomogeneous materials such as concrete blocks or clay tiles, or those materials that are not of uniform thickness such as some siding and roofing materials require different treatment. In such cases, effective thermal conductances and resistances for the thickness considered are obtained experimentally, and the values so obtained cannot be adjusted for different thicknesses.

Thermal Conductivity of Soils

It is the convention to give the thermal conductivity of soils for a thickness of one foot instead of one inch as is the practice for building materials. The numerical values are therefore only 1/12th of the others, a fact that must be borne in mind when making any comparisons. Values for soils range from about 0.3 to 1.3 Btu/(hr)(ft)(°F), depending upon factors such as soil type, density, and moisture content. Fine-grained soils such as clay tend to have lower values than granular materials, and increasing the moisture content will increase conductivity. In general, the soils surrounding house basements will have conductivities of between 0.7 and 0.9 Btu/(hr)(ft)(°F). As a rule of thumb 3 ft of soil will have the same thermal resistance as 1 in. of mineral wool insulation.

Air Surfaces and Air Spaces

Whenever there is an interface between a solid material forming part of the enclosure and air heat is transferred by a combination of conduction, convection and radiation. Under these conditions, which occur at the inside and outside surfaces of the enclosure and at any air space within its thickness, it is not strictly rational to talk of a coefficient of conductance. Nevertheless it is convenient to do so even if only because there is no other single word which is suitable, and it is possible to assign suitable values to this conductance in an approximate way.

Because of the role played by radiation it is necessary to probe into the situation somewhat more deeply than in the case of nonhomogenous materials. There is also a difference between heat flow across an air space and heat transfer at the interior and exterior surface of the enclosure.

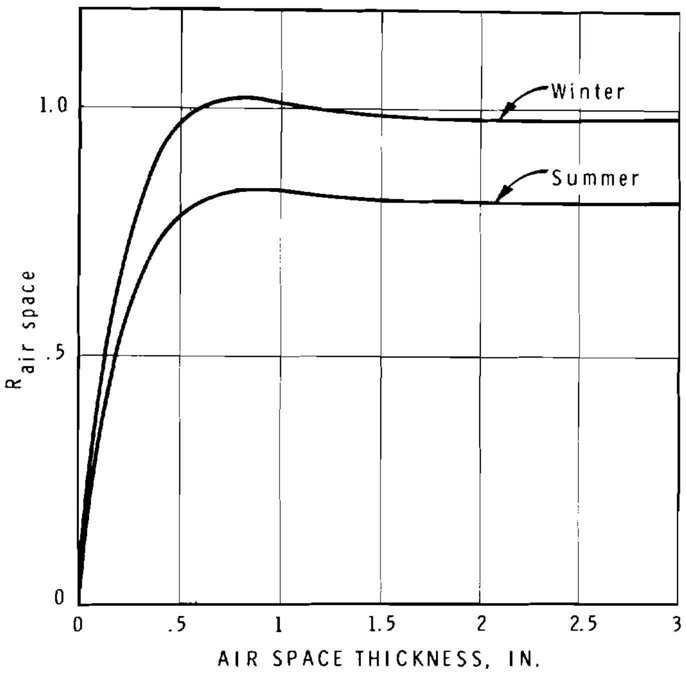


Fig. III.1 Variation in the thermal resistance of an air space with thickness

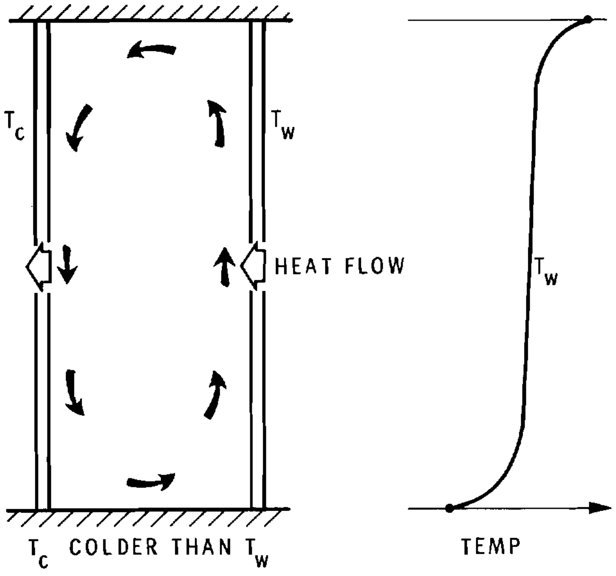


Fig. III.2 Effect of convection in an air space on the warm side surface temperature

(1) Heat flow across an air space

Of the three possible methods of heat transfer-conduction, convection and radiation - consider first the combined effects of conduction and convection. With conduction, the longer the heat flow path the smaller will be the quantity of heat transferred, thus a wide air space is required to reduce the heat transferred by conduction. With convection, the more difficult it is for the air to circulate the smaller will be the quantity of heat transferred, thus to reduce the heat transferred by convection a narrow air space is required. With a vertical air space and a horizontal heat flow there is practically no convective air movement for air spaces less than 1/4 in. thick. If the width of the space is reduced to less than 1/4 in. there is no benefit to be obtained by way of reduced convective heat flow and there will be an increase in the heat lost by conduction. As the thickness is increased above 1/2 in. the heat lost by conduction is reduced but convection begins to play an increasingly important role. It is found that the minimum total heat transfer under the combined actions of conduction and convection is obtained at a thickness of about 5/8 in.; above this value the increase in convection more than compensates for the decrease in conduction. When the air space thickness exceeds 1 1/4 in. the combined heat transfer is practically independent of thickness.

The effect on the thermal resistance of a vertical air space caused by varying the thickness is shown in Figure III. 1 The difference between summer and winter is due to the increase in resistance for the same temperature difference with a lower mean temperature in winter.

A further consequence of the convective transfer of heat across an air space is that there will be a vertical temperature gradient on the two bounding surfaces. Heat picked up by the air as it rises past the warm surface will be given up to the cold surface at the top thus warming it. Conversely, the air that has been cooled while descending past the cold outer surface will cool the bottom of the inner surface. This effect is shown diagramatically in Figure III. 2 which shows the form of temperature variation on the warm surface.

Across an air space enclosed by horizontal surfaces the heat flow under the combined effects of conduction and convection depends upon whether the heat flow is upward or downward. For downward heat flow the warmest air is next to the top surface and the coldest at the bottom, so that there is no tendency for convection currents to be set up and the heat flow is inversely proportioned to the thickness regardless of thickness. When the heat flow is upward through a horizontal air space the air at the bottom of the space is warmed and convection occurs. Under these conditions the value of the heat flow cannot be calculated simply.

For all practical purposes, suitable values for the thermal conductances and resistances of plane air spaces have been determined for all these conditions. The overall figure must also take into account, however, the part played by radiation in transferring heat across the air space. This rate of transfer is practically independent of the thickness of the air space but it is affected to some extent by the temperatures of the boundary surfaces since their emissivities will vary with their temperatures. As is to be expected the principal factors affecting the rate of heat transfer by radiation are the emissivities of the two surfaces. Polished metallic surfaces have much lower emissivities than do most of the relatively rough and dull building materials and this factor can be used to reduce the overall transfer of heat across an air space. The radiative heat transfer across a space bounded by two polished aluminum surfaces, with emissivities of 0.03, will be only about 3 or 4 per cent of that between surfaces of more usual building materials with emissivities of between 0.90 and 0.95. It must be emphasized that we are discussing heat transfer across an air space; a thin sheet of polished metal which does not face an air space will do nothing to reduce the heat flow.

The practising designer is spared long and possibly difficult calculations to obtain suitable values for the thermal conductances and resistances of plane air spaces by using suitable tables such as those published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers in their Handbook of Fundamentals. To use these tables one first decides upon the type of material to be used for each surface and obtains an effective emissivity for the two surfaces combined from the first table. From a second table, one obtains the thermal conductance or resistance based on the effective emissivity and the position of the air space (vertical, horizontal or sloping), the direction of heat flow (up, horizontal or down) and the thickness (3/4 in. or 4 in.). The figure so obtained can then be used in the heat flow calculations for the building enclosure.

(2) Heat transfer at exterior surfaces

The use of a combined surface conductance for heat transfer at a surface is based on the assumption that heat flow by both radiation and convection is proportional to the same temperature difference. This is valid for an air space, but at a free surface the ambient

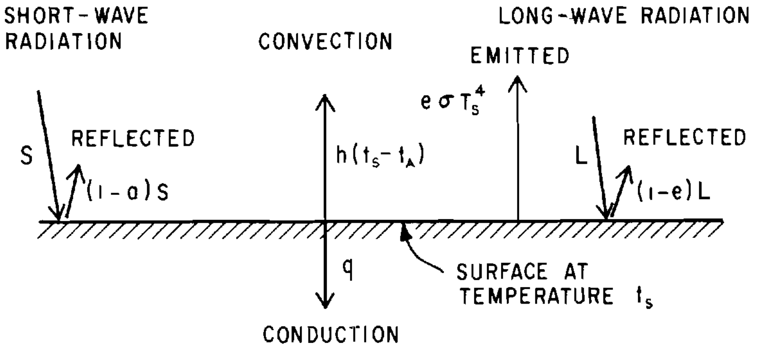


Fig. III.3 Components of heat balance at an opaque surface

where

s = the incident short-wave radiation

L = the incident long-wave radiation

a = the absorptance of the surface for solar radiation (see Table III-1)

e = the emittance of the surface for long-wave radiation (see Table III-1)

h = the surface conductance for heat transfer by radiation and convection combined; Btu/(hour)(sq ft)(°F)

t_a = outside air temperature ; °F

t_s = surface temperature; °F

T_s = absolute surface temperature; $°K \simeq (t_s + 460)$

σ = the Stefan-Boltzmann constant of radiation

q = the heat conducted into the wall

air temperature can be quite different from the temperature of the objects that are exchanging energy with the surface by radiation. For instance, the outside surface of a wall or window receives a great deal of energy from the sun, and this is quite independent of the temperature difference between the surface and the air. For the surface of a building exposed to solar radiation the various components of the heat flows towards and away from the surface are as shown in Fig. 111.3.

At every instant the total heat leaving the surface must be equal to the total heat approaching the surface and the temperature of the surface is always at the value where the heat gains and loses balance. If the solar radiation incident on a surface increases, the surface temperature rises, causing conduction, convection and long-wave radiation to increase just enough to offset the increased rate of energy absorption. This effect can be allowed for by adopting a fictitious outside air temperature called the sol-air temperature (S.A.T.), such that the heat exchange by convection from the surface to the air at this temperature would be the same as that which actually occurs by convection, and long and short-wave radiation combined. The heat exchange and surface temperature can then be calculated using the S.A.T. and a combined surface conductance for convection and long-wave radiation.

Average values for the sol-air temperature can be calculated using the formula

$$\text{S.A.T.} = t_a + \frac{a}{h}\left(\frac{\text{Daily Total Solar Irradiation}}{24}\right) - \frac{e\Delta R}{h}$$

where ΔR = the difference between the long-wave radiation incident on the surface from the sky and surroundings, and the radiation emitted by a black body at outdoor temperature, Btu per (hour) (sq ft).

Other symbols - see Fig. III-3.

Values for ΔR of 20 Btu/hr, sq ft for horizontal surfaces and zero for vertical surfaces are commonly adopted since horizontal surfaces often receive long-wave radiation only from the sky whereas vertical ones receive long-wave radiation from surrounding objects. These are often at higher temperatures than outside air at times of high solar radiation intensity thus compensating for the low emittance of the sky. The daily total solar irradiation can be obtained from the sum of the half-day totals of the solar heat gain factors for the particular orientation of the wall and for a corresponding orientation which is symmetrical with respect to south and then multiplying the result by 1.15 to compensate for the solar radiation excluded by a single sheet of ordinary window glass [Solar heat gain factors are discussed in Chapter IV page 62.]

The situation is further complicated in practice by the effects of the heat storage capacity of the components of the wall. The surface of a thick masonry wall does not become as hot during a clear summer day as the outer layer of a light curtain wall section, if both walls have the same exposure.

When the radiation incident on a wall or roof surface suddenly changes, as when a cloud moves away from in front of the sun, the S.A.T. increases abruptly, but the temperature of the exposed surface does not reach a new equilibrium value until some time later. The time required depends on the value of the surface conductance and the heat storage capacity of the wall or roof. Lightweight walls reach equilibrium in a fraction of an hour; very heavy walls require more than a day.

A precise determination of an external surface temperature taking into account solar radiation and heat storage capacity can be quite lengthy and is usually not justified for normal design consideration. An adequate approximation of the surface temperature of a roof can be obtained using the following simple formulae. With a material of low heat capacity (insulation) immediately below the roof surface, the maximum temperature is $t_A + 100a$, and the low temperature under a clear night sky at all seasons is t_A -20°F, where t_A is the air temperature in degrees Fahrenheit and 'a' is the coefficient of solar absorption.

The high and low temperatures for a roof surface on a high heat capacity substrate (eg. concrete) are $t_A + 75a$ and t_A - 10°F. Recommended design values of 'a' for representative colours and some weathered metals are given in Table III-2. The value of 'a', however, changes with the changing colour that results from accumulations of dirt. It should also be

TABLE III-2

RECOMMENDED VALUES OF THE SOLAR ABSORPTION COEFFICIENT, a

Surface Colour	a
black	0.95
dark grey	0.80
light grey	0.65
white	0.45
Weathered metals	
copper - tarnished	0.80
- patina	0.65
aluminum	0.60
galvanized iron	0.90

recognized that when a light-coloured wall reflects solar radiation onto a roof the incident radiation is increased. To allow for this the constants in the above formulae for summer high temperatures should be increased by approximately 30 per cent to $t_A + 130a$ and $t_A + 100a$.

All flat roofs not affected by higher reflecting walls receive their maximum irradiation at noon on midsummer's day. Walls, on the other hand, will receive theirs at different times of the day and at different times of the year according to their orientation. Tables III-3 and III-4 give the maximum temperature rise above ambient air temperature for various wall orientations at Ottawa on 21 July and 21 January. It has been assumed that the day is cloudless with no wind, that the atmosphere is clear, the surface of the wall is black ($a = 0.94$) and that the wall is of lightweight construction and well insulated. Light-coloured walls could reduce the temperature rise by half (e.g. for white, $a = 0.45$). For massive concrete or masonry walls the values would be lower due to conduction of heat into the walls and their high heat storage capacities.

TABLE III-3

MAXIMUM TEMPERATURE RISE OF VERTICAL WALL SURFACE DUE TO SOLAR RADIATION OTTAWA, 21 JULY

Time	Wall Orientation								
(Sundial)	N	NE	E	SE	S	SW	W	NW	N
6	13	46	51	26	4	4	4	4	13
7	10	55	71	46	7	7	7	7	10
8	10	48	74	58	12	9	9	9	10
9	11	31	66	62	23	10	10	10	11
10	12	16	50	59	35	12	12	12	12
11	12	13	27	49	43	16	12	12	12
12	12	13	14	33	43	33	14	13	12
1	12	12	12	16	43	49	27	13	12
2	12	12	12	12	35	59	50	16	12
3	11	10	10	10	23	62	66	31	11
4	10	9	9	9	12	58	74	48	10
5	10	7	7	7	7	46	71	55	10
6	13	4	4	4	4	26	51	46	13

TABLE III-4

MAXIMUM TEMPERATURE RISE OF VERTICAL WALL SURFACE DUE TO SOLAR RADIATION OTTAWA, 21 JANUARY

Time	Wall Orientation								
(Sundial)	N	NE	E	SE	S	SW	W	NW	N
8	1	1	22	26	15	1	1	1	1
9	3	3	46	68	50	4	3	3	3
10	4	4	39	78	70	18	4	4	4
11	6	6	19	74	82	41	6	6	6
12	6	6	6	61	87	61	6	6	6
1	6	6	6	41	82	74	19	6	6
2	4	4	4	18	70	78	39	4	4
3	3	3	3	4	50	68	46	3	3
4	1	1	1	1	15	26	22	1	1

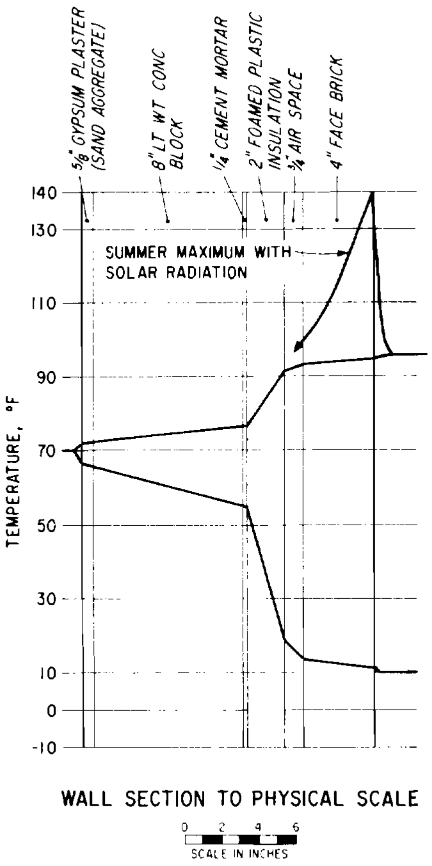


Fig. III.4 Temperature gradient through a wall. (determined arithmetically)

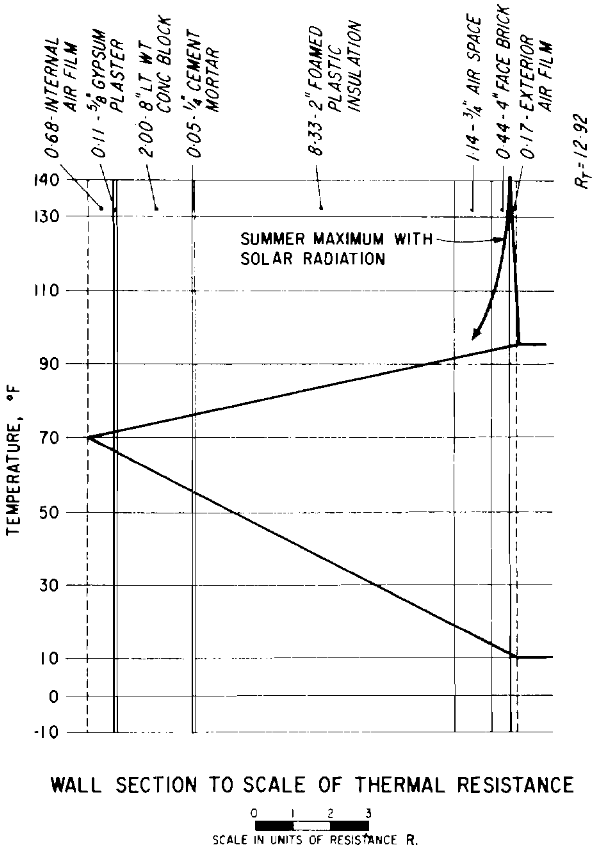


Fig. III.5 Temperature gradient through a wall. (determined graphically)

(3) Heat transfer at an interior surface

The inside surface of a wall or window exchanges heat by convection with the air in a room and by radiation with all the other surfaces that together enclose the room. It is often convenient to allow for the two independent heat transfer processes by using an inside surface conductance just as is done for an air space. This is all right so long as the surfaces that can be seen from the wall or window are close to the same temperature as the air in the room. This is usually the case for floors, ceilings and partitions that separate rooms at about the same temperature. It is not true, however, for a corner room, which has two outside walls; nor is it true for a room with a radiant heating system or a high level of artifical lighting. In these cases the radiation and convection can be combined by the use of a fictitious air temperature similar to the sol-air temperature for the outside surface.

Finally it can be said that for both exterior and interior surfaces it is possible to adopt combined values for the surface conductance of the air films which will give satisfactory results in most cases. Combined surface conductances for interior surfaces with various orientations, directions of heat flow and emissivities are listed in the American Society of Heating, Refrigerating and Air-Conditioning Engineers' Handbook of Fundamentals. They also list values for nonreflective (high emissivity) surfaces and two different wind speeds for exterior surfaces.

Calculation of Temperature Gradients

Now that we are equipped with some knowledge of how to obtain the thermal resistance of the various components of a building enclosure we can tackle the problem of calculating the temperature gradient. Under our assumed conditions these calculations are simple and can be performed either arithmetically or graphically. Under these assumed conditions all parallel paths through the wall have the same conductivity, all the components have reached steady temperatures, neither storing nor releasing heat, and heat flows through each component in turn under a temperature drop proportional to the resistance of the component. Thus, if all the components of the enclosure including the internal and external air films are listed, together with their thermal resistances, the total temperature drop can be apportioned to the various components in the ratio of their thermal resistance to the total thermal resistance. To do this arithmetically a tabular layout is used; in the graphical method each component of the enclosure is drawn with its thickness proportional to its thermal resistance. Then with a temperature scale on the cross-section a straight line joining the inside and outside temperatures will automatically distribute the change in proportion to the thermal resistance of each component.

To illustrate the procedure, using both methods, the temperature gradient through the wall shown in Figure III. 4 will be calculated assuming an outside temperature of 10°F and a controlled inside temperature of 70°F. In Table III-5 all the components of the wall, including the internal and external air films on the faces of the wall, are listed in sequence with their thermal resistances (R) listed opposite. It is usually necessary to list only resistances and temperatures. Conductivities and conductances have been shown in this example to further clarify some of the earlier discussions.

The total temperature drop through the wall in this case is 60°F and can be distributed among the individual components in proportion to their resistances. The interface temperatures can then be determined and recorded in the last column and the temperature gradient plotted as shown on Figure III.4. The over-all coefficient of heat transmission (U) is given by the reciprocal of the total resistance and the over-all heat loss through each square foot of wall is obtained by multiplying the total temperature difference between inside and outside by this value of U.

The arithmetic determination of the temperature gradient is not a lengthy calculation. It is probably the easier one to use if a wall is being designed to meet fixed internal and external temperature conditions and the components of the wall are selected to suit. On the other hand, if a tentative wall design is chosen and the effects of varying temperature conditions are to be studied, the graphical method may be more convenient as shown in Figure III. 5.

TABLE III-5

ARITHMETIC DETERMINATION OF TEMPERATURE GRADIENT

Component	Thickness n, in.	Conductivity, k	Conductance, C = k/n	Resistance, R = 1/C	Temperature Drop deg F	Interface Temperature deg F
						70
Internal Air Film (still air)			1.46	0.68	3	
						67
Gypsum Plaster (sand aggregate)	5/8		9.10	0.11	1	
						66
Concrete Block (lightweight aggregate)	8		0.50	2.00	9	
						57
Cement Mortar	1/4	5.0	20.00	0.05	0	
						57
Foamed Plastic Insulation	2	0.24	0.12	8.33	39	
						18
Air Space	3/4		0.88	1.14	5	
						13
Face Brick	4	9.0	2.25	0.44	2	
						11
External Air Film (15 mph wind)			6.00	0.17	1	
						10
TOTAL				12.92	60	

The Over-all Coefficient of Heat Transmission, U = 1/R = 1/12.92 = 0.08 Btu/sqft/°F/hr

Notes with Table III-5

The conductivity, conductance and resistance figures in the table are obtained from the Design Heat Transmission Coefficients published in the Handbook of Fundamentals of the American Society of Heating Refrigerating and Air-Conditioning Engineers (reprinted as NRC 7788) as follows:

1. Internal air film - from the table of surface conductance for still air with the surface vertical (heat flow horizontal) and a surface emissivity, e, of 0.90.
2. Gypsum plaster with sand aggregate - from the table of conductivities, conductances and resistances.
3. Concrete block with lightweight aggregate - from the table of conductivities, conductances and resistances.
4. Cement mortar - from the table of conductivities, conductances and resistances.
5. Foamed plastic insulation - from the table of conductivities, conductances and resistances for expanded polystyrene, extruded.
6. Air space - Firstly from the table of reflectivity and emissivity values with both surfaces of normal building materials the effective emissivity E is 0.82. Secondly, from the table of thermal conductances and resistances for a 3/4-in. air space placed vertically (horizontal heat flow) with E = 0.82 and taking the mean of the two values for mean temperatures of 50 and 0°F with a temperature difference of 10°F in each case.
7. Face brick - from the table of conductivities, conductances and resistances.
8. External air film - from the table of surface conductances for moving air at 15 m.p.h. with a surface emissivity of 0.90.

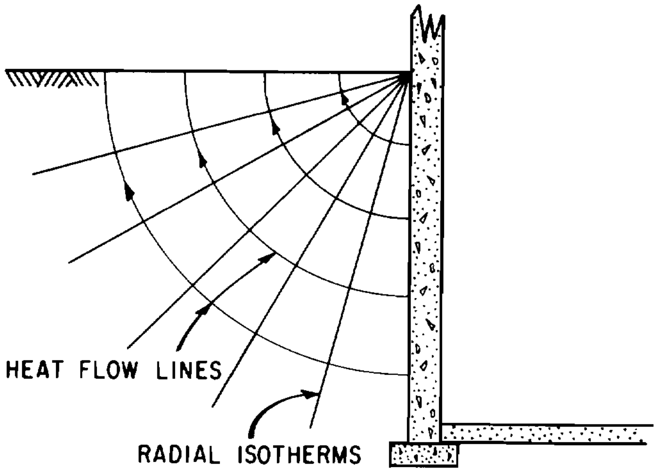


Fig. III.6 Paths of heat flow from a basement wall to the ground surface

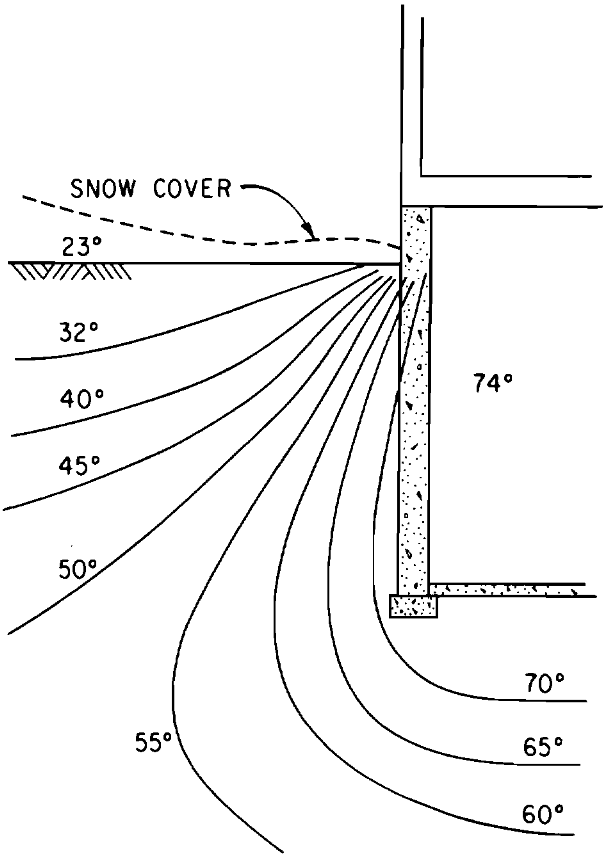


Fig. III.7 Isotherms of ground temperatures measured at Saskatoon

Heat Loss from Basements

The total heat loss from a basement can be divided into two parts: that which takes place through the wall above grade, and that which takes place through the wall and floor below grade. Above grade, the thermal properties and thicknesses in the direction of heat flow through the various materials can readily be established and the appropriate temperature difference predicted from long-term meteorological records. The thermal capacity of the wall is sufficiently small, even for concrete walls and the external design air temperatures sufficiently stable to permit the assumption of steady-state heat flow conditions. The methods described earlier can then be used to calculate the heat flow and temperature gradient.

To this loss must be added the heat loss involved in the infiltration of outside air. Once again methods exist that enable this to be estimated, but it should be pointed out that in addition to the air leadage around windows, there is a potential path of major leakage through the joint between the top of the basement wall and the sill plate of the superstructure.

Below grade, soil is interposed between the wall and the outside air. Although it may thus be regarded as forming part of the "wall" between inside and outside, the situation is very different from that above grade in several important aspects:

(a) The in situ thermal conductivity of the soil is difficult to establish with precision.

(b) The mass of soil and thus its thermal capacity is much greater than that of a wall, and modifies the effect of the oustide air temperature to a significant degree, as discussed in Chapter 1.

(c) The heat flow per unit area through a basement wall decreases with depth and is not so easily determined as that for above-grade walls, because it is no longer between parallel planes.

These complicating factors make a precise solution to the problem extremely difficult, but they should be taken into consideration in the development of any approximate method. For a specific situation such as a house basement, certain assumptions can be made that lead to a relatively simple approach to the problem.

Temperature Regime Around a Heated Basement

In the simple condition of steady-state heat flow between two parallel surfaces at different temperatures (as for a wall above grade) the paths of heat flow are parallel lines at right angles to the surfaces. When the two surfaces are not parallel but at an angle to one another and are separated by a homogeneous material, the paths of heat flow are still parallel but circular, with the centre of the circles at the intersection of the two surfaces (Figure III.6). From the symmetry of the situation it may be seen that the isotherms will be radial lines and that for equal increments in temperature they will be spaced an equal angular distances apart.

The actual temperature isotherms around a heated basement in Saskatoon are shown in Figure III.7. Examination of this diagram, bearing in mind the imperfect knowledge of the thermal properties of the soil, indicates that the assumption of radial isotherms is a reasonable one for the top 6 or 7 ft.

The internal temperature will, or should, be set by the requirements of the occupancy, and the outside air temperature can be determined as described in Chapter I. Following this it is possible to calculate the heat loss by the conventional means described, taking into account the thermal resistances of all items, including the soil, located between the air in the basement and the outside air. Care must be taken to ensure that all thermal resistances are expressed in the same units. In practice it is sufficient to calculate the heat loss for each square foot of wall area provided suitable allowance is made for the varying path lengths within the 1-ft depth of wall. Correct path lengths can be selected from Table III-6, which shows that below 3 ft the difference from the path of mean radius is negligible. Table III-6 also gives the heat loss per 1°F temperature difference through each square foot of basement wall when uninsulated and when insulated with 1, 2 and 3 in. of insulation.

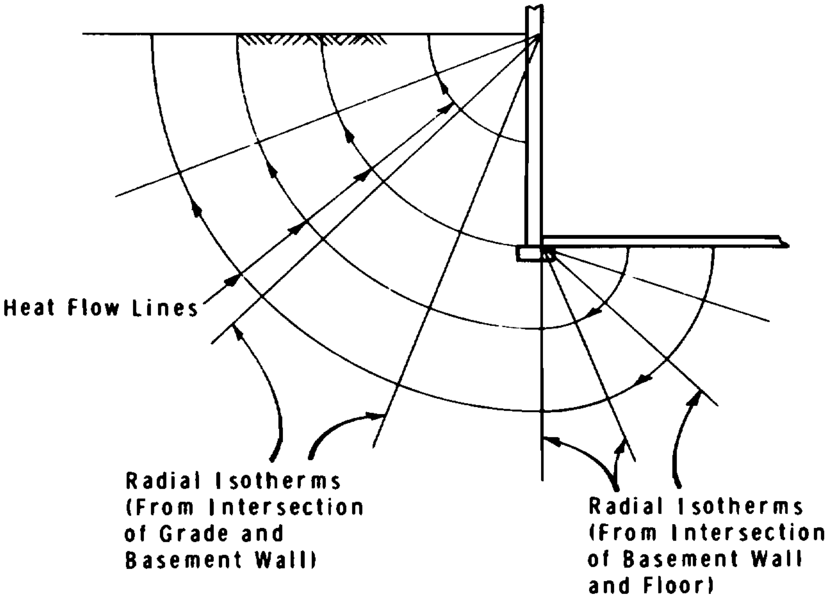


Fig. III.8 Paths of heat flow from a basement wall and floor to the ground surface

Heat Loss Through a Basement Floor

It is possible to calculate the heat loss through a basement floor for each square foot in the same way as the heat loss for the wall, using longer heat flow paths around the arcs of two circles (Figure III.8). Table III-8, however, shows that the heat loss from the 7th foot of the uninsulated basement wall is only a small fraction of the total loss through the wall; thus it can readily be appreciated that (with the much longer heat flow path) the loss through each square foot of basement floor rapidly becomes a negligible part of the total basement heat loss. It is reasonable, therefore, to take an average value for the loss through the basement floor. This value can be multiplied by the floor area to give the total floor heat loss.

The average rate of heat loss through the floor may be taken as equal to that from a point located one quarter of the basement width from the side wall. The path length from this point varies with both depth of basement below grade and width of basement. Shallow narrow basements will have a higher heat loss per square foot than will deep wide basements. Typical values are given in Table III-7 where it is assumed that all the heat flows out under the side walls of the basement and none under the end walls.

TABLE III-6

HEAT LOSS BELOW GRADE: Btu/(hr) (°F) (ft^2)
Insulation with k = 0.24 Btu/(hr) (ft^2) (°F/in.)
= 0.02 Btu/(hr) (ft) (°F)
Soil k = 0.8 Btu/(hr) (ft) (°F)

Depth (ft)	Path Length through Soil (ft)	Heat Loss			
		Uninsulated	1-in. Insulation	2-in. Insulation	3-in. Insulation
0-1 (1st)	0.68	0.410	0.152	0.093	0.067
1-2 (2nd)	2.27	0.222	0.116	0.079	0.059
2-3 (3rd)	3.88	0.155	0.094	0.068	0.053
3-4 (4th)	5.52	0.119	0.079	0.060	0.048
4-5 (5th)	7.05	0.096	0.069	0.053	0.044
5-6 (6th)	8.65	0.079	0.060	0.048	0.040
6-7 (7th)	10.28	0.069	0.054	0.044	0.037

TABLE III-7

MEAN BASEMENT FLOOR HEAT LOSS: Btu/(hr) (°F) (ft^2)

Depth of Foundation Wall below Grade (ft)	Width of House			
	20 (ft)	24 (ft)	28 (ft)	32 (ft)
5	0.032	0.029	0.026	0.023
6	0.030	0.027	0.025	0.022
7	0.029	0.026	0.023	0.021

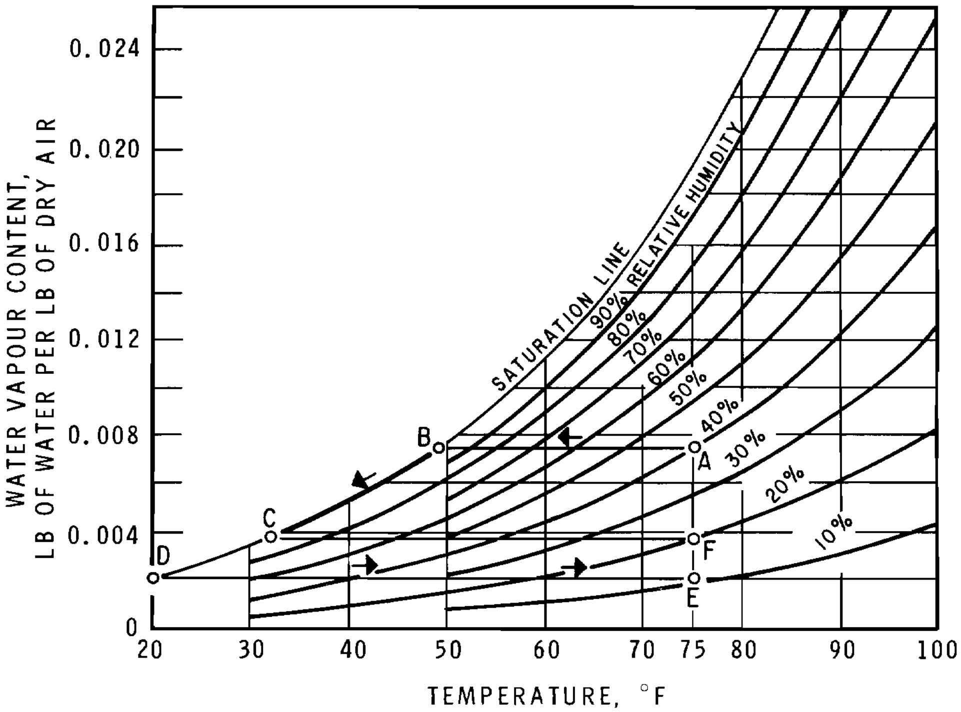


Fig. III.9 Psychrometric Chart

PSYCHROMETRY

Psychrometry is the branch of physics relating to the measurement or determination of atmospheric conditions, particularly regarding the moisture mixed with the air. In this section of our study of physics as related to buildings we are concerned with the subject of the latter part of this definition, i.e. the behaviour of moist air.

Water vapour is one of several gaseous constituents of air, the other principal ones being nitrogen, oxygen and carbon dioxide. Each exerts its own partial pressure in proportion to the amount of gas present, the sum of the pressures making up the total or barometric pressure of the air.

In the normal range of atmospheric temperatures and pressures, water can exist in three different states: gas, liquid and solid. The maximum amount of water that can exist in the gaseous state (vapour) in a given quantity of air is limited by the temperature. (To be precise, the pressure also has an effect, but in the majority of building enclosure problems, the pressure of the air/vapour mixture is closely related to ambient atmospheric pressure and the effects of the small changes in pressure which are involved are negligible.) Thus, if any air-vapour mixture is cooled, a temperature will be reached at which it will be saturated, and if cooling is continued below this point, water will condense. If the temperature at which the air becomes saturated, i.e., the dewpoint, is above the freezing point, the vapour will condense to a liquid; if it is below freezing, it will condense as ice in the form of hoar frost.

The ratio between the weight of water vapour actually present in the air and the weight it can contain when saturated at the same temperature is called the relative humidity of the air. It is usually expressed as a percentage. As the vapour pressures are set by the quantities of vapour in the air, the relative humidity is also given by the ratio between the actual vapour pressure and the saturation vapour pressure at the same temperature. Thus, if the temperature and relative humidity are known, the actual vapour pressure can be calculated from the product of the relative humidity (expressed in decimal form) and the saturation vapour pressure. These saturation vapour pressures and the corresponding quantities of water in the air are given in psychrometric tables.

A convenient way to follow the changes that take place in these inter-related phenomena is by means of a psychrometric chart which is a graphical representation of all possible conditions within the range for which the chart is constructed. One design of such a chart is shown in Figure III.9. The horizontal scale is air temperature or dry-bulb temperature and the vertical scale is moisture content expressed in pounds of water per pound of dry air. Vertical lines are, therefore, constant temperature lines; horizontal lines are constant moisture content lines. The curved line on the left is the saturation line or 100 per cent relative humidity line, which represents the maximum amount of vapour that can be held at various temperatures and is a boundary of the chart. The temperatures at points along this line are referred to as saturation, or dewpoint, temperatures. Other degrees of saturation are shown by the other curved lines for relative humidities of 90 per cent, 80 per cent, etc.

When an air vapour mixture is heated or cooled without the addition or removal of moisture, i.e. at constant moisture content, the resulting "process" can be represented by a horizontal line on the chart. Similarly if water vapour is added or removed at constant temperature the process can be represented by a vertical line.

Suppose that we have room air at 75°F and 40 per cent R.H. This will be represented by point A. Suppose now that this air is cooled, by contact with a cool window surface for example. Since there is no change in moisture content the process can be represented by line AB and when the air-vapour mixture reaches 49°F it will be saturated. If it is now cooled further, water will be removed by condensation and the combined change in both temperature and moisture content is represented by the curved line BC.

Consider now what happens in winter when cold outside air is brought into a building and heated to room temperature. Outside air at 20°F and saturated with moisture is represented on the chart by point D. If it is heated to 75°F without moisture being added the process is represented by the constant moisture content line DE. At 75°F the air, which was saturated at 20°F, now has a relative humidity of only about 12 per cent. To bring this up to 40 per cent RH water must be added at constant temperature represented by line EA.

It will be recalled that relative humidity by itself does not give a measure of the amount of moisture in the air. As its name implies it is the quantity of moisture relative to the amount the air could hold at that temperature. Thus we see that the outside (20°F) air although at 100 per cent RH has less moisture than the inside (75°F) air at 40 per cent R.H.

In the example of room air at 75°F with a relative humidity of 40 per cent when this air was cooled by contact with a cold window, it was forced to deposit some of its moisture on the window. It follows that if we wish to prevent surface condensation of this sort some change to the existing situation must be made. One solution would be to limit the moisture content of the air to a content that has a dew point lower than the temperature given by point C; i.e. below about 33°F. By moving horizontally from C to the 75°F line we see that this limits the relative humidity in the room to a maximum of about 20 per cent (point F). This illustrates the point that in many instances the relative humidity that can be maintained within a building is set by the design of the building enclosure. In many buildings, of course, some condensation on windows is tolerated despite the damage it causes to the paintwork around the window. In cases of surface condensation one can at least see what is happening and take appropriate remedial action before the problem becomes serious. If condensation occurs in concealed locations, such as in walls and attics, one may be oblivious to what is happening until serious damage has occurred.

Reducing the relative humidity in a room to lower the dewpoint to below the window surface temperature is a solution to the immediate problem of condensation on windows. But, since the whole purpose of the building is to enable the block of air inside it to be maintained at some desired condition, and since these desired conditions are set by the occupancy and if the occupancy of the particular room requires a 40 per cent RH then the design of the building will have failed in this respect if the 40 per cent RH condition cannot be maintained. Thus under these conditions reducing the relative humidity of the room is not an acceptable solution and something else must be done.

The correct approach to problems such as this one will be discussed in later sections but to anticipate these to some extent it can be seen that another solution to this particular problem is to keep the moist air away from the window, possibly by blowing dry air against it. If this dry air is also warmed it may raise the surface temperature of the glass to above the dewpoint of the air in the room. Another way of raising the surface temperature of the window would be to change the design of window so that its thermal resistance is increased, for example, by using a double instead of a single window. Table III-8 shows the relative humidities that can be maintained in the room before surface condensation takes place on the centre of the window pane with different outdoor conditions and window designs. The glass surface temperatures at the bottom will be lower than those at the centre (see Fig. III.2) and the limiting values of humidity for no condensation will be correspondingly lower. This example shows that it is possible, within limits, to modify the building enclosure to meet different requirements for inside and outside conditions.

VAPOUR DIFFUSION

At the start of this section on psychrometry it was stated that water vapour was one of the constituents of air as we know it in nature. In many respects these various constituents all act together as though there was only one gas present. We do not, for example, expect the temperature of the oxygen to be any different from that of the nitrogen and when a current of air moves the carbon dioxide it will also move the water vapour. This uniformity of temperature and movement among the various constituents has been implicit in our discussion of condensation on a window; where the air went the water vapour went too, when one was cooled so was the other.

TABLE III-8

MAXIMUM HUMIDITIES FOR NO WINDOW CONDENSATION
(at the centre of the pane)

Outdoor Temperature (°F)	Relative Humidites at 70°F			
	Single Window		Double Window	
	Wind	No Wind	Wind	No Wind
+20	24%	41%	53%	61%
0	12%	27%	41%	49%
-20	6%	17%	32%	39%
-40	2%	10%	23%	31%

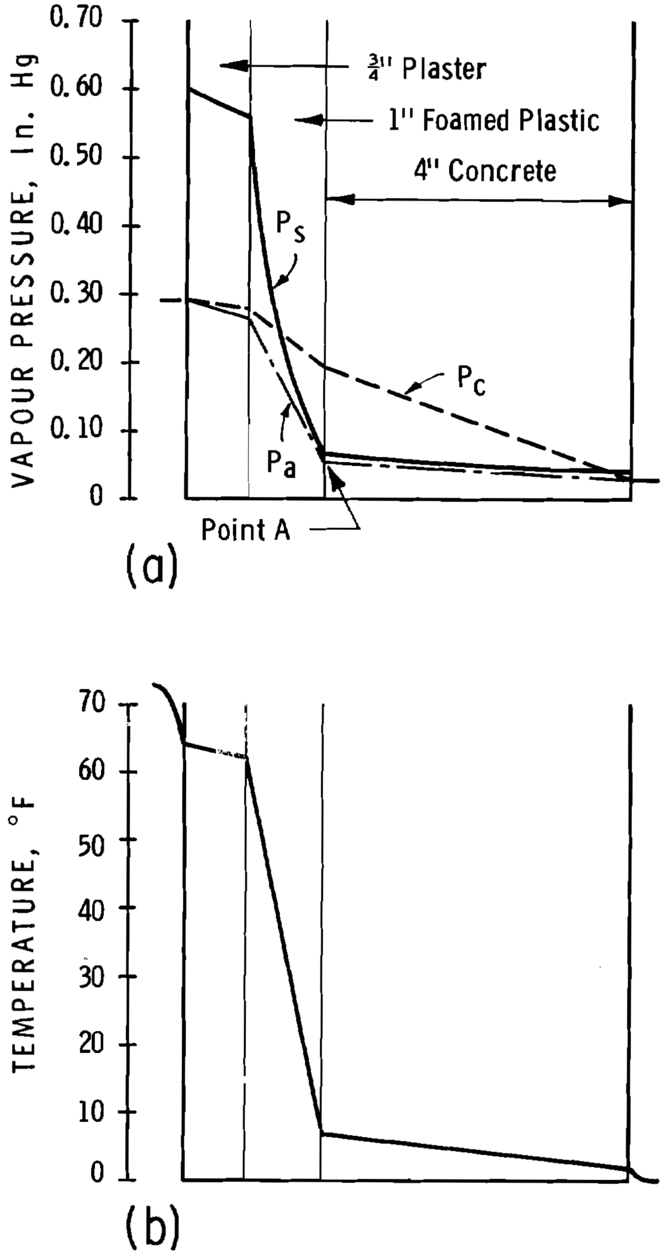


Fig. III.10 Vapour pressure and temperature gradients through an insulated concrete wall

Control of these air movements and changes in temperature are of vital importance to the correct design of a building enclosure. Nevertheless there is a second characteristic of water vapour which must be considered -- the phenomenon of vapour diffusion. Despite the prominence given some years ago to vapour diffusion and condensation and the need for vapour barriers this is now seen to be much less important than the control of air movement. Even so it should not be neglected, for an analysis of the building enclosure in terms of vapour diffusion will show whether there is a danger of a build-up of moisture occurring or whether the enclosure will be able to dry out should water get into it.

