revised metric edition

Reflective Insulation and the Control of Thermal Environments.

ACI
Fibreglass Insulation

Foreword to Metric Edition

Architects and engineers are frequently inconvenienced by the gap between the limited technical data supplied by trade catalogues, and the text-books which cover the general theory. Much time may have to be spent to bring together the relevant technical data for the less common design problems. I should like to commend ACI Fibreglass for making available in this booklet the technical information relevant to the use of reflective insulation for opaque building elements and windows, and Mr. David Hassall for his work in writing this concise text.

This metric version of the book should prove to be an extremely valuable aid to designers and students now that we are entering the period of maximum activity for metric conversion in the Australian Construction Industry.

One may hope that other manufacturers will follow this excellent example.

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1. INTRODUCTION TO METRIC EDITION

Following the ready acceptance of this reference book in its original form by specifiers and users of SISALATION products both overseas and in Australia and its extensive use by students of the Science of Building in Universities, Institutes and Colleges it was deemed necessary to produce this metric edition. The metric treatment of the subjects is complete, with no reference to the Imperial System of units except for a useful set of selected conversion factors at the end of the book.

A new section has been added, namely "Insulation for Windows" which outlines methods for assessing solar heat flow through windows both without any treatment and with REFLECTO-SHIELD or any other type of window insulation.

This project has been carried out by our Technical Service Department working under the direction of Mr. D. Hassall, B.E., M.Bdg.Sc.—Product Development Manager—Building.

The purpose of this reference book on the use of reflective insulation is twofold, firstly to bring together in one text the data necessary to calculate the "U" values of structures incorporating reflective insulation and secondly to outline the need and method for measuring thermal environment within building structures. There are included a number of examples covering both the theoretical and practical aspects of heat transfer calculations.

Where possible, references have been given to identify the original source of information so that a particular aspect of the subject can be studied in greater detail if required.

Revised July 1977 by F. R. Richards, C.Eng., F.C.I.B.S., M.I.Mech.E., M.N.Z.I.E., Technical Consultant-Building St. Regis-ACI Pty. Ltd.

2. HEAT AND HUMAN COMFORT

Heat, in all its forms, or the lack of it, has had a profound effect on man and his evolution. He has had to contend with such extremes as the Ice Age and present day tropical living conditions.

At one end of the scale the human body shivers in an attempt to create more body warmth, and at the other sweating commences when the body produces the means for additional "evaporative" cooling of the skin. Both shivering and sweating are stress conditions that can be tolerated only for comparatively short periods. Optimum living conditions produce reactions somewhere in between, and many researchers have conducted subjective surveys involving numbers of people dressed in various types of clothing and performing differing amounts of work. Environments on either side of optimum cause discomfort, inefficiency, distress and finally collapse and death, so that the necessity for attaining optimum conditions has been proved from both economical and humanitarian points of view. The main variables which affect human comfort are:—

Dry Bulb Temperature

Wet Bulb Temperature (i.e. Relative Humidity)

Air Movement

Thermal Radiation from Hot Surfaces. (Also loss of heat from the body by radiation to cold surfaces.)

To a lesser extent certain other climatic factors affect human comfort, such as atmospheric pressure, ion concentration, etc., but they are outside the scope of this publication.

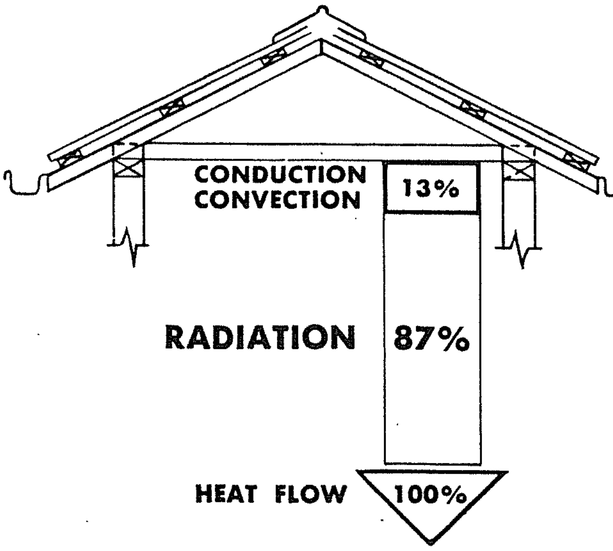
Many attempts have been made in the past to combine the various factors which affect environment into a simple **Comfort Index**[15]. The most important of these are covered in this text.