When there is a difference in concentration of water vapour between two points, there will be a corresponding difference in vapour pressure. This will cause a flow of water vapour from the point of higher concentration to the lower without any corresponding flow of air. When a vapour pressure difference exists between two sides of a material, the water vapour will diffuse through the material at a rate which will be determined by the vapour pressure difference, the length of the flowpath, and the permeability to water vapour of the particular material.

Calculation of Vapour Flow

Once the vapour pressures on the two sides of a building enclosure are known and a selection and arrangement of the building materials has been made, the vapour flow calculation is carried out in a manner similar to that used for heat flow. The relation that

$$\text{Vapour Flow} \propto \frac{\text{Vapour Pressure Difference}}{\text{Vapour Flow Resistance}}$$

is of the same form as that for heat flow. There is, however, one important difference owing to the ability of the vapour to condense.

In a steady state heat flow calculation it is assumed that all the heat which enters the wall at one side emerges on the other. With a vapour flow calculation one starts with the same assumption of continuity of flow and then checks its validity. If it is found that the assumption is invlaid and that, on its passage through the building enclosure, the vapour is cooled to below the dewpoint, condensation will occur and the basis of the calculation is upset. Even so, once the plane of condensation has been established the method can be applied to calculate the flow of vapour to it and away from it. The difference between the two gives the rate of accumulation of water within the enclosure.

The vapour flow resistance of a material is the inverse of the ability of the material to permit vapour to flow, i.e. its permeance. The unit of permeance is called the "perm", which is defined as one grain of water passing through one square foot in one hour under the action of a vapour pressure differential of one inch of mercury. The corresponding unit of permeability is the "perm-inch", the permeance of unit thickness. Values of the permeance of various building materials can be found in various tables. Unfortunately, the information available provides only partial coverage of even common materials. One reason for this is that the simple flow approach inadequately describes the real situation in many materials, and unlike heat flow, it is often impossible to describe the flow properties of a material in terms of a single coefficient applicable over a wide range of conditions.

The present information, however, does provide a basis for the design of building enclosures that avoid many of the problems associated with moisture migration. The following example illustrates the process of calculating the vapour pressure gradient.

Consider a wall of 4-in. reinforced concrete with an inside finish of 3/4-in. plaster over 1-in. of foamed plastic insulation that separates an internal condition of 73°F and 35 per cent RH from an outside condition of 0°F and 80 per cent RH.

As was explained earlier the relative humidity is given by the ratio between the actual vapour pressure and the vapour pressure at the same temperature when the air is saturated. The saturation vapour pressure for various temperatures is given in tables and on looking up the value for 73°F we get 0.818 in. Hg. Taking 35% of this we find the actual vapour pressure for the internal conditions of 73°F and 35% RH to be 0.818 x 0.35 = 0.286 in. Hg. Similarly that for the external conditions of 0°F and 80% RH is 0.038 x 0.80 = 0.030 in. Hg. The total pressure difference between inside and out is thus 0.286 - 0.030 = 0.256 in. Hg. This pressure difference must be apportioned among the various components of the enclosure in proportion to their resistance to vapour flow. These calculations are tabulated in Table III-9, and the resulting vapour pressure gradient for continuity of flow is plotted in Figure III.10 as curve p_c. Up to this point the method is the same as that for the arithmetical determination of temperature gradient.

To discover whether condensation will take place the temperature gradient must be determined, the corresponding saturation vapour pressures looked up in tables and the saturation vapour pressure curve drawn. This has been done in tabular form in Table III-9; the saturation vapour pressure curve is plotted in Figure III.10 as curve p_s. The values for the temperature gradient have been rounded off to the nearest degree. Although no greater accuracy than two decimal places is warranted in the vapour flow calculations, the third decimal place has been retained in the example for clarity. Note that a uniform drop in temperature through a material gives a curved saturation vapour pressure line. It may be seen that the saturation vapour pressure curve (p_s) is above the curve for continuity of flow (p_c) on the warm side of the wall, crosses to below it in the foamed plastic, and finally rises above the p_c curve again near the cold face of the concrete. As the maximum amount of water that can exist as vapour is set by the temperature, which also establishes the saturation vapour pressure, the actual vapour pressure curve can never be above the saturation vapour pressure curve. Thus, when the calculated p_c curve lies above the p_s curve the conditions for continuity of flow cannot be satisfied and an accumulation of moisture from condensation should be expected.

Under equilibrium conditions condensation does not take place at the point where the two curves cross; it can usually be assumed to occur at the next interface, point A in Fig. III. 10. The actual vapour pressure gradient between the inside and point A and between point A and the outside can now be determined by calculation, using the saturation vapour pressure of 0.054 in. Hg obtained previously from tables for point A. The vapour pressure drops of 0.286 - 0.054 = 0.232 in. Hg between the inside conditions and point A and of 0.054 - 0.030 = 0.024 in. Hg between point A and the outside conditions are distributed between the various components in proportion to their resistance to vapour flow. This calculation is tabulated in Table III-9 and plotted in Figure III. 10 as curve p_a.

Now that we have established the actual vapour pressure curve the vapour flow to and from point A can be calculated using the expression

$$\text{Vapour Flow} = \frac{\text{Vapour Pressure Difference}}{\text{Vapour Flow Resistance}}$$

The flow to point A is thus

$$\frac{0.286 - 0.054}{0.07 + 0.62} = 0.34 \text{ grain/sq ft/hr}$$

and that from point A

$$\frac{0.054 - 0.030}{1.25} = 0.02 \text{ grain/sq ft/hr,}$$

giving a rate of accumulation of condensation of

$$0.34 - 0.02 = 0.32 \text{ grain/sq ft/hr}$$

If an analysis such as this shows that condensation may occur fairly frequently then the enclosure is in danger of building up a high moisture content since the moisture can get in more easily than it can get out. If it is shown that condensation will not occur under design conditions then any moisture that may get in has a good chance of drying out.

TABLE III-9

TABULATED VAPOUR AND TEMPERATURE CALCULATIONS

			Air Film		Plaster		Insulation		Concrete		Air Film		Total
Thickness	n		—		¾		1		4				
Permeance	M		—		15		—		—		—		
Permeability	μ		—		—		1.6		3.2		—		
Vapour Resistance	$\frac{1}{M}, \frac{n}{\mu}$		0		0.07		0.62		1.25		0		1.94
Vapour Pressure Drop for Continuity			0		0.009		0.082		0.165		0		0.256
Vapour Pressure for Continuity	p_c	0.286		0.286		0.277		0.195		0.030		0.030	
Thermal Conductance C			1.46		6.66		—		—		6.00		
Thermal Conductivity k			—		—		0.25		12.0		—		
Thermal Resistance	$\frac{1}{C}, \frac{n}{k}$		0.68		0.15		4.00		0.33		0.17		5.33
Temperature Drop			9		2		55		5		2		73
Temperature		73		64		62		7		2		0	
Saturation Vapour Pressure	p_s	0.818		0.601		0.560		0.054		0.042		0.038	
Actual Vapour Pressure	p_a	0.286		0.286		0.264		0.054		0.030		0.030	

AIR MOVEMENT

Air that is in motion carries with it all the various pollutants it contains: gases from cars and chimneys, dirt and water vapour. Air that is taken into or exhausted from a building deliberately can be treated to control these pollutants; dirt can be filtered out, water vapour can be added or removed and the air can be heated or cooled as needed. The ducts through which the air passes can also be constructed so as to resist the effects of the contaminated air.

On the other hand air that leaks in or out at uncontrolled locations cannot be treated in this way. If we do not want the pollutants to enter the building or to harm the fabric of the building enclosure as they migrate within its thickness the only effective approach is to control the movement of the air. If a building is to fulfil its basic purpose of separating the controlled conditions inside from the uncontrolled ones outside, uncontrolled movement of air through the enclosure must be prevented. It is perhaps not quite so obvious that movement of air into the thickness of the envelope at one point and back again to the same side at another can also lead to serious problems.

The first law of motion applies to air as to any other object: before air will move there must be a force to make it move. Thus in order to control the movement of the air and to be able to understand what can happen in a building it is necessary to have some understanding of the forces that cause the air to move. There are three of these

Wind pressures
Stack effect, and
Ventilation pressures.

WIND PRESSURES

As soon as wind pressures are mentioned it is usual to think in terms of the maximum pressure that can be exerted. This is the dramatic aspect of wind pressures, when roofs are ripped off, trees are uprooted and windows are blown in. Although the subject is of great importance, it is not, however, the only one that concerns us here. The maximum pressure that acts on a building will occur only once in the lifetime of the building and it may never be subjected to the maximum possible wind pressure that could occur at that location. This maximum pressure must be taken into account in the structural design of a building and its various components and information is available from the meteorological records as to how great it might be.

On the other hand the building will be subjected almost continuously to the smaller pressures caused by relatively gentle breezes. It is these pressures that will move the greater mass of air, together with its water vapour, simply because they act for a much longer time. The precise magnitude of the pressure is of no concern to us here; it will obviously vary from nothing to the maximum and we will not use it in any rigorous analysis. It is sufficient to know that a pressure exists. What is important is to know how the pressure may vary from inside to outside and from one location to another on the enclosure of the building for it is this difference in pressure that promotes the flow of air.

Wind pressures exerted on a structure depend on the speed of the wind as well as the interaction between the air flow and the structure. Since wind is air in motion the pressures it can exert are related to its kinetic energy. If the full kinetic energy is transformed into pressure, i.e. the wind is brought to rest at that point, then the resulting increase in pressure is given by the expression

$$P_v = \frac{\rho V^2}{2}$$

where ρ is the mass density and V the velocity of the air. This is called the "stagnation pressure" and is the maximum positive increase over ambient pressure that can be exerted on a building surface by wind of any given speed. For air at standard density and with the wind speed in miles per hour the formula reduces to

$$P_v = 0.000492\ V^2$$

giving P_v in inches of water. Under the colder Canadian climatic conditions the air is slightly denser and the formula is modified to

$$P_v = 0.000519\ V^2.$$

Values for the stagnation pressures for winds from 5 to 25 mph under Canadian conditions are given in Table III-10.

TABLE III-10

STAGNATION PRESSURES

Wind Speed mph	Pv, in. of water
5	0.013
10	0.052
15	0.117
20	0.208
25	0.324

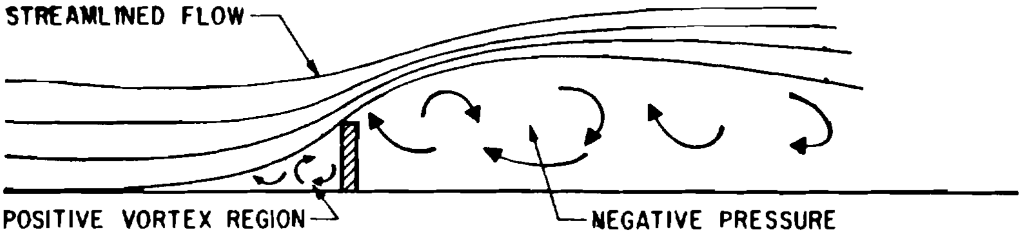


Fig. III.11 Wind flow over a long wall

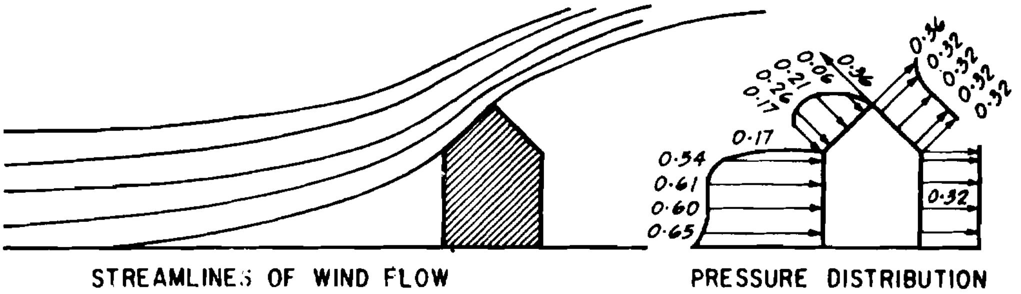


Fig. III.12 Two-dimensional wind flow over a building (after Jensen)

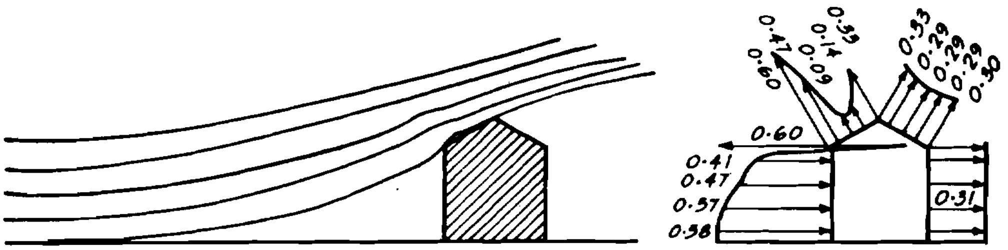


Fig. III.13 Separation of wind flow at eave causing high suction (after Jensen)

It should be noted that although the magnitudes of the pressures and suctions are proportional to the square of the wind speed, the distribution of pressures and suctions does not change greatly with speed for most "sharp-edged" structures and buildings. The pressure distributions can readily be expressed independent of wind speed by means of coefficients that relate the wind-induced pressures to the stagnation air pressure. Normally these coefficients will always be less than +1.0, will reduce to zero when there is neither a positive pressure nor a suction and will then become negative when a suction is induced. In some instances it is possible to have a positive coefficient greater than +1.0 depending upon the position at which the reference velocity is measured. It should be noted that at localized areas suctions much greater than the maximum positive pressures possible can be induced leading to negative coefficients as great as about -3.0.

The distribution of pressure over a building depends upon how it disturbs the air flow. In this respect it is useful to picture the air flow as it approaches the building as a series of parallel horizontal lines. In order to get over and around the building these lines will be bent and will be crowded together or spread out at various locations as need be to get by. This is a description of streamline flow. When the building is on the convex side of the streamlines the pressure on it will be increased above the ambient barometric pressure in the undisturbed air flow. Conversely when the building is on the concave side of the streamlines, the pressure will be reduced below the ambient, i.e. there will be a suction on the building. In either case the sharper the bend the greater will be the pressure or suction. Similarly when the streamlines are bunched together the velocity of the air is increased in order to get the same quantity of air through a narrower space. The pressure will lessen at these points since the total energy content of the air stream must remain constant and the increased kinetic energy is obtained by a reduction in pressure energy. Conversely when the streamlines are spread out there will be an increase in pressure. All of the foregoing relates to streamline flow but the flow of wind around most buildings is far from streamlined. The picture of streamlined flow is nevertheless a useful aid in visualizing the probable wind pressure distribution over a building.

Consider now what happens when the wind strikes a simple structure such as a free-standing wall which is infinitely long so that the flow is two dimensional. Figure III.11 shows such a situation and it can be seen that the streamlines are deformed just as if the obstruction were shaped like a smooth hump. The deficiencies of "streamlining" are made up by the formation of a positive vortex region in front and a larger, negative vortex region behind.

In the triangular vortex region in front of the wall the "trapped air" is under a positive pressure. Behind the wall the streamlines of flow are unable to drop down to ground level immediately because of the inertia of the air and a wake is left where they are separated from the wall. Air from the wake region is "entrained" by the fast-moving flow lines, thus reducing the pressure below the ambient pressure of the undisturbed flow and creating "suction."

The mathematical relations between the velocities at various points and the constancy of total energy can only be applied in a streamlined flow. If the obstruction were itself streamlined, as is an aircraft wing, the streamlines would follow its surfaces and vortex regions would not form. Even the aircraft wing is not fully streamlined for some conditions of flow. With buildings the shape of the region that separates streamlined from turbulent flow is not known and so precise mathematical analysis is not possible. In practice the pressure distribution on buildings is found by experiment on scale models in a wind tunnel.

Figure III.12 shows a complete building (still in two-dimensional flow) in which the roof is steep enough to protrude into the flow boundary formed by the front wall alone. This causes the streamlined flow to be pushed up even further, so that pressure occurs on the windward slope. If the slope of the roof is reduced, a point will be reached at which pressure on the windward slope becomes zero; if it is reduced further, the flow boundary will at first be sucked down and will continue to flow along the slope, and a change from pressure to suction will occur. As the slope is reduced even further, high local suctions will develop near the eave, and a third vortex region, highly negative, will suddenly form, as is shown in Figure III.13.

At a critical slope angle, maximum suctions occur; with further reduction there will be an easing of the suction, when the small vortex will merge with the larger "wake" of the building. The whole roof is then completely immersed in a region of fairly uniform, moderate suction, and further changes in the slope or shape within that region will not greatly affect the pressures.

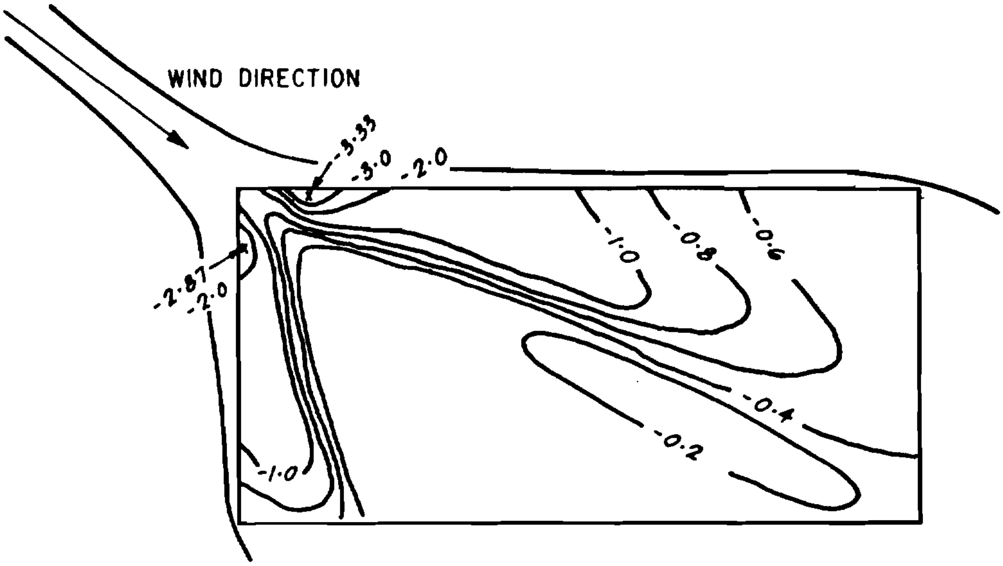


Fig. III.14 Plan view of roof with contours showing negative pressure distribution (after Leutheusser)

In three dimensions the streamline flow is diverted around the sides as well as over the top, with separation at sharp edges and the possibility of reattachment to the side walls at certain orientations of the wind. The important parameters in determining the shape of the flow are the ratios of height to width and width to length of the building.

The greatest local suctions on roofs occur, especially with long, low-slope roofs, near the windward corner when the wind blows at an angle of 45 to 50 degrees to the eave. This is shown in plan view of Figure III.14, where the lines of equal pressure are plotted as contours. Peak suctions up to 3.0 times the stagnation pressure of the wind may occur close to a corner, because a strong negative vortex is formed at this location as the flow curves up and over the two windward walls and separates at the sharp edge. When the roof is long, the flow can be sucked back down to reattach itself to the roof surface, so that the vortex region is effectively sealed off on all sides, preventing any reverse flow along the roof to relieve the high suction.

Overhangs and parapets on roofs can have a considerable effect on the pressure distribution behind them either increasing or reducing the pressures. If a parapet is a certain height it can lift the flow high enough to prevent the streamlined flow from becoming reattached to the roof, so that one large vortex region forms to "absorb" the small tightly sealed one, thus reducing the suction. If the parapet is too low, on the other hand, the local suctions can be greater than if there had been no parapet at all.

Just as a roof may be subjected to a high suction at the windward edge a side wall may also have a high suction on it where the wind curves around the corner from the windward face. Because of this suction on the roof and on the side wall the windward wall itself will have a steep pressure gradient at the periphery and there may even be a suction on the windward wall over a narrow band around the outside edge. This rapid change of pressure can lead to some problems in design and special consideration must be given to it.

The foregoing discussion of the behaviour of wind around buildings is only an introduction to a very complex subject. Many situations where complicated shapes are involved and where a number of different objects interact cannot be analyzed satisfactorily in this way. Where the size of the project warrants it, the only way to assess such effects is to test a scale model in a wind tunnel. Nevertheless the basic ideas can be applied in less complicated situations to obtain a qualitative feel for the distribution of pressures and suctions.

So far no mention has been made of the change in pressure inside the building as a result of wind action. Obviously if the building is tightly sealed this pressure will remain unchanged. This is not a realistic situation and it is reasonable to assume that the change in internal pressure will be affected by the size and location of the various openings through the envelope. If openings predominate in a suction region, the internal pressure will tend toward suction; if the opeinings are mostly on the windward side, the internal pressure will be positive. To take an extreme case, an airport hangar with huge doors open on the windward side receives the positive pressure of the front vortex region inside it. With the wind coming from the opposite direction the effect is reversed. Thus one must always consider the pressure distribution over the building for all wind directions.

Tables of pressure coefficients are available which have been obtained from wind tunnel experiments and which give the pressure distribution over buildings of various shapes. One such table is published in Supplement No. 4 to the National Building Code of Canada. These pressure coefficients give the actual pressures in relation to the stagnation pressure and are of help in determining the pressure distribution over a building.

STACK EFFECT

The second force that produces air movement is the result of what is called stack effect since it is analogous to the draught produced in a chimney stack. When air is heated it expands and so each cubic foot of heated air is less dense than the same volume of unheated air. If two columns of air of equal height, one of which is warm and the other cold, are placed side by side, the denser cold air will exert a greater pressure at the bottom than will the lighter warm air. It will undercut the warm air causing it to rise producing the familiar draught up a chimney with cold air entering at the fireplace, being heated and leaving at the chimney pot. During cold weather a similar action occurs in buildings, although the inside-to-outside air temperature difference is much less than in a chimney. Even for one- or two-storey houses the stack effect in winter is sufficient to affect certain aspects of air leakage significantly; and in very tall buildings it can lead to pressure differences as great as 1 in. of water through exterior walls.

Suppose that we have a building with no openings to the outside except for a single one at the bottom and with no internal air separations, i.e., rather like an upturned jam jar.

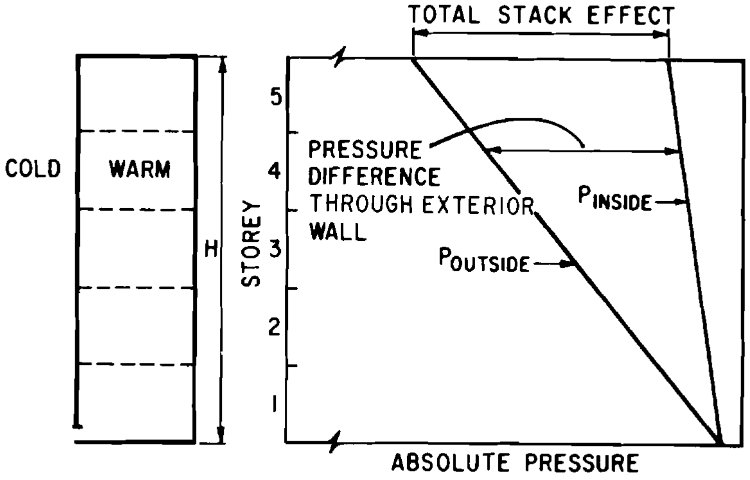


Fig. III.15 Air pressures inside and outside a heated building with a single opening at the bottom and no internal partitions

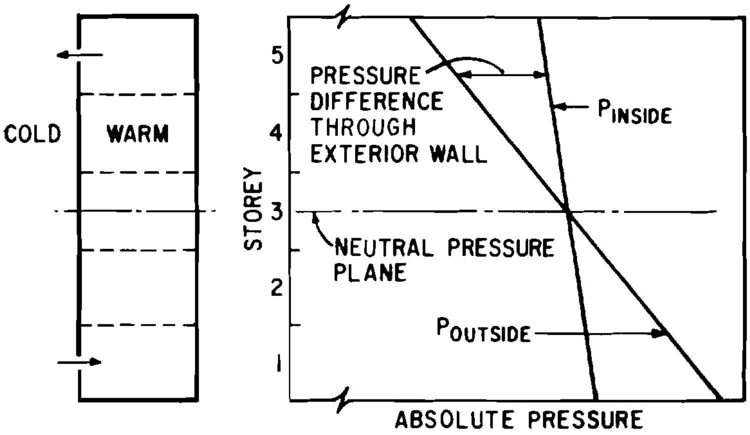


Fig. III.16 Air pressures inside and outside a heated building with equal openings at top and bottom and no internal partitions

Suppose also that the temperature inside the building is higher than that outside so that the column of air inside the building is less dense than the column of air of equal height outside it. In a chimney this would produce a flow of air but in the hypothetical case there is no way for the air to get out at the top of the building and so no air can come in at the bottom. As it is fundamentally impossible for there to be a difference in pressure through the opening at the bottom without a corresponding flow of air through the opening, an additional factor must have been brought into play to equalize the pressures at this point. This factor is the containing effect of the building which holds down the air inside it. If this were not the case, the whole building would take off like a hot air balloon.

The situation concerning air pressures in a heated building with a single opening at the bottom is shown in Fig. III.15. The absolute air pressures decrease with height because of the reduction in the total weight (per unit area) of the air above. Thus the outside air pressure decreases more rapidly than the inside pressure and the absolute pressure inside is greater than that outside at all levels above the opening. This difference in pressure is the stack effect. It acts through the enclosure of the building and is equal to the horizontal distance between the lines representing the inside and outside pressures; the maximum value occurs at the top and is the stack effect for the total height of the building.

If the opening were at the top of the building instead of at the bottom the inside and outside pressures would be equal at the top. Then, since the warm inside air is less dense than the cold outside air, the increase in pressure on descending to the bottom will be less inside the building than it is outside leading to an inward pressure on the building enclosure. The magnitude of the pressure difference at the bottom is equal to that of the outward pressure at the top in the case with the opening at the bottom.

Under the conditions of no air flow the stack effect can be calculated from the formula

$$p_s = 0.52\ PH\left(\frac{1}{t_o + 460} - \frac{1}{t_i + 460}\right) \text{in. of water}$$

Where p_s = total pressure difference caused by stack effect, in. of water

P = ambient atmospheric pressure, psia

H = effective height for stack effect

t_o = outside temperature, °F

t_i = inside temperature, °F.

Adding 460 to t_o and t_i converts these temperatures to absolute values rather than the arbitrary zero normally used with the Fahrenheit scale. The effective height for stack effect is the distance from the point at which inside and outside pressures are equal and the point under consideration, i.e. the full height of the building in the previous cases. If the commonly adopted figure of 14.7 psi for the atmospheric pressure at sea level is used, then the formula becomes

$$p_s = 7.6\ H\left(\frac{1}{t_o + 460} - \frac{1}{t_i + 460}\right) \text{ in. of water}$$

Now consider the case of a building with no internal separations and with two openings of equal size through the enclosure, one at the top and the other at the bottom. With a heated building this is similar to the situation with a fireplace and chimney: air flows in at the bottom opening, is warmed, rises and flows out at the top opening. The pressure difference required to cause flow through the openings is provided by the stack effect. Air flow takes place from high to low pressure, thus the pressure outside must be higher than that inside at the bottom and lower than that inside at the top. Because the openings at the top and bottom are of equal size they impose an equal resistance to flow. The pressure differences through them are therefore of equal magnitude.

It follows that, if the pressure difference through the building enclosure changes from positive to negative in the height of the building, there must be a level at which this pressure difference is zero. In this example, since the pressures at top and bottom are equal in magnitude, the point of zero pressure difference will be at mid-height. This plane is called the neutral pressure plane and the situation in this case is shown in Fig. III.16.

The effective height used in the formula for p_s is the vertical distance above or below the neutral plane. In the earlier example of a building with only one opening, the neutral plane is at the level of the opening and the effective height is the full height of the building.

With real buildings the openings in the enclosure will seldom be uniformly distributed from top to bottom but in all cases the inflow must equal the outflow. If the openings at the bottom, for example, are larger than those at the top, a smaller pressure drop would be required through them relative to the top openings to give the same flow. The neutral pressure plane would be lowered since the pressure from stack effect is directly proportional to the effective height. In effect, in Fig. III-16 the

Fig. III.17 Air pressures inside and outside a heated building. Each storey being completely isolated and having equal openings at top and bottom

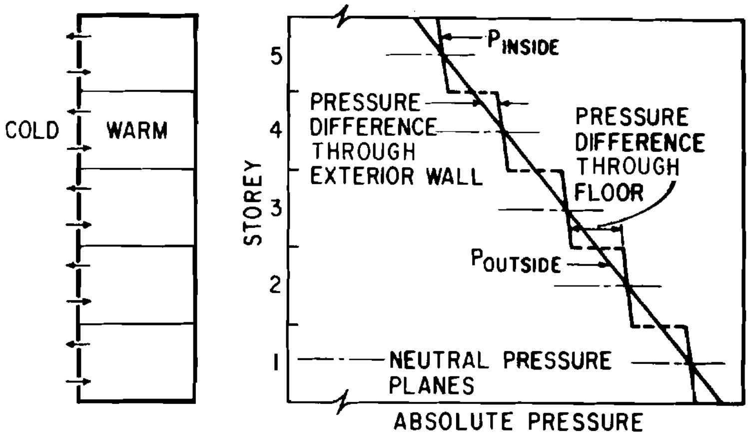


Fig. III.18 Air pressure distribution inside and outside a heated building with a uniform distribution of openings through the enclosure, the floors and the walls of the elevator shaft

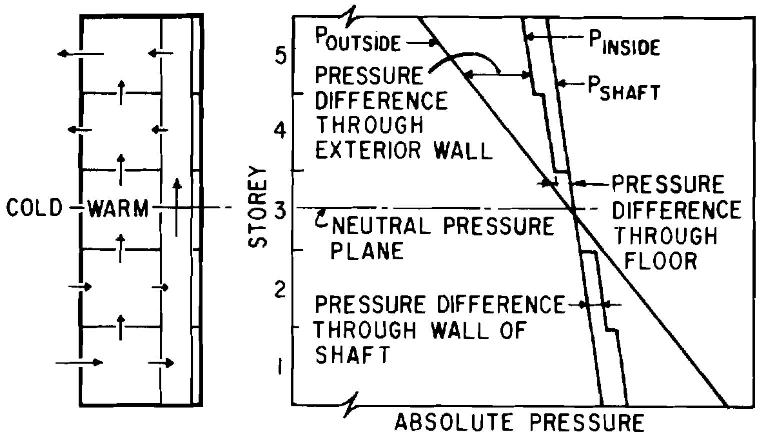
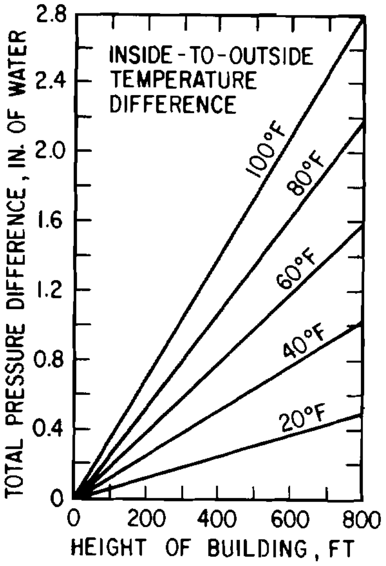


Fig. III.19 Total pressure difference between inside and outside of a heated building



inside pressure line would have been moved to the right and in the ultimate would reach the position shown in Fig. III.15.

Suppose now that we have a building with perfectly airtight separations at each floor level (so that there can be no flow of air between storeys) and with openings of equal size in the exterior wall of each storey, top and bottom. Each storey thus acts independently, its own stack effect unaffected by that of another level. Air will flow in at the bottom and out at the top of each storey, with a neutral pressure plane in between. The sum of the pressure differences through the exterior walls at the top and bottom of any storey, therefore, is equal to the total stack effect for that storey. This is equivalent to the pressure difference acting through each floor, and is represented by the horizontal line at each floor level. The total stack effect for the total building height is the same as that in Figure III.16 and is equal to the sum of the pressure differences through the floors, plus the pressure difference through the exterior walls at top and bottom of the building.

Fig. III.17 illustrates this situation which is of considerable importance since it shows how chimney action between a heated building and a cold vertical air space incorporated in walls can develop in the same way as that between the building and outside. When such a space is connected to the inside of the building by cracks or openings at two levels, air can flow into the space at the upper level, deposit some of the moisture it contains and flow back into the building at the lower level. This happens with double windows with tight outside sash, furred spaces around columns or vertical risers in outside walls.

In reality, multi-storey buildings are not completely open inside, nor are the separations between storeys completely airtight. There are passages for air to flow directly through the floors, and there are stairwells, elevators and other service shafts that penetrate the floors and provide passages for air to flow between stories.

In such a building the total pressure difference from inside to out is a function of the temperature difference and the height of the building. The location at which this pressure change takes place is a function of the relative airtightness of the various components. For a heated building with an elevator shaft and with a uniform distribution of openings in the enclosure, through each floor and into the elevator shaft at each floor, the pattern of pressure distribution caused by stack effect is as shown in Fig. III.18.

The total stack effect for the building remains unchanged but under the dynamic conditions of air flow it is used up in maintaining the flow through the various openings in the enclosure, the floors and into and out of vertical shafts. The pressure difference through the enclosure is therefore less than if there was no resistance to flow within the building. Measurements made on several multi-storey buildings have shown that up to 80 per cent of the total pressure difference is taken through the enclosure, and that the remainder is distributed among the various interior separations. This indicates that with present construction there is a relatively low resistance to air flow from storey to storey compared with that through the enclosure. The level of the neutral pressure plane, which depends upon vertical distribution of the openings through which air flows into, through, and out of buildings, is generally near mid-height.

Fig. III.18 also indicates the pattern of pressure difference and air flow for the vertical shaft. It is assumed that there is no significant resistance to flow within the shaft, so that the line representing pressure has a uniform slope determined by the density of inside air for the building as a whole (as in Figure III.16). The horizontal distance between this line and that for the pressure within the building proper represents the pressure difference through the wall of the shaft and any openings it contains. With a uniform resistance to air flow through the floors and a uniform resistance to flow into the shaft at each floor level, air enters the shaft at lower levels and leaves it at higher levels in a symmetrical pattern. The neutral pressure plane for the shaft with respect to adjacent spaces in the building occurs near mid-height. The pressure difference through the wall of the shaft is maximum at the top and bottom. The change in this pressure difference from storey to storey corresponds to the pressure difference through the intervening floors. Thus the sum of pressure differences through the shaft wall at the bottom and top is equal to the sum of the pressure differences through all the floors in the building.

The total pressure difference for a heated building, i.e. the sum of the inward pressure at the bottom and the outward pressure at the top, can be estimated from Fig. III.19. With a neutral pressure plane at mid-height this total will be divided equally between the top and bottom of the building.

For a building 600 ft high with an inside-to-outside temperature difference of 100F degrees the total stack effect is about 2 in. of

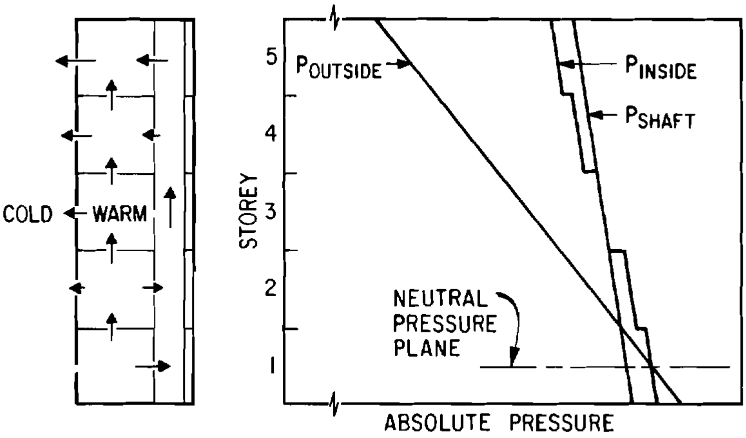


Fig. III.20 Air pressure distribution inside and outside a heated pressurized building water. With a pressure distribution as shown in Fig. III.18 and with 80 per cent of the total taken through the enclosure with the balance through the wall of the elevator shaft at ground floor level this gives a pressure difference through the entrance of about 0.8 in. of water.

When the pressure difference through a 20-sq-ft door exceeds 0.6 in. of water, the force required to open it is greater than can easily be applied by the average adult when standing. In order to reduce the force required to open the door and to reduce air infiltration, it is common practice to incorporate vestibule and revolving door entrances in high buildings. A vestibule divides the pressure difference through the entrance, so that each bank of doors sustains only half the total. Exterior doors at the top of buildings leading to roof areas also sustain pressure differences similar to those building entrances, but these act in the opposite direction.

Air flow induced by stack effect within a real building occurs through each path illustrated in Figure III.18. As the height and number of floors increase, however, the total resistance of the flow path through openings in floors increases more rapidly than that through the vertical shafts; thus with high buildings, upward air flow occurs mainly through the vertical shafts.

During the summer, when the outside air temperature is higher than that inside, the pattern of pressure differences and air flow is reversed. Infiltration occurs through the enclosure at the upper levels and exfiltration at lower levels, and air flows downward within the building. The stack effect is much less, however, than under winter conditions because of the smaller inside-to-outside air temperature difference, and its importance is reduced correspondingly.

VENTILATION PRESSURES

The third force that produces air movement through the building enclosure is that produced by the ventilation system.

Buildings are sometimes pressurized by a substantial excess of supply over exhaust air. The purpose of such pressurization is to reduce infiltration, presumably to overcome drafts and prevent the entry of dust. The amount of excess air required to achieve a given degree of pressurization will depend on the airtightness of the structure. The forces that have to be overcome to prevent infiltration are those resulting from wind pressure and stack effect; to achieve significant reduction in infiltration the building must be unusually airtight.

In relating the effects of ventilation pressure to the results of stack effect, if the excess air supply is introduced uniformly at all levels, the pressure difference through exterior walls at lower levels (causing infiltration) will decrease; that at upper levels (causing exfiltration) will increase by a similar amount. This is shown in Figure III.20 which indicates the effect of uniform pressurization of the idealized building (Figure III.18) to the point where inside and outside pressures are equal at the first-floor level.

From this Figure it will be seen that pressurization does not eliminate stack effect, but it alters the distribution of pressure differences through the exterior walls. The lines representing the pressure distribution inside the building and vertical shaft are displaced to the right; pressure differences between storeys and through walls of vertical shafts, and the resulting upward flow of air within the building, are essentially the same as with no pressurization (Figure III.18). Although infiltration through exterior walls is minimized, exfiltration is greatly increased, and there is the penalty of higher heating costs because it is necessary to heat the additional outdoor air that must be brought in to provide the pressurization. In the example, the total required outside air supply is equivalant to about three times the air infiltration when there is no pressurization.

Pressurization aggravates condensation problems that result from exfiltration of air and the practice is of doubtful merit in most Canadian climates. Instead, more attention should be given to increasing the airtightness of the building enclosure. In general, humidified buildings should not be pressurized. It might be advantageous to provide a slight suction in such buildings if condensation problems are anticipated.

In theory, a mechanical ventilation system could be designed to minimize pressure difference through the exterior wall of each storey by providing an excess of air supply to lower floors and an excess of exhaust air from upper ones. Under this condition, all of the pressure difference from stack effect would be resisted by the walls of any vertical shafts and the floors. Upward air flow through the building would be very large unless the airtightness from storey to storey were greatly increased. Such a system would not, therefore, be practicable without major changes in building design. It's use would aggravate the already difficult problem of the control of smoke movement within a tall building in the event of fire.

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CHAPTER IV -- THE CONTROL OF HEAT

The materials from which a building is built are what they are; and it is up to designers and builders to use these materials so they will not be subjected to conditions they cannot withstand. To ensure this, the various components that make up the building enclosure must be selected and positioned in such a way that the environment surrounding any given material will not vary beyond acceptable limits. The purpose of Chapter III, on the physics of heat, moisture and air movement, was to provide a basis for this control. In this chapter we will turn to the methods and the problems of achieving effective control of heat gains and losses. For the sake of clarity the methods of controlling individual phenomena, such as solar radiation, will be discussed separately. The measures needed to control water in its various forms will be discussed in Chapter V and the integration of all these measures into the final over-all solution to building enclosure design will be left until Chapter VI.

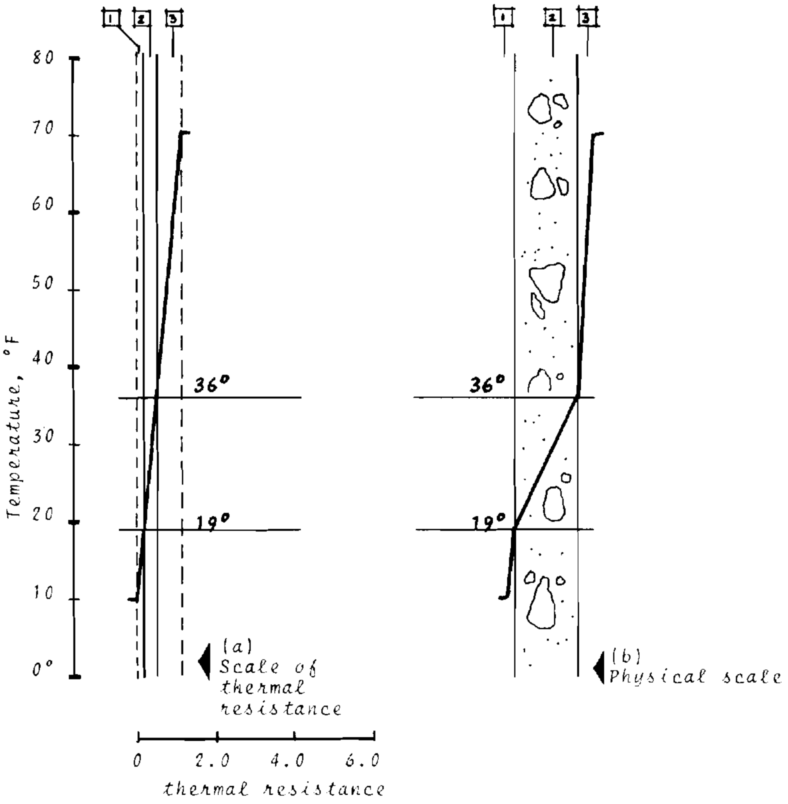
There may be many sources of heat within a building including living bodies (human or animal), machinery, lights, cooking and, of course, the heating system provided deliberately. As far as the enclosure is concerned, however, it matters little where the heat comes from -- it has to be controlled and either dispersed or conserved so as to maintain the desired internal conditions. Outside the building there are usually two possible sources of heat: the ambient air and the sun. The principles to be applied to control heat moving into a building from the air are the same as those for heat leaving the building. The control of solar radiation, however, requires some different techniques to be employed. For most buildings the more serious condition occurs in winter when temperature differences of 100 F degrees or more may have to be contended with. Even with an air-conditioned building, there will seldom be a temperature difference in summer of more than 30 F degrees. With a cold storage building the situation will be entirely reversed and in some locations the outside temperature may never be as low as those inside such buildings.

There are two principal reasons for wishing to control the flow of heat through the building enclosure: to maintain the inside surface temperatures within satisfactory limits and to reduce the over-all operating cost of the building. Surface temperatures must be controlled in order to achieve the primary function of a building -- desirable inside conditions. If some degree of humidity is required in a building and if the desired value cannot be maintained because the moisture is condensed out of the room air on cold surfaces, then the building will have failed since it cannot perform its intended function. Similarly, if the objective is to maintain some degree of comfort for people or specialized equipment, this will be difficult if not impossible to achieve if heat is lost by radiation to a cold surface.

The second objective of reducing the over-all operating costs may at first sight appear to be outside the scope of this book. In so far as a discussion of the thickness of the insulation required to balance the cost of the insulation against the reduction in the heating costs is concerned this is true. It is sufficient to say that this balance depends on various factors including the cost of fuel, the cost of the heating system, the cost of supplying and installing the insulation, and the cost of any additional work needed to accommodate the insulation. It can also be seen that each additional inch of insulation installed gives a smaller saving than the previous one until a point is reached when the saving just equals the amortized cost of the last inch of insulation set in place. This is the economic limit. On the other hand, when one discusses the over-all operating costs of a building the discussions must include consideration of the cost of maintaining and repairing the fabric of the building. If failure to control the flow of heat satisfactorily leads to increased maintenance costs or to a reduction in the efficiency of operations inside the building then once again one can say that, in some respect at least, the building has failed.

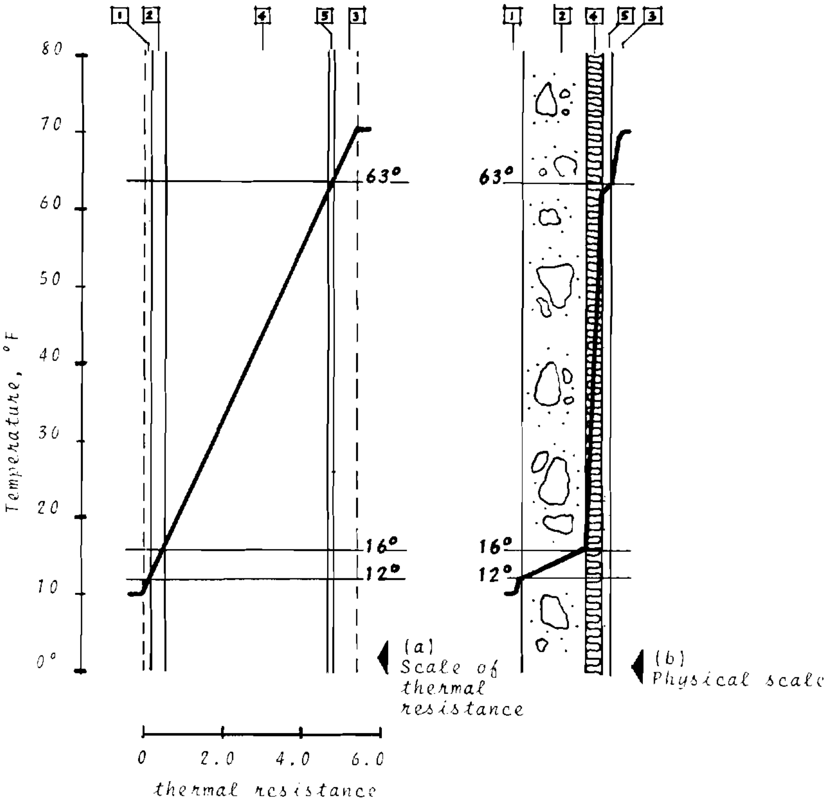
INSULATION

Old buildings had little or no insulation in the enclosure and so were poor both with regard to control of surface temperatures and economically. It is usual in modern buildings to improve both of these conditions by adding insulating material. Only relatively small amounts of insulation are needed to raise the surface temperature to a satisfactory value. In order to explore the effects of adding insulation to a wall let us consider the case of an industrial building with a precast concrete frame and with walls of precast concrete panels 4 in.



1 -- external air film
2 -- 4" precast concrete
3 -- internal air film

Fig. IV.1 Temperature gradient through uninsulated concrete wall



1 -- external air film
2 -- 4" precast concrete
3 -- internal air film
4 -- 1" insulation
5 -- 3/4" plaster

Fig. IV.2 Temperature gradient through a concrete wall, insulated on the inside

TABLE IV. 1

CALCULATION OF TEMPERATURE GRADIENT -- UNINSULATED CONCRETE WALL

	Thickness n, in.	Conductivity, k	Conductance $C = \frac{k}{n}$	Resistance $R = \frac{\text{one}}{C}$	Temperature Drop, °F	Interface Temperature, °F
						70° Inside Air
Internal Air Film	-	-	1.46	0.68	34	
						36
Precast Concrete	4	12.0	3.00	0.33	17	
						19
External Air Film	-	-	6.00	0.17	9	
						10° Outside Air
TOTAL THERMAL RESISTANCE				1.18		

Drop in temperature through any component

$$= \frac{\text{Difference between outside and inside air temperatures}}{\text{Total Thermal Resistance of Wall}} \times \text{Thermal Resistance of Component}$$

For example, drop in temperature through concrete $= \frac{60}{1.18} \times 0.33 = 17°F$

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thick, firstly with no insulation and then with the addition of the relatively small amount of 1 in. of foamed plastic insulation. Thermally the uninsulated wall consists of three parts: the internal and external air films and the 4 in. of concrete (Fig. IV. 1). The temperature gradient can either be calculated following the arithmetic method given in Chapter III or drawn by the graphical method. The arithmetical calculation is shown in Table IV. 1 for an inside temperature of 70°F and the relatively mild outside temperature of +10°F. This figure corresponds approximately to the mean January temperature at such places as Quebec City, Thunder Bay and Calgary; it also approximates the winter design temperature on a 10 per cent basis at Toronto and Halifax. Thus it is by no means an extreme figure and can be considered as acting for reasonably long periods of time.

From Table IV. 1 it can be seen that the inside surface of the wall is at 36°F, only slightly above freezing point. If condensation on the wall at this point is to be avoided, the maximum relative humidity that can be tolerated in the room air is 29 per cent, based on the assumption that all paths of heat flow through the wall have the same resistance. At any location where this is not true, the surface temperature and corresponding maximum permissible relative humidity may well be considerably lower, as will be discussed later.

Now let us suppose that an attempt has been made to improve the thermal properties of the wall by adding 1 in. of foamed plastic insulation to the inside face of the concrete panel. To protect the insulation a hard surface is required and so 3/4 in. of plaster is applied over the insulation (Fig. IV. 2). The calculation for this revised situation is given in Table IV. 2 from which it can be seen that the inside surface of the plaster has a temperature of 63°F. Under these conditions the maximum permissible relative humidity in the room at this point has risen to 78 per cent. In all probability these revised conditions will be satisfactory when one considers the centre of the wall where the assumed conditions of parallel heat flow apply.

TABLE IV. 2

CALCULATION OF TEMPERATURE GRADIENT -- CONCRETE WALL INSULATED ON INSIDE

	Thickness n, in.	Conductivity k	Conductance $C = \frac{k}{n}$	Resistance $R = \frac{\text{one}}{c}$	Temperature Drop, °F	Interface Temperature, °F
						70° Inside Air
Internal Air Film	-	-	1. 46	0. 68	7	
						63
Plaster (sand aggregate)	3/4	-	7. 70	0. 13	1	
						62
Foamed Plastic Insulation	1	0. 24	0. 24	4. 17	46	
						16
Precast Concrete	4	12. 0	3. 00	0. 33	4	
						12
External Air Film	-	-	6. 00	0. 17	2	
						10° Outside Air
TOTAL THERMAL RESISTANCE				5. 48		

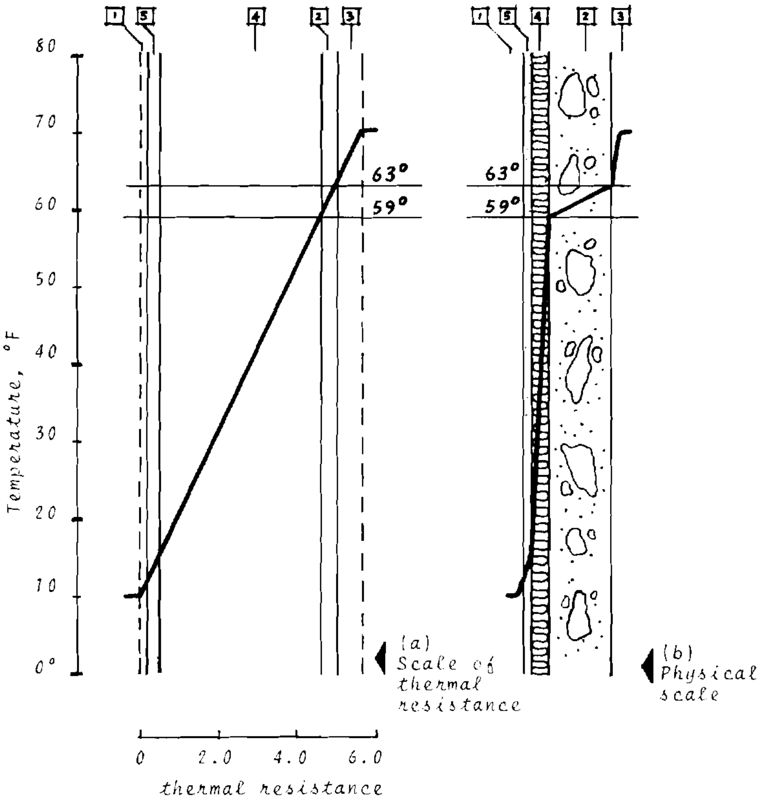
Drop in temperature through any component

$$= \frac{\text{Difference between outside and inside air temperatures}}{\text{Total Thermal Resistance of Wall}} \times \text{Thermal Resistance of Component}$$

For example, drop in temperature through insulation $= \frac{60}{5.48} \times 4.17 = 46°F$

Two additional points are illustrated by this example. In the first place it will be seen that the total thermal resistance of the wall has been increased more than fourfold by the addition of this small amount of insulation. This in turn suggests that there may be economic advantage in adding a larger thickness of insulation but this would have to be checked by the type of analysis outlined earlier. In the second place, although the inside surface temperature has been raised significantly, the concrete panel has become considerably colder. This stems from the fact that the purpose of insulation is to slow down the flow of heat from one location to another.

It has been stressed repeatedly in this text that the fundamental purpose of the building enclosure is to separate the controlled internal conditions from the uncontrolled external ones. In doing so it follows that the temperature of the inside surface of the enclosure will be reasonably close to the room temperature and the temperature of the outside surface will be reasonably close to the outside temperature. Neglecting for the moment the effects of solar radiation on the outside surface temperature, it can be said that the two surface temperatures will differ from the air temperatures to the extent that the thermal resistances of the air films form a large or a small proportion of the total resistance of the enclosure. This is shown by the calculation in Tables IV.1 and IV. 2.
If the total thermal resistance of the enclosure is increased by adding more and more insulation, the difference between surface and air temperatures will differ less and less. If it were possible to increase the insulation to an infinite amount then all components of the enclosure outside of the insulation would have the same temperature as the outside air once they had had sufficient time to warm up or cool down following a change in the weather. Another way of looking at this situation is to say that no



1 -- external air film
2 -- 4" precast concrete
3 -- internal air film
4 -- 1" insulation
5 -- 3/4" stucco

Fig. IV.3 Temperature gradient through a concrete wall, insulated on the outside heat would escape from a heated building in cold weather to warm up the outer components of the enclosure. In practice since an infinite amount of insulation is an impossibility some heat will escape and the outer components of the enclosure will be warmer than air temperature. Conversely, the inner components will be cooled to slightly below room temperature. In hot weather the situation in a cooled building will be reversed: the outer components will be slightly below outside air temperature and the inside slightly above room temperature. As the room temperature is controlled to some extent but the outside temperature is not, it follows that the outer components will be subjected to a wider range of temperatures than will the inner components. Thus if we do not wish to subject a component to a wide range of temperatures it is logical to position the insulation outside of that component.

To return now to a consideration of the insulated concrete panel wall there are several possibilities for problems to develop. Since the panel will follow, more or less, the fluctuations in external air temperature it will also expand and contract considerably. The plaster on the inside face, however, will not be subjected to the same fluctuations and will not have the same degree of expansion and contraction. The resulting differential movement between the two components must be accommodated in some way. If the two are rigidly connected then it is probable that the plaster will crack; if the connection through the insulation is sufficiently flexible, the plaster will probably remain intact. Other problems could arise however because of the interaction between the concrete frame and the wall panel.

If the wall panel is an infill panel between the frame members then these members will form thermal bridges through the insulation. Consideration of thermal bridges will be left until later but it is clear that the outside surface of the frame will be colder than the inside leading to some additional stressing of the frame which should be considered by the structural engineer. Because of the drain of heat past the insulation the surfaces of the frame exposed to the room will be cooler than the plaster surface of the wall and the relative humidity that can be maintained will thus be reduced. Relative movements between the frame member and the panel will make it difficult to maintain a weathertight seal in this joint.

If the wall panels are not infill panels but are carried outside of the structural frame there is often a space between the frame and the panel in which insulation cannot be installed once the panel has been erected but in which air currents can circulate. Room air is then brought into contact with the inside face of the panel which is now very cold because of the insulation on the remainder of its surface. Severe condensation will result unless the relative humidity in the room is lower than the 29 per cent which the uninsulated panel could withstand. Because of the low temperature of the panel (about 16° F) condensation will be as hoar frost which will all be released as water at one time when it melts following a rise in temperature. It is difficult to seal this space from the room air because of the relative movements which will open various cracks. It is also difficult to make an effective and durable seal between the concrete panels because of the expansions and contractions which will take place, leading to problems of rain penetration and excessive air leakage. Other problems can arise with any windows mounted in the concrete panels because of excessive cooling of the edges of the glass. Thus the more we examine the situation the more it becomes apparent that while one problem may have been solved by adding insulation onto the inside surface of the concrete panel, many others have been compounded.

What can we do to improve this situation? An examination of the various potential problems will show that most of them arise either because the concrete panel is now colder than before or because if follows the fluctuations of the outside temperature more closely and so has a greater expansion and contraction. If the panels are kept in the warmer and more stable conditions inside the building then these problems would disappear. But how can one bring the wall inside the building? Thermally this can be achieved simply by placing the insulation on the outside of the panel. If this is done then it must be protected by some suitable hard opaque covering both from the deteriorating effect of the sun and from physical damage. Let us assume a stucco covering which in many respects can be considered comparable to the plaster applied to the inner surface in the previous case (Fig. IV. 3). The thermal gradient through the wall can be calculated as shown in Table IV. 3.

Comparing these results with those in Table IV. 2 it will be seen that, apart from the small difference between the thermal properties of stucco and plaster, all the figures are essentially the same except for the all-important ones in the last column. The inside surface temperature remains unchanged at 63° F which, as noted before, will support a relative humidity of 78 per cent. This confirms the point that as far as the inside surface temperature is concerned it is of no consequence

TABLE IV. 3

CALCULATION OF TEMPERATURE GRADIENT --
CONCRETE WALL INSULATED ON OUTSIDE

	Thickness n, in.	Conductivity k	Conductance $C = \frac{k}{n}$	Resistance $R = \frac{\text{one}}{c}$	Temperature Drop °F	Interface Temperature °F
						70° Inside Air
Internal Air Film	-	-	1.46	0.68	7	
						63
Precast Concrete	4	12.0	3.00	0.33	4	
						59
Foamed Plastic Insulation	1	0.24	0.24	4.17	45	
						14
Stucco	3/4	5.0	6.67	0.15	2	
						12
External Air Film	-	-	6.00	0.17	2	
						10° Outside Air
TOTAL THERMAL RESISTANCE				5.50		

Drop in temperature through any component

$$= \frac{\text{Difference between outside and inside air temperatures}}{\text{Total Thermal Resistance of Wall}} \times \text{Thermal Resistance of Component}$$

For example, drop in temperature through insulation $= \frac{60}{5.50} \times 4.17 = 45°F$

where the insulation is placed. Now, however, the insulation encloses the whole building and the frame and panels will be in practically the same relatively stable thermal environment. Movements between the panels and the frame, and between adjacent panels will be reduced to negligible proportions. It follows that if the necessary air barrier to keep the wind out is still formed by the panels and the joints between them (rather than the stucco), then these joints will be less severely stressed and so less subject to failure. It is no longer of any consequence that room air can circulate in the space between the structural frame and the panels because the panel is now as warm at that point as at any other. Any windows mounted in the panels will no longer have their edges cooled and so will be less susceptible to breakage from thermal stressing. Possibly one might contend that although the concrete panels are now in a more stable thermal regime the stucco is in a very unstable one, and that it will be subjected to more sever strains than was the plaster on the inside and so will be liable to crack very badly permitting the rain to penetrate the wall. Thermally there is some truth in this argument but there are ways of overcoming these difficulties. In the discussion (Chapter V) of control of rain penetration it will be seen that it is not necessary to have a completely airtight and impervious external skin on a building; in fact it is not even desirable. Thus we can say that the simple expedient of changing the position of the insulation from inside to out with the substitution of the comparable material stucco for plaster has greatly reduced the possibility of thermal problems in this wall.

Insulating a Basement

In calculating the heat loss through a basement wall adding insulation can be considered as equivalent to increasing the length of the heat flow path, i. e., the insulation can be converted to an equivalent thickness of soil. As far as heat loss is concerned it makes no difference where this added length is inserted along the heat flow path, and insulation laid on the surface of the ground is just as effective as the same amount placed on the inside surface of the wall. The temperature conditions in the wall and the soil will, however, be affected because everything outside the insulation will become colder.

Applying insulation to the inside face of the wall makes both the wall and the soil colder. The lower temperatures in the soil may pose problems of frost heave, if the soil is frost susceptible, and of plant growth with some types of plants. Moving the insulation to the outside of the basement wall will keep the wall warm, but has no effect on the soil temperature. The insulation, if of foamed plastic, needs no protection below grade, but near and above the surface it must be covered to protect it from damage and for aesthetic reasons. Should there be any frost heave this covering may be damaged. Laying the insulation horizontally just below the ground surface keeps the soil warm and thus solves the frost-heave problem, but it requires that only shallow rooted plants be planted in the thin layer of soil above it.

A final word of caution must be added about the effect of a concrete block wall. In the previous discussion a solid concrete wall has been assumed in which there is no air movement. With a concrete block wall this is not true and convection currents can circulate within the wall. As part of the wall will be exposed above grade the air in the core space of the block will be cooled and will sink by convection, displacing the warmer air in the lower parts of the wall. This constitutes an additional method whereby heat is lost from the basement and the lower portions of the wall will thus be cooled. In such a case consideration should be given to insulating the outside of the wall to minimize this effect or, if this is not practicable, insulation on the inside face should be carried down to floor level.

A problem often encountered in an occupied basement is that the floor feels cold. To raise the temperature of an unheated floor it is necessary to increase the thermal resistance of the heat flow path which was shown in Figure III. 8. This path is, however, already a long one, and adding insulation (which may be considered the equivalent of lengthening it) will not have any marked effect. Furthermore, the use of insulation under the floor is rendered ineffective by two other factors. One, the high heat capacity of a floor will produce a sensation of cold until the body has remained stationary on that part of the floor long enough to warm it; and second, once the heat reaches a layer of high conductivity it can flow laterally, increasing the amount of material to be warmed.

To restrict the flow of heat from the body into the floor requires that an insulating material be placed between the body and the first layer of material that is of high conductivity. The most economical way for an adult to provide the necessary insulation is to wear thicker soled footwear. For children who may play on the floor this is not a practical solution and some form of carpeting should be provided. If there should be a problem of moisture rising through the floor, then the type of carpeting must be chosen with care.

THERMAL BRIDGES

The previous discussion about the significance of the position of the insulation has been based almost entirely upon considerations of uniform parallel heat flow paths through the enclosure although it was intimated that this is not always the case. Now we must turn our attention to situations where all heat flow paths do not have the same thermal resistance. Problems usually arise when there are special paths through the enclosure that have lower resistance and through which the heat flows away more rapidly producing cold spots on the interior. Because of this increased heat flow these situations can be compared to, say, a bridge over a river which permits a more rapid passage of traffic from one side to the other and so they are generally referred to as thermal bridges across, or through, the insulation.

Practical construction cannot avoid such situations. In the previous example of the insulated concrete wall where the insulation was on the inside, the panel had to be held onto the structural frame, usually by means of steel connections, and these connections formed thermal bridges. When the insulation is moved to the outside of the concrete panel these connections no longer bridge the insulation and so that problem is solved. However, there is still the stucco on the outside which must somehow be held onto the wall panels. Thus we have in effect exchanged one problem for another and the question to be resolved is whether the new problem is easier to solve than the old one. Have we made things better or worse by the change? To answer this question we must know

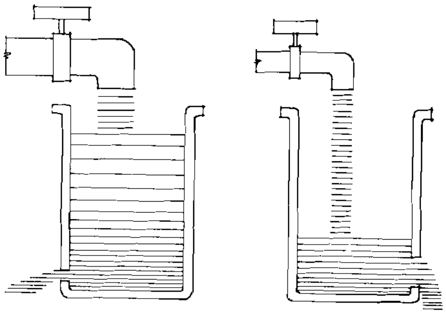
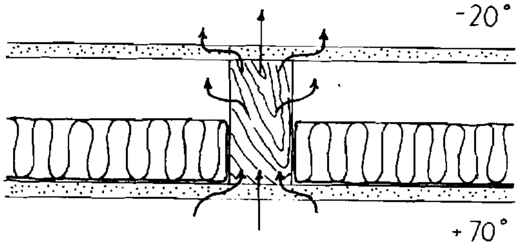


Fig. IV.4 Analogy showing how temperature of a thermal bridge is related to the relative ease with which heat can enter and leave



Fiv. IV.5 Thermal bridge formed by a wood stud

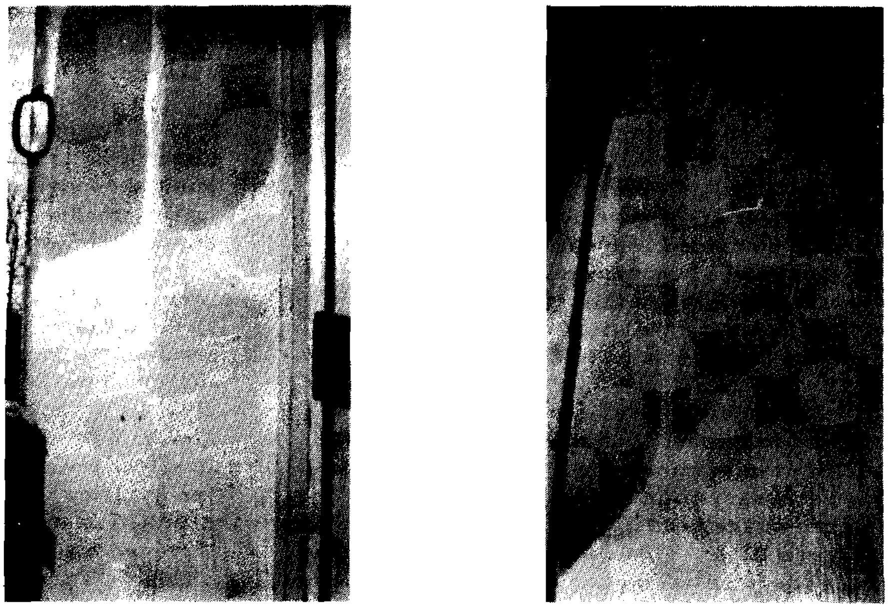


Fig. IV.6 Effect of thermal bridge formed by a wood stud shown by frost pattern on outside something of the characteristics of thermal bridges.

The analogy between a thermal bridge and a bridge carrying traffic across a river, in addition to showing the increased flow over, or through, the bridge, also illustrates two other important characteristics of thermal bridges. Firstly, traffic will be drawn toward the bridge from other locations along the banks of the river, will cross over the bridge where the crossing is easy and spread out again on the other side. Some further reflection on common experience will lead to the conclusion that there will be a traffic jam on the bridge if more traffic is trying to get on than can get off, that is, if the access roads at the approach side are better or more numerous than the exit roads at the other side. Secondly, it can be appreciated that even though both the access and exit roads are well able to handle the volume of traffic, if the bridge itself is not big enough to do so there will still be a traffic jam on the approach side. If the narrow one-lane bridge which causes this tie-up is replaced by a four-lane bridge then the situation is relieved and the traffic can flow easily.

Thus we can see that because of the bridge there will be more cars at the location of the bridge than at other places along the river bank where there are, say, only primitive ferries to carry them across. We can also see that there will be a greater density of cars up to the point which exercises the greatest restriction on their free passage than there will be beyond that point.

A second analogy that may be helpful in understanding the behaviour of thermal bridges is that of two cans being filled with water. Suppose that we have two cans of the same size which have water running into them, one from a big hose and the other from a small one. Now suppose that the can being filled by the big hose has a small hole in the bottom and the other has a big hole in the bottom. It is clear that the can with the big hose and the small hole will fill up with water to a greater depth than will the can with the small hose and big hole (Fig. IV.4). Thus a thermal bridge will be relatively warm if the means of feeding heat into it are greater than the means of leading it out, and relatively cold if the situation is reversed.

With these analogies in mind let us now consider thermal bridges in building construction. In the first instance consider a normal wood stud wall with 1/2-in. plasterboard on each face and with 2-in. semi-rigid insulation (nominally giving 8 thermal resistance units, i.e. R 8 insulation) between the studs and close to the warm side of the wall (Fig. IV.5). The temperature gradient through the centre of the stud space can be calculated using the unidirectional heat flow method. Such a calculation is shown in Table IV.4 for an inside temperature of +70° F and an outside one of -20° F. It can be seen that the face of the plasterboard has a temperature of 65° F. Similarly the temperature gradient through the stud can be calculated as shown in Table IV.5. In this case the total thermal resistance has been reduced and the surface temperature over the stud has dropped to 60° F.

These are calculated values, however, and it is to be expected that in reality slightly different values will be obtained. An 8-ft-square panel of this construction was made and tested in the laboratory; the measured temperature in the centre of the stud space was found to be 65° F, as calculated but that over the stud was 61.5° F. This increase from the calculated value can be attributed to lateral heat flow in the plasterboard, but, because of the small difference in temperature this heat flow would affect the temperatures of the plasterboard for only a very short distance on each side of the stud. This situation is not serious and except for some dust marking over the stud caused by the temperature difference should cause no problems. On the outside the increased heat flow promoted through the wood stud will raise the surface temperature of the sheathing over the stud relative to that over the insulated stud space. As can be seen from the calculated values in Tables IV.4 and IV.5 this may only be a degree or two but under the right conditions this can make the difference between condensation on the outside surface or not as is shown in Fig. IV.6. These photographs are actually of an outside test hut with no internal finish other than a polyethylene sheet, 2 in. of mineral wool insulation and plywood sheathing. Such condensation is only transient and causes no problems.

Now let us replace the wood studs by heavy channel steel studs (Fig. IV.7 (a)). This changes the picture completely for the temperature of the plasterboard over the stud has dropped to 44° F although the temperature on the surface of the plasterboard in the centre of the stud space is still unchanged at 65° F. With a room temperature of 70° F the relative humidity must be below 39 per cent if condensation is not to occur on the wall over the stud. In many situations this is not an excessively onerous requirement but in others it could be; even in houses relative humidities of over 40 per cent can occur, especially in bathrooms, kitchens and laundry areas. It is probable that dirt marking will occur in too short a time to be acceptable and so something

TABLE IV. 4
CALCULATION OF TEMPERATURE GRADIENT THROUGH AN INSULATED STUD WALL -- THROUGH THE CENTRE OF THE STUD SPACE

	Resistance, R	Temperature Drop, °F	Interface Temperature °F
			70°F Inside Air
Inside Air Film	0.68	5	
			65
1/2" Plasterboard	0.45	4	
			61
2" Insulation k = 0.25 $R = \frac{2.0}{0.25}$	8.00	66	
			-5
1 5/8" Air Space	1.26	10	
			-15
1/2" Plasterboard	0.45	4	
			-19
Outside Air Film	0.17	1	
			-20°F Outside Air
TOTAL THERMAL RESISTANCE	11.01		

Drop in temperature through any component

$$= \frac{\text{Difference between outside and inside air temperatures}}{\text{Total Thermal Resistance of Wall}} \times \text{Thermal Resistance of Component}$$

For example, drop in temperature through insulation $= \frac{90}{11.01} \times 8.00 = 65°\text{F}$

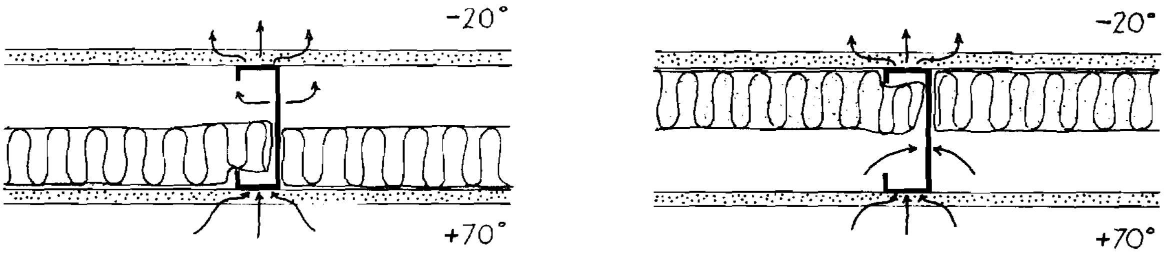
TABLE IV. 5
CALCULATION OF TEMPERATURE GRADIENT THROUGH AN INSULATED STUD WALL - THROUGH THE STUD

	Resistance, R	Temperature Drop, °F	Interface Temperature °F
			70°F Inside Air
Inside Air Film	0.68	10	
			60
1/2" Plasterboard	0.45	6	
			54
3 5/8" Wood	4.55	65	
			-11
1/2" Plasterboard	0.45	6	
			-17
Outside Air Film	0.17	3	
			-20°F Outside Air
TOTAL THERMAL RESISTANCE	6.30		

Drop in temperature through any component

$$= \frac{\text{Difference between outside and inside air temperatures}}{\text{Total Thermal Resistance of Wall}} \times \text{Thermal Resistance of Component}$$

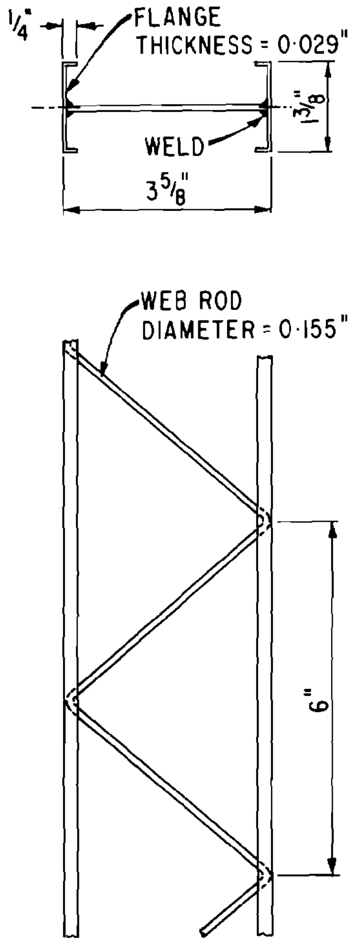
For example, drop in temperature through wood $= \frac{90}{6.30} \times 4.55 = 65°\text{F}$



(a)

(b)

Fig. IV.7 Thermal bridge formed by a steel stud



OPEN-WEB (WELDED RODS)

Fig. IV.8 Open web steel stud having reduced paths for conduction of heat should be done to improve the situation: the question is, what?

From the analogy of the traffic flow it is clear that if we increase the means by which heat can get into the thermal bridge and reduce the means for it getting out then there will be a greater amount of heat (density of traffic) in the bridge itself. Let us therefore expose more of the steel stud to the warm side conditions and less to the cold by moving the insulation from the warm side of the stud space to the cold (Fig. IV. 7(b)). This location for the insulation may not be acceptable for other reasons as will be discussed in Chapter VI. For the moment, however, let us make the change to illustrate a point with respect to thermal bridges. Under the same test conditions of 70° F on the warm side and -20° F on the cold this change raised the surface temperature of the plasterboard over the stud to 52° F which allows a relative humidity of 53 per cent to be maintained without condensation. This may be a satisfactory humidity level but it should be noted that the over-all heat transmission coefficient (the U value) for the wall with the steel studs is still higher at 0. 152 Btu/(hr) (sq ft) (° F) than was the wood stud wall at 0. 098 Btu/(hr) (sq ft) (° F) because of the conductivity of the steel. However, a further improvement can be made by restricting the outflow of heat at the cold end still further by replacing the relatively conductive plasterboard with a 1-in. thickness of fibreboard. When this is done the surface temperature over the stud is now 59. 5° F which is only 2° lower than that over the wood stud when the wood stud has the 2 in. of insulation towards the warm side of the stud space. The U value also is now closer to the value for the wood stud wall at 0. 107 Btu/(hr) (sq ft) (° F).

The technique of adding 1 in. of fibreboard insulation on the cold side of the wall, while it illustrates a point about restricting the flow of heat out of a thermal bridge, is more akin, however, to the technique of placing all the insulation on the outside of the wall as was discussed earlier in relation to the concrete wall. If all the insulation were removed from the stud space and equivalent thermal resistance added outside of the studs then there would be no significant difference between the thermal performance of the wood and the steel studs for neither of them now forms a thermal bridge. Also it is probable that another thermal bridge would be introduced through the insulation in its new position by whatever is provided to support the exterior sheathing in its new position. These discussions are however digressing from stud construction which essentially uses the studs to support vertical loads and the interior and exterior sheathing. Let us therefore consider what else might be done to reduce the thermal bridge effect of the studs while still using them in a more or less conventional manner.

Returning once more to the analogy of traffic flowing over a bridge, if the width of the bridge (i. e. its flow capacity) is reduced then the traffic will be backed up in the approach roads. Similarly with steel studs, if their cross-sectional area for heat flow is reduced then the thermal bridge effect is reduced and the warm-side surface temperature should be raised. Let us therefore replace the heavy channel stud with an open web stud made up of welded rods (Fig. IV. 8). Under the same test conditions as before with 1/2-in. plasterboard on each face and the insulation on the cold side of the stud space the surface temperature over this stud is 61° F as compared with 52° F for the heavy channel stud and 61. 5° F for the wood stud with the insulation on the warm side of the stud space. Thus the steel stud construction has been made to give much the same surface temperature conditions as the conventional wood stud wall although its U value of 0. 120 is still not as good.

Before leaving this discussion of the effects of various changes on the thermal bridge effect of a steel stud it should be pointed out that the values quoted are for particular types of construction under particular test conditions. The important factor is therefore not to use these particular values in all circumstances but rather to use the processes of reasoned thought which have been illustrated by reference to them. For example, since the warm-side surface temperature differential of the steel stud wall has been improved by moving the insulation from the warm side to the cold side of the stud space, thus exposing more of the stud to warm conditions and less to cold, would not the same effect be achieved with the wood stud? The answer of course is yes; when this was done no temperature difference could be measured between the surface over the stud and in the centre of the stud space. Furthermore, if one wishes to improve the over-all U value of the wall the stud space can be filled with insulation. If this is done then one no longer has the option of changing the position of the insulation and other steps must be taken if it is necessary to mitigate the effect of the thermal bridge.

The calculated value of the thermal gradient through the wood stud using the simple unidirectional heat flow method can only be applied to a relatively uniform block of material This method cannot be applied to a material of variable cross-section, such as the welded-rod steel stud. There is, however, an adaptation of the calcu-

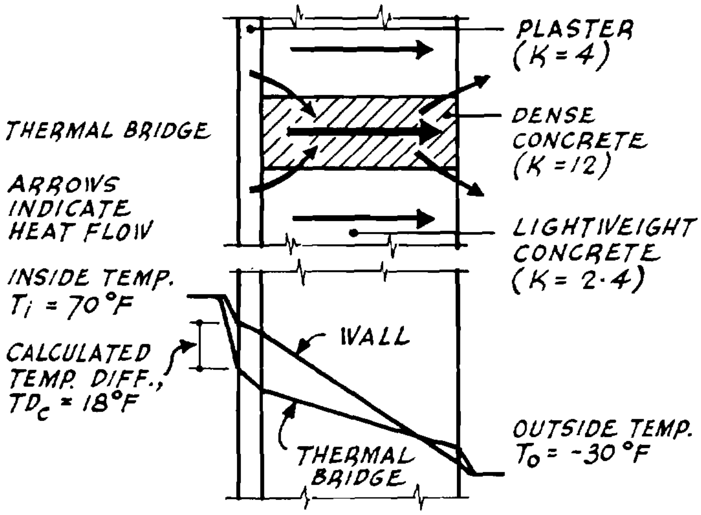


Fig. IV.9 Calculated temperature gradients through both the wall and the thermal bridge

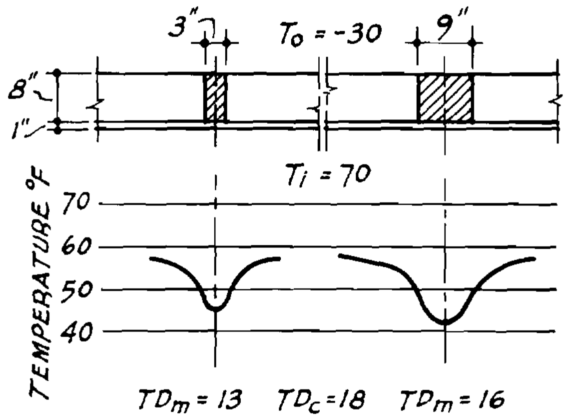


Fig. IV.10 Measured surface temperatures on a wall and over two thermal bridges lation called the zone method which attempts to take into account these complicating factors. It is not proposed to discuss this technique in detail but the essence of it is as follows. Firstly, a zone surrounding the thermal bridge is determined based upon the width of the thermal bridge and the depth at which it is embedded from each surface. Outside of this zone the simple heat flow calculation is applied. Within the zone, whenever at any given depth within the wall there are parallel heat flow paths of different conductivity, these two paths are combined by adding area conductances, i. e. A x C. The resistance of this layer of combined materials is given by the reciprocal of the sum of the area conductances, i. e. $\frac{1}{A \times C}$. The resistances of the various layers obtained in this way are then added together in the normal way for elements in series to give the over-all resistance for that area of wall. This method is explained in greater detail in the Handbook of Fundamentals of the American Society of Heating, Refrigerating and Air-Conditioning Engineers. When it was applied to the stud walls which we have been discussing it was found to give over-all thermal resistances that were comparable to the measured values for the wood stud wall but 4 to 15 per cent higher for the steel stud walls. The calculated temperature differences between the wall surface over the stud and in the centre of the stud space were close to the increased values for only those walls that had the insulation located on the warm side. Thus this slightly more complicated method of calculation, although better than the simple one, has only limited value in assessing the effect of a thermal bridge.

The previous discussion of the thermal bridging effect of steel studs should not be taken as a criticism of steel studs nor a recommendation for wood studs for both have their appropriate uses and economic advantages in different circumstances. In order to clarify further the thermal bridge effect, a few more examples will be presented based upon work carried out at the Centre Scientifique et Technique du Bâtiment in Paris. A difference between inside and outside air temperatures of 100°F is assumed in all cases and the surface temperatures have been calculated on the basis of unidirectional heat flow as was done for the wood stud. The difference between the temperature over the thermal bridge and the temperature on the wall away from the thermal bridge is designated TD_c for the calculated values and TD_m for the measured values. Values for TD_c or TD_m for air temperature differences other than 100°F can be obtained by proportion.

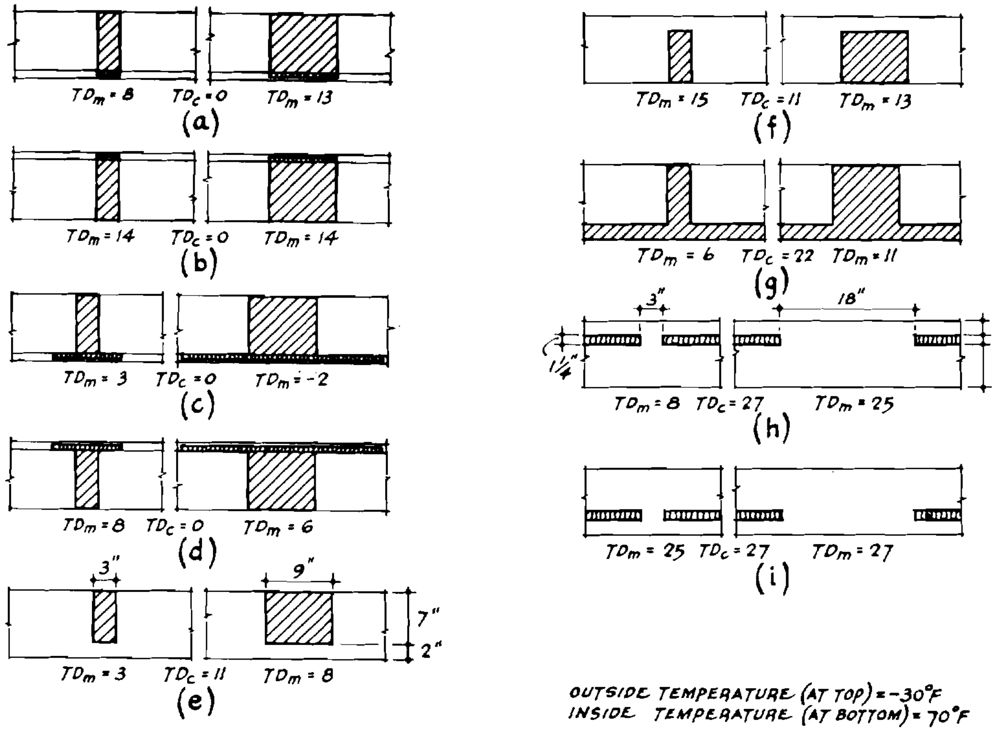
Figure IV. 9 represents a dense conrete structural member [thermal conductivity, k, of 12 Btu per (hour) (sq ft) (°F per inch)] that bridges a lightweight concrete wall (k = 2. 4), except for the interior plaster coating. There is a calculated difference in temperature (TD_c) of 18°F. It will be noted that the bridge is colder than the wall toward the inside and warmer than the wall toward the outside. In Figure IV. 10 the measured inside surface temperature pattern for the construction in Figure IV. 9 is given for two widths of the structural member. It may be noted that TD_m is less than TD_c for both widths or member, and that TD_m approaches TD_c as the width increases.

Figure IV. 11(a) shows thermal bridges similar to those of Figure IV. 9, with insulation just covering the inner surface of the members to a thickness that will ensure the same calculated U-value at the member as that of the rest of the wall. In this case $TD_c = 0$, but measurements show that $TD_m = 8$ for the narrow bridge and $TD_m = 13$ for the wide bridge. With insulation placed in a similar way on the outer surface of the members (Figure IV. 11(b)) $TD_m = 14$ for both. Insulation thus placed is not very effective in raising the minimum surface temperatures, although the (surface) temperature patterns are altered.

If insulation is placed on the inside, the structural members are colder than if there was no insulation, and toward the inside there is greater lateral heat flow into the member from the adjacent wall. Minimum surface temperatures thus occur on the wall adjacent to the member, and the temperature over the member is increased relative to the uninsulated case. With insulation on the outside, lateral heat flow out of the member into the adjacent wall (in the outer part of the wall) largely nullifies the effect of the insulation.

If insulation is extended on both sides of the members by the width of the member (Figures IV. 11 (c) and (d)) the surface temperatures are improved appreciable, particularly with interior insulation. The negative value of TD_m indicates that the surface over the bridge is warmer than the surface of the wall. To reduce TD_m to zero using exterior insulation would require that the insulation overlap the members by a considerable amount. It will be noted that with the insulated members the actual inside surface temperatures can be lower than those given by one-dimensional heat flow calculations (TD_m is greater than TD_c), in contrast with the results for the thermal bridges in Figure IV. 10.

With partial thermal bridges in masonry, where the structural members do not extend



OUTSIDE TEMPERATURE (AT TOP) = -30°F
INSIDE TEMPERATURE (AT BOTTOM) = 70°F

Fig. IV.11 Calculated and measured temperature differences between the surface temperature on a wall and over various thermal bridges

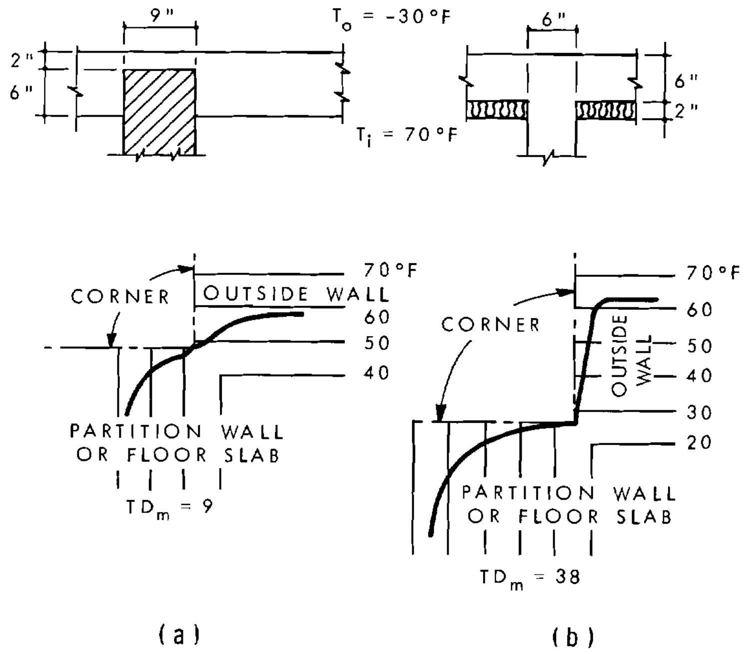


Fig. IV.12 Measured surface temperature distribution in a corner at an intersection of a partition wall or floor slab with an exterior wall completely through the wall, the wall material between the member and the wall surface acts in part as insulation. With the member placed toward the outside (Figure IV. 11 (e)) lateral heat flow in the wall material on the warm side raises the surface temperature over the bridge and TD_m is less than TD_c. In contrast, with the structural member placed toward the inside (Figure IV. 11 (f)) the surface of the bridge is colder and TD_m is larger than TD_c, as it is with exterior insulation.

This shows once more that one means of improving surface temperatures over a thermal bridge is to induce lateral heat flow on the warm side of the wall into the region of the bridge. The thermal bridges of Figure IV. 11 (g) are similar to those of Figure IV. 10, except that the plaster coating has been replaced by 2 inches of dense concrete; TD_m is less, even though TD_c is greater.

A further example of the effect of lateral heat flow on surface temperature distribution is given in Figures IV. 11 (h) and (i). These illustrate a panel consisting of two concrete slabs (k = 12) with foamed polystyrene insulation between (k = 0. 24); examples of two widths of joint are given. The TD_c value for the panel is high because the U-value of the section at the joint is much higher than that at the insulation. With a narrow joint, however, actual surface temperature variations are greatly reduced by lateral heat flow from the heavy slab on the warm side of the insulation into the joint (Figure IV. 11 (1)). This lateral heat flow does not extend far enough into the wider joint to alter significantly the temperatures at the centre. If the slabs are reversed so that the narrow slab is on the inside (Figure IV. 11 (i)), lateral heat flow in the inner slab is greatly reduced and that in the outer slab correspondingly increased. This has the effect of lowering the surface temperatures over the joints.

Thermal weaknesses often occur at wall-floor or wall-partition intersections. Figure IV. 12(a) represents a heavy concrete slab intersecting an exterior wall having the same thermal properties as the lightweight concrete wall shown in Figures IV. 9 and IV. 10. This will be recognized as similar to the partial thermal bridge of Figure IV. 11(f), but with the bridge extended into the building where it can pick up heat which will be fed into the thermal bridge. There is a drop in wall surface temperature towards the corner but in this case TD_m = 9° F compared with 13° F for the partial bridge in Figure IV. 11 (f). With the partition wall slab extended to the outside of the exterior wall TD_m = 11° F.

In Figure IV. 12(b) a heavy concrete slab (k = 9) bridges insulation (k = 0. 22) placed over the inner surface of the wall. The temperature at the corner is greatly reduced in relation to the rest of the exterior wall and TD_m is very large. The problem is further aggravated if the floor slab or partition is allowed to project on the exterior, for example, to form a balcony slab. The fin formed by the projection drains heat from the wall and correspondingly lowers the inside surface temperature. The problem might be overcome by insulating both faces of the slab or partition inside the building for a sufficient distance from the wall, until the effect of the heat loss would no longer affect the surface temperature of the exposed surfaces. This is not always practical or even possible, and it would result in even lower temperatures behind the insulation at the intersection. Better results could be obtained by insulating the exterior surfaces.