In **cold climates** man has had considerable experience in creating warmer conditions and it is usually acknowledged that average people feel comfortable within the "dry bulb" temperature range 18°C to 24°C with air speed at about 0·13 m/s.

To combat loss of body heat by radiation to cold surfaces, Rogers[11] has suggested that with an inside ambient of 24°C "superior comfort" can be achieved by ensuring that surfaces are at least 21°C. (See Fig. 6.1.)

In **hot climates** man has largely had to "put up with" the conditions encountered, and only recently has technology enabled him to remove heat and moisture from air so as to produce more comfortable environments. However, there are millions of people living in tropical areas around the circumference of the earth who must be housed but who cannot afford refrigerated air conditioning systems. Therefore examination and control of other factors affecting comfort, such as air movement, and radiation of heat from ceilings and walls are most important.

Excessive thermal radiation from the ceiling or other surfaces can be extremely uncomfortable, particularly in a hot environment. Radiation may increase the globe temperature by only a very few degrees. However, this instrument is an "integrating" device which gives an average, whereas the human body can receive the radiation all from one direction and can feel a "hot spot". Thus, radiation has an undesirable directional property which has so far not been allowed for in comfort indices.



PROPORTIONS OF HEAT FLOWING DOWNWARDS FROM CEILING
FIG. 2.1

As a practical example Fig. 2.1 illustrates that, of the total amount of heat entering a room from a normal domestic ceiling, approximately 87% is by radiation, hence the necessity for keeping the ceiling cooler by use of insulation. An additional measure is to use a ceiling material with a low emissivity (i.e. a low rate of emission of radiant heat).

As regards radiation from hot surfaces it is clear that a limit should be placed on the excess of ceiling temperature above ambient. Very little research has been done into the effects of excessive radiation on everyday living in warm to hot climates. Drysdale[12] found with some exploratory investigations (3 subjects only), that a rise of 2·8K in temperature of a radiant source panel was equivalent to a rise of 0·6K Dry Bulb temperature. For example, the threshold of discomfort of 30°C in a temperate climate, coupled with low air movement, will be reduced to 29·4°C with a ceiling temperature of 32·8°C.

Based on available references(12, 13, 14) it is not unreasonable to conclude that the discomfort effect of hot ceilings is actually greater than this, and that optimum thermal conditions are more likely to be achieved if the ceiling temperature is not more than 32°C with an indoor ambient of 30°C and equal to indoor ambient when the latter reaches the approximate head temperature of 31·7°C quoted by Billington[14]. (Beyond this point, increased air movement or air conditioning becomes essential in order to achieve optimum thermal conditions.)

The American Society of Heating, Refrigerating and Air Conditioning Engineers is sponsoring research into the effect of heated or cooled, walls and ceilings on comfort. The application of their findings will be a step forward in comfort design.

Long neglected in building design, thermal radiation is beginning to receive the attention it warrants.

3. THE NATURE OF HEAT

3.1 The Kinetic Theory

When a bar of iron is placed in a fire it gets "hot" and when removed from the fire and allowed to remain in the room air for a time, it becomes "cool". It is important to understand exactly what the fire does to the bar to give it the property of being "hot".

The question can be answered by an examination of the Kinetic Theory of Matter. Any material, such as the bar of iron, is made up of myriads of particles called molecules; a molecule being the smallest part of a material which can exist independently. These molecules have continuous movement relative to each other and when heat (which is a form of energy) is applied to the bar of iron, the molecules move more rapidly and the bar is said to be **"hotter"**. Alternatively if the bar is placed in a refrigerator and heat is removed from the bar, its molecules will slow down and move less rapidly and it is said to be **"colder"**.