The wall temperature pattern at the intersection of exterior walls and partitions will be distorted even if the partition does not extend into the wall. This is due in part to the reduced air convection in the corner that lowers the surface temperature there. It is also due to the influence of the partition on heat flow into that part of the wall that it covers. If the partition is of low conductivity (lightweight masonry) it will reduce heat transfer into the wall and this, combined with the reduced air convection, may cause a significant lowering of the wall surface temperatures at the corner. The exterior corner of a building also will experience reduced wall surface temperatures because of both the reduced convection on the inside and the increased exposed surface on the outside.

Thermal Breakage of Windows

The breakage of panes of glass in some double-glazed windows is a problem that may result from some aspects of thermal bridges. The whole purpose of multiple glazing is to reduce the heat flow through the window and to raise the surface temperature of the glass exposed to room conditions both to increase comfort and raise the humidity level that can be maintained before condensation can form on it. Factory-sealed multiple-glazing units require a spacer at the edges both to set the required distance between the panes of glass and to assist in making the seal. This spacer, which is often of metal, acts as a thermal bridge through which heat drains from the edge of the warm inner pane to the cold outer pane. Thus the edge of the inner pane is colder than the centre which is not subjected to the same heat loss. It therefore tends to contract relative to the centre and so is placed in tension. Breakage occurs when the tensile stress exceeds the edge

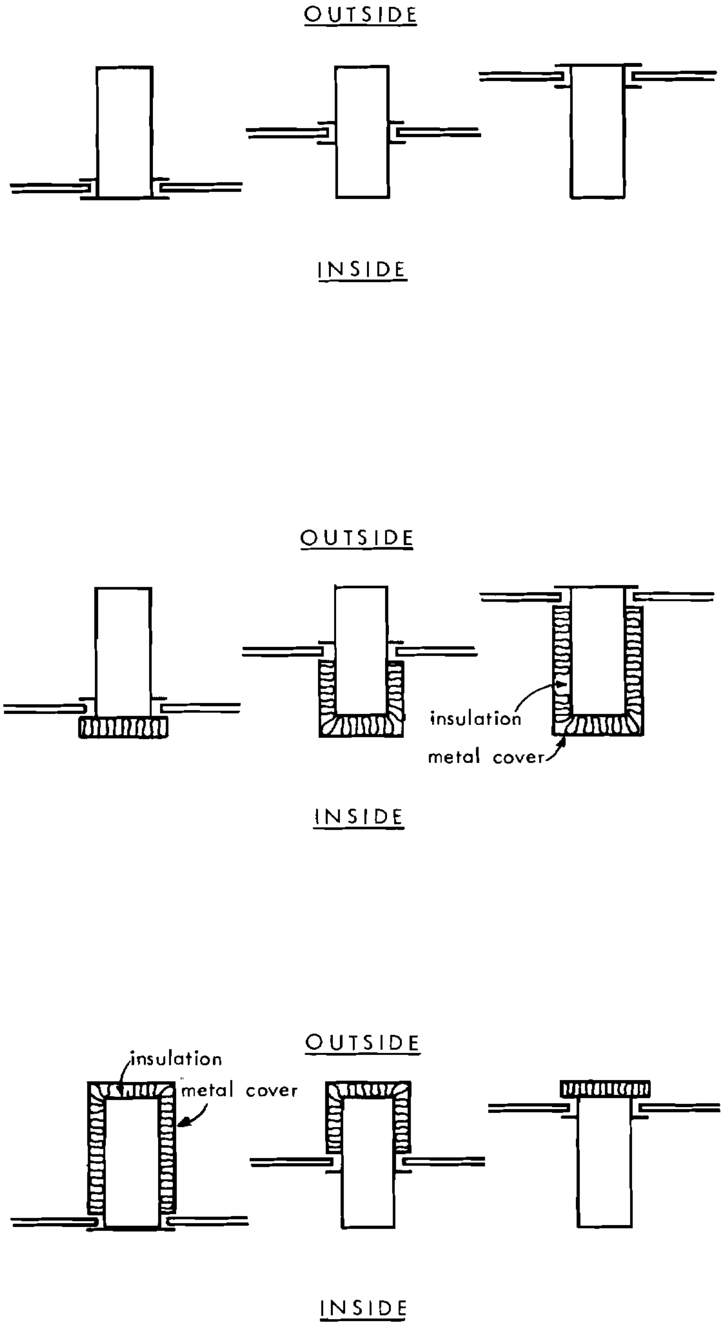


Fig. IV.13 Thermal bridge effect of a mullion with and without insulation strength of the glass.

Various factors will either increase or reduce the breakage potential. Obviously anything that increases the temperature difference between the centre and the edge will increase the potential; anything that reduces the difference will reduce the breakage potential. If heater units are located so as to discharge heated air against the window with the intent of minimizing condensation, they will usually raise the temperature in the centre but not at the edge. If heat-absorbing glass were installed as the inner pane, it would obviously cause the temperature of the centre to rise when the sun was shining; this is one reason why it is never installed in this position. (See page 61.) Even if it is installed as the outer pane it will still have the same effect, but to a lesser degree, becuase the transfer of heat to its warmed surface from the inner pane will be reduced. A reflective metallic coating on one of the glass surfaces facing the air space, although intended primarily to reduce the solar heat transmission, also reduces the long-wave radiation transfer across the air space thus increasing the thermal resistance of the air space. Hence the temperature of the inner pane is increased when the heat flow is outward.

The thermal bridge formed by the metal spacer at the edges is not the only factor that must be considered; the method of mounting the glazing unit into the frame, the design of the frame, the method of mounting the frame into the wall and the temperature of the wall will all affect the edge temperature. It would be futile to attempt to discuss all possible variations in, and combinations of, these factors and so the problem will be approached through a general consideration of the nature and effect of a thermal bridge. By doing so it is immediately apparent that the temperature of the edge of the glass will be set by the balance between the ease with which heat can get into and out of it. Thus if there are large highly conductive paths on the inside and restricted ones on the outside the edge will be warm; if the conditions are reversed, it will be cold.

Considering in this manner the nine mullions shown in Figure IV.13 it can be seen that in each row the edge condition for the glass is improved by changing from the layout shown at the left to that in the centre then to that at the right. Each change increases the area available for the pick-up of heat on the inside and reduces the area available for the loss of heat on the outside. Similarly, for a given mullion layout it can be seen that adding insulation on the inside, while giving a better surface temperature condition on the mullion, gives a worse condition for the edge of the glass by restricting the entry of heat. Conversely, insulating the outside of the mullion restricts the outflow of heat and so gives a better condition for the edge of the glass. Combining the two effects, it can be seen that the worst condition for the glass is with the maximum exposure of the mullion to the outside and insulation on the inside, whereas the best is with the maximum exposure of the mullion to the inside and insulation on the outside.

When one considers a conductive frame mounted in a wall it is clear that if the wall is warm and if the wall and frame are in good thermal contact then heat will flow into the frame and the edge of the glass will be warmed. This will be the situation when insluation has been placed on the outside of the component of the wall that supports the window. The reverse situation will exist when the insulation is on the inside of the wall as was mentioned earlier when discussing the effects of adding insulation to a precast concrete slab wall.

Connections

The foregoing discussions about the properties of thermal bridges may leave the impression that they are the villains of the piece, providing all sorts of problems without producing any beneficial results. To a large extent this is true but they are not all bad and occasionally can be used to advantage. In any case, like building materials, we must learn to accommodate their deficiencies and peculiarities as best we can. One situation when their characteristics can be used to overcome a problem is when we wish to keep something warm, possibly to prevent condensation on it. The external cladding of a building must be supported by some means and it is often necessary to use a conductive material such as steel for this purpose. If such a steel connection becomes wet there is danger of corrosion and eventually the cladding may become detached. It is not possible to keep the connection warm by keeping it inside the insulation, for to fulfil its essential function it must, in part at least, be outside the insulation and so forms a thermal bridge. If it is attached to a massive conductive component on the warm side of the insulation, however, e.g., the structural frame of the building, there will be plenty of opportunity for heat to get into the connection. If the exposure of the connection on the cold side is kept to a minimum and also if the cladding is relatively light and nonconductive then the connection will be kept relatively warm.

Thermal bridges have been discussed at considerable length as they do not lend themselves to a simple mathematical solution. Heat flow through a wall that has no thermal bridges

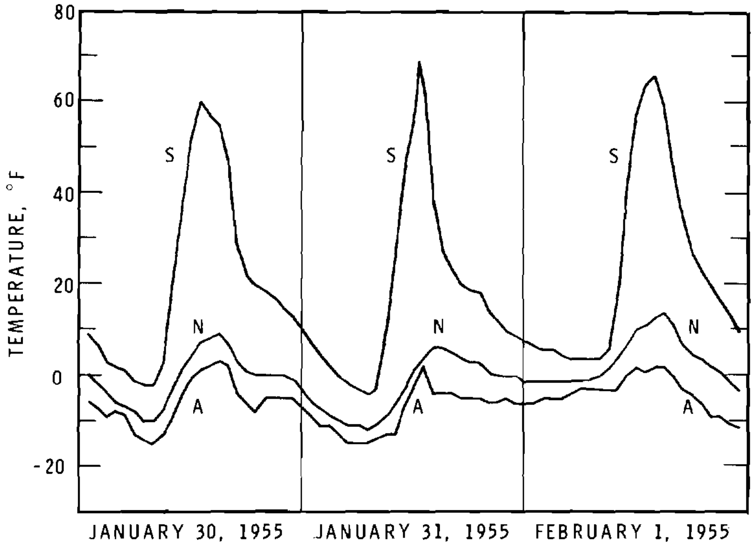


Fig. IV.14 Effect of solar radiation on the surface temperature of a south-facing (S) brick wall as compared with a north-facing (N) wall and air temperature (A) can be calculated without difficulty and the effect of changing the construction can be easily assessed. Thermal bridges, on the other hand, cannot be so readily assessed and usually must be approached on a more intuitive basis. Although tests have been made on various different types of construction the results must be interpreted with care, before assuming that they will apply in any other situation.

CONTROL OF SOLAR RADIATION

Understanding the problem of controlling solar radiation must begin with an appreciation of the effects of the sun's warmth. This source of heat affects control of temperature conditions inside a building and its operating and maintenance costs.

When the sun shines on a building it is partly reflected away, partly absorbed by the surface materials thus warming them, and partly transmitted through to the inside thus warming the inside of the building. The portion reflected away has no further effect on the surface reflecting it but it can create a problem with the object onto which it is reflected and so cannot be ignored by the building designer. If it falls on another part of the same building it becomes part of the incident radiation on that part. If it falls on an adjacent building, or even on the site of a future building, it becomes a problem to be solved by the designer of the other building and the first designer has not really solved the problem he has merely "passed the buck" to the second designer. If the reflected radiation is in the visible portion of the wave band then a problem of glare may be caused in the vicinity of the building. The remainder of the radiation will ultimately be absorbed by some component of the building, or its contents, and so will raise the temperature of that component. The extent to which the temperature is raised will depend upon the intensity of irradiation, the mass of the object and the balance between the rate at which the radiation is absorbed and the rate at which the object loses heat again to the air or to surrounding objects.

Various problems can arise with the building component, or the object, that is heated by the sun. Expansion and contraction of the object can be increased greatly over the values that would be expected from variations in ambient air temperature. Exposed structural frames can have stresses induced in them and the increased movements of wall and roof components must be allowed for either by suitable clearances, flexibility or restraints which distribute the stresses so that they can be suitably absorbed.

The number of freeze-thaw cycles to which the object is subject will also be increased over that of an object subjected to the same air temperatures but not exposed to solar radiation. This is illustrated by Figure IV. 14 which shows the variations over a three-day period of the air temperature and corresponding surface temperatures of north-and south-facing walls of a test building constructed of brick and located in Ottawa. The temperature of the bricks on the south wall rose above and fell below 32° F, causing a thawing and freezing cycle in the brickwork. The air temperature remained below 32° F, as did the temperature of the bricks on the north wall.

During the three winter months, bricks of the north wall of the test building were subjected to 27 freeze-thaw cycles; those of the south wall experienced 67 cycles. The number of freeze-thaw cycles experienced by bricks exposed over one winter in Ottawa and Halifax is given in Table IV. 6. Winters with below-normal temperatures would show the greatest difference in freeze-thaw cycling between northern and southern exposures. In most areas of Canada such winters have above-normal sunshine, with corresponding increase in freeze-thaw cycles for walls with a southern exposure.

TABLE IV. 6

GEOGRAPHICAL AND DIRECTIONAL EFFECTS ON FREEZE-THAW CYCLES OF BRICKS

Brick Facing	Number of Freeze-Thaw Cycles In One Winter	
	Ottawa	Halifax
North	65	81
East	70	83
South	98	108
West	79	88

Further problems may be caused with organic materials which may deteriorate under the action of solar radiation both because of the ultra-violet component of the spectrum and also because of elevated temperatures. Failure of sealants between components can result from a combination of this deterioration and the increased expansions and contractions of the components caused by heat gains from the sun.

Solar radiation which falls on transparent portions of the building enclosure, e. g., windows and skylights, will also be partially reflected, partially absorbed by the glass and the remainder will pass into the building. Direct sunlight falling on a bright surface can cause problems of glare with attendant visual discomfort unless the level of illumination in the other parts of the room is not too different from that of the sunlit areas. Thus, paradoxically, a high level of direct solar illumination requires a concomitant high level of general illumination, which may have to be provided artificially at additional cost. On the other hand, control of the entry of solar radiation will permit lower levels of illumination to be specified, because the eye can accommodate itself without strain to function within a wide range of illumination provided there is not a great difference between the brightness of the objects that it sees.

Solar radiation that enters a building will warm the inside of the building and so modify the heating or cooling load. Whether this modification will be beneficial or otherwise, will depend upon the circumstances. In winter, heat gain from the sun can be helpful in reducing heating costs although occupants on whom the sun shines directly may be too hot even though the general room conditions are satisfactory. This problem can usually be solved quite easily by a simple shading device such as a curtain controlled by the person concerned. With sensitive items of equipment, however, this is not a satisfactory solution and a permanent shading device should be provided. Obviously a thermostat should never be positioned where the sun can shine on it, or be reflected onto it, for under such conditions the whole heating system will fail to operate properly. In spring and fall uncontrolled solar radiation can cause further problems in that some parts of a building may need to be cooled while others require heat. A heating and cooling system can be designed to deal with such a situation but it may be more expensive in first cost than one that does not have this capability. Similarly, heat gained from the sun in summer may have to be removed by an air-conditioning system leading to additional operating costs and possibly also additional first cost.

Fortunately not all of the transmitted solar radiation acts immediately to increase the cooling load; some is stored in the floor, internal walls, furnishings, etc., which will release this heat to the air at a rate which depends upon the difference in temperature between the item and the air. The difference between the instantaneous heat gain through the transparent sections of the enclosure and the corresponding increase in the cooling load will depend upon many factors such as the heat storage capacity of the building and the ratio between the transparent and opaque areas of the wall. It is not possible therefore to give precise figures to cover all situations but one theoretical study of a building with about 80 per cent of the exterior wall made of glass indicated that the cooling load would be between 60 and 80 per cent of the instantaneous heat gain. Even allowing for this reduction there can still be economic justification for providing some control over the solar radiation. There are various procedures open to the designer to effect this control.

Methods of Control

Shading

The first, and most effective, method, is to keep the sun off the building. It is virtually impossible to shade a complete building and this could only be considered for small buildings, such as houses which could be shaded by tall trees during periods of maximum heat gain. The landscaping around taller buildings can give some relief to the lower floors. Trees could intercept the sun's rays in the early morning and late afternoon but would have to be very close to the building to cast a shadow on a south wall in summer. Lawns and shrubbery are of benefit in reducing the radiation reflected onto a building. Neighbouring structures may also shade a building. It is an obvious first step in designing a shading system to determine which parts will be in direct sunlight and which will be shaded at any particular time.

With many buildings, however, the shade that can be provided is limited to that which can be provided by the building itself and the configuration of the walls and any shading devices attached to them. In this respect the orientation of the building can be used to good effect to reduce some of the problems. It is difficult to restrict the heat gain through east-and west-facing windows and so it is logical, if other requirements permit, to orient a long thin building with its long axis running east and west. In this way the wall area exposed to the direct action of the sun in early morning or late afternoon is reduced to a minimum. The interior of the building can always, of course, be shielded completely from solar radiation by the simple expedient of eliminating all transparent sections in the building envelope. Such a solution may sound like a counsel of despair but in fact it is often adopted e.g., in theater auditoria. With other occupancies, however, such as apartment blocks, it is quite unacceptable for the building as a whole although it can reasonably be adopted for parts of the building, in bathrooms, for example. This last idea leads to the suggestion that the layout of a building might be modified so as to group and locate the occupancies that are sensitive to sunlight at some location where the entry of sunlight can

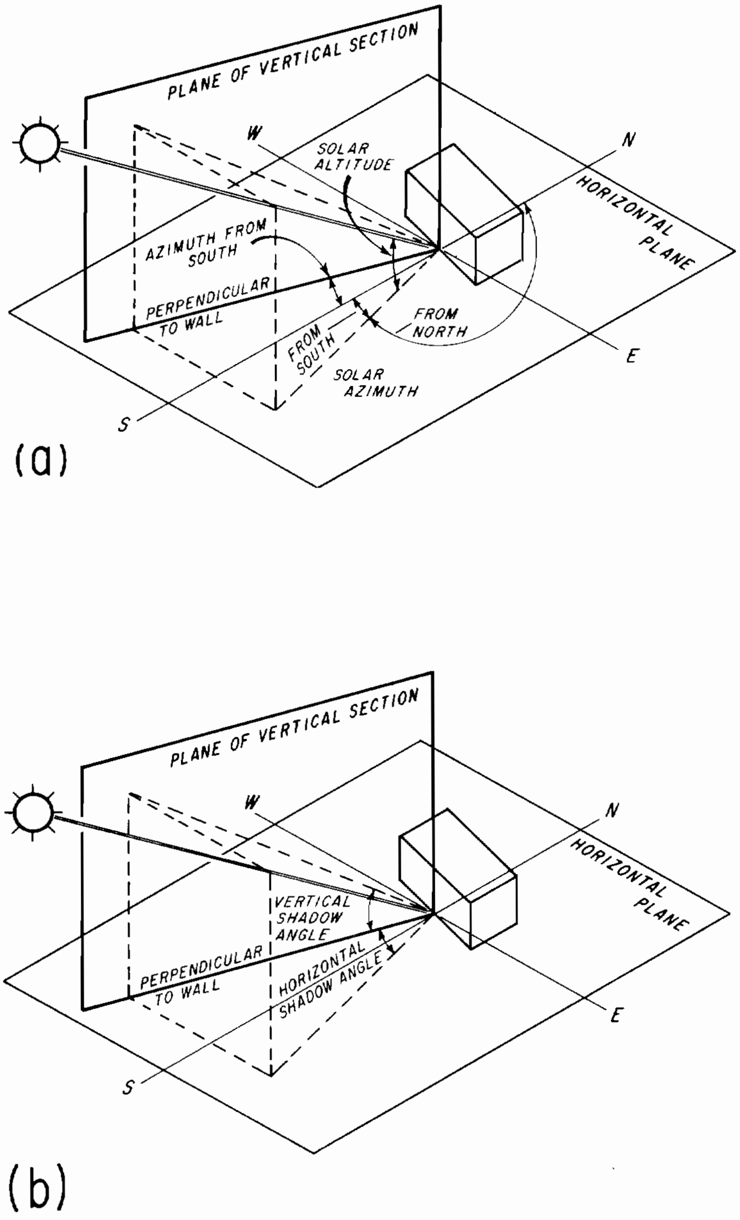


Fig. IV.15 Horizontal and vertical shadow angles reasonably be restricted in a positive manner.

(1) External shading devices

To design a shading device or to determine the shading effect of an adjacent object it is necessary to be able to determine the boundaries of the shadow. These can be found by projecting the outline of the shading object onto the wall - the lines of projection being parallel to the sun's rays. In the case of a simple shade, such as a vertical or horizontal projection from a vertical wall, the area shaded can be determined by calculation (to be described later). In more complicated cases and when an architectural model of the building is available, it is more convenient to mount the model on a heliodon and to illuminate it with a bright source of light to simulate the sun. A heliodon is a special turntable that can be tilted in such a way (taking into account latitude and date) that when the model is rotated on it it moves relative to the light in the same way that the real building will move relative to the sun on the chosen date. One difficulty is the generation of a beam of parallel light rays large enough to illuminate all the model but satisfactory results can be obtained using a simple slide projector or photo spot light at a distance of about 30 feet.

To calculate the position of a shadow on a vertical wall it is necessary to know the position of the sun relative to the wall. To know this one must know the orientation of the wall and the position of the sun in the sky. The orientation of the wall is easily obtained from the drawings of the building and the position of the sun in the sky can be expressed most conveniently by two angular co-ordinates: the solar altitude above the horizon and the solar azimuth measured from south (Figure IV. 15 (a)). These two angles will vary with the time of day, the date and the latitude of the building site. They can be obtained from navigation tables but these are usually so voluminous that they are not very convenient for architectural purposes. Fortunately several organizations have prepared tables or charts specifically for building designers, one of these being "Tables of solar altitude, azimuth, intensity and heat gain factors for latitudes from 43 to 55 degrees north" published by the Division of Building Research (NRC 9528). Once the orientation of the wall, and the altitude and azimuth of the sun are known, the direction of the sun's rays relative to the wall can be defined by the horizontal and vertical shadow angles (sometimes called the wall solar azimuth and profile angle, respectively).

The horizontal shadow angle (H. S. A.) is the angle on a plan drawing between a line perpendicular to the wall and the projection of the sun's rays on the horizontal plane and is equal to the algebraic difference between the solar azimuth angle and the azimuth of the normal to the wall, both measured from South. Similarly the vertical shadow angle (V. S. A.) is the angle on a vertical section drawn at right angles to the wall between a line perpendicular to the wall and the projection of the sun's rays on the plane of the drawing (Figure IV. 15 (b)). The V. S. A. is related to the H. S. A. and the solar altitude angle by the relationship.

$$\tan \text{V. S. A.} = \frac{\tan \text{(altitude angle)}}{\cos \text{H. S. A.}}$$

When these angles are known it is a simple matter to establish, by trigonometry or by drawing, the boundaries between the sunlit and shaded areas on the façade, and inside the building too if part of the sunlit façade is transparent. Shadow angles are for a specific time, date, latitude and wall orientation, but are completely independent of the shape or position of the shading surface.

When considering the effectiveness of a shading device one should remember that a wall receives its maximum irradiation when the sun is directly in front of it and between 30 and 35 degrees above the horizon. The time and date when this occurs will vary with the wall orientation; for a south-facing wall it occurs in late fall or winter when problems with heat gain are low, but east and west façades experience their maximum in summer when the problems are greater. With the sun directly in front of the wall, the horizontal shadow angle is zero and so vertical shading devices have no effect unless they are directly in front of the window when they cast a shadow equal to their width. Under these conditions to shade the window completely would require the window to be blanked out. Even if the shading device were held out from the face of the building the shading would be completely effective only with the sun directly in front of the wall and the restriction on the view from the window would not be acceptable in most cases. A smaller window would usually be preferable.

With the sun directly in front of the wall the vertical shadow angle equals the altitude angle of the sun. With the sun only 30 to 35 degrees above the horizon it is clear that a horizontal shade above the window would have to project at least 1 1/2 times the height of the window to give complete protection under these specific conditions. Where the sun is at a lower angle the projection would have to be even longer although the intensity of irradiation is reduced from the maximum value. Table IV. 7 gives the length of horizontal projection necessary to cast a shadow 1 foot high on a wall facing different directions at 44 degrees north latitude. The values for orientations east of south also apply for the same angle west of south if the times are reflected about noon.

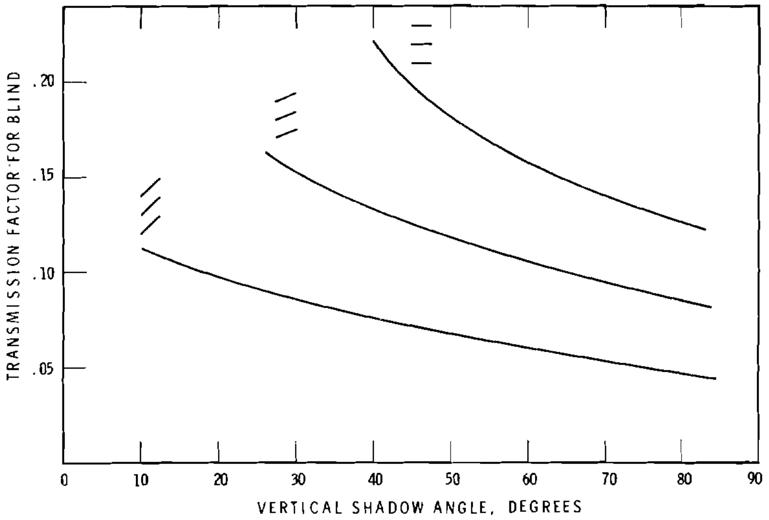


Fig. IV.16 Transmission factors for light coloured venetian blinds

TABLE IV.7

LENGTH OF PROJECTION IN FEET REQUIRED TO CAST A SHADOW 1 FOOT HIGH ON A BUILDING AT 44° NORTH LATITUDE

Wall Orientation

Time (Sundial Time)	South		30° East of South		60° East of South		East	
	21 May 21 July	21 March 21 Sept.	21 May 21 July	21 March 21 Sept.	21 May 21 July	21 March 21 Sept.	21 May 21 July	21 March 21 Sept.
8	0.14	0.97	0.83	2.04	1.29	2.56	1.41	2.40
9	0.30	0.97	0.73	1.53	0.95	1.68	0.93	1.39
10	0.39	0.97	0.62	1.24	0.69	1.18	0.57	0.80
11	0.43	0.97	0.51	1.02	0.45	0.81	0.27	0.37
12	0.45	0.97	0.39	0.84	0.22	0.48	—	—
13	0.43	0.97	0.24	0.65	—	0.16	—	—
14	0.39	0.97	0.05	0.44	—	—	—	—
15	0.30	0.97	—	0.14	—	—	—	—
16	0.14	0.97	—	—	—	—	—	—

The numbers in the table show that windows facing south can be completely shaded from 21 March to 21 September by a projection just a little shorter than the height of the window, whereas a window facing only 30 degrees from south needs a projection of more than twice the height of the window to achieve essentially the same shading. Tall windows can be shaded, however, by using several shorter shades spaced at regular intervals between the sill and head. As the number of shades increases and the size of the individual shade (and the gap between them) is reduced such a system evolves into a venetian blind.

(2) Slat-type blinds

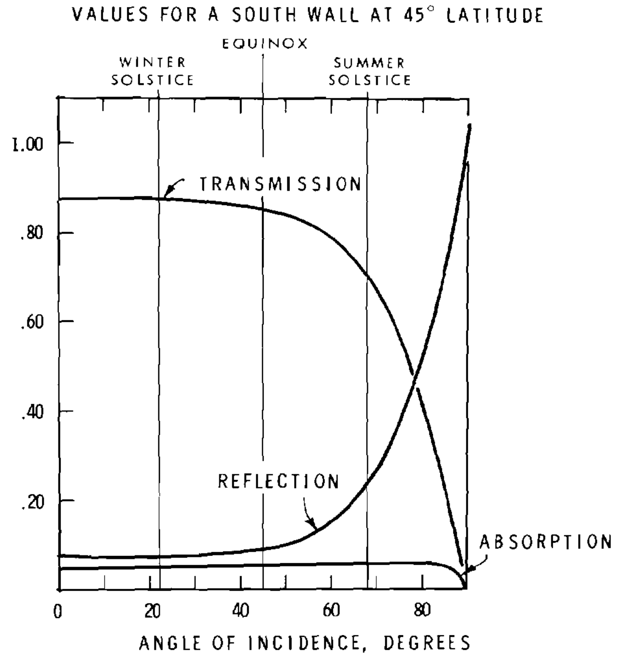
A horizontal slat-type of blind with the slats slightly wider than the gaps between them can be adjusted to intercept all of the direct sunlight coming through any window at any time of the year. The light that enters the room in this case has been reflected at least once from the surfaces of the slats. The amount of light that gets through a venetian blind depends on the colour of the slats, the angle at which they are set, and the vertical shadow angle that obtains for the window at the particular time in question. Figure IV. 16 shows the transmission factors for a typical light-coloured venetian blind with slats set horizontally, and tilted at 22 1/2 degrees and 45 degrees. Each of the curves starts at the V. S. A. where no direct sunshine can penetrate the blind. The curves in this figure show that a horizontal slat-type of blind can transmit from about 12 to about 22 per cent of the direct solar radiation even though no direct sunshine passes between the slats.

A little over half of the light that is transmitted through the blind enters the room in an upward-sloping direction, as if it were from a source on the ground in front of the window. This light falls on the ceiling where it is again partially reflected and so adds to the general illumination of the room. The remainder of the transmitted light enters the room as though the blind itself were a source of diffuse light. The brightness of the blind can be reduced by painting the under surface of the slats a dark colour. This causes only a slight reduction in the amount of light that falls on the ceiling, because this comes mainly from the upper surface of the slats.

A light-coloured blind with slats at about 20 degrees absorbs about half of the direct solar radiation falling on it and reflects about 35 per cent toward the outside. If the blind is inside the room, most of the absorbed energy is transferred to the room air and contributes to the room heat gain -- the only reduction is the radiation reflected back through the window. If the blind is on the outside of the window, however, the absorbed energy is transferred to the outside air and the heat gain is much less.

With *double-glazed windows there is* sometimes the possibility of placing a shade between the panes of glass. In this case, some of the absorbed energy is transferred to the room and the rest to the outside air. Thus, the use of an interpane blind is intermediate in its effectiveness in reducing solar heat gain, although it has almost the same light transmission characteristics as an inside or outside blind.

Fig. IV.17 Variation with the angle of incidence of the reflection, transmission and absorption of solar radiation for a single sheet of ordinary glass



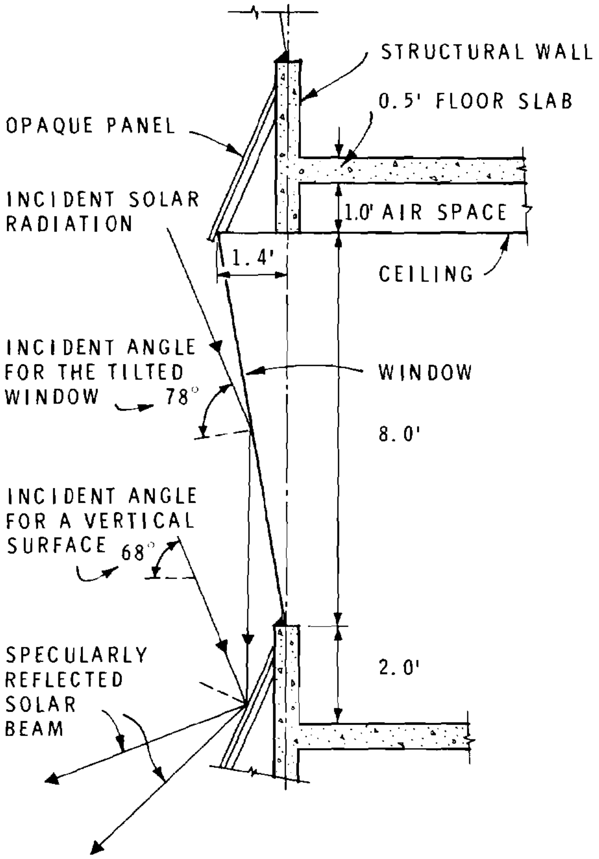


Fig. IV.18 Schematic arrangement of a tilted window in a south facing facade

A slat-type blind can be made with the slats vertical instead of horizontal. Its characteristics are similar to those of the horizontal slat-type except that the transmission depends on the horizontal rather than the vertical shadow angle. Figure IV. 16 applies, therefore, for a vertical slat blind if the abscissa is taken as the horizontal shadow angle. The most important difference is that the bright outer surface of the vertical slats may be in the field of view of some of the occupants of the room and consequently may cause glare. Also, the transmitted light will not be distributed as uniformly as if the slats were horizontal.

(3) Drapes

Drapery is not usually as reflective as white painted blinds and does not transmit light toward the ceiling more readily than towards the occupants of a room, as a venetian blind does. In these respects, drapery is inferior to venetian blinds for solar control. If drapery is required, however, as part of the decoration of a room, it can also be used to control glare. As with inside blinds, drapes can be easily adjusted to allow an uninterrupted view when they are not needed to intercept sunlight.

Reduction of Transmittance

The heat gain from the solar radiation that falls on transparent portions of the building enclosure can be considered in two parts:

i) Solar radiation transmitted through the window.

ii) Heat transfer from the inside surface of the window.

All the techniques for reducing heat gain through a window depend upon reducing either or both of these components. In some cases, however, a reduction in solar transmission results in an increase in the other component so that the over-all reduction is less than the reduction in transmission would indicate.

For ordinary windows the portion of the solar radiation that is absorbed is quite small; the transmitted portion forms by far the largest part. It is not always appreciated, however, that the reflection from the surface of glass varies considerably with the angle of incidence, i. e., the angle between the light rays and a line perpendicular to the surface. Figure IV. 17 shows the variation of the reflection, absorption and transmission of solar radiation by a single sheet of ordinary glass.

The proportion that is absorbed is virtually constant and does not vary with the angle of incidence until values approaching 90° are reached. The proportions transmitted and reflected are also more or less constant until an angle of incidence of about 45° is reached but thereafter they change with increasing rapidity. The values of the angles of incidence of the sun's rays on a vertical south-facing wall at 45 degrees latitude at noon on the summer and winter solstices and at the equinox are shown on Figure IV. 17. It can be seen that at these times 70 per cent of the incident radiation will be transmitted at mid summer, that this will increase to 85 per cent at the equinox and by only a further 2 percentage points (to 87 per cent) between the equinox and mid winter.

If the angle of incidence at mid summer could be increased by about 10° then the percentage of incident radiation transmitted would be reduced to about 45 per cent. The angle of incidence under these conditions can be increased by tilting the window 10 degrees as shown in Figure IV. 18. The energy falling on the window in this configuration is the same as would occur if the window were vertical and had a 1. 4-foot projecting shade along the lintel. This effective shading in itself reduces the total amount of radiation falling on the glass and then the tilted glass reflects 45 per cent of this reduced amount compared with 23 per cent of the larger amount when the glass is vertical. This difference in reflectivity decreases as the season progresses toward the winter solstice; in winter the tilted and vertical windows transmit essentially the same amount of solar energy.

In cases where tilting the glass is not acceptable or where it is not efficient, the reflected portion of the incident solar radiation can be increased by the use of heat reflecting glass. This type of glass is made by applying a thin film of gold (or some other metal) onto one surface. Unlike the tilted plain glass, which can only increase the heat reflected at the higher angles of incidence, the reflecting type of glass will be effective at all angles of incidence. Most of the metallic films used are not sufficiently tough to be used on exposed surfaces. It is possible to protect the film by overcoating it with a hard transparent material but in most cases the films are applied to one or other of the inner surfaces of double-glazing units. In this way advantage can be taken at the same time of the increased U-value of the double-glazed window.

The other property of the glass that can be altered so as to reduce the proportion of

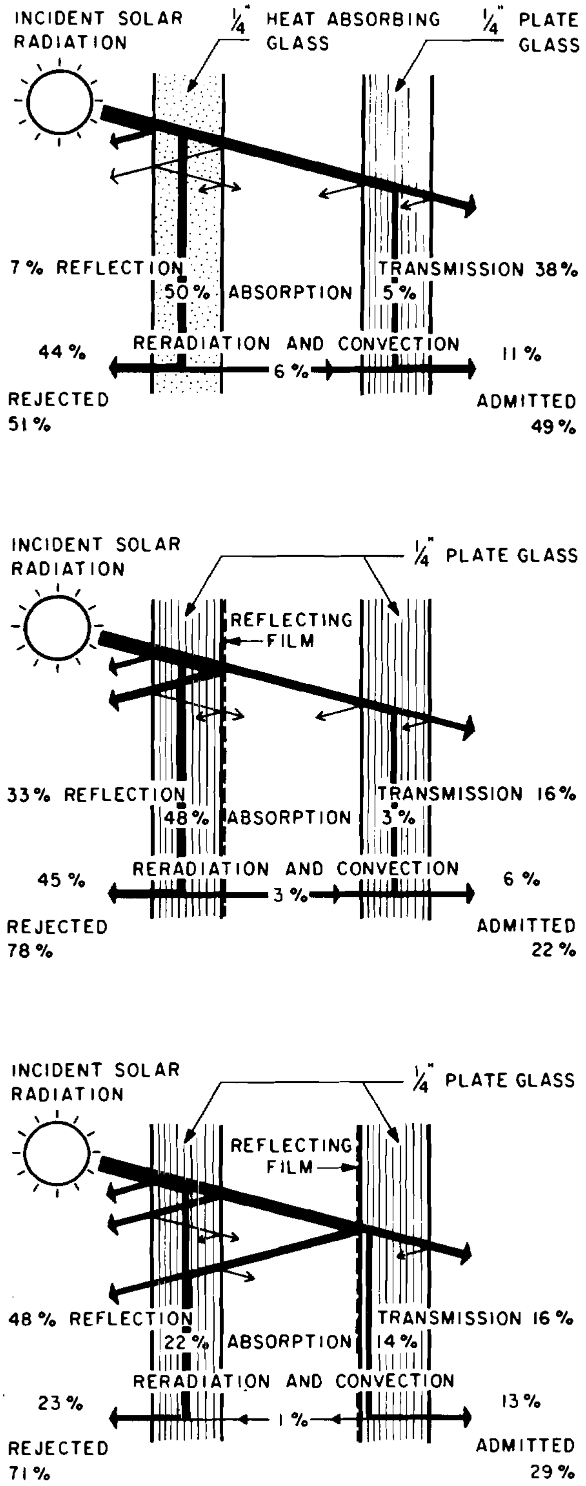


Fig. IV.19 Components of heat admission and rejection for heat absorbing and heat reflecting double-glazing units transmitted solar radiation is its absorbtivity. The proportion of incident energy that is absorbed depends upon the type of glass and the length of the path the rays must travel in passing through it. Thus it is convenient to specify the absorption properties of glass by the KL value, where K is the absorption coefficient of theglass and L is the thickness of the pane. Table IV. 8 gives some values of KL and the percentage of the radiant energy striking the surface at right angles which is transmitted.

TABLE IV. 8

Type of Glass	KL	Transmission For Normal Incidence (Per Cent)
Ordinary Window Glass	0. 05	85
Ordinary Plate Glass	0. 20	75
Heat Absorbing Plate	0. 80	40

Of the balance, the portion that is absorbed will raise the temperature of the glass and be dissipated to the air and objects on each side of it. The proportion that is dissipated on each side will depend upon the relative values of the temperatures and the surface conductances. An air-conditioned building is cooler inside than out and if cool air is introduced through a grill along the window sill more than half of the heat absorbed by single glazing may still end up inside the building. If heat-absorbing glass had been used in an attempt to reduce the peak cooling load it is probable that this will not be achieved because the additional absorbed energy will be transferred to the room air almost immediately. With ordinary glass this energy is transmitted straight through to the inside to be absorbed by the floor, walls, and furnishings and released later. The effectiveness of heat-absorbing glass may be increased by using it as the outer pane of a double-glazed window so that the absorbed energy can be more readily dissipated to the outside air than to the room air.

When there is free circulation of outside air over both sides of heat-absorbing glass, most of the absorbed energy is dissipated to the air and the room heat gain is correspondingly reduced. Heat-absorbing glass absorbs both the visible and near infrared radiation in the solar spectrum, but the absorption factor for the infrared is usually larger than for the visible. In situations where the view is of primary importance, a semi-transparent glass shade of heat-absorbing glass held away from the window on brackets may be the best type of solar control device. It can sometimes be used to advantage for south windows if shading or tilting are unacceptable for architectural reasons but it has its best application for east-and west-facing windows where effective outside shading becomes expensive and the simple expedient of tilting has no appreciable effect.

There are many possible combinations of the different sorts of glass that can be used; Figure IV. 19 shows the proportions of incident solar radiation that are transmitted, reflected, and absorbed by typical double-glazing units of the absorbing and reflecting type. The lower total admission of the reflective-type unit is mainly due to lower solar transmission. When the reflective coating is on the inside surface of the outer pane, that pane absorbs almost as much as if it were heat-absorbing glass, but the transmission is reduced because of the higher reflection. The total admission is also reduced because less of the energy absorbed by the outer pane of the reflective unit is transferred to the room - - a direct consequence of the higher resistance of the air space in the reflective units.

When the reflective film is on the outside surface of the inner pane the over-all reflection of the unit is greater but the total admission is also higher. This is because the energy absorbed by the coating on the inner pane is mostly transferred to the room side. Thus, from the point of view of minimizing heat gain, the best place for a reflecting film is on the inside of the outer pane. With this arrangement, however, the outer pane gets quite hot when it is in strong sunlight. There is, therefore, a slightly increased chance of thermal breakage in summer.

To assess the heat gain through various different types of windows with different combinations of window glass would be a tedious task starting from first principles each time. Fortunately, two factors, the solar heat gain factor (SHGF) and the shading coefficient, offer considerable assistance. The solar heat gain factor is determined by the characteristics of the environment and is independent of the particular type of window; the shading coefficient gives a measure of the characteristics of the window and is independent of the environment.

Tables of these factors are published in the American Society of Heating Refrigerating and Air-Conditioning Engineer's Handbook of Fundamentals. The solar heat gain factors have been extended in the Table of Solar Altitude, Azimuth, Intensity and Heat

Gain Factors for Latitudes from 43 to 55 Degrees North published by the Division of Building Research (NRC 9528).

The solar heat gain factor is the instantaneous rate of solar heat transfer through unit area of unshaded double-strength sheet glass in some specific situation. It includes the amount of solar radiation transmitted directly through the glass plus that portion of the radiation absorbed by the glass which is ultimately passed on to the inside of the building. These will change as the angle of incidence of the sun changes with time of year, time of day, latitude, orientation and tilt of the window. Furthermore, the solar radiation includes the scattered radiation from the sky and the radiation reflected from the ground and surround objects in addition to the direct rays from the sun. Thus the tabulated values can only be values for average conditions and must be adjusted, if the design of the building warrants it, for atypical situations.

To reduce the size of the tables to manageable proportions only selected latitudes (at 2-degree intervals) are considered. The position of the glass is assumed to be either horizontal or vertical with the vertical glass facing north or some multiple of 45° from north. An average value for the clarity of the atmosphere has been assumed although the direct solar radiation which impinges on a surface at right angles can vary 20 per cent on either side of this value for very clear or for smoggy industrial regions. Only a portion of this radiation, however, is transmitted through the glass. Similarly, the radiation reflected from the ground is assumed to be that reflected from an average ground surface with no snow cover. The presence of snow will increase the radiation and this can be allowed for by increasing the solar heat gain factors for vertical windows by about 20 per cent. With all these limitations taken into account, some maximum values of the solar heat gain factor are given in Table IV. 9.

As the shading coefficient is set by the characteristics of the window, it will vary with the type of glass used, whether single-or double-glazed, the relative positions of the different types of glass and the presence or absence of curtains or blinds. The shading coefficient is the ratio of the total solar heat gain through the given window, including the portion absorbed and subsequently released to the inside, to that through a single standard sheet of clear glass under exactly the same conditions. Thus these coefficients, being ratios, are dimensionless numbers that have a value between zero and one. The smaller the value of the shading coefficient the smaller is the amount of heat admitted to the building.

Values of shading coefficients for three types of single glazing and three types of double glazing are given in Table IV. 10 along with the corresponding U-values and values of light transmittance and solar transmittance. These show that the reflective type of glazing without blinds or curtains can have a lower shading coefficient than other types of double glazing combined with inside shades.

The light transmittance value is merely the ratio of solar radiation in the visible spectrum which is admitted by the window to that which is incident on it. Since there is no fundamental difference between light and other forms of solar radiation except in the eye of the beholder, the heat value of the light admitted is included in the solar heat transmittance factor.

The heat from the sun which in transmitted through the window is given by the product of the solar heat gain factor and the shading coefficient. That is, by the product of the heat which would pass through a simple sheet of unshaded clear glass in the given location and the fraction of this heat gain which the actual glazing arrangement will admit. The heat admitted by conduction through the window must be added to the solar heat gain to give the total heat gain.

$$\text{Total Heat Gain} = [\,\mu \text{ x } (\Delta T) + (\text{shading coefficient}) \text{ x } (\text{SHGF})\,] \text{ x area}$$

where μ = the over-all conductance of the window

and ΔT = the difference in air temperature inside and outside the building.

TABLE IV. 9

MAXIMUM VALUES OF SOLAR HEAT GAIN FACTORS THROUGH VERTICAL WINDOWS AT 45° N LATITUDE

		Direction	
Date	N	East West	S
21 Jan	16	134	251
Feb	21	176	249
Mar	26	210	221
Apr	32	222	176
May	36	219	137
June	37	215	120
July	37	215	133
Aug	34	213	169
Sept	28	197	214
Oct	22	169	240
Nov	17	131	246
Dec	14	108	244

Values are in Btu/ft^2 hr.
These data are taken from NRC 9528.