The Kinetic Theory applies also to liquids and gases. It should be noted that most compounds have solid, liquid and gaseous stages depending on the speed of movement of their molecules.

For example, consider a block of ice. This is the **solid** state, with molecules vibrating to a limited degree, but more or less anchored relative to each other so that the block of ice retains its shape.

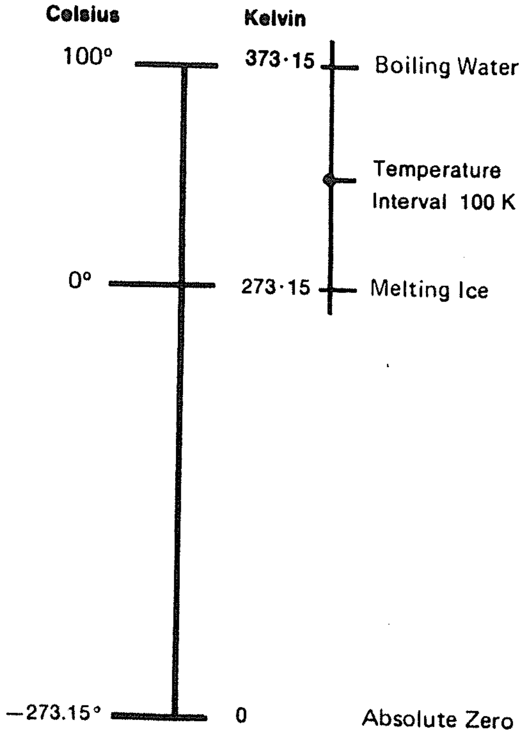
If heat is supplied to the ice the molecules begin to move more rapidly and break free from their anchored position and behave as a **liquid** (water). If still more heat is applied the molecules eventually attain such a speed that they begin to fly off into the atmosphere as a **gas** which is known as "water vapour".

3.2 The Difference Between Heat and Temperature

A bar of iron allowed to remain in a fire will eventually become red hot. In contrast a pin placed in the flame of a match will become red hot in a few seconds. It is not difficult to comprehend that although the two pieces of iron, the large bar and the small pin, are both at the same **temperature,** it has taken different quantities of heat to achieve the result. This example illustrates the concept that the temperature of a body indicates its "level of hotness" above a certain fixed datum.

3.3 Absolute Zero

Absolute zero is the temperature at which, theoretically, the previously mentioned molecular vibration stops altogether. In the **Celsius scale,** where 0°C is the temperature of melting ice and 100°C is the temperature of boiling water, absolute zero is 273·15 degrees below freezing. Unit temperature difference is written 1K.



COMPARISON OF CELSIUS AND KELVIN TEMPERATURE SCALES

FIG. 3.1

3.4 Experiments to Demonstrate "Quantity" of Heat

Consider that two identical containers, A and B, are filled with "cold" water in the following proportions:

Container A = 1 kg of water (1 litre)
Container B = 2 kg of water (2 litres)

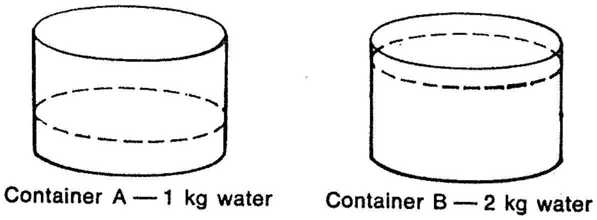

Container A — 1 kg water Container B — 2 kg water

FIG. 3.2

If these containers, so filled with water, are placed on identical gas jets and brought to the boil, the water in Container B will take approximately twice as long to heat as that in Container A. This is because Container B needs twice as much heat to come to the boil as does Container A.

3.5 Units of Heat and Heat Flow Rate

The unit of heat is the JOULE (J). The heat capacity of water at 15°C is 4185·8 Joules per kilogram for a 1K rise in temperature.