TABLE IV. 10

SHADING COEFFICIENTS AND U-VALUES FOR SOME SINGLE- AND DOUBLE-GLAZING UNITS

Type of Window and Shading	Transmittance without Shades		Shading Coefficient				U-Values Btu/ft^{2}hr°F	
	Light	Solar Heat	No Shade	With Curtain		With Venetian Blind	No Shade	With Curtain or Blind
				Min	Max			
Single Glazing								
1/8" Clear Sheet Glass	0.90	0.80	1.00	0.45	0.65	0.55	1.0	0.8
1/4" Regular Plate Glass	0.87	0.77	0.95	0.45	0.65	0.55	1.0	0.8
1/4" Heat Absorbing Plate Glass	0.50	0.45	0.70	0.40	0.50	0.47	1.0	0.8
Double Glazing								
1/4" Regular Plate 1/2" Air Space 1/4" Regular Plate	0.77	0.60	0.83	0.40	0.60	0.50	0.6	0.5
1/4" Heat Absorbing Plate 1/2" Air Space 1/4" Regular Plate	0.45	0.35	0.55	0.33	0.43	0.36	0.6	0.5
1/4" Regular Plate Reflective Film 1/2" Air Space 1/4" Regular Plate	0.35	0.16	0.25				0.3	

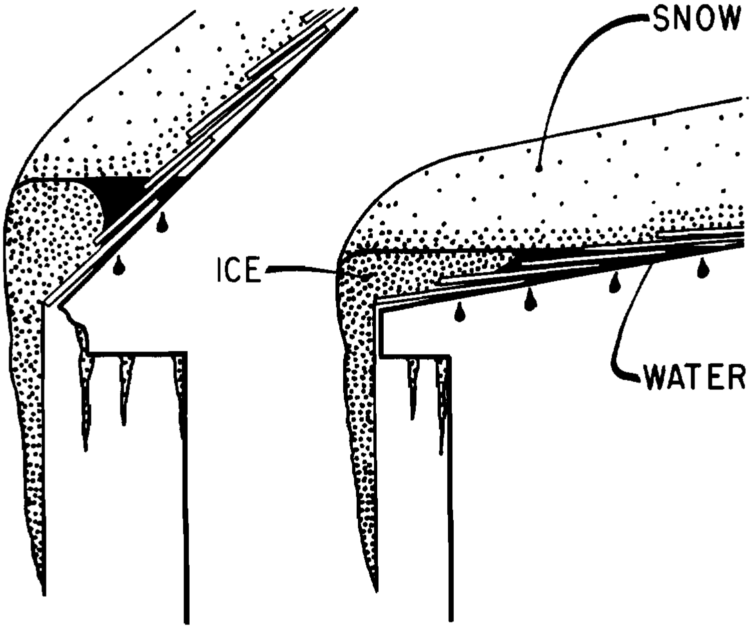


Fig. IV.20 Ice dam at the eave of a sloping roof

ICE DAMS

Before leaving the subject of the control of heat flow through the building enclosure some consideration will be given to the problem of ice forming on sloping roofs and icicles at the eaves. These form when the air temperature is below freezing and the roof surface is warmed to above freezing by solar radiation and heat loss from the building. Under these conditions the snow in contact with the roof melts, runs down to the eave and freezes again on exposure to the air. As this continues layers of ice are built up and water is trapped behind the dam which is formed. With a shingled roof there is no positive seal between the shingles and when the depth of trapped water becomes greater than the vertical overlap of the shingles water will leak through the roof (Figure IV. 20).

To solve a problem of this sort the prime objective should be to reduce the temperature of the roof surface so as to prevent the snow from melting. One can do nothing to stop the sun from shining nor can one prevent the sun's rays from penetrating the snow to some extent. It may be possible to lower the roof temperature slightly by using light-coloured shingles which will absorb less solar radiation than will dark coloured ones. The difference, under a blanket of snow, can only be small however, and one must turn to the control of heat loss from the building as being a more effective means of attack.

There is always loss of heat from a heated building to the outside. This takes place by conduction through the fabric of the enclosure and by air changes in the building. To keep the roof surface temperature down both of these heat losses must be reduced by adding insulation and by blocking all passages through which warm air can leak into any space below the roof. Even after taking whatever steps one can to minimize heat loss it can never be entirely eliminated. Thus it is necessary to make sure that any heat that does manage to enter the space below the roof is whisked away before it can affect the temperature of the roof. Ventilation is the answer here. As it is achieved primarily by wind action, vents should be provided in all eaves so the wind can blow through the roof space from any direction. In some cases, where the wind blows through relatively restricted spaces over the top of low density mineral wool insulation, the top of the insulation should be covered to prevent the wind from blowing through it and thus reducing its effectiveness. Some ventilation can be obtained on still days through ventilators at different levels in the building but this is not so effective since their performance depends upon a difference in temperature between the attic and the outside air.

If all possible means of reducing the roof temperature are still not effective one must try to control the water. Here there are two possible methods: either to make impervious a sufficiently large area of the roof along the eaves so the ice dam cannot back up the water high enough to cause a leak, or to drain the water away. The former can take the form of impervious flashing underneath overlapping units (although nail holes may still be a problem) or a continuous unbroken impervious strip, such as metal, at the eaves if aesthetic considerations allow. The steeper the pitch of the roof the narrower can be the impervious strip for a given ice dam condition or alternatively the greater must be the ice dam before leakage takes place. This is true for an ordinary shingled roof. To drain the water away heating cables can be used to maintain drainage channels through ice dams that form at the eaves and to keep gutters and downspouts open.

In most cases an ice dam forms only where there is an open end of snow and where the water would normally drip off. Ice dams do not form where the water runs off a warm roof over a heated house onto a cold roof over an open carport for example. In this case, although a thin layer of ice may form on the carport roof, much of the water continues to flow under the snow until it emerges at the edge of the carport, possibly 10 to 12 ft away from the wall of the house, where it freezes and forms an ice dam. This suggests that it is necessary for the water to be retained temporarily at the exposed face of the snow by capillarity in order that an ice dam will form.

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Fig. V.1

CHAPTER V -- THE CONTROL OF WATER

As already discussed, water plays a prominent part in causing materials to deteriorate. It is probable that there are more complaints from occupants or owners of buildings as a result of the unwanted presence of water than for any other reason. This does not mean that the initial defect that allowed the water to cause the damage was necessarily related to water alone. The roof leak, for example, could have been caused by the effect of ultraviolet radiation and high temperatures on an exposed membrane but it is water which damages the ceiling and drips through into the room thus disclosing that something has gone wrong. After all, the membrane was installed to keep the water out not to control the solar radiation. Water in all its forms must therefore be controlled if the building is to perform satisfactorily for a reasonable period of time.

Within the range of temperatures normally experienced by buildings water can exist in any of its three forms of vapour, liquid and solid. Ice, i.e., water in the solid state, does not have to be controlled in buildings for it does not move from place to place. In some circumstances the formation of ice must be controlled but this is done by controlling the flow of heat (as in the case of ice dams on roofs) or the flow of water as a vapour or liquid to a point where it can change into ice. Thus we can concentrate on the steps that must be taken to control the movement and accumulation of water as a vapour and as a liquid.

WATER VAPOUR

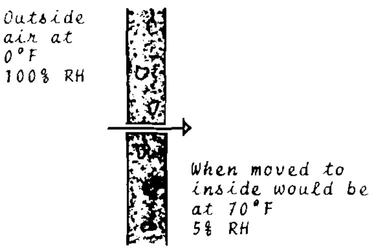
Water vapour can move from one place to another in two different ways: either by being carried along in a current of air or by diffusion under the action of a difference in vapour pressure. Of these two mechanisms the former is by far the more important. The latter should not be neglected, however, since it is desirable to design walls and roofs capable of drying out again should water get into them by any means.

Movement of Water Vapour by Air Currents

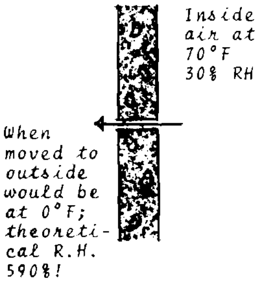
Air in motion carries with it any pollutants which it contains: gases, dirt, water vapour, etc. These pollutants may be picked up at one location and deposited at another; dirt blown in through an open window settles on the desk, sticks in one's eye or irritates the lungs. It is only after the dirt has settled on something that it creates a problem (Fig V.1). The same situation occurs with water vapour. As long as it remains in the air no harm is done but once it settles out by condensation, the problems start. This is not entirely true for the moisture content of a material is set very largely by the relative humidity of the air to which it is exposed. Warm dry air passing over a moist material will dry it out which is why it is so important to protect freshly placed concrete from these conditions. Very often, however, such a drying action is beneficial in that it dries out excessive moisture which has collected at some point just as the housewife dries her laundry by hanging it on the clothes line. Her problems start when the rain clouds come and soak her partially dried laundry once again.

So it is in buildings. As long as moisture stays in the air and keeps moving no harm is done but once it condenses a build-up of water occurs where we don't want it and usually leads to deterioration of the building enclosure. Water will condense only if the air containing it is cooled and for this to happen the air current must move from a warm location to a cold one. Thus water vapour in air leaking from outside into a heated building cannot condense (Fig. V.2(a)) but that in air leaking outwards can (Fig V.2(b)). In fact it is not necessary for the air to pass right through the enclosure to the outdoors; condensation can occur at any point where the air may be cooled enough to reach its dewpoint. As discussed earlier, insulation is added to the enclosure to reduce the rate of heat loss and in so doing keeps anything on the warm side of it warmer but makes those things on the cold side colder. If moist air is allowed to pass from the warm side of insulation to the cold side, there is a serious risk of condensation occurring (Fig V.2(c)). Thus it is of prime importance that no such transfer should take place and some sort of a barrier to this air movement must be provided. This barrier can conveniently be called an air barrier.

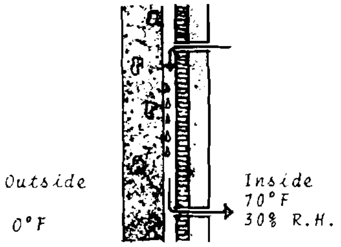
Insulation itself cannot be considered as forming an air barrier. Air can pass relatively freely through mineral wool insulation and also some types of board insulation. With other types of board insulation, which may themselves



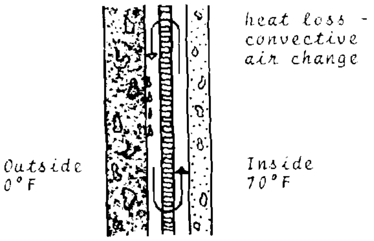
(a) Air movement from cold to warm -- condensation not possible



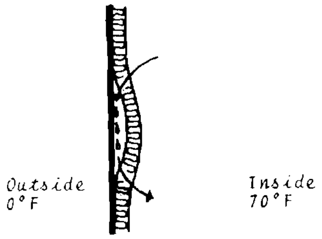
(b) Air movement from warm to cold -- condensation possible



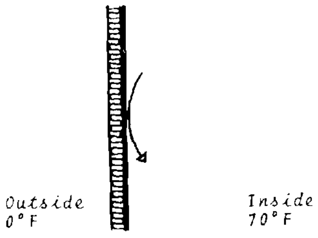
(c) Air movement from warm to cooler -- condensation may occur



(d) Air space on both sides of insulation -- condensation may occur



(e) Air barrier on cold side -- danger of condensation



(f) Air barrier on warm side -- no danger of condensation

Fig. V.2 Effects of various possible air movements through and within a wall be airtight, it is virtually impossible under site conditions of application to seal all the joints between the boards. Even if this were possible one must face the consequences of doing so. An air barrier is installed to stop air movement. If it succeeds in doing so, the air barrier will be subjected to the loads of whatever forces are causing, or are trying to cause, that movement. Thus the air barrier must be structurally strong enough to carry these loads. Once again insulation by itself cannot do this, thus another material must be provided to perform this function.

The next question is where should this air barrier be placed? Must it be in contact with the insulation or can it be placed elsewhere; if it must be in contact, which side should it be on? Suppose we did not put the air barrier in contact with the insulation, what then? Since the insulation itself does not form an air barrier and since the air on one side will be warm and on the other side cold there will be a convective air change from one side to the other. This will diminish, and possibly destroy, the effectiveness of the insulation in reducing the transfer of heat and since this is the sole function of insulation this cannot be tolerated (Fig V. 2(d)). Thus the air barrier must be in contact with the insulation, but on which side? If it is on the outside, it and anything supporting it, will be subjected to a wide fluctuation in temperature with consequent expansion and contraction making the maintenance of an adequate air barrier difficult. Furthermore the air barrier will be cold in winter and should any moist air come in contact with it there is a danger of condensation taking place -- the very thing we are trying to prevent. There is a grave danger of this happening when a space is left, perhaps inadvertently, between the insulation and the air barrier, for as we have seen air can bypass the insulation by convection, and deposit water on the cold air barrier (Fig V. 2(e)). If, on the other hand, the air barrier is placed on the inside it will not be subjected to widely changing conditions and so will not be strained to the same extent as one on the outside. It will also be kept warm, thus virtually eliminating the possibility of condensation on it. Hence, to control the movement of water by air currents an air barrier must be provided. Ideally this air barrier should be in contact with and on the warm side of the insulation (Figure V. 2 (f)). If, for some reason, it is not possible to provide an air barrier on the warm side then special care must be taken to eliminate all air spaces between the cold side of the insulation and the air barrier.

Basements

Basements present special problems because here condensation problems may be encountered in winter particularly in the upper corners of an uninsulated basement. In this location heat is lost from two faces directly to the outside air and air circulation on the inside, which could bring heat (as well as moisture) to the wall, is restricted. Adding insulation on the outside will retain heat in the wall and can raise it above the dew-point temperature. It is more common, however, for insulation to be added on the inside which will have the effect of making the wall colder. In such a case it is essential to keep the air away from the concrete wall. With most basements, in houses at any rate, it is not reasonably possible to make an effective air seal between the top of the wall and the interior wall finish because of the layout of floor joists, heating ducts, etc. The insulation should therefore be placed tight against the concrete wall with no intervening air space in which air could circulate. Since basement walls are seldom smooth and flat a mineral wool batt type of insulation which is compressed slightly between the concrete and the interior finish can be effective in following the irregularities and eliminating all air spaces. Board type insulation is not recommended in this case because it tends to span from high point to high point and leave gaps between it and the wall. Vertical furring strips which are shimmed out to true up a wall leave vertical spaces in which convective air currents can circulate as may also happen in the space which is sometimes formed between the edge of the batt and the furring strip. For these reasons horizontal furring strips are to be preferred.

Condensation problems can also be encountered in a basement in summer. The mass of soil surrounding a basement has a high heat storage capacity and prevents rapid changes in temperature between summer and winter. Hot summer air naturally remains in the upper portions of the house and a pool of relatively cool air remains in the basement. If the basement windows are opened for ventilation or the furnace fan is used to circulate the basement air to the upper floors to cool them, hot humid air can be drawn into the basement and condensation can take place on the cool walls and floor. Where the occupancy permits the windows should be kept closed during humid weather and opened for ventilation during drier periods.

Movement of Water Vapour by Diffusion

Despite the prominence given some years ago to this mechanism by which water can pass into the fabric of a building enclosure it is now considered less important than the movement of water vapour by air currents. Even so it is not to be dismissed completely for an analysis

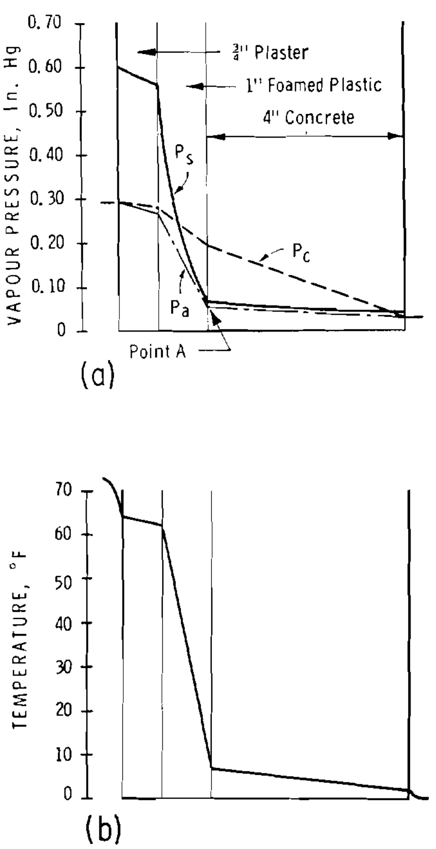


Fig. V.3 Vapour pressure and temperature gradients through an insulated concrete wall

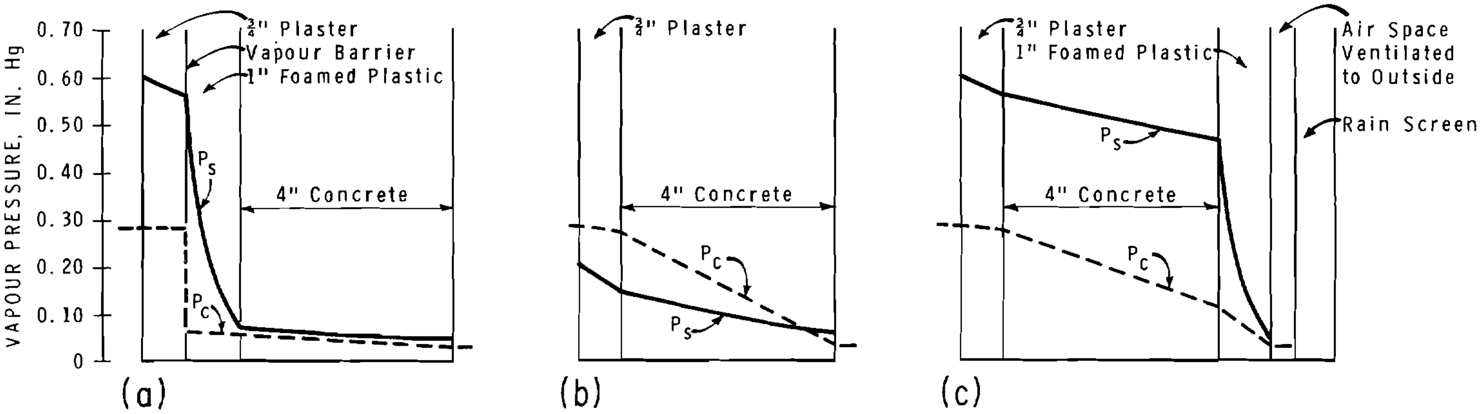


Fig. V.4 Vapour pressure gradients of the concrete wall of Fig. V.3 modified in various ways of the vapour diffusion characteristics of the enclosure will show if it has the ability to dry out should water penetrate it from any source. As a design is being developed rough checks should be made from time to time to ensure that insuperable problems are not being created which will require a complete redesign and before the final design is settled one thorough examination should be made. This is not a complicated procedure being only slightly more involved than that for the determination of a thermal gradient, in fact the thermal gradient is required as part of the analysis.

The method of analysing a wall or roof section was given in Chapter III. The question now confronting the designer is what can be done if the results show that there may be a danger of a build up of water? Let us explore the possibilities by continuing the analysis of the insulated concrete wall used in the explanation of the method of calculating the vapour pressure gradients. The actual wall design is not, of course, of great importance; it is the techniques available to overcome potential problems and the method of thinking which should be mastered. This particular wall design has a 4-in. thick reinforced concrete panel with 1 in. of foamed plastic insulation faced with 3/4 in. of plaster on the inside. The assumed interior conditions are 73°F and 35 per cent R.H. giving a vapour pressure of 0.286 in. Hg; the exterior conditions are 0°F and 80 per cent R.H. giving a vapour pressure of 0.030 in. Hg. The vapour pressure and temperature gradients are found to be as shown in Fig V.3 from which it is seen that condensation can be expected to take place at point A.

To ensure that condensation does not take place the fundamental requirement is that, at all points through the thickness of the building enclosure, the vapour pressure set by the condition of continuous flow (p_c) must be less than the maximum permissible vapour pressure set by the saturation vapour pressure (p_s) corresponding to the temperature at that point. This condition can be achieved either by changing the various vapour flow resistances to reduce the values of p_c, by changing the various thermal resistances to raise the temperature and thus the values of p_s, or by a combination of both methods.

To lower the p_c curve one may either increase the vapour flow resistance on the high vapour pressure side or lower the resistance on the low vapour pressure side. Suppose that one chooses to do the former by adding a vapour barrier -- this after all has been the conventional approach. The vapour flow resistance on the high vapour pressure side must be increased until the vapour flow to point A is equal to or less than the maximum rate of flow from point A to the outside. This maximum rate of flow was calculated previously as 0.02 grain/sqft/hr and since the vapour pressure drop from the inside to point A cannot exceed 0.232 in Hg. (see Chapter III) we can calculate the maximum resistance from the formula

$$\text{Vapour flow} = \frac{\text{Vapour pressure drop}}{\text{Vapour flow resistance}}$$

i.e. minimum vapour flow resistance

$= 0.232/0.02 = 11.6$ units of resistance

The plaster and the insulation provide 0.69 unit of resistance, leaving 10.9 units to be provided by the vapour barrier. Thus, the vapour barrier should not have a permeance greater than 1/10.9 =0.09 perm. Adding such a vapour barrier between the plaster and the insulation will produce the vapour pressure curve for continuity of flow shown in (Fig. V.4 (a)). It will not materially alter the temperature gradient or the p_s curve.

The installation of such a vapour barrier, which would have to be of 4-mil polyethylene or better, raises various practical problems. The plaster can no longer be applied directly to the foamed plastic insulation and lathing must be used which in turn must be supported on furring strips. This leads one to consider the alternative method of changing the p_c curve: reduction of the vapour flow resistance between point A and the outside. The maximum resistance tolerable is given by the quotient of the pressure drop to the outside and the rate of flow from the inside to point A, i.e., $0.024/0.34 = 0.071$ unit of resistance, giving a required permeance of at least 14 perms. This can only be achieved in this case by replacing the concrete with a structural member of the required permeability.

Both attempts to eliminate the danger of condensation in this wall by reducing the p_c curve have encountered some difficulty. The problem of installing a suitable vapour barrier could be overcome fairly easily but replacing the concrete panel may be totally unacceptable, particularly if it was selected in the first place as a component of the building structure. One should therefore explore the second approach to the problem which is to raise the p_s curve above the the p_c curve. Examination of the curves shown in Fig. V.3 show that this could be achieved if the temperature of the concrete slab could be raised. Removing insulation from the warm side of the wall will have this effect but, with this particular design, condensation will still take place (Fig. V. 4 (b)). In any case, the reduction in insulation will increase the heat loss through the wall and reduce the inside surface temperature, neither of which may be acceptable.

Alternatively, additional insulation can be added on the outside, but the same effect can be achieved simply by reversing the relative positions of the concrete and the insulation.

This results in a satisfactory wall design (Fig. V: 4(c)) but requires an exterior weathering surface to protect the insulation. Such a surface should either have a high permeance or be designed as an open rain screen as will be discussed later. The plaster finish to the concrete could be omitted if an acceptable finish can be provided by the concrete panel and the joints between panels.

In this example the different methods of dealing with the problem have been examined separately in order to show clearly the effect of each. In practice it is usual to adjust various factors by trial or error to obtain the most satisfactory solution. It will also be seen that although a component of the enclosure may be selected initially for some particular reason, such as structural strength, thermal resistance or aesthetic qualities, all the components together make up the enclosure and each will have an effect on the vapour and thermal properties.

Movement of Water Vapour by a Temperature Gradient

This is not a major factor in the design of a building enclosure but it is mentioned briefly since it can sometimes be of assistance in explaining some problems. When a partially saturated material is subjected to a temperature gradient the water in it will be caused to move from the warmer location to the cooler. The precise mechanism whereby this takes place is not clearly established but there is evidence to indicate that the water moves as vapour rather than as liquid since the movement can take place across an air gap. Thus the movement cannot be stopped by the introduction of an air gap although it is possible that a problem associated with it could be.

Such a problem can arise when the cladding of a building has absorbed rain water and, following the rain storm, it is warmed by the sun. The absorbed rain water will be driven deeper into the wall under the temperature differential. Subsequently, as the surface dries out, the liquid water will move back to the outside and evaporate. If in the course of this circular tour some salts have been dissolved by the liquid water these will be left on the surface of the wall. This deposition is called "efflorescence." Should the water moving inward as vapour cross an air gap, however, the salt-laden liquid water would not be able to return across this gap and so salts cannot be moved across it to form the efflorescence on the outer surface of the wall. Furthermore, if this air gap is ventilated to the outside the vapour will, in all probability, be carried away from the back of the cladding which will thus be dried out again more quickly.

In conclusion it should be pointed out that to stop the inward movement of water vapour under the action of this temperature differential would require an impermeable vapour barrier near the outer surface of the wall. A vapour barrier in such a location would be in conflict with the need for high permeability at this location as was discussed earlier.

LIQUID WATER

Liquid water will move from one location to another when acted upon by a variety of forces, some of which are obvious, such as gravity, while others are rather more subtle. The more easily recognized forces are usually those that move relatively large quantities of water over sufaces or through reasonably clearly defined passages. The other forces deal more with the redistribution of water within a material although it would be wrong to make any hard and fast distinction on this basis. Since in bulding construction we are primarily concerned with the task of separating, in what is sometimes a rough and ready manner, the outside conditions from those we wish to maintain inside it is natural that the larger forces are of greatest concern to us.

Capillarity

In nature, all forms of energy seek a uniform level. Thus when a material has absorbed a quantity of water the capillary forces which drew that water into the material will endeavour to reach a state of balance. With a homogeneous material in a uniform environment this state will be reached when the water is uniformly distributed throughout the material. With non-homogeneous materials or with two different materials that are in contact the quantity of water retained in each part will be set by their relative capillary potentials. Thus a material with fine capillary passages, which will give it a high capillary potential, will attract and retain a greater quantity of water than will one with relatively coarse capillary passages. This fact can be of assistance in removing stains from a porous material as, for example, when oil has been spilled on concrete. A finely divided powder which has a greater capillary potential than the concrete can be applied over the area of the stain to draw some of the oil out of the concrete. The severity of the stain can thus be reduced althrough it cannot be eliminated entirely since there will always be some proportion of it left in the concrete.

If, on the other hand, a homogeneous material separates two different environments the moisture content of the material may be different on the two sides. With a porous material the moisture content is controlled very largely by the relative humidity to which it is exposed. Thus with differing relative humidities on the two sides the face of the material on the side of high relative humidity will have

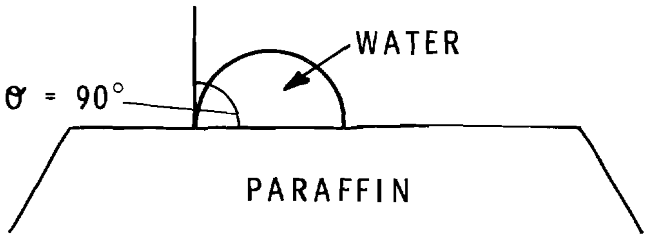


Fig. V.5 Contact angle of water on paraffin a higher moisture content than that on the side of low relative humidity and a flow of water will take place between them.

For a material to absorb water or to redistribute water under the action of capillary forces it is essential that the material be wettable by water and that it has capillary-size passages. When a drop of water is placed on a flat surface it may spread completely over the surface or it may remain as a drop having a definite angle of contact with the solid surface. When the drop is on a paraffin surface, for example, it does not spread and the contact angle is about 90° as shown in Fig. V.5.

When the drop is placed on a porous wetted material the contact angle $\theta = 0$, which results when the forces of attraction between liquid and solid are equal to or greater than those between liquid and liquid, and the solid is completely wetted. This principle may be applied to a capillary when the capillary potential will vary directly with the cosine of the contact angle ($\cos \theta$) and inversely with the radius. Thus the smaller the passage the greater will be the capillary potential. When the contact angle $\theta = 0$, $\cos \theta = 1$ and the capillary potential is at a maximum for a given size of capillary passage. As θ increases $\cos \theta$ reduces becoming zero at 90° at which point the capillary potential will be zero. When θ becomes greater than 90°, $\cos \theta$ becomes negative and there is a repellency between the liquid and the solid and a capillary depression rather than a rise, as can be seen with mercury in a glass tube.

There is a common misconception, however, about the possibility of saturating a porous material the surface of which has been made non-wettable by a silicone treatment. Such a treatment will prevent capillary attraction of liquid water but will not stop water from being pushed in by pressure differences as may be developed by wind and will not prevent condensation of water vapour inside the capillary space if the dewpoint is reached. Thus these materials can be saturated. The interruption of the capillarity may work against the rapid drying of such materials because one of the processes of bringing water to the surface from where it can evaporate has been eliminated.

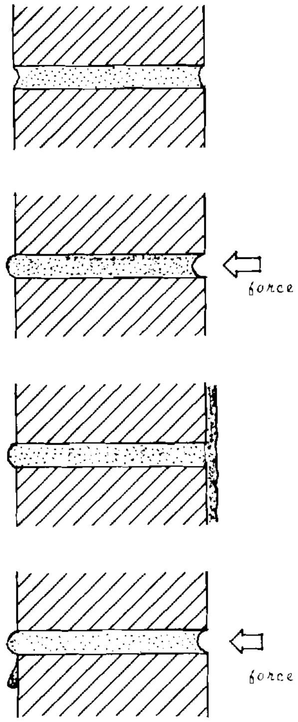
Most building materials are wettable by water and any attempt to make them non-wettable usually involves a coating or surface treatment of some sort. Since such a treatment is applied to the material rather than being inherent in it, it follows that it can be expected to have a limited life and will have to be renewed from time to time. This will incur an added operating expense and there is always the possibility (or should it be probability) that the treatment will not be reapplied when needed. Thus the control of water movement under capillarity by making the materials non-wettable would appear to be of dubious effectiveness.

The alternative approach is to eliminate the capillary-size passage. These can be reduced to zero size by the use of a sheet material such as a metal or a plastic or a liquid-applied coating as is done with built-up roofing. Under normal construction conditions sheet materials will have to be joined together and capillary-size passages will usually be re-introduced at the joints. The alternative therefore is to make the passages bigger than capillary size by the introduction of an air gap into the construction at some suitable point.

In some cases liquid water may be sprayed against the inside of the wall or roof but in the vast majority of cases the liquid water which we wish to control is the rain on the outside. Some of the rain water on the wall will be absorbed by the capillary passages in the cladding material and in the joints between cladding units. This water will penetrate into the wall until the capillary potential of the material is satisfied or until it reaches a barrier, in the form of an air gap, which it cannot cross.

With solid walls of massive construction, such as old masonry walls, it is unlikely that capillarity alone will lead to serious problems of rain penetration since the storage capacity of the material is so great. Before this storage capacity is satisfied the rain storm will usually have passed and the wall can start to dry out again from the outside. However, should water penetrate the wall from other causes it is possible that capillarity will spread it into internal finishes such as plaster leading to staining and deterioration. With lightweight walls that do not have the same water storage capacity a capillary passage which is unbroken by an air gap will have a greater possibility of leading water through to the inside to damage interior finishes.

With a basement wall below grade it is theoretically possible to devise a drainage system that will prevent water from reaching the basement wall, as will be discussed later. As always, however, it is probable that perfection will elude the designer and some water will reach the wall. If this occurs, it should be prevented from moving into the wall by capillarity by a damp-proof coating of bitumen. This is often applied as a painted-on coat of bituminous emulsion which can be effective in sealing the smaller pores but which cannot bridge over larger cracks. For more important jobs it is preferable to seal over these openings with a mopped-on membrane rein-



(a) No disturbing force

(b) Disturbing force balanced by surface tension

(c) Added water fills meniscus – disturbing force no longer balanced

(d) Disturbing force once more balanced by surface tension – surplus water exuded on inside

Fig. V.6 Effect of a disturbing force on a capillary full of water

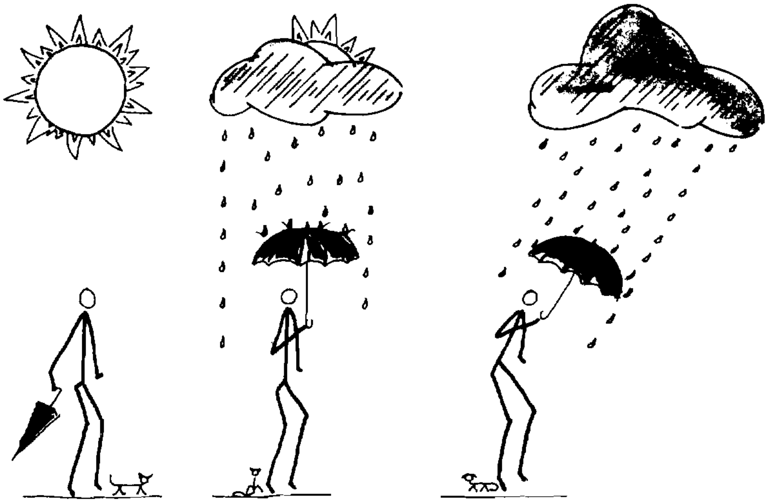


Fig. V.7 Control of rain penetration caused by the momentum of the rain drop forced with a glass fibre fabric.

Damp rising through the floor can be prevented by similar techniques. A drainage layer of crushed stone should be provided which can be covered with a sheet of polyethylene on which the concrete floor is cast. A layer of coarse sand can be spread over the stone if there is a danger of the polyethylene being punctured by it.

Capillarity alone will never cause moisture to exude from a material. The forces are such that they draw water into the capillary passages and then hold it there. Once the capillary passage is completely filled, however, the menisci at each end will be flat and flush with the end of the passage. Only a small force is required under these conditions to move the column of water to one end of the tube when the water surface will be concave at one end and convex at the other. The surface tension forces are now reintroduced to balance the applied force. If more water is added at the end with the concave meniscus this meniscus will be filled in, the surface tension destroyed, and the balance of forces upset. To restore the balance the column of water will move through the capillary passage to re-establish the menisci at each end and in so doing some water will be exuded from the material (Fig V.6). In a rain storm water is continually being placed on the face of a building where it runs down the wall over the outer ends of the capillary passages in and between the building materials. These passages are not usually simple single passages but a network of inter-connecting passages in three dimensions. Under these conditions gravity or a wind pressure will provide the necessary disturbing force to cause water to exude from the inner face of the wall. On the other hand, without the assistance of the capillary forces, in moving water through the wall neither gravity nor wind pressure would be able to move the water, at the same rate, through the small-size passages involved.

Momentum

On a calm day raindrops fall vertically and one can shield oneself from them completely by carrying an umbrella over one's head. On a windy day the raindrops have a slanting path and the umbrella no longer gives complete protection. So it is with a building: vertically falling rain can be kept off the walls by means of a projecting roof but more normally the wind will blow the rain against the wall and if there is any opening in the wall through which the rain drop can pass it will do so. If the window is open the rain will blow in.

The rain drop will have some momentum which may carry it through an opening even though it may pass into a dead air space. This is not likely to be the case with an open window for there will be sufficient leakage out of the room into other parts of the building to allow a continual stream of air to enter. An opening through the outer cladding may lead to a more or less closed space within the wall from which air cannot leak readily and so little or no air will enter. Nevertheless a rain drop which is aimed sufficiently accurately can be carried through the opening by its own momentum and so wet the inner parts of the wall. If the opening is narrow or if the trajectory of the drop is such that it cannot pass directly through the opening some water can still penetrate into the wall by splashing: a rain drop landing on the window ledge will splash in through an open window.

To prevent this form of rain penetration it is possible to do what the user of the umbrella does which is to hold the umbrella on the windward side so as to intercept the rain drops before they strike his body. The umbrella does not have to be sealed to the user to be effective in this way (Fig V.7). Similarly a shield in front of the opening will stop the flying rain drops. This shield can be incorporated in the joints between components of the cladding as caulking, baffles, splines or as a labyrinth which will prevent the rain drops from either flying straight through the gap or from splashing through. As with the umbrella it is not necessary for these shielding devices to be sealed tightly to prevent the entry of rain from this cause and so the inevitable small imperfections in caulking are of no consequence. Baffles, splines and labyrinths make no pretence of forming tight seals.

If a joint is recessed between fins or similar projections on the face of a building no special shielding device may be necessary. The number of rain drops which will be aimed sufficiently accurately to penetrate to the bottom of such a recess will be very small. Others may strike the sides of the recess and splash inwards to some extent but it is unlikely that much water will penetrate the joint under those conditions from this particular cause.

Gravity

The effects of gravity are obvious for they are all around us: the book stays on the table unless it is knocked off and falls to a lower level - the floor. Water runs down hill and so to prevent water from running into a building it is necessary to ensure that there are no passages sloping downward from the outside to the inside. It is normal practice to apply shingles and other cladding materials with the upper ones overlapping the lower ones so as to shed the water. Window-sills and other projections are sloped to the outside so that the water will run off. Drainage passages must also be provided to lead to the outside any water that may accumulate in the wall from any cause such as condensation or which may penetrate the cladding. This again is normal practice: flashings and sloping members are used to do this.

If carried out carefully these well-known measures will prevent the entry of water under the action of gravity through any openings which can be foreseen in the outer cladding. Problems can still arise however in those cases where unforeseen openings are left in the cladding or with cracks which develop later. In such cases the water will trickle inwards so long as there is a surface to support it. When the passage which it is following is interrupted by an air space the water will not cross this space but will run down in it, clinging to the back of the outer cladding. Where such an air space is provided in a wall it is easy to provide flashing periodically to deflect any water back to the outside. In conjunction with the provision of this air space any ties or other members that must cross it must be detailed and installed with care to ensure that they do not form bridges to which the water can cling and so cross the space. Mortar droppings in the cavity of a masonry wall can also be troublesome and every care should be taken to eliminate them as far as possible. In cases of sloppy workmanship an excessive amount of mortar may collect on the flashing and so block the drainage openings. Such a situation almost invariably leads to a water-soaked wall at these points and subsequent deterioration.

In the absence of malpractices such as this a suitably drained air space behind the outer cladding in conjunction with proper detailing of the components of the envelope can give complete control over the entry of water under the action of gravity.

With a basement wall below grade a similar drainage space should be provided either by a specially designed space or by a layer of free draining material. The first step, however, should be to drain away as much of the water as possible above ground and thus reduce the quantity of water to be handled in the drainage space. Where possible water from roofs should be led away in suitable drains or eavestroughs and the ground around the building should be graded so as to take surface water away from the basement wall.

Similarly water that has penetrated the ground must be drained away from around and underneath the basement. If this is not done the ground will become saturated and an hydraulic head will act on the outside of the structure which must be constructed to withstand it. Normal concrete weighs approximately 150 lb/cu ft and so a floor slab 6 in. thick has a dead weight of 75 lb/sq ft. This is all that is available to resist an hydraulic uplift under the floor. Since water weighs approximately 64 lb/cu ft, a head of water of only 15 in. above the bottom of the slab is all that is needed to lift it. If the slab is suitably reinforced then the entire weight of the building can be used to resist the uplift. To do so could be quite expensive and it still would not solve the problem of water penetration. Water would enter the building through any cracks or honeycombing in the concrete and to stop this, one would have to eliminate all such holes with a complete waterproof membrane. This may be easier to do below ground than it is above because of the absence of windows and because there are few if any joints and also because of the more stable conditions. But it is still difficult to achieve complete success. In some circumstances it may be the only thing to do but in the majority of cases it is preferable to drain the water away.

The normal method of draining water away from outside a basement is to provide a drainage channel in the form of open jointed tile at the level of the footings and to backfill above this with a free-draining material such as crushed stone or gravel. This free-draining material should be carried right up the wall to within a few inches of the ground surface with only a covering of top soil for landscaping purposes. This unfortunately poses a minor construction problem and all too often only a foot or two of crushed stone is placed over the tile and the remainder of the backfilling is done using the excavated material. This is done for reasons of economy since the side of the excavation slopes in most cases and considerable quantities of crushed rock would be needed to fill it completely. The quantity can be reduced by placing a layer of stone about 1 ft thick against the wall and backfilling the remainder with the excavated material. This, however, requires either that a temporary separator be placed between the stone and the backfill which is structurally strong enough to retain whichever material is placed first until the other is in position, or that both materials be placed simultaneously in small lifts. Both procedures present some difficulty and are more costly than simple backfilling. Nevertheless there is the basis of an idea contained in this suggestion for a possible alternative method of draining the outside of the wall.

Basically what is required is a space down which water can drain freely to reach the drain tile at the footing and across which water will not be drawn by capillary suction. Such a space might be formed by placing corrugated sheets of an inert material, say asbestos cement, against the wall with the corrugations running vertically and covering it with a second sheet either plain or corrugated with the corrugations horizontal. Some Norwegian tests have indicated that a layer of semi-rigid fibre glass insulation might be adequate in forming the necessary drainage space. The option is thus open for the designer to devise whatever system meets the requirements and economics of his particular circumstances.

Wind Pressure

It is one of the requirements of most buildings that wind should be prevented from blowing through the inside space. It must therefore be stopped or deflected by the building enclosure and so exerts a pressure which the enclosure must be strong enough to resist it. From time to time some part of a building enclosure, a large window for example, proves to be too weak to resist this pressure and is blown in. Such occurrences are fortunately relatively rare since they occur only with strong winds.

Let us now consider a comparable situation on a greatly reduced scale, and with a structurally weak material -- water. Suppose, that, during a rain storm, the water on the wall bridges over a crack in the cladding. The water, having little or no structural strength, will not be able to resist anything other than the most minute force and so will be blown in through the crack by wind pressure much as the window glass was blown in through the opening which it bridges. The results are not so dramatic nor are they so immediately apparent but over the passage of time they can be much more extensive and difficult to overcome. The question is how to prevent this water penetration and the damage which it causes.

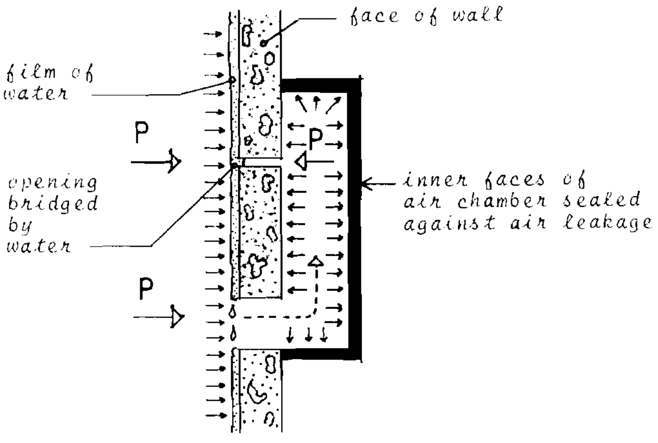
Before water can penetrate the building enclosure three conditions must exist simultaneously -- there must be water on the enclosure, a hole for it to pass through and a force to move it through the hole. This is true for water penetration under any driving force, e.g. capillarity or gravity, and not just under the action of wind pressure, although the size of the hole required will vary with the force. If any of the three conditions is eliminated the water will not penetrate the enclosure.

It is not possible to keep water (rain) off the walls of a building. The walls can be shielded to a small degree from the rain by means of wide root overhangs but with any building much bigger than a dog kennel it is not possible to keep wind-blown rain off the walls. Thus we must expect that in a rain storm the walls and roof will be covered by a film of water and that this film will get thicker as the water runs down the building until some projection with a drip throws it clear of the face of a vertical wall. In passing it should be pointed out that when a wall is tilted in towards the building for aesthetic or other reasons it is never possible to shed the water in this manner and the wall must be designed as a roof.

Since the water cannot be eliminated, can all the holes through which it could pass be eliminated? The answer here must be a qualified no. "Qualified" since this is the method of keeping the rain out which has been tried since time immemorial and if the attempts have persisted for that long some degree of success at least must have been achieved. With a more or less flat roof it is the only method by which the rain can be kept out. Even though some success has been achieved, the problem still exists.

Problems can arise from a number of sources -- the design of a building and its components, the method of manufacture and erection, the quality of materials used to seal between components, the skill with which they are applied and the deterioration of these materials with time. Individual components of a building are usually, although not invariably, free of holes through which the water can pass. The problem is to seal the inevitable gaps that must be left between them. To achieve a complete seal a good material must be applied into a properly designed and sized space by a competent, conscientious workman working under good conditions. All too often these conditions are not met on the construction site. Good materials made by reliable manufacturers may have been improperly mixed or stored, or they may not be suitable for the particular application. The design of the components may be such that some part of the joint is virtually inaccessible or some combination of construction tolerances may lead to a joint which is too wide or too narrow. The workman may be tired or possibly not in the best of health and the weather conditions may be adverse but the construction schedule may not allow the work to be delayed. Even if all the possibilities that could lead to a poor seal being made in the first place are avoided or overcome there is still the probability that the seal will deteriorate with time under the action of temperature, water and ultra-violet radiation. Roof membranes

Fig. V.8 Control of rain penetration caused by wind pressure by balancing the pressure on each side of the wetted face



P = Wind pressure

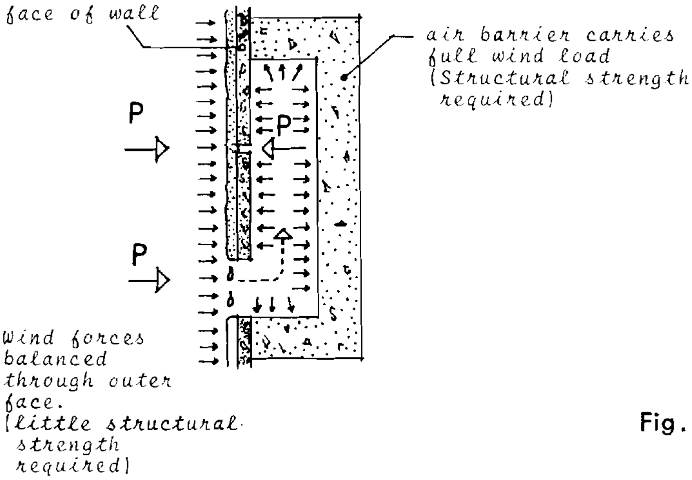


Fig. V.9 Outer face reduced in thickness on being relieved of major wind loads

P = Wind pressure

too, although usually more accessible, are subject to the same problems of construction and deterioration. When all these factors are considered it is surprising that so much success in keeping out the water has actually been achieved. No one should ever make the mistake of assuming, however, that a waterproofing problem can be solved for any length of time by simply "bunging" up the hole. Even the little Dutch boy with his finger in the hole in the dike could only hold out until help arrived.

If the water on the enclosure cannot be eliminated and if it is unreasonable to expect that no holes will be left through the outer skin of the enclosure or that some will not develop later then the only method left to try to prevent the entry of water is to eliminate the force which moves the water inward. But how can we stop the wind from blowing? Obviously, we cannot and so whenever the wind does blow there will be a pressure at least on the windward side of the building, which will try to force the water in through any opening. Although this force cannot be eliminated it can be cancelled by applying an equal force acting outwards at the inner end of the opening. The film of water bridging the outer end of the opening will be squeezed between these two forces but will not be moved inward or outward by either of them.

In some wild flight of imagination it is possible to dream up a pump system which would pressurize an otherwise sealed space at the inner end of the opening and so exert this necessary outward force. This is not very practical however and some other method must be found. It would be most convenient, to say the least, if we could induce the wind to exert its own self cancelling force for then this would be exerted automatically whenever the wind blew. This, in fact, is what one attempts to do. Suppose that on the face of the building near an opening which could be bridged by a film of water a second larger opening had been made, too big to be bridged by the water. Then the wind pressure would act through this opening unhindered by the water on the face of the building and without forcing any water in through it. Preferably one should position the second hole at some point where it is shielded from water. In either case the wind pressure can be lead through some passage to an otherwise sealed chamber behind the outer cladding of the building. Since this pressure is a fluid pressure it will act equally in all directions and so act outward through the original opening thus balancing the inward pressure exerted by the wind on the outer end (Fig V. 8).

This is the basic principle of the so-called open rain screen wall design but various fundamental points should be noted. It is absolutely essential that the air chamber be sealed on the inside or at least sealed as tightly as reasonably possible (more about this later). If no such seal is provided then there is no means whereby the wind pressure can be contained so as to counteract the wind pressure which would otherwise force the water inwards. Adding the second hole under these conditions would only increase the air leakage through the wall.

With a completely sealed chamber as shown in Fig V. 8 it is clear that the inner wall of this chamber will be subjected to the full wind pressure and so must be strong enough to withstand that pressure. On the other hand since the wind pressures have been balanced at each end of any opening through which the water would otherwise have leaked, it follows that the wind pressures at all points through the outer face of the chamber will have been balanced. Over the area of the air chamber the outer face of the wall will thus be relieved of the wind load; it will be squeezed from both sides but there will be no unbalanced wind force to be resisted by structural strength. Under these conditions the outer face of the wall can be relatively thin (Fig V.9).

It may well be argued that all of the foregoing discussion relates to a theoretical air chamber which has a perfect air seal, but what happens in practice? The provision of the inner air barrier (or air seal) will be subject to most of the same difficulties which made the elimination of all holes in the outer skin of the building virtually impossible. Won't the wind pressure leak through the holes in the air barrier thereby preventing the balancing of the pressures through the outer face of the wall and thus render the whole theory invalid? This can, and will, happen if the air barrier is excessively leaky but it is possible to obtain an adequate degree of air tightness in the air barrier under normal construction conditions.

In the first place the possibility of eliminating holes is better at some plane buried in the wall than on the outer surface. Sheet materials such as polyethylene, which would not be acceptable on the outer surface, can be used in some types of construction to cover over an otherwise porous wall. Sealants are not subjected to the severe outside weather conditions and will not deteriorate so rapidly.

In the second place a perfect air seal is not necessary to control rain penetration. This should not be taken to mean that air tightness is not important; it is, and every effort must be made during both design and construction to make the wall as air tight as possible. Let us now convert the air chamber shown in Fig V. 9 from the theoretical case of a perfect

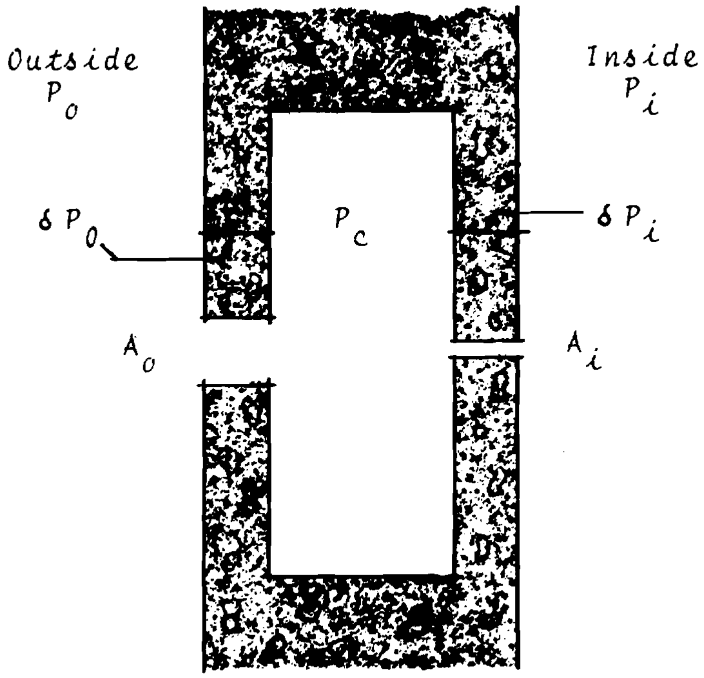


Fig. V.10 Effect on pressure equalization of an imperfect inner air seal air seal to the more practical case of an almost perfect air seal as shown in Fig V. 10. For simplicity all the openings in the outer wall of the chamber have been grouped together to form one single hole; the same has been done for the inner wall.

When the wind blows on the face of the building, some air will leak through the two openings in the wall. Since there is only one way into the air chamber and one way out the same amount of air which enters the chamber through the outer hole must leave it again through the inner one. If we take the two holes as being equivalent to sharp-edged orifices then the flow of air through each of them will be proportional to the area of the hole and the square root of the pressure difference from one side to the other.

i.e., $Q \propto A \sqrt{\delta p}$

where Q = the quantity of air
A = the area of the hole
δp = the pressure difference.

Since the same quantity of air passes through each hole and if suffixes I and 0 are used to designate the inner and outer holes respectively, we get

$$A_I \sqrt{\delta p_I} = A_0 \sqrt{\delta p_0}$$

which can be expressed as

$$\delta p_I = \delta p_0 \left(\frac{A_0}{A_I}\right)^2 \qquad (1)$$

Thus, if

$$A_0 = A_I, \text{then } \delta p_I = \delta p_0$$

$$A_0 = 2A_I, \text{ then } \delta p_I = 4\,\delta p_0$$

$$A_0 = 10A_I, \text{ then } \delta p_I = 100\,\delta p_0$$

and it will be seen that as the relative sizes of the holes change the relative pressure drops change, not directly with the ratio of the hole sizes, but with the square of this ratio.

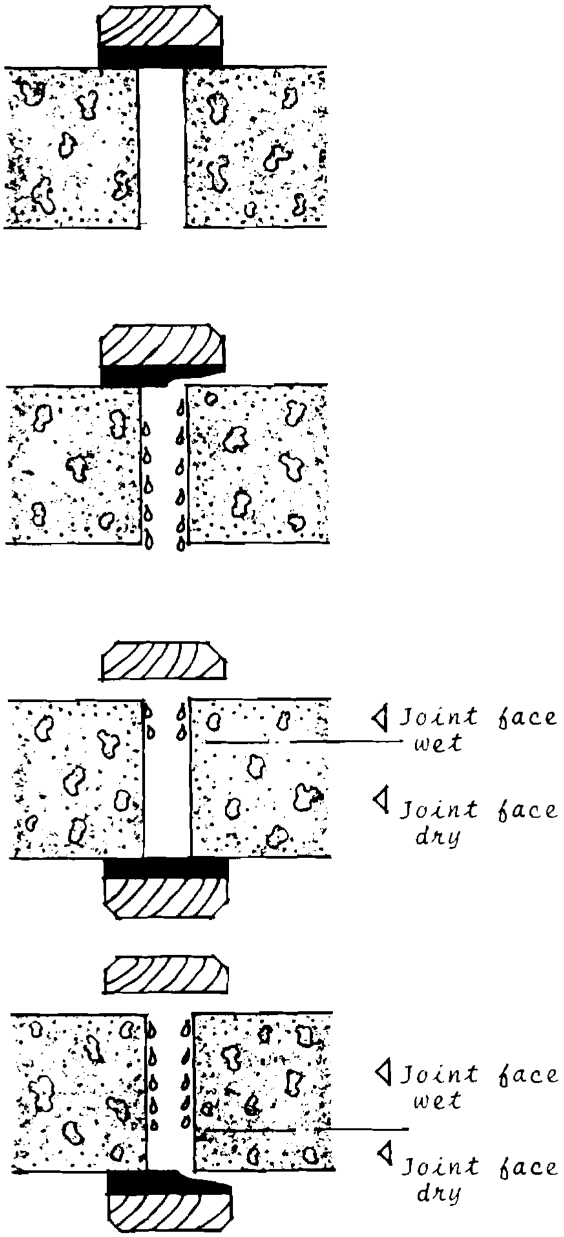
As already stated, the total pressure drop between the conditions on the outside and the conditions on the inside of a wall is produced by the combined effects of wind pressure, stack effect and ventilation pressures. It is this total pressure difference which, in the absence of the air chamber, would act to force water through any holes in the wall. Since the objective is, in the ideal situation, to reduce the force acting on the water on the outer surface to zero it is desirable that the pressure drop through the outer hole be zero. From equation (1) it can be seen that this is only possible if the hole in the inner wall is reduced to zero; i.e. for A_I to be zero, making δp_I infinitely greater than δp_0. Such a degree of perfection is not reasonably obtainable on practical buildings and so complete pressure equalization between the air chamber and the outside will continue to be unattainable except on rare occasions.

All is not lost however for, from the examples given, we see that if we make a suitable hole in the outer wall of the air chamber which is 10 times the aggregate size of the holes through inner wall then the pressure drop through the outer wall will be only 1/100 th of that through the inner wall. Thus for any given total pressure change from outside to inside the building, less than 1 per cent of it will take place between the outside and the air chamber and over 99 per cent between the chamber and the inside. For practical purposes, pressure equalization has been achieved. Perfection may have eluded us but to have reduced the force that produces rain penetration of the wall to less than 1 per cent of what it was before and thus to have reduced the quantity of water driven in to less than 1/10th of what it was before is no mean achievement. Furthermore, by providing the air chamber we have provided a means of collecting this smaller quantity of water and draining it back to the outside through suitable drain holes in the bottom of the chamber. These drain holes must be big enough not to be plugged by the water and in practice they can often be combined with the hole provided for pressure equalization as an open horizontal joint between overlapping cladding units.

One snag remains in the design process: we do not know the size of the hole through the inner wall of the air chamber. This is not provided intentionally as is the one in the outer wall, but occurs accidentally as the result of the construction process. Some guidance can be obtained from typical figures for air leakage through different types of wall construction. However, we are not seeking any specific degree of pressure equalization but as much as possible. Thus the inner wall should be made as air tight as possible and the total area of opening in the outer wall should be made as large as possible.

Sometimes an objection to this theory of pressure equalization is raised on the grounds that wind is not a steady force but fluctuates with the gustiness of the wind. This is of course true, the wind is not steady but before dismissing the whole theory one should consider how much air must pass into the chamber to build up the required pressure.

Suppose that we have a storey-high wall panel, say 10 ft high, that there is an air chamber 1 inch from front to back behind it, and that we are considering a 10-ft length of



(a) Gasket on outside with no defects - no leakage to inside.

(b) Gasket on outside with defects - leakage to inside.

(c) Gasket on inside with no defects - no leakage to inside.

(d) Gasket on inside with defects - no leakage to inside.

Fig. V.11 Some results of laboratory tests on joints sealed at the outer (wetted) face or at the inner (dry) face; with and without defects in the seal wall which may be pressurized through an open horizontal joint at the bottom of the panel. The air chamber which we are considering is thus 10' x 10' x 1" giving a volume of 14,400 cu. in. From elementary physics, for a given mass of a gas

$$\frac{\text{Pressure x Volume}}{\text{Temperature}} = \text{a Constant}$$

Since we are concerned with relatively rapid fluctuations in pressure the temperature can be taken as constant and so,

$$\text{Pressure x Volume} = \text{a Constant}$$

or $$P \times V = \text{Const.}$$

and under fluctuating conditions

$$P_1V_1 = P_2V_2$$

Where P_1 and V_1 refer to one condition and P_2 and V_2 to a second. In this case let P_1 and V_1 be the pressure and volume of a mass of air at normal atmospheric pressure (14.7 p.s.i.), i.e. with no wind pressure, and let P_2 and V_2 be the pressure and volume of this same mass of air when occupying a volume equal to the air chamber and subjected to some wind pressure over and above the normal atmospheric pressure. Note that in each case the pressure is absolute pressure and not just the increase over atmospheric pressure. Let the wind pressure be the design wind pressure for Ottawa of 15 lb/sq foot = $\frac{15}{144}$ = 0.104 p.s.i.

Thus P_1 = 14.7 p.s.i.

P_2 = 14.804 p.s.i.

V_2 = 14,400 cu. in.

and we get

$$V_1 = 14{,}400 \times \frac{14.804}{14.7}$$

$$= 14502 \text{ cu. in.}$$

That is, if the air space is full of air with no wind blowing, a further 102 cu. in. of air at normal atmospheric pressure must be squeezed in to raise the pressure in the space to that equal to the full design wind pressure at Ottawa. This extra 102 cu. in. or less than 3 pints is an increase of 0.7 per cent in the quantity of air in the space even for the extreme case of a rise from no wind pressure to the full design pressure at Ottawa. Such a gust, although possible, is rare and much smaller changes in pressure represent the normal state of affairs. Even with such gusts there is bound to be a lull following the gust when the air pressure in the air space will exceed that on the face of the wall. At this time there will be a temporarily unbalanced force acting outwards and any water in the crack will be sucked back out again.

One final point must be dealt with before leaving this subject and that is the area of the face of a wall that can be backed by a single air chamber. No hard and fast rule can be given about this and one must consider the expected pattern of wind pressure over the building. If a single air chamber extends between two locations which are at different pressures and if there are openings connecting the chamber to the outside air at these locations the wind will blow in at the point of higher pressure and out at the point of lower pressure. Under these conditions effective pressure equalization is impossible. Whenever large pressure differences are expected to occur between two points which are relatively close together it is essential that separate air chambers be provided. Such a situation occurs at the corner of a building and also between one side of a parapet and the other; at such points a separation between the air chambers is essential.

To summarize, control over the entry of water under the action of air pressure can be achieved as follows. On any potential path of water entry an air chamber should be provided in which the air pressure is equalized with that on the face of the building through suitably sized or protected openings. Although it is always difficult to separate the action of air pressure from the other forces affecting the flow of water through the building enclosure, the success of this method has been demonstrated in the laboratory. A number of joints were tested for leakage aginst simulated wind-driven rain and four such joints are shown in Fig V.11. Joint (a) has an external seal with no defects and, as would be expected, no leakage took place. When defects were introduced into the air seal to simulate a practical building situation [joint (b)] there was leakage to the inside. Joint (c) has an external baffle to prevent the entry of water drops by momentum and is sealed at the inside. The sides of the joint were wetted for a short distance but there was no leakage to the inside. When defects were introduced in this inner seal the joint face was wetted a little more but still no leakage took place to the inside.

In conclusion it must be pointed out that although the principle of pressure equalization is a simple one and while there is no doubt that it is effective if carried out properly it is a means of controlling the entry of water under the action of air pressure only. For complete success in preventing rain penetration all potential methods of entry must be controlled and under practical construction conditions it is sometimes difficult to ensure that this is done.

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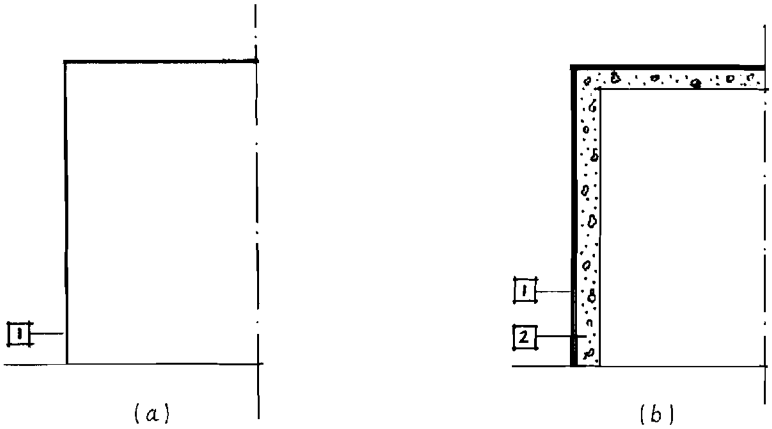


(a) (b)

1. Air barrier
2. Structural support

Fig. VI.1 Structurally supported air barrier

CHAPTER VI -- THE BASIC SOLUTION

THE ESSENTIAL REQUIREMENTS

In Chapters IV and V we discussed each of the various factors which must be controlled by the building enclosure and have shown how this control can be achieved in each case. Now it is necessary to consider these individual control measures with a view to integrating them into one over-all solution. To do this it is desirable to start once more from a consideration of what it is that the building enclosure is required to do.

At the risk of being excessively repetitious -- the basic technical function of a building enclosure is to protect the inside conditions from the uncontrolled weather conditions outside. It is required to do this so that the inside conditions can be controlled and adjusted in various ways to enable the occupants of the building, whoever they are, to do whatever they have to do most satisfactorily and to ensure that the contents, whatever they may be remain in sound condition. The enclosure is thus a barrier which separates the different conditions and to do this it must stop or limit the flow of both mass, as represented by air and moisture, and energy in the form of heat and solar radiation. Furthermore it must do this in such a way as to provide the most economical building taking into account first cost, operating costs and maintenance costs. This is largely the crux of the problem for it is relatively simple to provide a barrier which works for a while but then deteriorates rapidly and requires excessive maintenance. To give an extreme illustration a roof that stands up during the summer and sheds the rain satisfactorily but which collapses under the snow load in winter could not be considered to be a satisfactory design.

Control of Air Flow

The minimum construction that could be considered to be a building at all is a floor covered by a roof held up on posts. This would give some protection for the "inside" of the building from rain and sun, but not very much. When the sun was at any position other than directly overhead its rays would strike the floor some way in under the roof. Shortly after sunrise and before sunset they would be able to pass right through such a shelter. Similarly with rain; wind-blown rain would wet the floor some considerable distance in under the roof. This minimal building would give no control over temperature (other than some shade), nor over humidity, nor against wind and any dust or dirt blown along with it. It is clear that to make anything that is really worth calling a building it is necessary to complete the box by adding walls between the roof and floor.

This closing-in of the box will make tremendous improvements to the conditions inside. The occupants can remain in relatively still air and it now becomes possisble to heat the building. Before this any heat, other than direct radiant heat, would quickly be carried away by the wind and even with radiant heat the body being warmed by it would be cooled again by the cold air flowing over it. The humidity level can be adjusted to some extent if need be and with some hope of success, either by adding or removing moisture. Thus it can be said that one essential function of any building enclosure is to control the movement of air, i.e. it must form an air barrier. (Fig. VI. 1(a)) A building that does no more than this is really only a tent. However anyone who has lain in his tent and listened to it flap as the wind howled outside will know how valuable a tent can be. Climbers on Mount Everest and explorers in Antarctica could not exist for long without theirs.

The flapping tent illustrates the inescapable consequence of erecting an air barrier, which is that if the barrier is to stop or deflect the flow of air it must be strong enough to do so. If it isn't it will be blown down. Any building must be sufficiently stable not to be blown over and sufficiently strong not to be damaged structurally by the strongest winds which may reasonably be expected to occur at the site. Such considerations are, however, in the realm of structural engineering and need not be considered further here. What must be considered is that, just as the whole structure must be strong enough to resist the wind force, so must each individual piece of the air barrier. (Fig. VI. 1(b)) Furthermore, these forces may act either inward or outward depending upon the direction of the wind and the relative conditions inside and outside the building.

Control of Rain Penetration

A second essential function of a building enclosure is to keep the rain out. Once again this function can be fulfilled with at least some degree of success by a tent -- the minimal form of building. Tents are limited in their durability, however, and also with regard to size although

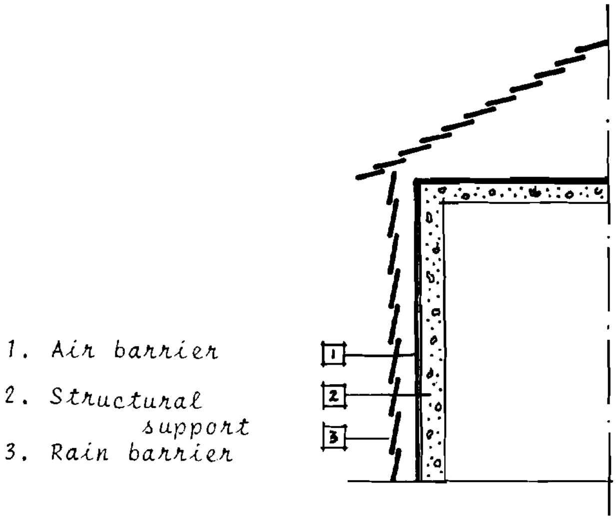


Fig. VI.2 Structurally supported air barrier with rain protection

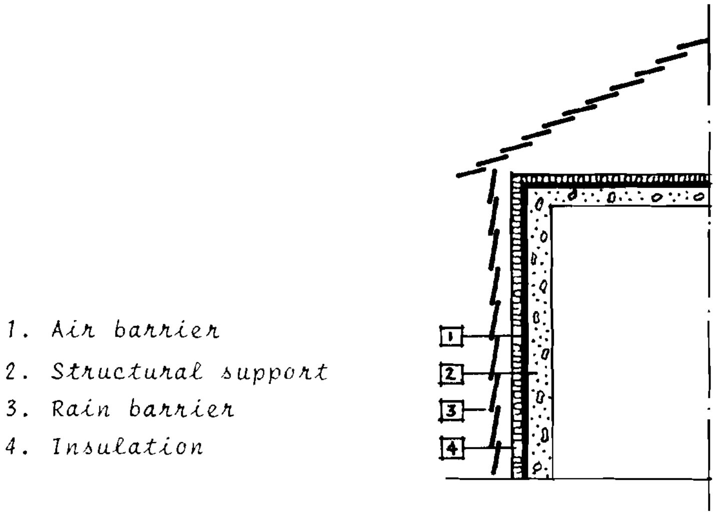


Fig. VI.3 Insulated, structurally supported air barrier with rain protection air-supported structures are now available which can cover very large areas. The air-supported structure does not carry any floor load and if more than one storey is required a separate structure must be provided to carry it. With modern materials the life span of tents and air-supported structures has been improved but at present, under conditions of continuous use, it is limited to about 10 years. For more permanent buildings a rigid enclosure is required which can exert greater control over the separation of the inside and outside conditions.

Basically there are two possible ways in which one can approach the problem of trying to keep the rain out of a building. One can either attempt to eliminate all the holes through which the water could pass or one can attempt to control the forces which would move the water through these holes. Under practical building conditions we have seen that the former method is more or less doomed to failure and that one can expect better results from the latter method. We have also seen that this method involves the use, on any path of potential rain leakage, of an outer skin to shed the rain, an air space behind that skin into which outside air pressure is admitted and an air barrier closing this air space on the inside. (Fig. VI. 2) This air barrier is a vital part of the system which is sometimes referred to as two-stage weatherproofing. In some circumstances this approach is not possible and one must try to eliminate all holes through which the water may pass. A flat, or more or less flat, roof is such a situation. If, however, one succeeds in eliminating the holes one will also have made an air barrier. The roof membrane is such an air barrier and one must take care that it is adequately supported and secured so that it will not be damaged by wind forces.

Thus we can see that an air barrier must be provided with even a minimal type of building in order to achieve each of the two essential functions of keeping out the wind and rain. It is also an inescapable consequence of providing an air barrier, that it be strong enough, or sufficiently well supported, to carry the wind loads and other air pressures, which can act either inwards or outwards.

Control of Heat Flow

Now that we have such an air barrier what next? Probably the next most important thing is to control the heat flow through the building envelope. This control is required for two reasons - to control the inside surface temperature and to make the operation of the building more economical.

Control over surface temperatures is required for various reasons. A body in the building will exchange heat with the wall or roof if they are at a temperature which is different from that of the body. A person sitting near a window in winter will often feel cool because of heat loss by radiation to the cold surface even though the room air temperature may be satisfactory for comfort. Conversely in summer a nearby hot surface will make a person uncomfortably hot. The relative humidity that can be maintained satisfactorily in a building will be set by the temperature of the coldest surface with which the humid air can come into contact. As some occupancies require or produce high relative humidities it is essential, if problems are not to be produced by condensation, for the exposed surfaces to be kept warm.

Economy of operation of the building requires that the heat exchange with the outside be kept to an economical minimum. This heat exchange through the opaque parts of the enclosure can be reduced by the addition of insulation. The economical thickness of insulation will be reached when it will cost more to add further insulation than will be saved in the over-all operating costs, taking into account the costs of heating or cooling and any possible reduction in the size and therefore in the amortized cost of the equipment. With transparent portions of the enclosure heat can be conserved in winter by the use of multiple glazing units and unwanted heat gain in summer can be reduced by shading, multiple glazing units and the use of heat-absorbing or reflecting glass.

Having decided to add insulation to control the flow of heat through the building enclosure and having decided upon an economic thickness for this insulation we must now decide where within the thickness of the enclosure it should be placed. It was pointed out earlier, when discussing the insulated concrete wall panel that it makes no difference to either the inside surface temperature or to the over-all heat flow through the wall where a given amount of insulation is placed. We also saw that various problems could be avoided by placing the insulation outside the main structural components of both the wall and the building. (Fig. VI. 3) Thermally induced stresses and movements could be greatly reduced; thermal bridging problems could also be minimized if there were an adequate means of feeding heat into them on the warm side of the insulation. Similarly, windows mounted in the warm structural element of the wall can have their edges kept warm which will minimize the possibility of thermal breakage of the glass.

Since the air barrier must be supported by the structural element or even be formed by it, as in the case of the concrete panel, then it follows that the most convenient position for the air barrier also will be inside the insulation.

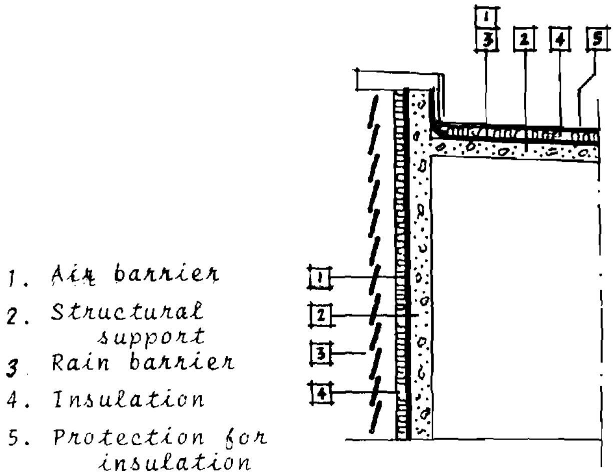


Fig. VI.4 Drained, insulated, structurally supported air barrier on roof

Fortunately, this is also the most satisfactory place for it to be since it will be protected from thermally induced stresses, from the action of ultraviolet radiation which would cause organically based components to deteriorate, and where it is unlikely that it will be wetted either by rain or condensation. Finally we have seen that the insulation must be in contact with the air barrier so as to prevent the possibility of air movement from one side to the other. Such a movement reduces the effectiveness of the insulation and if from the warm side to the cold could cause problems of condensation.

Wall Cladding

The insulation and air barrier must now be protected by some form of external cladding. The preferable solution is that this protection should be against both rain and solar radiation and should be provided by an open rain screen type of cladding in which the entry of rain is prevented by controlling as far as possible the forces which would otherwise move the water inwards. In some situations complete control is not possible and in others, although it may be possible, it may not be achieved; due in most cases to the inevitable human errors. The system should therefore be designed to be "fail safe" and provision made to drain back to the outside any water that may penetrate the rain screen.

With many types of cladding and building components the components themselves will be relatively impervious and the principal path for rain leakage is through the joint between them. In such cases, the designers' efforts to stop this leakage should be concentrated on the joints and it is logical to reduce the quantity of water which must be dealt with by giving the outer surface of the cladding a shape that will deflect water away from the joint. Outstanding ribs along side vertical joints will protect them from the lateral movement of water from the panel and horizontal joints can be protected by projecting noses above them with suitable drips to throw the water clear of the face of the building. Even so, some water may penetrate the joint and provision should be made in the joint itself to collect the water and drain it back to the outside.

There are other types of building components that are relatively pervious and water will penetrate them through capillary-size pores or hairline cracks. In such cases if the rain storm continues to supply water once the capillary system has been saturated gravity or a wind pressure will cause water to exude from the inner face. Masonry construction often has this characteristic and there are two possible methods of dealing with it. The first is to add a layer of dense material, such as a cement parging, which has such finely divided capillary passages that the rain will have stopped long before the water has penetrated and saturated this layer. There are two dangers with this approach: firstly there may be cracks through the dense layer which permit water to pass relatively easily and secondly such a layer may reduce the walls' ability to dry out again. The second method of dealing with the situation is to accept that some rain will penetrate the outer cladding and so make provision to drain it back to the outside at regular intervals. This method is usually to be preferred but it too can be less than perfect in practice. The chief problem is to ensure that adequate drainage is provided and that drain holes will not be blocked or flashings displaced. If this happens, water will collect at the blocked drainage openings and the wall will be wetter than ever at those points.

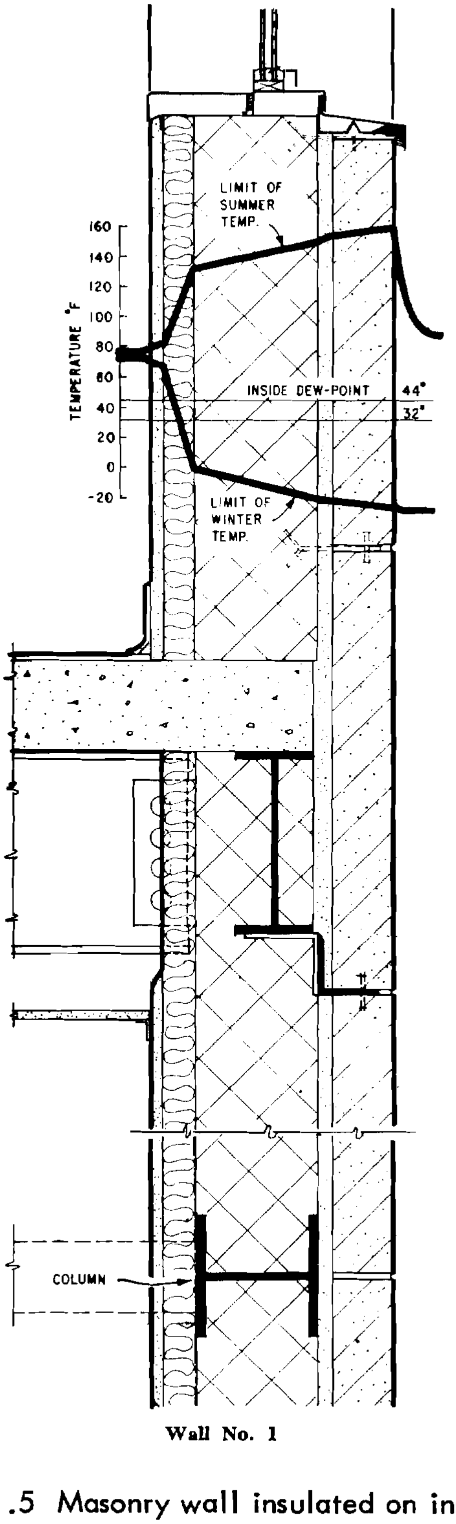
Care must also be taken to prevent the water from migrating across the drainage space and penetrating the inner part of the wall. This is the prime purpose of the rain screen and drainage space. Connections and ties must be detailed and constructed to prevent this migration and mortar droppings and other possible bridges eliminated. As always, design consists of choosing the most satisfactory solution for the particular set of circumstances and then keeping a constant vigilance at all stages of both design and construction to ensure that the desired results are in fact achieved.

Roofing

In some situations, e.g., a more or less flat roof, the use of the open rain screen cladding is not possible and one must adopt the alternative solution of providing an impermeable membrane to prevent the entry of water. This membrane then becomes the air barrier and in accordance with the requirements cited previously, that the air barrier be both structurally supported and protected from wide fluctuations in temperature, the membrane should be positioned between the structural element and the insulation. (Fig. VI.4) It then follows that the insulation must be of a type that is not adversely affected by water since it will now be outside the waterproofing membrane. The insulation must then be protected from mechanical damage and, if of an organically based type such as foamed plastic, from deterioration under the action of solar radiation. It is not essential however to attempt to prevent the rain from penetrating this covering.

Control of Vapour Diffusion

Following the previous arguments the basic layout of the building enclosure has now been set



Wall No. 1

Fig. VI.5 Masonry wall insulated on inside but before making a final decision about the components to be used and their relative positions the designer should carry out one further check. Since it is possible that some water may penetrate into the enclosure either from inside the building or from outside it is desirable that the enclosure should have the ability to dry out again once the conditions change. This means that at no point should a component be sandwiched between two vapour-impermeable layers. A check should therefore be made on the vapour diffusion characteristics of the enclosure.

THE BASIC CONFIGURATION

Thus we have built up the basic configuration for a technically satisfactory building enclosure. We need a structural element that can withstand the wind forces and can support the other components including any special ones, e.g., windows. The vital element of an air barrier must either be formed by the structural element or be supported by it for it is on the air barrier that the wind forces act. Both the structural element and the air barrier should be protected from wide fluctuations in temperature by a layer of insulation placed outside the air barrier and in contact with it. Rain penetration is prevented by either an open rain screen type of cladding which protects the air barrier and the insulation from rain water or by making the air barrier completely impervious and protecting the insulation from mechanical damage by some form of covering. Both the rain screen and the protective covering must protect organic type insulation and air barriers from deterioration from solar radiation.

COMPARISON OF TWO WALL DESIGNS

Let us now see how this basic design of building enclosure may be used for a masonry wall and the different results which may be expected in comparison with a comparable wall of a type which has been widely used in Canada over the past 50 years or more. Wall No. 1 (Fig. VI. 5) is representative of a number of designs that have been used quite extensively in the past and consists of a 4-in. facing of stone with an 8-in. back-up wall. Insulation is often added to the inside, and may take several forms including mineral wool between strapping or foamed plastic serving also as plaster base. Full mortar backing, which usually requires a very wet mortar, has commonly been used behind the facing stone.

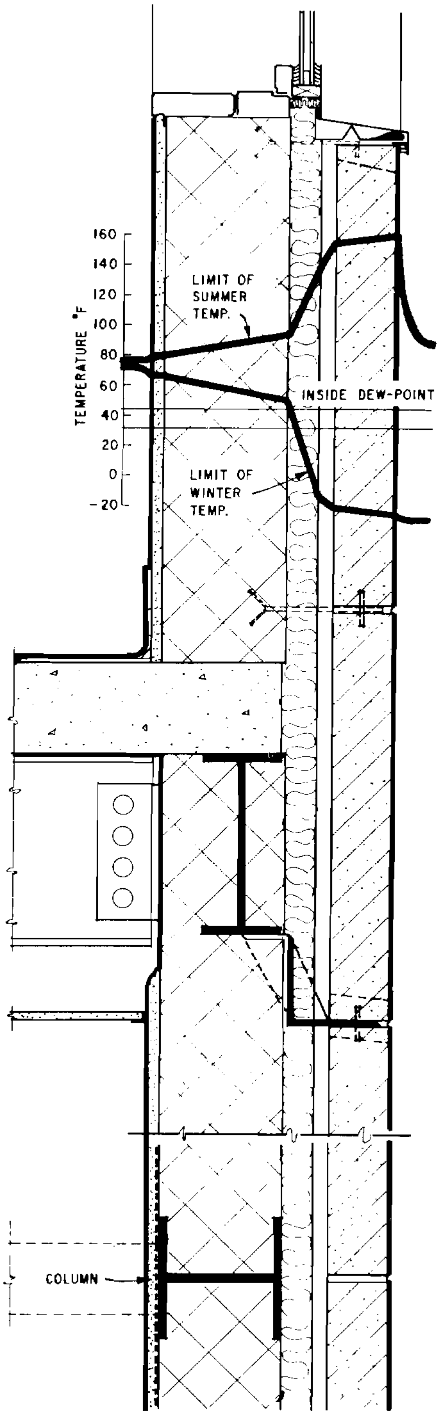
The calculated limiting temperature gradients for winter and summer are superimposed on the wall section. Winter conditions are assumed to be 73°F inside and -27°F outside. An indoor relative humidity of 35 per cent, which might commonly be desired in winter, corresponds to a dewpoint temperature of 44°F, which has been drawn on the diagram. Summer conditions are assumed to be 75°F indoors and 90°F air temperature outdoors, with a surface temperature due to solar radiation of 150°F. The summer gradient is drawn for an assumed steady flow condition that is never realized in practice but does represent for present purposes a reasonable estimate of the limiting gradient conditions to be encountered.

The very large range in temperature of the back-up and cladding from winter to summer, averaging about 160°F, produces changes in dimension in these components of about 0.1 per cent from winter to summer. The spandrel beams and columns are enclosed in the wall material outside the insulation and thus tend to follow the temperature changes and to experience roughly the same expansions and contractions. Meanwhile, all of the interior structure remains at a nearly uniform temperature and may resist the movements of the attached members, which are changing in temperature. These effects lead at times to cracks in portions of both the exterior walls and cross-walls.

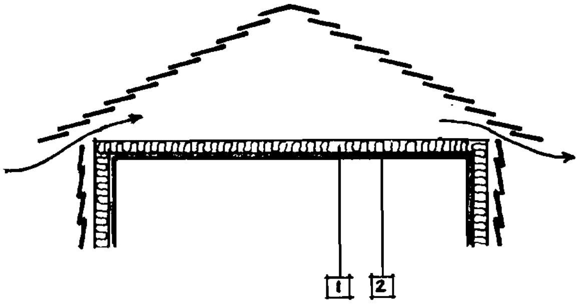
Penetration of the insulating layer by cross-beams, cross-walls and slabs creates thermal bridges. Cool interior surfaces may thus be produced on which condensation may form in winter unless relative humidities are kept to low values. Windows also suffer thermally from contact with the main portion of the wall, which is outside the insulation. The temperatures of metal frames, sills and sash in contact with cold masonry in winter are lowered, thus complicating the critical thermal condition at the window and in many cases reducing markedly the already low relative humidity that can be carried without condensation forming.

The thermally induced cracks can lead to an accumulation of water in the wall from two causes. Warm air leaking outwards in winter will lead to condensation whenever it comes into contact with a surface which is below its dewpoint. As can be seen from the winter temperature gradient all of the wall that is outside the insulation will be below the dewpoint of 44°F for the assumed interior relative humidity of 35 per cent except in relatively mild weather. Rain penetration at other times can also deposit considerable quantities of water in the wall. The full mortar bedding of the cladding usually requires a weak porous mortar which will retain much of this water. Displacement of the face stones may result, because of ice lensing, when the mortar is susbsequently frozen. Even if ice lensing does not occur, the deposition of substantial amounts of water within the wall may lead to staining, efflorescence, corrosion of ties, and to deterioration of the wall materials.

Fig. VI.6 Masonry wall with insulation moved towards the outside



Wall No. 2



1. *Insulation*
2. *Ceiling and air barrier*

Fig. VI.7 Roof over ventilated attic

Following the design principles which we have developed a dramatic difference in temperature conditions and their attendant dimensional changes can be effected by moving the location of the insulation (see Wall No. 2, Fig. VI. 6). The main wythe and all the parts of the structure in contact with it are subjected to a much smaller range of temperatures. The possibility of disruptive dimensional changes arising in them from temperature effects is thus greatly reduced. Since the main wythe forms, or supports, the air barrier in the wall it follows that the possibility of this barrier being damaged is reduced and so, in turn, is the danger of condensation resulting from the outward leakage of moist air.

The window frame, bedded in or fastened to the warm interior wythe, is now relieved of the substantial edge-cooling effect of the former arrangement. Advantage can be taken of an inside metal sill to collect and conduct heat to the frame, and a thermal break may be incorporated on the outside to minimize the loss of heat in winter.

The exterior cladding can be arranged as shown for Wall No. 2 in the form of an open rain screen. It may be set out to form an air space and supported by ledger angles and ties as before. Open joints in the cladding, that need only be arranged to prevent the direct entry of rain drops, serve also as expansion joints. Any rain that does migrate to the back of the cladding will run down and can be intercepted by suitable flashing above each ledger angle and drained to the outside. In practice care must be taken to ensure that these flashings and drain holes are effective otherwise the concentration of water at these points may be greater than before.

The problem of thermal bridges has been greatly reduced, though the need for ties and ledger angle support for the cladding still remains. The metal connections between the ledger angle and the spandrel beam must be kept to the minimum necessary for structural support so as to minimize the thermal bridging; on the other hand, however, they can now be fastened to a relatively large, relatively warm, high-conductivity member capable of supplying the necessary heat to make up the loss through the connection without undue reduction in temperature. The possibility of condensation occurring on the connection is thus reduced and since water deposited on them can be readily re-evaporated later in the space behind the cladding the time of wetness is greatly reduced as will be the rate of corrosion.

This comparison between the two walls shows that the difficulties and problems which may be encountered are greatly reduced by following the principles of design which were discussed earlier. It would be both foolish and arrogant to claim that all the problems have been solved but at least we are moving in the right direction.

ROOFS AND ROOF TERRACES

The previous example shows how the basic principles can be applied to a wall design; roofs present special problems, which will now be discussed. If we consider the ventilated attic type of roof (Fig. VI. 7) such as one finds on most houses it can very quickly be seen that most of the principles are met. The air barrier is at the ceiling level, or at least it will be if there are no holes through it for light fixtures, wires or pipes and if possible leakage paths through the stud spaces are suitably blocked off. The insulation is then installed in the ceiling joist or roof truss spaces in contact with the air barrier and finally a rain screen in the form of a pitched roof is provided over it all. With the attic ventilated through eave or gable ventilators on all sides, any heat or moisture that finds its way into the attic will be carried away without doing any harm. Because of this cross ventilation the wind pressure on the roof will never be balanced by that in the attic. This is seldom of any consequence since the overlap of the roof shingles is usually sufficient to prevent wind-driven rain from penetrating the roof. Some roof maintenance will be required in time as roof shingles deteriorate although the situation is not as critical as the need to preserve a flat roof membrane intact.

With a more or less flat roof the situation is somewhat different (Fig. VI. 4). Here it is essential that a completely impervious membrane be provided to prevent the entry of rain. Following the principles developed earlier this membrane forms the air barrier and must be both structurally supported and protected from wide fluctuations in temperature. The membrane should therefore be applied directly to the structural roof deck with the insulation on top of it. Drainage must be provided at the interface between the membrane and the insulation and this can be done by means of a porous layer or by chamfering the bottom corners of board-type insulation. It might seem that to provide such an air passage between the insulation and the air barrier violates one of our design principles in that an air change from the cold to the warm side of the insulation can now take place. Theoretically this is so but because this air space is horizontal very little of such movement will take place by convection. Furthermore, the passages are relatively small and restricted which will reduce further any such movement. It might also be thought that rain water flowing in these passages on the warm side of the insulation will reduce the effectiveness of the insulation. Here again this effect is limited. Heavy rains occur primarily in summer when outside temperatures are relatively high; in winter, when the insulation is needed most, the precipitation is as snow which does not melt until the temperatures moderate and even then it will melt only slowly.

Finally the insulation must be protected from damage and from solar radiation and it must also be held down against wind forces which can be very high at some locations on some roofs. An insulation which is adhered to the membrane and so to the roof deck will be held down and only a relatively light covering is required provided it too is held down. Where a drainage layer is provided between the membrane and the insulation it is necessary to weigh it down with a heavier covering. If the roof is also to be used as a terrace or a traffic deck then the top covering must be designed to carry the loads and transfer them to the structural roof deck. This can normally be done most satisfactorily by spreading the superimposed loads over a large enough area so that they can be carried through the insulation without crushing it. With a plaza to which heavy truck traffic has access this may require a foot or more of fill over the insulation. In cases where this added dead weight is not acceptable or where the construction depth is restricted it may be necessary to transfer the loads directly to the structural deck through pedestals or upstanding beams at preselected points. Such a design should only be used as a last resort because of the serious difficulty in making and maintaining a suitably waterproof membrane around these load transfer points and also because of the thermal bridges introduced and the more difficult construction. In most cases it would be preferable to use a greater thickness of a stronger insulation which may not have such a high thermal resistance per unit thickness.

RAIN-TIGHT JOINTS

Many problems with buildings are caused by joints between components which fail to keep the weather out satisfactorily. Considerable time and effort is spent in designing the individual components so that they will be:
(1) structurally strong enough to withstand the stresses induced during manufacture and erection as well as in service,
(2) be artistically pleasing,
(3) of suitable configuration and with the desired surface colour and texture.
The components themselves usually work satisfactorily, at least in their ability to prevent rain penetration. Unfortunately the same degree of success has not been achieved with the joints between the components. In the past the failure to achieve rain-tight joints can be attributed, very largely, to a lack of understanding of the factors causing rain penetration. Now that knowledge of these factors is becoming more wide-spread the designer pays more attention to the detailing of the joints but, even so, he sometimes fails to achieve the complete success for which he was striving. This may be due to an incomplete understanding of the situation, a failure on the part of the component manufacturer or the workmen to carry out his instructions properly or, possibly because the designer has not followed a systematic procedure when detailing the joint and so has not given the joint the best possible chance of remaining rain-tight. The following approach to the design of joints may help to remedy this situation to some extent. It is not claimed to be a complete solution to the problem nor is it to be followed slavishly; as with much of the content of this book it is more of a mental readjustment than a mathematically precise system.

For water to penetrate a joint requires three things: the presence of water, a hole through which it can pass and a force to move it through the hole. We have discussed earlier the practical impossibility of eliminating all holes in the enclosure of the buildings. Our efforts to eliminate rain penetration must therefore be directed to either keeping water away from any hole where there is a force acting which could move the water inward, or eliminating the force at any hole to which the water has access. Even so, since complete control over the movement of water is not possible and also since some mistakes in design and construction will probably be made, some water will penetrate the outer skin of the enclosure. The system must therefore be designed to be fail safe and any water that penetrates the outer skin must be collected and drained back to the outside at suitable points. Hence the design of rain-tight joints can be approached in three steps:

1. Deflect water away from the joint so as to reduce the water load on it,
2. Detail the joint so as to counteract the forces which could move the water inward,
3. Drain back to the outside any water which does manage to pass the outer skin.

This could be called the 3D approach - Deflect, Detail, Drain.

It is obvious that if there is no water on a joint no water can penetrate it. It is also a reasonable extension of this fact to observe that the less water there is on the joint the less is the potential for troublesome rain penetration and the easier is the task of controlling what water there is. It is easier to dam and deflect

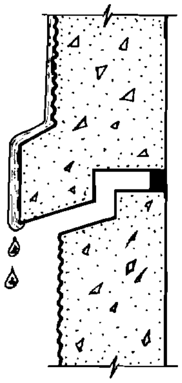
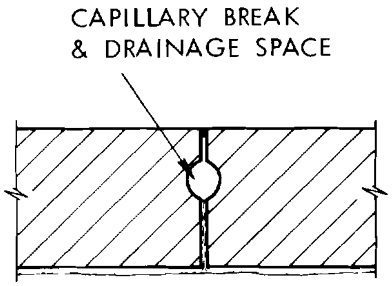


Fig. VI.8 Horizontal joint protected by a drip

Fig. VI.9 Limitation of capillary suction by means of an enlarged space



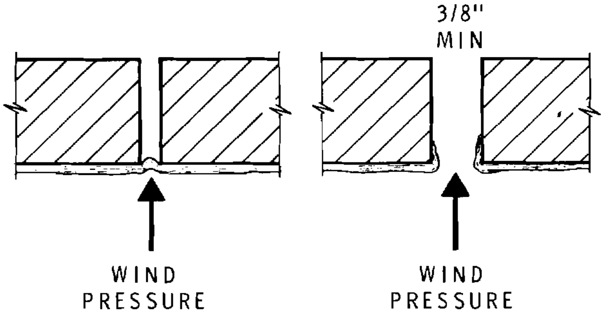


Fig. VI.10 Enlarged opening to prevent bridging by a film of water a small stream than to control the flow over Niagara Falls. Some of the water on a joint is there because the rain drop lands directly on it, but the vast majority flows onto the joint from adjacent surfaces unless steps are taken to stop it. With a relatively wide (11/16") joint which was effectively sealed against air leakage at the inside face it was found that 70 per cent or more of the water which entered it came from the adjacent storey-height panels. When the air seal was removed the total quantity entering the joint doubled although the directly impinging part increased by only 20 per cent. This tells us two things: the inside air seal is of great importance in reducing the quantity of water that can enter a vertical joint and the width of the joint does not have a great influence on the quantity of water flowing over it. Very little benefit is therefore to be gained in this respect by varying the width of the joint; its size can be set by other considerations. On the other hand it is clear that considerable benefit is to be derived from some form of vertical channeling which will stop the water from migrating laterally over the adjacent surfaces and onto the joint. Ribbed panels or panels with outstanding edges alongside the joints should be effective in deflecting the water away from vertical joints. Horizontal joints can also be shielded from water running off the surface above by means of projecting nosings with drips to throw the water clear of the building. (Fig. VI. 8). If this is not desirable for some reason then the horizontal surfaces of the joints can be sloped to the outside to prevent water from running inward. The build-up of the film of water can however be very large towards the lower storeys of a tall building if it is not deflected away from the surface. Extra care is therefore necessary in the design of horizontal joints to prevent their being sealed over and failing to act satisfactorily. This leads us into consideration of the details of the joint which is the next step in design of rain-tight joints.

As has been discussed earlier the most promising method by which rain-tight joints can be achieved is to control the forces that can move the water inward. There are four such forces - momentum, capillarity, gravity and wind pressure - and it is as well to consider the size of opening which each of them requires to be effective, in so far as they can be considered separately.

It was shown above that the bulk of the water load on a joint comes from adjacent surfaces and that varying the joint width cannot be expected to make a large contribution in keeping out the rain. Nevertheless one can hardly leave the window wide open and not expect the rain to come in. Some Norwegian tests showed that directly impinging rain did not penetrate a joint which was only 45 mm (1 $\frac{3}{4}$ in.) deep and which was open at the outside face, provided it was sealed at the inside and was less than 3 mm (1/8 in.) wide. Some rather limited British tests showed that some water did enter a 1/8 in. wide joint but perhaps one could take this value as the maximum permissible for an open-fronted joint if one wishes to exclude directly impinging rain from the joint entirely. Such a narrow opening, while no doubt possible with joints between window sash and frame for example, is not a practical design for joints between wall elements where manufacturing and erection tolerances will usually be much greater than this value.

A further objection to attempting to control rain penetration by means of very narrow openings is the effect caused by capillarity. In an ideal capillary tube with a diameter of just under 1/8 in., water can rise to a height of 1 cm. The capillary passages are not ideal in practical building materials. They are often in the form of cracks, and so must be considerably smaller than 1/8 in. to have any appreciable effect, probably 1/50 in. or less. Such openings will occur at defects in sealant materials, around defective gaskets, between units that are in contact at intermittent positions, as well as through unintentional cracks. Where there is a possibility that there will be small openings of this sort it is desirable to limit the depth of penetration of the water by providing a space larger than a capillary space, from which any water can be drained (Fig. VI. 9).

For wind pressure to be effective in moving water inward, the opening must be bridged by a film of water so that the wind has a suitable plug to push against. The size of opening needed to prevent this cannot be stated with any degree of confidence as it will vary with circumstances. The thickness of the film of water running over the face of the joint will obviously be a critical factor. The prudent designer will strive to limit this whenever possible by making provision for the water to be shed clear of the building at frequent intervals and by limiting the sideways movement of water onto vertical joints. An absolute minimum width of gap of 1/4 in. might be used in conjunction with the other precautions already mentioned and only then in relatively unexposed locations; a minimum of 3/8 in. would be preferable. (Fig. VI. 10). It should always be borne in mind that these values are not those shown on a drawing but relate to the actual width of joints as constructed on the job where they will vary with construction tolerances and inaccuracies. Joint widths wider than 3/8 in. are really to be preferred and technically there is no objection to their use. They eliminate wind pressure effects and capillary

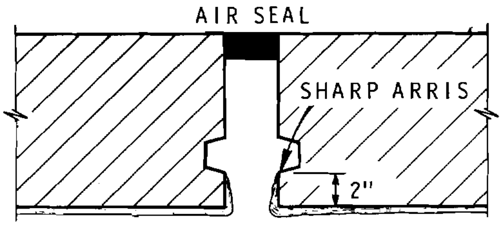
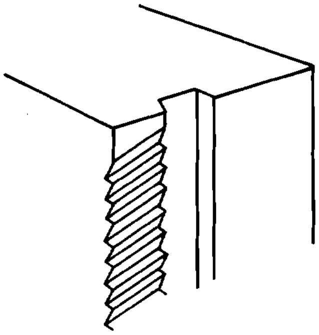


Fig. VI.11 Grooves in face of a vertical joint to limit the inward migration of water

Fig. VI.12 Washboard on face of a vertical joint to drain water back to the outside



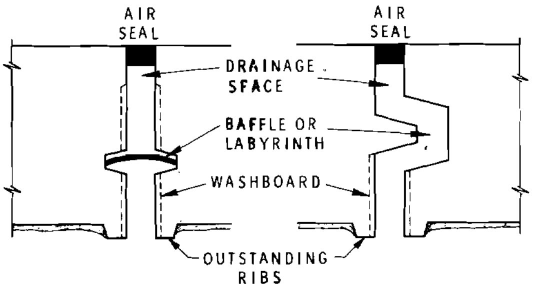
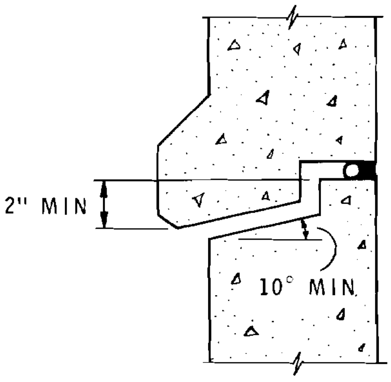


Fig. VI.13 Suggested basic designs for vertical joints

Fig. VI.14 Suggested basic design for horizontal joints



suction and they do not increase the quantity of water to be dealt with to any appreciable extent. They were also less critically affected by erection tolerances.

Any water that does enter a vertical joint clings to the sides of the joint and drains down within it. Provided the joint is sealed effectively at the back against air leakage, the bulk of the water will in fact run down within 2 inches or so of the open face of the joint even in a plain sided joint with no baffles or other deterents to the inward movement of water. Here again the importance of air tightness is displayed. Vertical grooves in the sides of the joint will limit the movement of water towards the back of the joint, apparently by providing a sharp edge which curtails this sideways flow rather than by providing vertical drainage channels. (Fig. VI. 11) To give such vertical grooves the best chance of being effective they should be located where they have the least amount of water to deal with, i.e., 2 in. or more in from the face of the joint. Let us use natural effects where we can rather than fight against them; better still, let us try and do something to help them work in our favour. If the sides of the joint are given a washboard profile which slopes towards the front, water that has penetrated some distance into the joint will be lead back to the outside. (Fig. VI. 12)

Despite these measures some water will penetrate to the back of the joint where it may wet the air seal. In such a case the wind pressure acting on the air seal will force some water through the ever-present minor imperfections. The air seal should be shielded from this water by some baffle or labyrinth to prevent the direct entry of rain. The space between this shield and the air seal must have the wind pressure admitted to it so as to prevent water on the shield from being forced into it. Despite this, some water may enter this space and provision should be made to keep it from reaching the air seal and also to drain it back to the outside at some suitable location. A system of inclined grooves on the sides of the joint, similar to the inclined washboard in front of the shield, will achieve the first objective and flashing in conjunction with an open horizontal joint the second. (Fig. VI. 13)

Thus all three requirements of our 3D approach to joint design will have been provided. After deflecting as much water away from the joint as possible, then detailing the joint to limit the inward movement of water, we have now drained away what little water may get in.

The same basic principles apply to horizontal joints since we are still dealing with water and the same forces that can move it inward. Water should be deflected clear of the joint as has been mentioned before but this has an additional importance in many cases since it is often through an open-faced horizontal joint that the wind pressure is admitted to the air chamber of the vertical joint. Should the horizontal joint be closed by the film of water then the wind pressure will not be balanced in either joint and leakage can be expected. Relatively wide ($\frac{3}{4}$ in. or more) joint openings should be used unless they are shielded from both directly impinging rain and the film of water on the face of the building by projections with drips on their under surfaces.

Surfaces of joints must be suitably shaped to prevent water draining in by gravity. Relatively flat slopes (say of up to 10°) may be adequate to control gravity alone but whenever there is air leakage through an imperfect air seal the air flow may drag the water up such slopes. Steeper slopes (about 20°) should be used or preferably a vertical overlap between the panels to form a positive drip on the bottom of the upper panel. The air seal should be located on top of the upstand of the lower panel where it will be well protected from any water blown along the lower surface of the joint by air currents. If a perfect air seal is achieved there will be no air currents right through the joint but there may be eddy currents in the joint caused by the configuration of the wall and wind pattern on it. In any case it is unlikely that perfection will be achieved and one should design accordingly. The overlap between the panels should be about 2 in. unless the exposure is very severe or a good air seal is not likely to be achieved, possibly because the configuration of the joint makes it difficult to insert, when it should be increased to 4 in. (Fig. VI. 14)

Finally we come to the intersection between vertical and horizontal joints. Although this is often one of the more difficult points to detail satisfactorily in a wall jointing system, all too often it is not given sufficient thought but it is left to the man on the site to fix it up as best he can. The requirements of both of the joints must be met simultaneously which means in the first instance that the air seals must intersect effectively. The drainage requirements must also work together. The upstand and air seal in the horizontal joint must pass behind at least the drainage zone of the vertical joint and preferably behind the drained air space as well for water may have to be drained out of this space while admitting air to it at the same time. The effective overlap of the upper and lower panels in the horizontal joint must be maintained across the

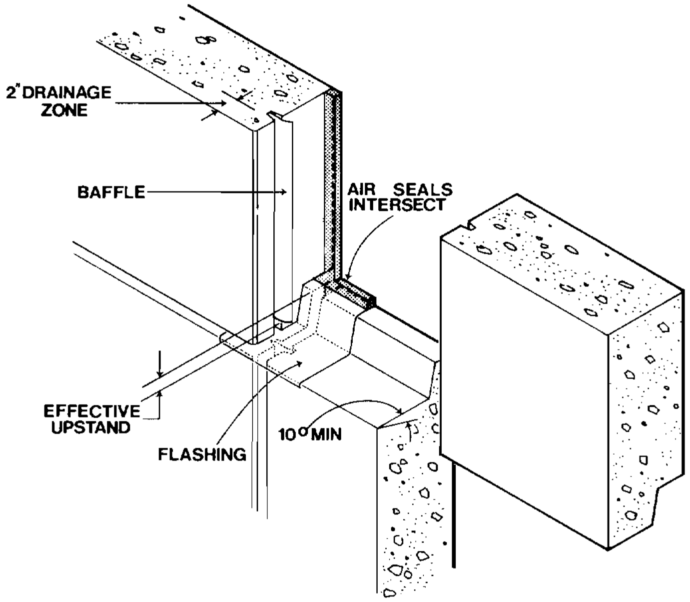
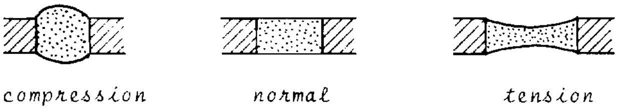
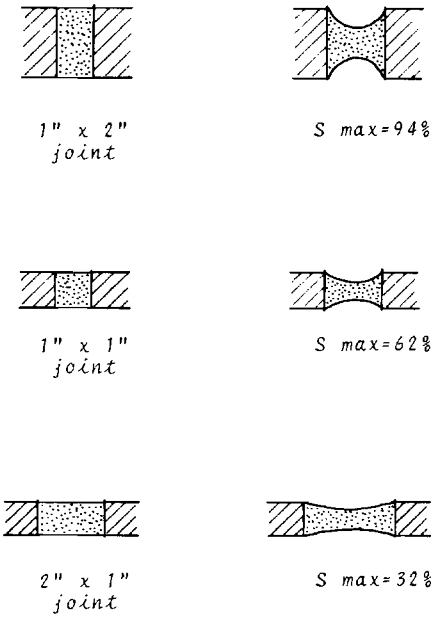


Fig. VI.15 Exploded view of the intersection of a vertical and a horizontal joint

Fig. VI.16 Change in shape of sealant bead under strain



compression *normal* *tension*



1" x 2" joint

S max=94%

1" x 1" joint

S max=62%

2" x 1" joint

S max=32%

Fig. VI.17 Strain on the extreme fiber of a sealant bead for a 1/2" extension of different joint design vertical joint. This overlap is measured from the bottom of the shield or baffle in the vertical joint and allowance must be made for any displacement of this shield. Flexible baffles drawn into place down a grove may be stretched in the process and creep upward as the induced stresses relax. (Fig. VI. 15)

The basis for the design of joints between wall panels whch we have now developed should, with reasonable workmanship, give joints that will perform as satisfactorily as the panels themselves. It is not suggested that all details must always be follwed strictly although any deviation from the layout suggested may lead to more difficult conditions for the joint. In such a case greater care must be taken with the detailing and execution to prevent failure. For example, there is evidence to support the idea of locating the baffle which shields the air space and air seal 2 in. from the wall face. This will give the appearance of an open joint which in some circumstances may not be aesthetically pleasing. In such a case the shield should be moved forward to the face of the wall but in so doing the designer must accept the fact that the water load on it will be increased and it will also have a greater exposure to the deteriorating effects of sunlight water and temperature.

Shape of Sealant Bead

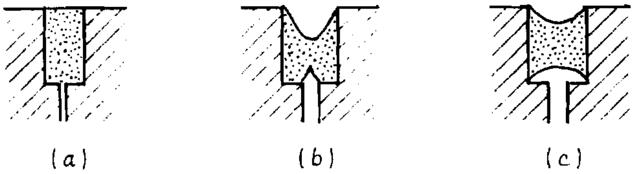
No matter how a joint is designed and detailed at some point through the thickness of the wall a seal must be made to complete the essential air barrier of the building. This can be effected in various ways but one of the most common is by using a caulking or sealant. Many excellent materials have been developed for this purpose and their manufacturers are always willing to give advice as to how to use them to best advantage. It is not intended to attempt to discuss the different materials available and their various properties since any such discussion would necessarily be only superficial. One factor, however, is relevant to our discussion of the design of rain-tight joints and that is the best shape for the bead of sealant.

Most sealant materials when acted upon by a force will change their shape as they deform but not their volume. Thus when a ribbon of material is stretched it must get thinner as its length increases just as does a rubber band. In practice a sealant is never used in this manner but rather it is a relatively chunky piece of material inserted between and bonded to two rigid bodies. As the distance between these two bodies varies, the cross-section of the sealant bead must change in shape so as to retain the same area and thus the same volume of material per unit length of joint. As this change takes place the two sides that are bonded to the faces of the joint must remain unaltered in length; if they do not, the adhesion of the sealant to the faces will have failed and the joint will no longer be sealed. To effect this change in shape without change in volume the sealant will "neck in" as the joint opens and bulge out as it closes (Fig. VI. 16)

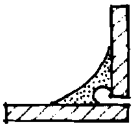
Now consider the strains that are imposed, as the joint opens, on two fibres in this sealant bead, one on the surface and the other in the centre. The fibre in the centre will be strained by the amount that the joint opens but the one on the surface must stretch around the curved surface and so will be strained more. If this strain is greater than the sealant can withstand under the given conditions the surface fibre will fail. A stress raiser condition will then be formed and the tear will be propagated through the sealant. The adhesion of the sealant to the joint surface will also be endangered by this increased strain on the surface fibre. Not only will the stresses be greater at the outer fibre but they will also act at an angle to the plane of adhesion which could initiate a peeling failure.

The extent to which the bead necks in and the severity of the increased strains induced in the surface fibres is a function of the proportions of the sealant bead. If a joint were 1 in. wide and 2 in. deep and it extended by $\frac{1}{2}$ in. the centre fibre would be strained by 50 per cent but the surface fibre would be strained by 94 per cent. Reducing the joint to a 1- by 1-in. cross-section leaves the strain on the centre fibre unchanged at 50 per cent but reduces that on the outer fibre to 62 per cent. If the width of the joint is now increased to 2 in. with a depth of 1 in. the centre fibre will be strained by 25 per cent for a $\frac{1}{2}$-in. extension and the outer fibre by 32 per cent. (Fig. VI. 17) From these considerations it can be seen that some advantage is to be gained by reducing the depth of the sealant bead and increasing the initial width of the joint. Other factors, such as sagging of the sealant in the joint, may set an upper limit to the width of joint that can be used.

Changing the shape of the bead can also be helpful in controlling the strains and adhesion stresses. If it is formed initially with concave inner and outer surfaces most of the strain will take place in the narrow centre portion without excessive necking or surface deformation. The possibility of a cohesive failure in the sealant is thus reduced. Furthermore the area for adhesion on the joint faces is relatively large leading to low stresses and generally good performance. Beads of this shape can be formed by first inserting into the joint a back-up



(a) 1" x 2" joint normal
(b) No bond breaker, 50% extension
(c) With bond breaker, 50% extension



corner bead shape

Fig. VI.18 Showing the need for a bond breaker behind a bead of sealant material that has a convex surface to form the inside surface. The outer surface can be formed by means of a suitably shaped nozzle or preferably by tooling since that helps to press the sealant firmly against the sides of the joint. In either case, the joint must be completely filled and, for the sealant to get in, the air must be able to get out otherwise bubbles will be formed in the bead which could initiate failures. To ensure that the joint is filled properly some fluid sealant must be forced into it ahead of the nozzle.

Sealants in general cannot tolerate the same strain in compression as they can in tension and this must be taken into account when detailing the joint. Too great a compression may give them a compression set after which they will no longer retain their ability to return to their former shape when the joint opens up again. A sealant which is forced too far out of a joint will not be pulled back into it again and the joint may subsequently fail in tension from a shortage of material in it.

Whether in compression or tension the strain on a sealant will be set by the size of the joint, the amount of movement in it and the shape of the sealant bead. The effective size of the joint as far as the sealant is concerned is that portion to which it is not bonded. The back-up material used in the joint must therefore be of a type to which the sealant will not bond. When a narrow joint, or a crack, is increased in width at the surface so as to accommodate a suitable sealant bead a bond breaker must be placed in the bottom of the reglet. Without such a bond breaker the effective width of the joint will be the narrow inner joint width and cohesive failure may be initiated from the inside face of the sealant (Fig. VI.18). Similarly, with a corner bead, if any movement is expected a bond breaker must be placed in the corner so as to give the bead the necessary shape and unbonded length to reduce the strain on it (Fig. VI.18).

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APPENDIX

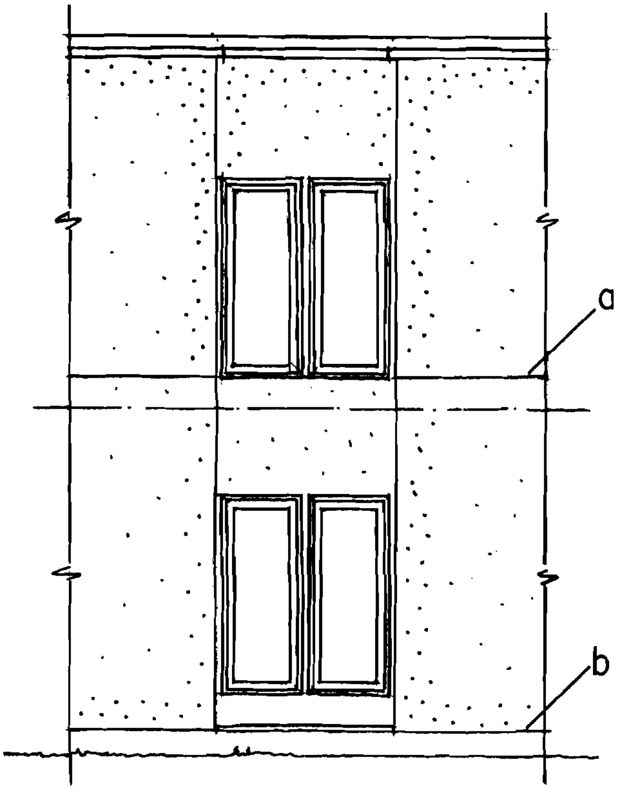
BUILDING DETAILS

AI - Laboratory Building
AII - Office Building
AIII - Improved Brick Rain Screen
AIV - University Building
AV - Entertainment Centre
AVI - Windows
AVII - Office Building

AI - Laboratory Building

This two-storey building, which has laboratories maintained at 72°F and 50 per cent RH in the centre core and offices at 72 to 75°F and 30 to 35 per cent RH round the perimeter, was completed in 1970. In the short period of occupancy since then no problems associated with rain penetration or air leakage have been encountered nor are any anticipated because of the carefully executed exterior enclosure.

Air pressure equalization behind the rain screen is achieved through continuous openings along lines (a) and (b). The opening at line (a), which also acts as a control joint in the rain screen, is designed to prevent rain penetration by kinetic energy (see Fig. Al.4).



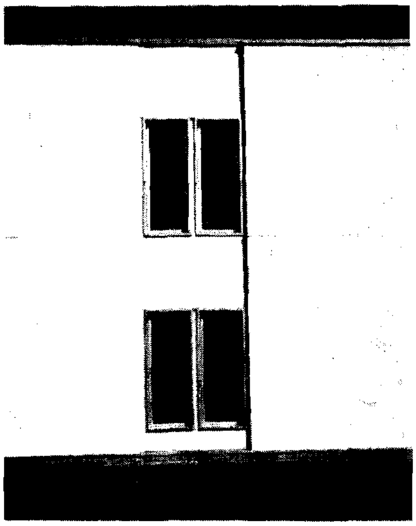


FIG. Al.1

The rain screen consists of stucco on metal lath fastened to trussed steel furring. Air pressure equalization is achieved through continuous openings along lines (a) and (b) (see Fig. AI.1) and above window heads at (c). The cavity is closed at window sills and parapet coping. The insulation is on the outside face of the structural wall of concrete blocks which is parged on the outside and fills all web openings between structural steel members. The structural wall can therefore be considered to be continuous between structural floor slabs. Air tightness of this wall is achieved through the parging on the outside face of the block. Shrinkage of the block away from the structural steel has been allowed for by a caulked joint at this point.

The structural steel cannot be relied upon as an air barrier because of gaps at cleated joints. The plaster, while helping to increase air tightness, is not in contact with the insulation and may have holes punched in it later allowing room air to circulate in the core spaces of the blocks.

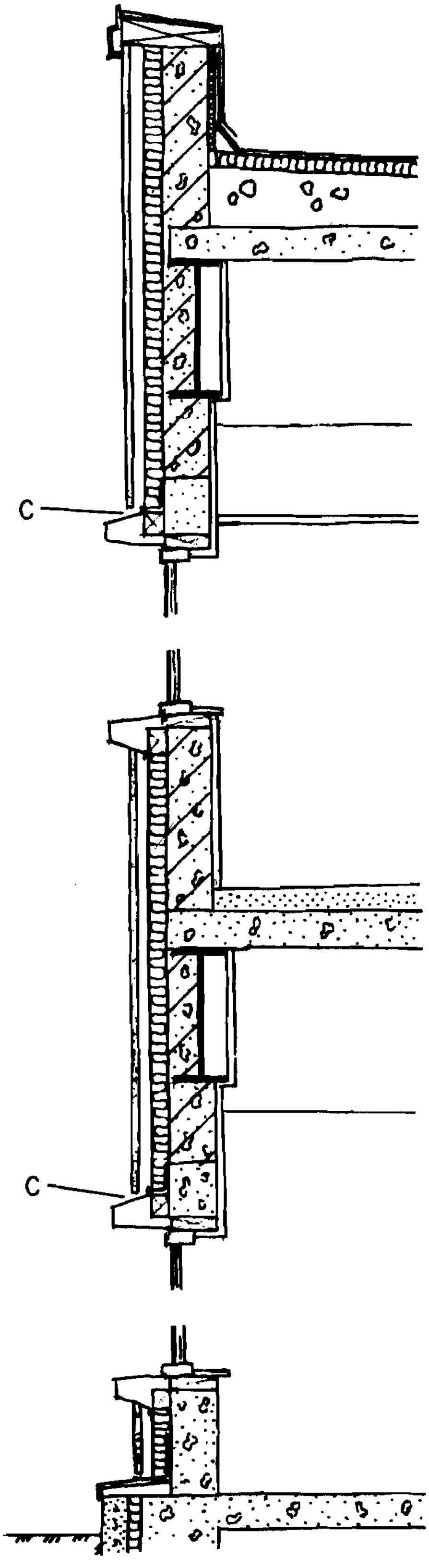
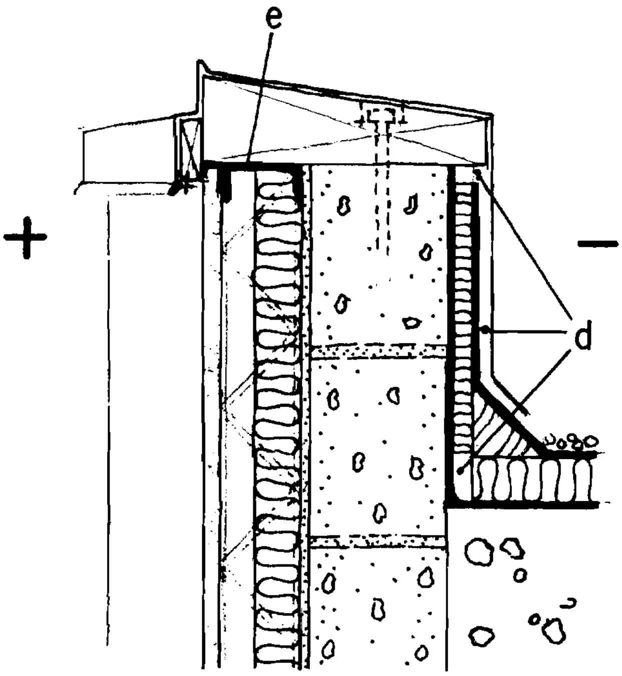


FIG. AI.2

Detail at parapet coping shows space behind rain screen closed at top. Continuous steel channel at (e) prohibits air flow from face of positive pressure (+) to face of negative pressure (-) inside coping structure. The roof – sloped toward the drain – is of a double membrane type with the primary membrane installed below the insulation. The secondary membrane leads water quickly toward the drain and protects the insulation from U.V. radiation. Changes in pressure in the drainage spaces through the insulation caused by changes in temperature, vapour pressure and wind action, are relieved through the openings at (d), which are interconnected, and at the double drain arrangement (not shown in detail).

Detail at foundation wall shows opening for pressure equalization behind rain screen at (b). Insulation in concrete foundation wall extends to approximately 2 ft 0 in. below finish grade.



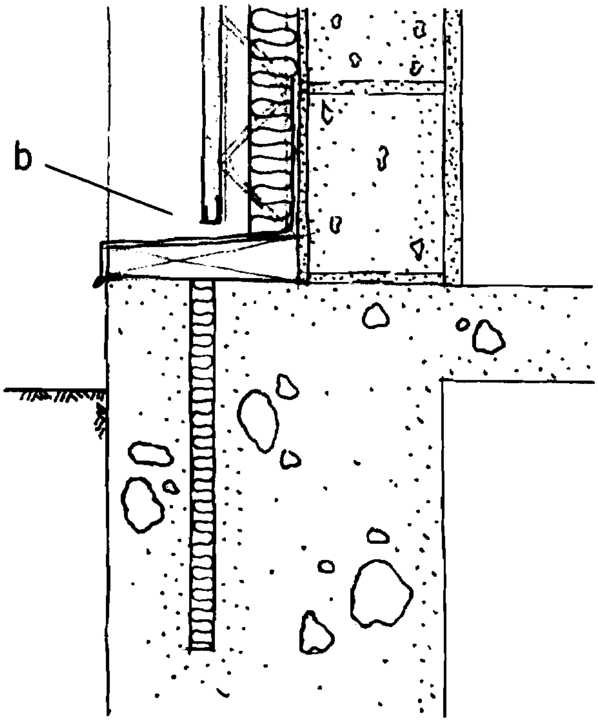
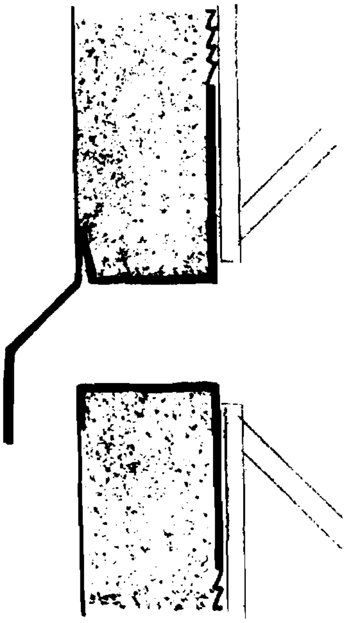


FIG. A1.3

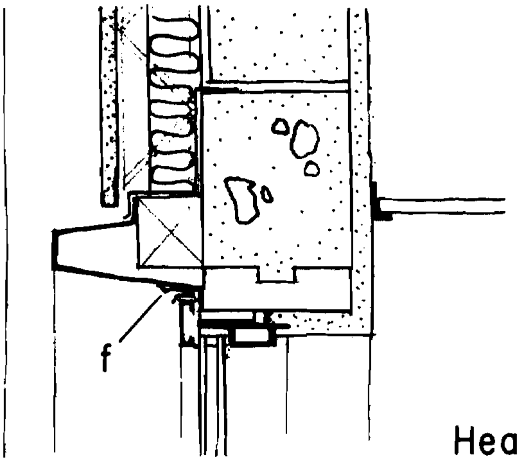


The location of the window in the warm part of the wall reduces the danger of glass breakage by thermal movement.

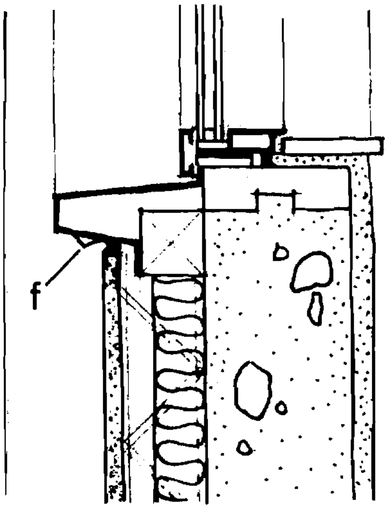
The detail at the junction between wall and window frame provides continuity in the line of air seal, thus eliminating problems of air leakage at window head, sill and jamb.

Window head and joint between rain screen and window sill are flashed against rain penetration.

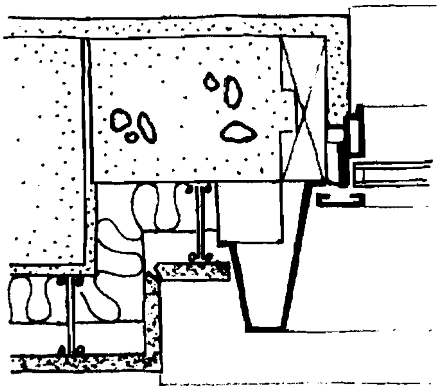
The horizontal control joint is open for air pressure equalization of the cavity behind and protects the cavity from the kinetic force of the raindrop.



Head



Sill



Jamb

FIG. AI.4

All - Office Building

All - Office Building

This office building was erected during 1970/71 in eastern Ontario. No performance test has been possible to date. The designers decided on a currently quite common wall construction, using the one-stage weatherproofing system. In this system, the outside cladding has to provide the deterrent against wind and rain penetration. Good performance of this wall depends on the tightness of the air seal at (a). Faulty installation of this air seal, such as cracks or discontinuity, may result in rain penetration or air leakage into the joint, caused by a pressure difference between the exterior and interior. There is also the possibility that holes may develop in the air seal by the seasonal strain of thermal movement in the cladding acting upon it. It is important, therefore, to give particular attention to the design of the joint itself.

The space (c) between the water deterrent (b) and the air seal (a) should be pressure equalized with the outside air pressure. The degree of pressure equalization achieved depends on the tightness of the air seal (a). Therefore, the location of the air seal (a) must be such that easy physical installation is guaranteed. This is not always possible when the vertical joint coincides with the centre of columns or the access to the horizontal joints lies near the centre of heavy beams.

The insulation and vapour barrier (d) do not provide an air seal when they are not structurally supported.

The change in the plane of the insulation at (e) is not recommended. Condensation is likely to occur on the interior face of the cladding.

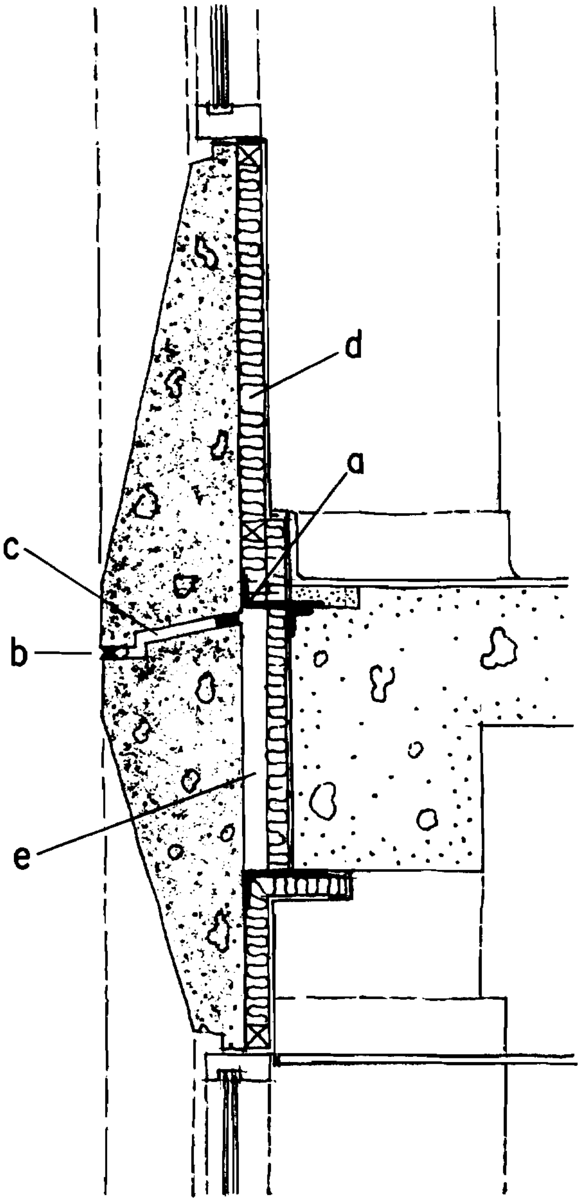
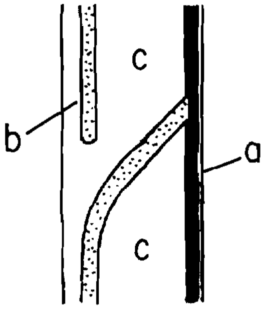
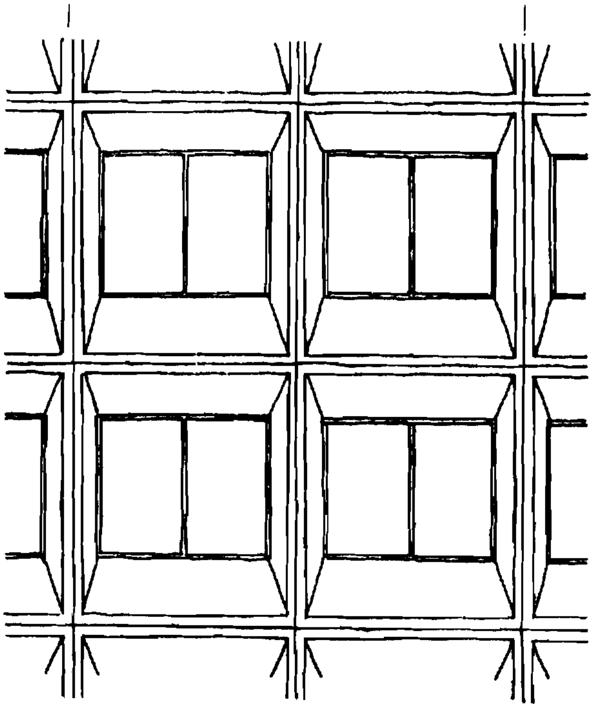


FIG. All.1



Pressure equalization of the joints (c) can be achieved by openings in the water deterrent rope (b) of the vertical joint. No caulking in front of this rope is required.

Air seal (a) has to be tight and continuous.



This detail illustrates the difficulty of installing the air seal at (a) when only limited working space is available between the column and the cladding.

As it is also difficult to apply the insulation tightly against the face of the cladding, spaces between the insulation and cladding are likely to occur in which condensation may take place.

The open space at (f), interconnecting all floors, may present a smoke channel in case of fire and is, therefore, undesirable.

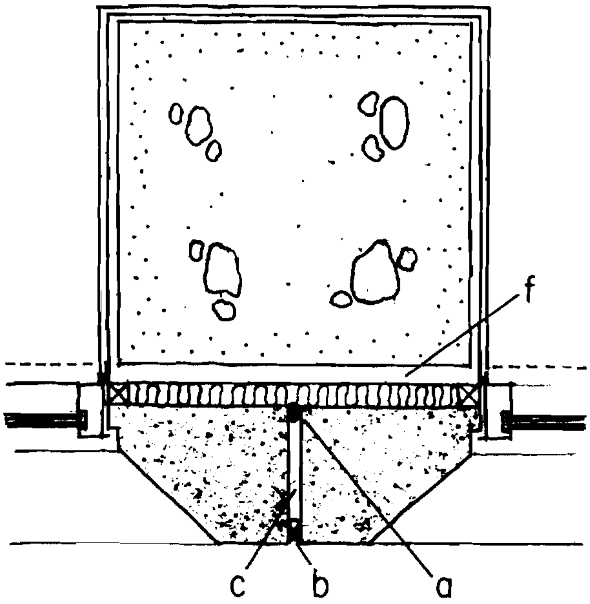


FIG. AII.2

AIII - Improved Brick Rain Screen

In some instances brick rain-screen-designed walls have not performed satisfactorily. There may be two reasons for this poor performance. Firstly, the openings are, for practical reasons, generally formed by open vertical joints on the face of the brick wall. Thus they may not protect the air space from rain penetration both under the kinetic energy of the drop and by gravity, if the top surface of the lower brick is sloped inward slightly. Secondly, openings are needed above shelf angles to drain out the water that almost inevitably penetrates the wetted wythe of brick. These openings frequently are blocked by mortar dropping leading to excessive water accumulation in the brickwork at these points. Even where the drain holes are clear, unless each supporting shelf angle is flashed in such a way that the flashing projects beyond the face of the wall with a drip to shed the water (which may be unacceptable to the designer), the water is likely to run back into the brickwork.

It is desirable, therefore, to design a brick rain screen wall without openings on the face of the wall (particularly in areas with severe rain storms) and to provide special openings that are protected from the rain for pressure equalization and drainage.

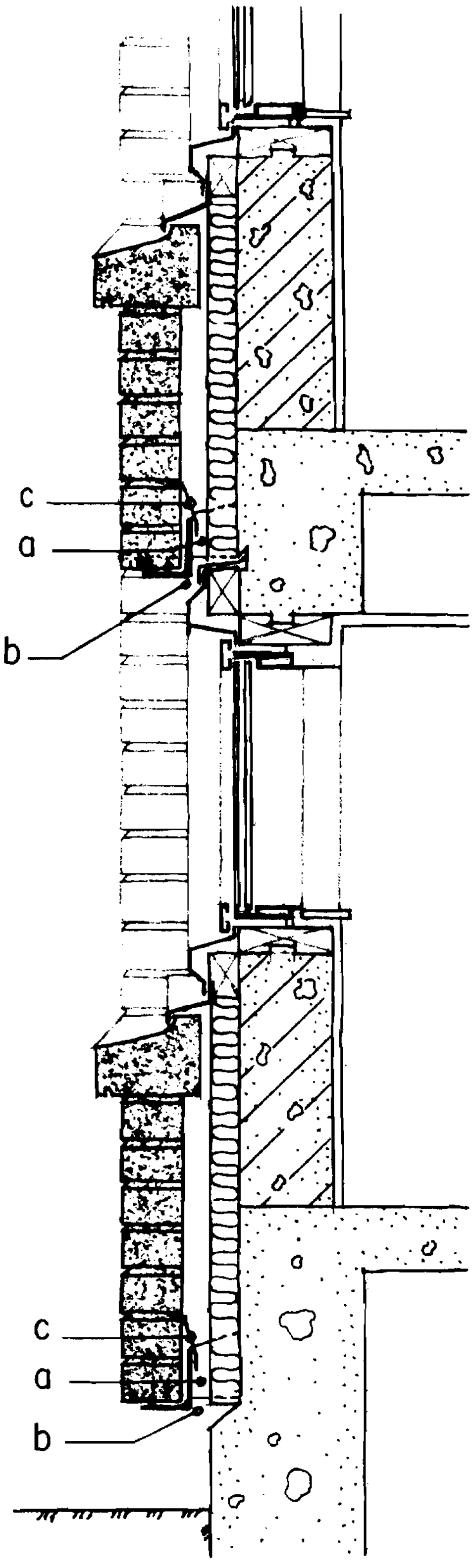


FIG. AIII.1

AIII - Improved Brick Rain Screen

This detail is one attempt to overcome this problem: The shelf angles are supported by steel brackets (a) to provide a continuous cavity behind the face brick. In this way air pressure equalization of the cavity will be achieved through the opening at (b). This opening is protected from wind-driven rain. Openings for air pressure equalization on the brick face are therefore unnecessary. Should water enter the brick by gravity through cracks in the rain screen, it will freely run down the backface of the brick and leave the cavity at (b). The supporting shelf angle is protected by the "inward" flashing at (c).

This arrangement has the further advantage that mortar droppings could be removed at (b), eliminating common moisture problems at shelf angles and at the brick base.

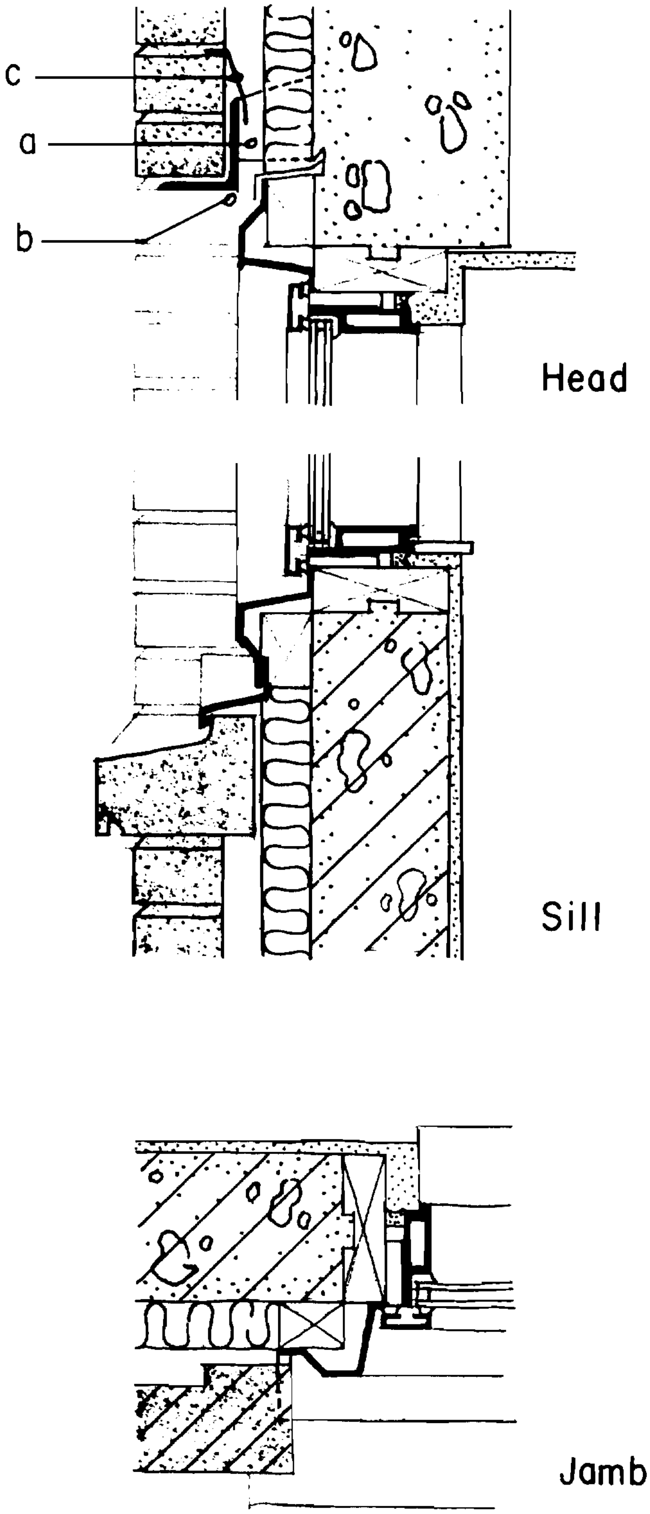


FIG. AIII.2

AIV - University Building

AIV - University Building

This educational building located in the eastern Maritimes, was completed in the mid 1960's. The rain-screen-designed wall of brick and glass panels has performed extremely well, even though heavy rainstorms are quite common.

Glass panels and brickwork are clean, with only slight indication of efflorescence on the face of the brick above the concrete foundation wall. Mortar droppings may have blocked the drain holes at this location.

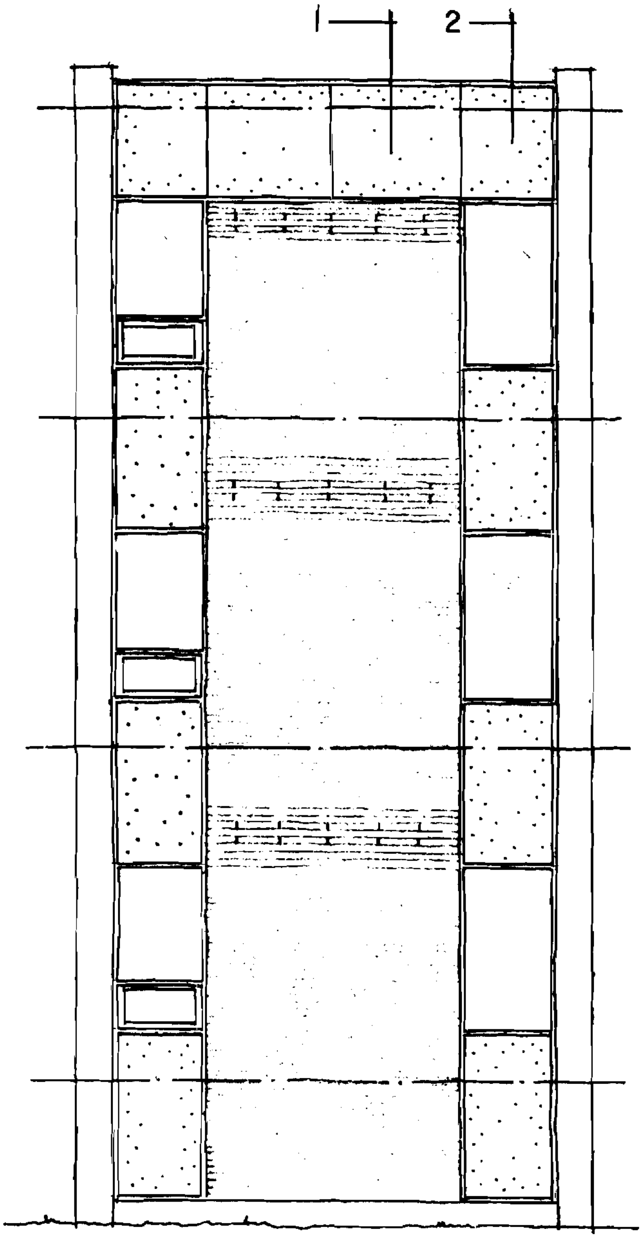
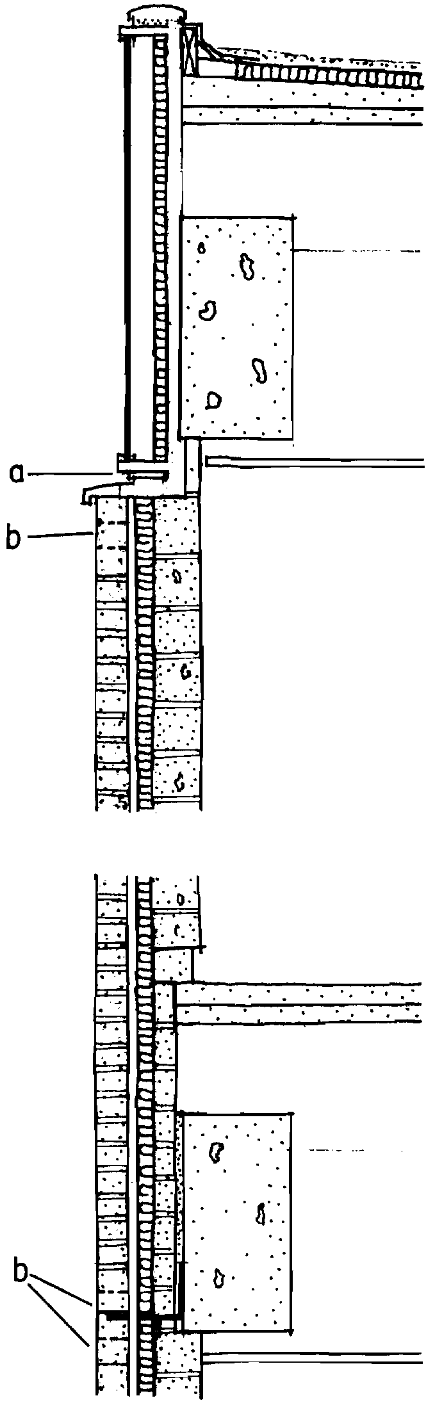


FIG. AIV.1

Air pressure equalization of the space behind the brick is achieved through open vertical joints in the brick at (b). Air pressure equalization of the space behind the glass panels is achieved through openings in the frame at (a). This is shown more clearly on Fig. AVI.4.

The airtightness of the concrete block back up wall seems to be sufficient for the occupancy of this building. The change from a concrete block and brick wall to a metal panel one is a possible point of weaknes which must be designed and constructed with care.



Section I

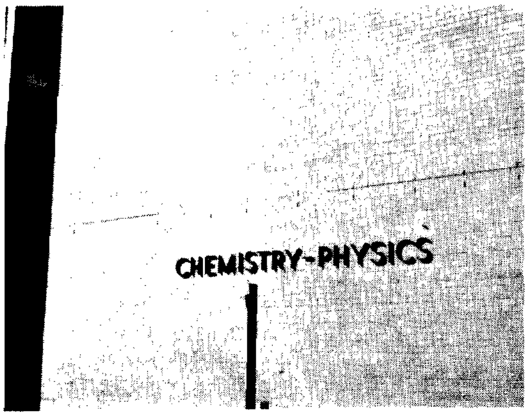
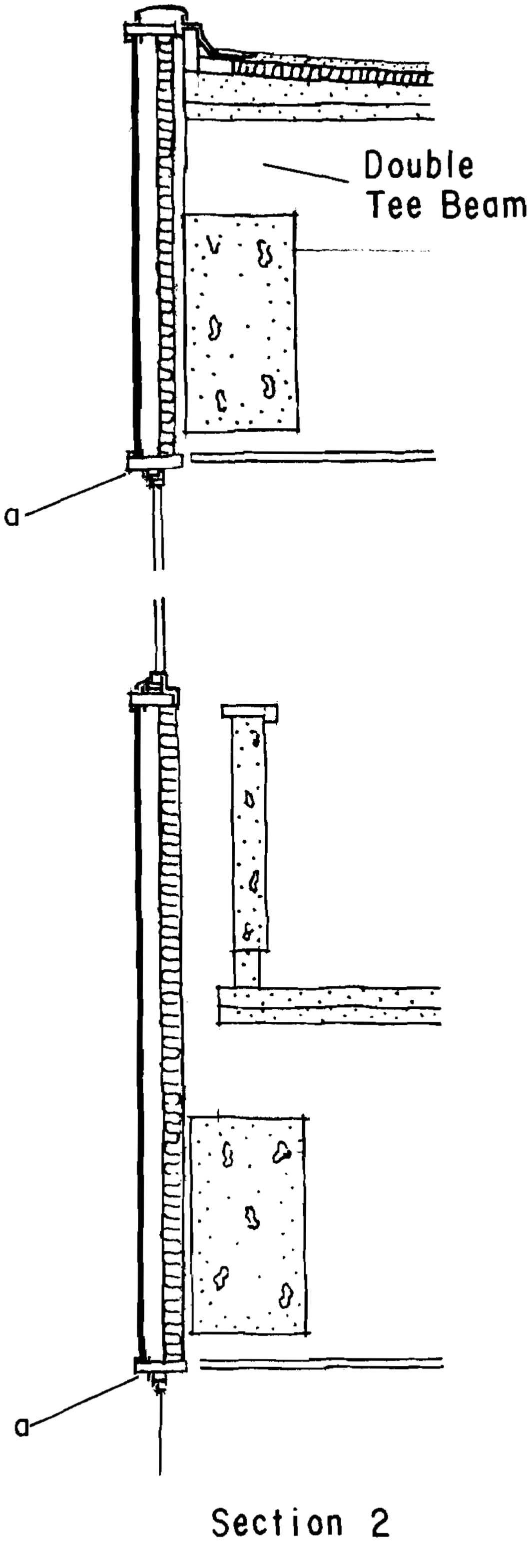


FIG. AIV.2

When the space behind the glass panel is pressure equalized with the outside, as in this building, the pressure drop occurs at the metal panel surrounding the insulation. Therefore, this panel becomes the structural wall and must be strong enough to resist the pressure and tight enough at joints and connections to prevent air leakage in either direction. If these requirements are not fulfilled, rain penetration or air leakage, or both, into the wall may result in moisture problems.



Section 2

FIG. AIV.3

Openings at (a) in the frame of the insulated glass panels provide air pressure equalization of the space behind the panel. The metal panel at (c) surrounding the insulation must ensure airtightness of this part of the wall.

Open vertical joints at (b) in the brickwork allow for pressure equalization of the space behind the brick. The concrete block wall, although structurally sound to resist the pressure, may not always provide an acceptable air seal when it is not given a surface finish.

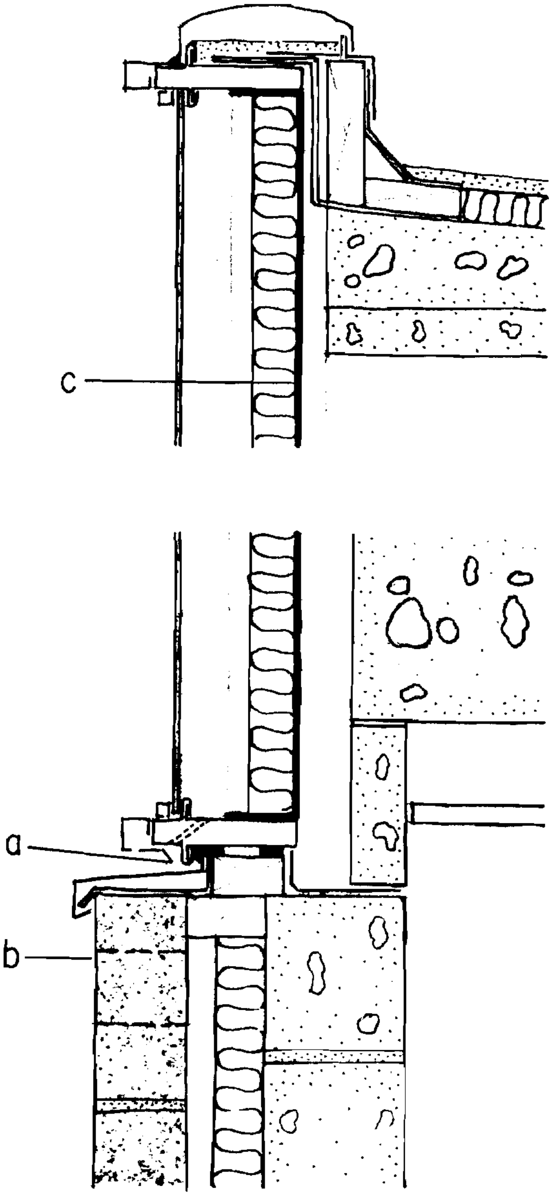


FIG. AIV.4

Open vertical joints in the brickcourse above the shelf angle and also in the second course below it provide air pressure equalization in the air space behind the brick. Drainage is provided both through the opening above the shelf angle and through the rectangular slot cut in it and in the flashing. These slots also permit air to circulate in the air space which may be disadvantageous in a tall building that would have considerable variation in wind pressure with height. In view of the relatively small size of these isolated brick panels on this three-storey building it is probable that, in this case, these slots help to drain the back of the brickwork.

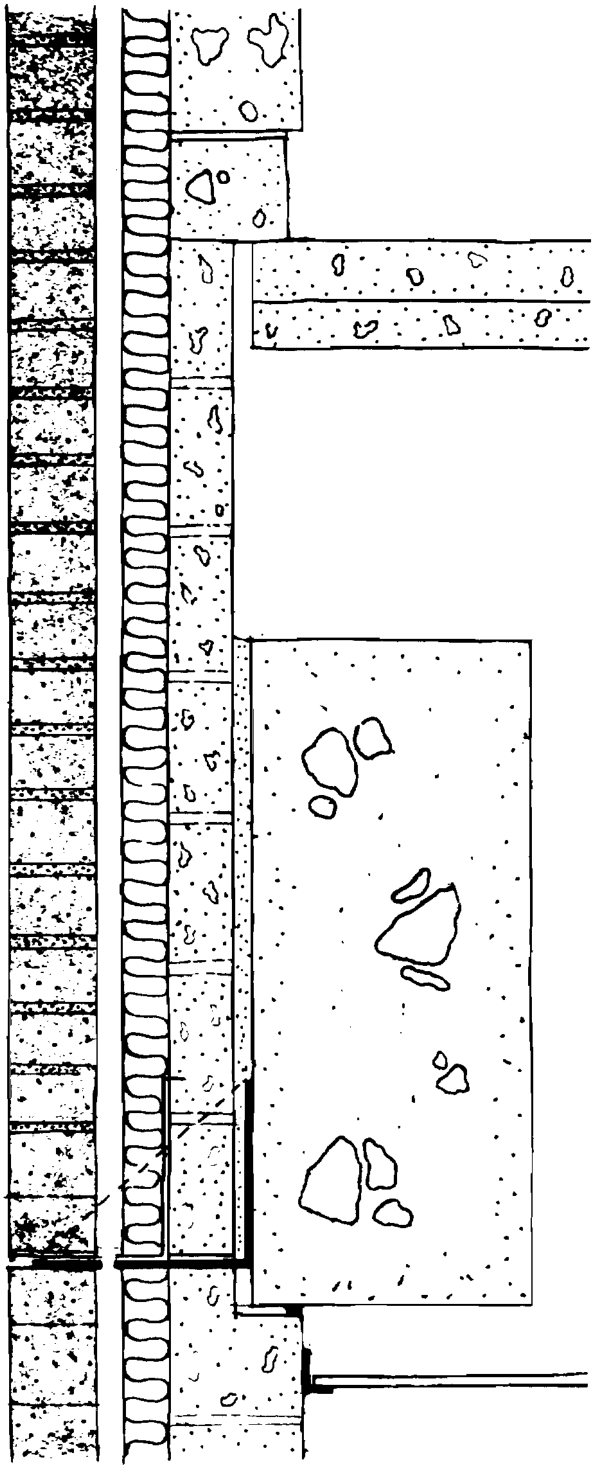


FIG. AIV.5

AV – Entertainment Centre

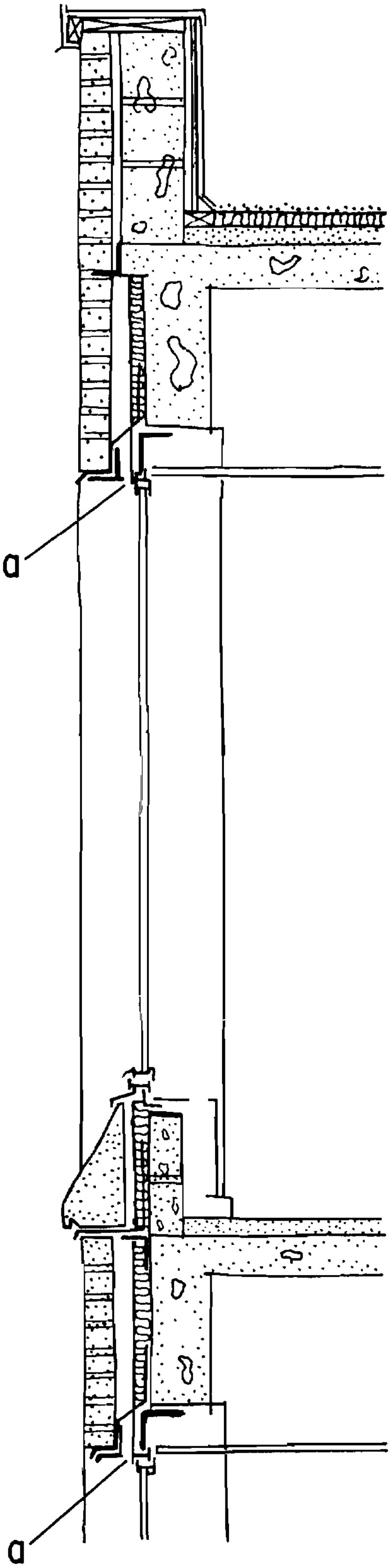
AV - Entertainment Centre

This building, located in the eastern Maritimes, is an entertainment centre and was completed in 1966.

The rain-screen-designed brick wall, although exposed to severe rainstorm , has performed quite satisfactorily. Minor moisture problems, however, have occurred around windows, doors and along the first few brick courses above the concrete foundation wall.

Air pressure equalization of the space behind the rain-screen is achieved through the openings at the window heads (a) and through open vertical joints in the brickwork.

Considering the heavy rainstorms, the designers have restricted the number of these openings to one opening in approximately 65 sq ft of wallface.



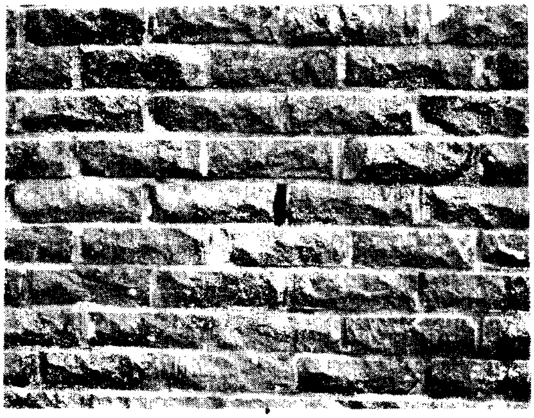


FIG. AV.1

While the space at (b) is pressure equalized, it appears that that at (c) is not. This may have been done purposely to compartmentize the air space and prevent air currents flowing from (b) through the parapet. Without special treatment, the concrete block parapet wall cannot be relied upon to form an air barrier.

Moisture that may penetrate the brick face at (c) should be drained back to the outside by flashing at the shelf angle. The general leakiness of the parapet construction, aided by the air space at (d), will in all probability dry out the remaining moisture.

Photograph shows that moisture can accumulate at the wall sill when drainholes are blocked with mortar droppings.

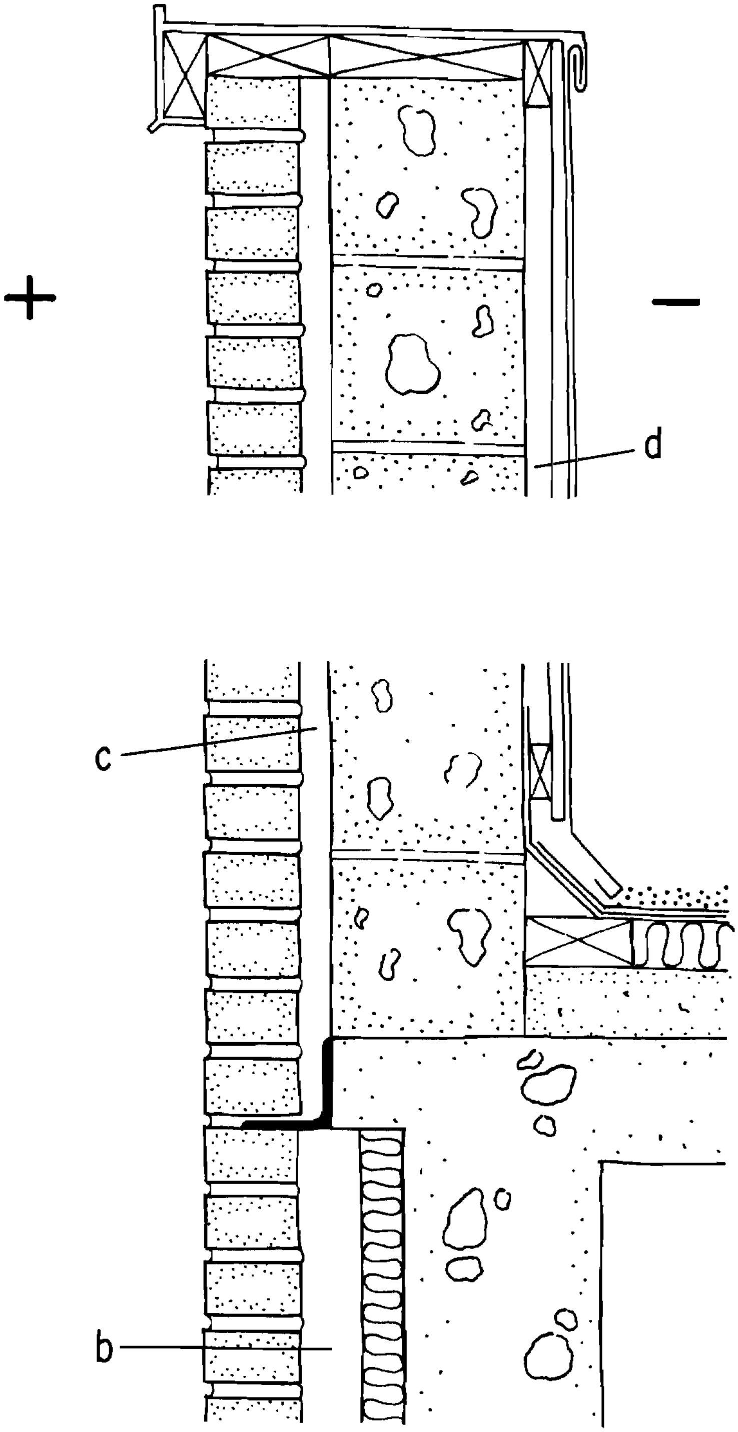
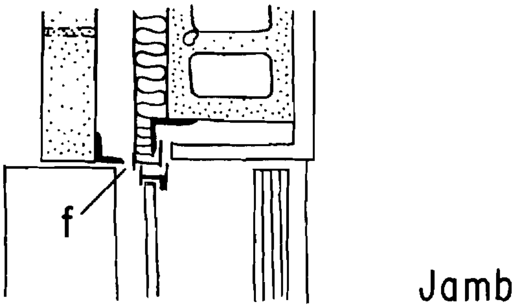


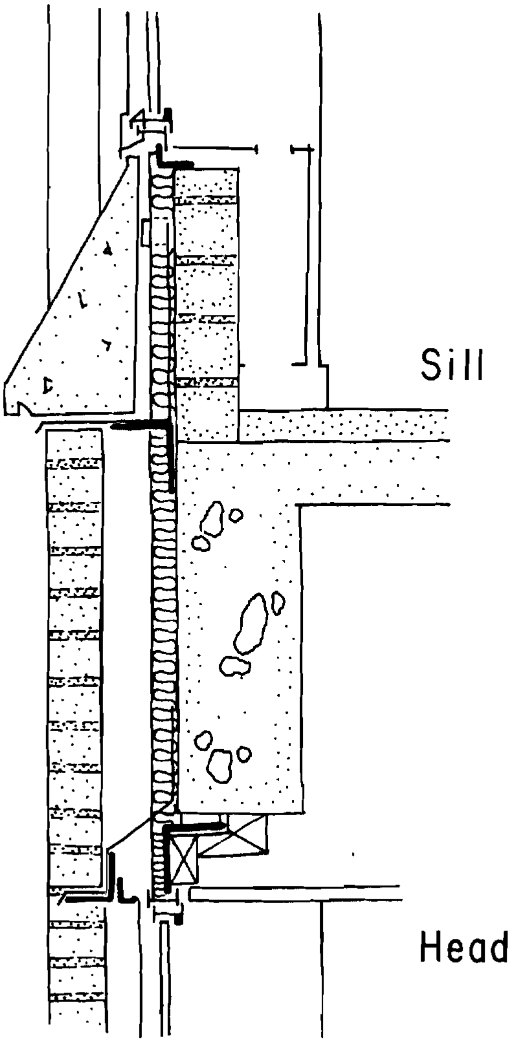
FIG. AV.2

The plane of air tightness here runs from the concrete spandrel beams, through the wood blocking and the steel angle to the window frame, down the sheets of glass to the concrete block wall via the steel angle at the sill, and so back to the spandrel beam. (Similarly through the steel angle at the jamb.) Because of inaccuracies in construction such a seal is very difficult to achieve and demands painstaking workmanship which is usually not possible under construction conditions. An unfinished concrete block wall cannot be considered as being airtight.

Efflorescence shown below the window sill (of a slightly different window installation) is probably indicative of air leakage rather than rain penetration.

The cavity opening (f) at the jamb was caulked when rain penetration occurred at this point.





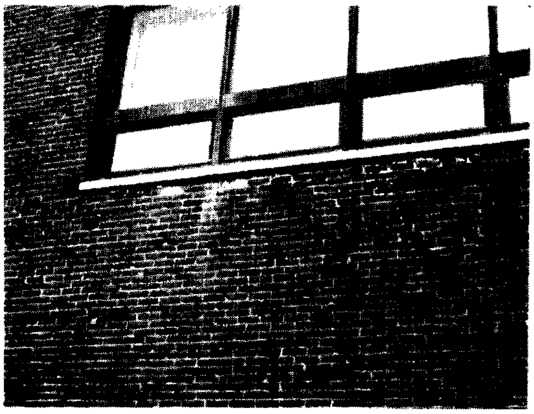
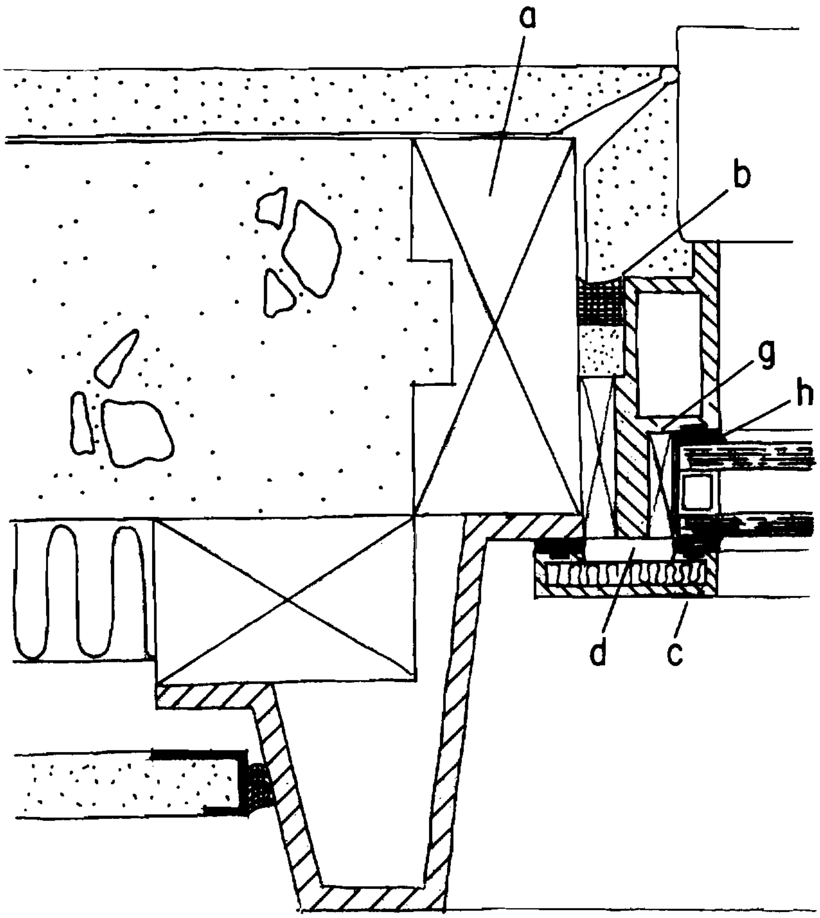


FIG. AV.3

AVI - Windows



When two different materials are jointed, in an exterior wall, great importance must be given to the detailing of the components. It is around windows, doors and other openings in the exterior wall that problems often occur, indicating discontinuity in the line of the air seal.

The detail illustrated, taken from a laboratory building in the eastern Ontario region, is a good example of a well designed and performing joint and window. The structural wall has been keyed into the woodblock (a) to reduce air leakage through this joint. Interior plaster finish ensures air tightness of the structural wall and provides additional protection to the air seal at (b). The window is placed in the warm part of the wall, reducing the danger of glass breakage caused by differential thermal stresses. The window stop (c) is insulated and the space (d) is pressure equalized and drained by an opening in the bottom gasket at (e) (Fig. AIV.2). This opening would also permit evaporation of any moisture that might penetrate the joint between wall and frame. The rigid frame at (g) is designed to resist wind pressure on the window without causing movement in the important air seal at (h). The flashing at (i) keeps rain away from the window head, the flashing at (k) drains water that might penetrate the rain screen (1).

FIG. AVI.1

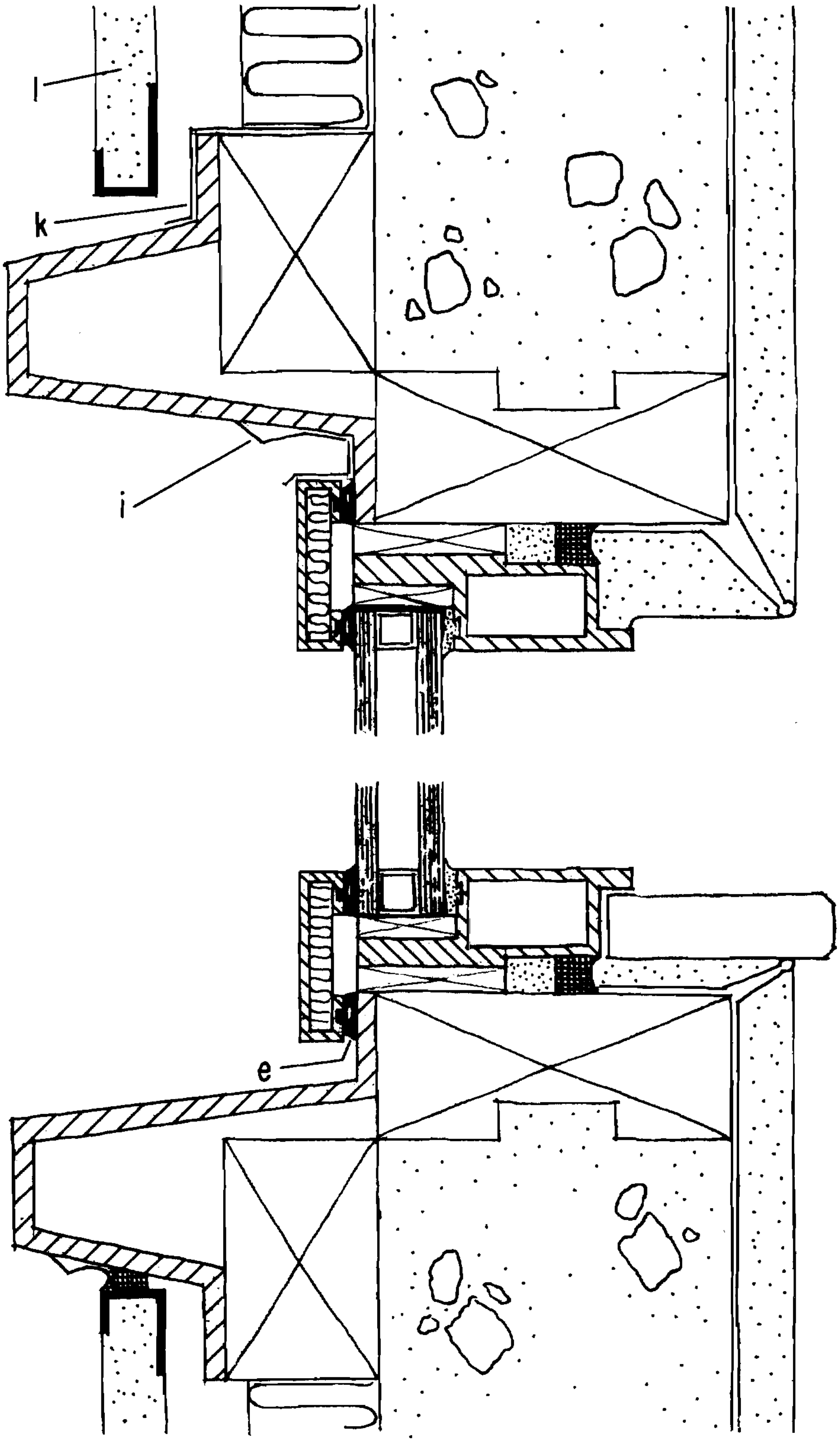


FIG. AVI.2

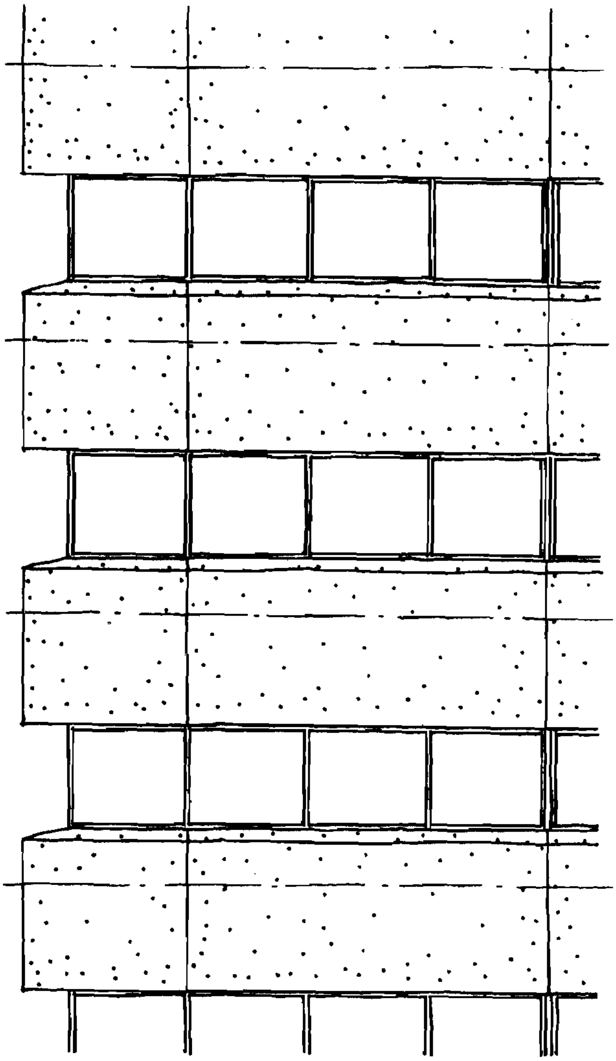
AVII - Office Building

AVII - Office Building

This recently completed office building has not yet been occupied so no assessment of its performance can be made. However, as it appears to have been carefully designed and constructed, no major difficulties are anticipated.

Basically, the wall is formed by an inner insulated metal panel air barrier with a precast concrete rain screen panel extending between the window head and the next higher window sill.

The roof construction is of the protected membrane type.



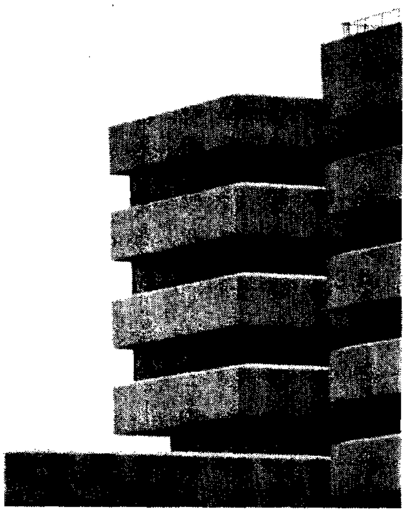


FIG. AVII.1

The precast panels are supported on haunches resting on the floor slab or the roof perimeter beam. Elastic deflexion of these can largely be absorbed at the time of construction but subsequent creep deflexion could lead to some misalignment of the panels and of the windows which are supported by them.

Joints in the wide sill surface are potential points for entry of rain or melting snow. In an endeavour to control this, these joints have been caulked at both the upper and lower faces and the top surface of the floor slab has been sloped to the outside to shed water. The upper surface of the lower leg of the panel has also been sloped to drain water to drain holes near the outside. Thus no alkaline water should run off the concrete onto the glass to etch and disfigure it with deposits of calcium carbonate. Should excessive quantities of water collect above the lower leg and not drain quickly it is possible that some efflorescence may occur on the under side. The top surface of the lower leg was painted with a silicone paint to reduce the possibility of this occurring.

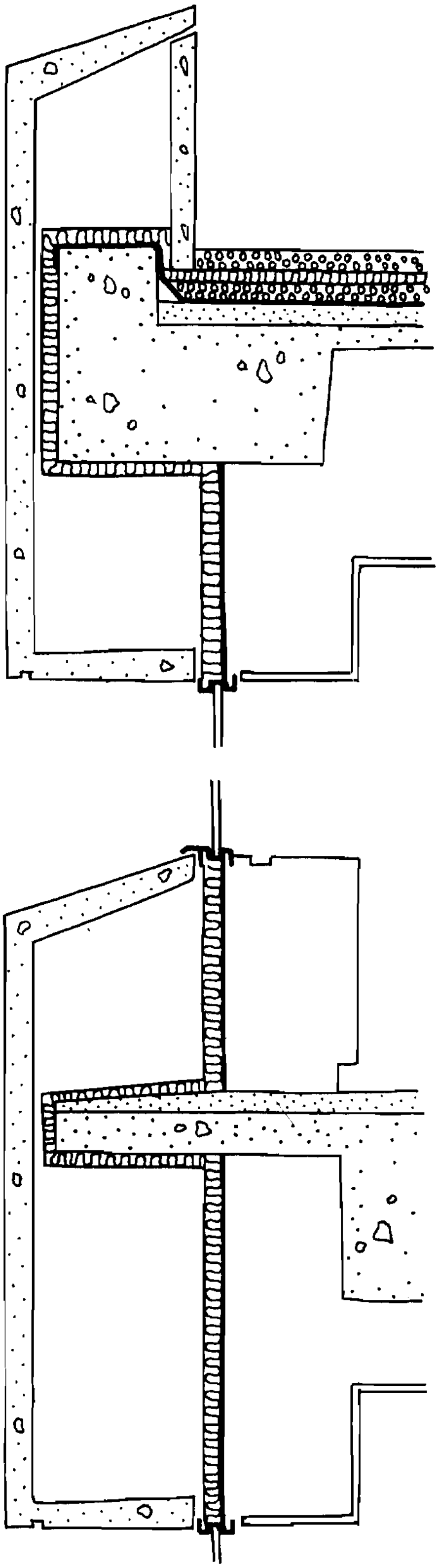


FIG. AVII.2

The metal panel air barrier is stiffened to resist the wind loads and is supported by the floor top and bottom, and by the window frame which, in turn, is supported by the precast panels, with a rigid support at the sill and a sliding connection at the head. Movement between the metal panel and the under side of the floor above is accommodated by a Z-shaped flexible support.

Air tightness is achieved by means of caulking or tape seals as appropriate.

The thermal bridge effect of the steel angle attached to the cold concrete is minimized by most of the connecting bolts and the projecting leg of the angle itself being on the warm side of the insulation applied outside of the window frame. The edge of the inner pane of glass is further protected thermally by the thermal break in the frame

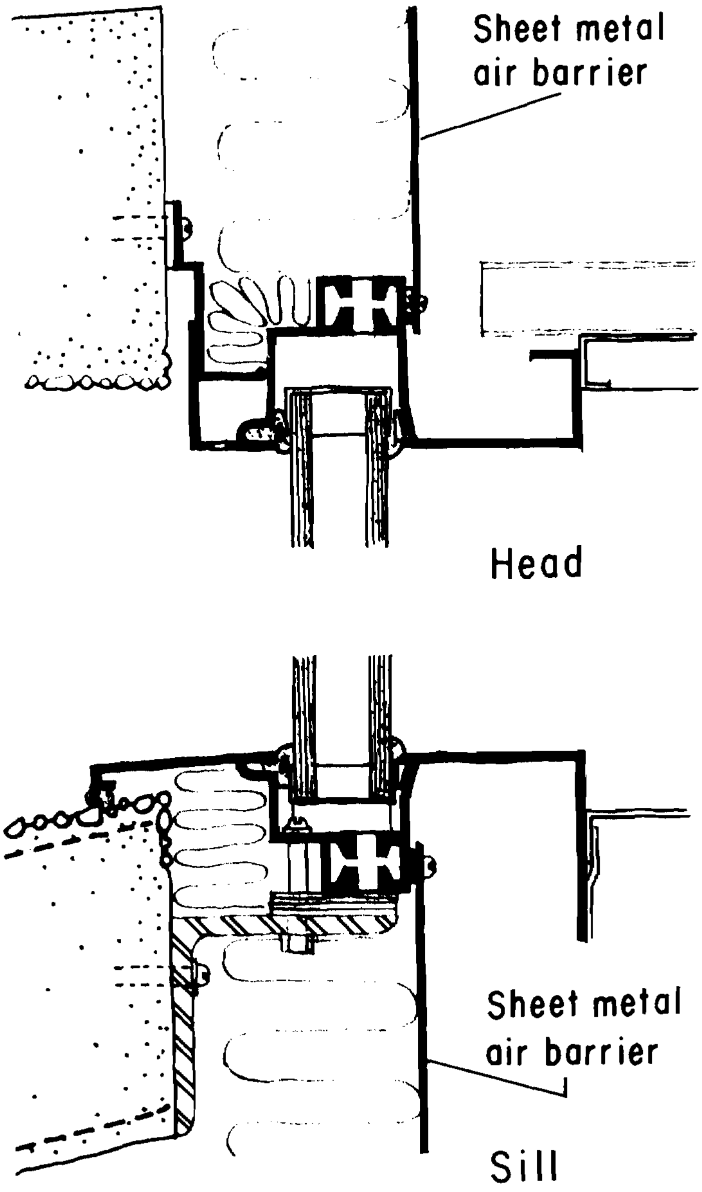
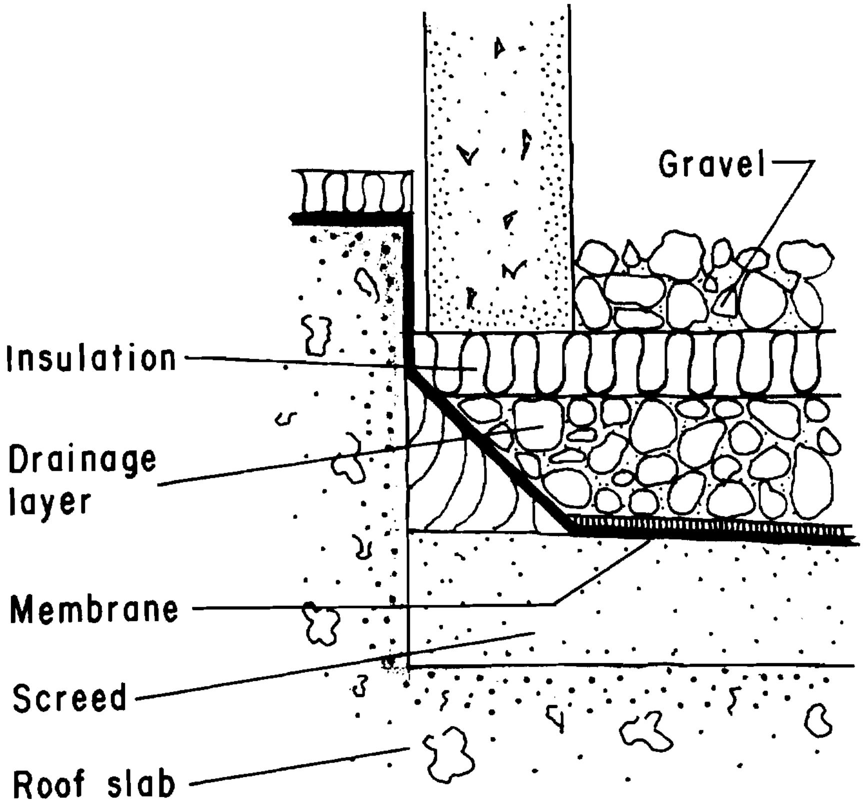


FIG. AVII.3



The roof slab is graded to suitable falls towards the roof drains by means of a screed layer of concrete laid on the structural roof slab. The waterproof membrane is laid on top of this and is carried up and over the perimeter beams. A protective board is laid over the membrane and then a drainage layer of gravel. Two in. of ridged insulation is then placed on the gravel with open joints for good drainage. Finally, the insulation is protected by a further layer of gravel which also prevents it from being blown off by the wind.

FIG. AVII.4