In the example above, suppose that the water placed in the containers had an initial temperature of 10°C and heat was added until the temperature of each was 20°C, i.e., a rise of 10K.

$$\text{Heat gain in Container A} = \text{Number of kg of water} \times \text{Temperature rise, K} \times 4185.8$$

$$= 1 \times 10 \times 4185.8$$

$$= \mathbf{41\,858\ J}$$

$$\text{Heat gain in Container B} = \text{Number of kg of water} \times \text{Temperature rise, K} \times 4185.8$$

$$= 2 \times 10 \times 4185.8$$

$$= \mathbf{83\,716\ J}$$

i.e., the heat gain of B was double the heat gain of A though its temperature increase was the same.

The unit of heat flow rate is the WATT (W). A WATT is the power used when work is done or energy is expended at the rate of one joule per second.

i.e., 1 W = 1 J/s

The size of this unit can be gauged by imagining the amount of heat generated by a 1 kW domestic radiator element.

3.6 Specific Heat Capacity

Originally the basic heat unit was defined in terms of raising a unit mass of water through one degree and specific heats were compared with that of water taken as unity. This was not satisfactory, since heat units were defined for different positions in the temperature scale by different authorities and specific heats vary with temperature. There is now an international agreement defining the joule as the basic heat unit which does not involve the use of water. The term now adopted includes the word capacity to distinguish it from the old term. It is now Specific Heat Capacity instead of as previously Specific Heat.

3.7 The Three Modes of Heat Transfer

A knowledge of the heat transfer processes is required to understand how to control heat flow through building structures.

There are three methods of heat transfer; namely

(a) Conduction
(b) Convection
(c) Radiation

(a) Conduction

If the end of an iron bar is placed in a fire, heat will be transferred along the bar until eventually the other end becomes hot to the touch. This is called **conduction** of heat.

Similarly the end of a piece of wood can be placed in the fire and it can be comfortably held until the end is on fire. It is evident therefore that wood is not as good a "conductor" of heat as is iron. All materials vary in their ability to conduct heat and those that conduct to the least extent are called "insulators". As a matter of interest gases and liquids **at rest** also conduct a certain amount of heat by transfer of Kinetic energy from molecule to molecule.

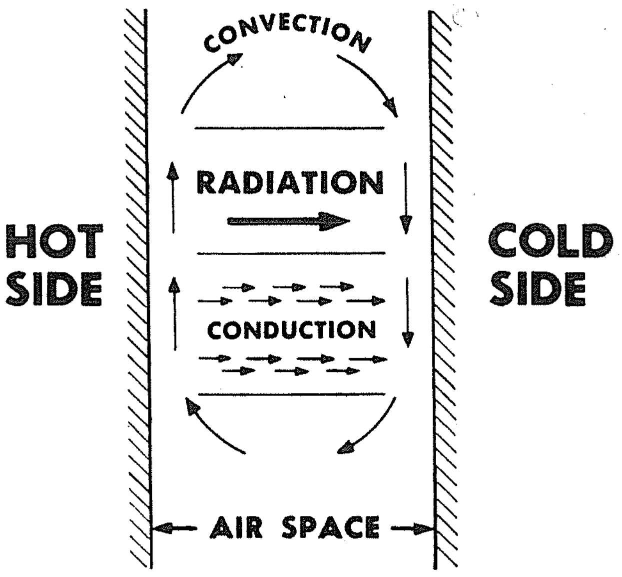


FIG. 3.3

(b) Convection

It is well known that hot air rises. This fact is demonstrated by studying a convector in a closed room. The hot air can be felt rising vertically upwards from the appliance, its place being taken by colder air from near the floor. An observer standing on a chair would be able to feel the accumulation of hot air near the ceiling. A similar thing happens in the case of liquids. Heated gases and liquids usually expand (i.e. become less dense), and rise, being displaced by denser, colder material at the lower level. Anyone who has swum in a still pool of water will realise that if heat is applied at the top of a liquid, in this case from the sun, convection will not take place. Heat is transferred downwards very slowly by conduction only and the deeper water can be quite cold.

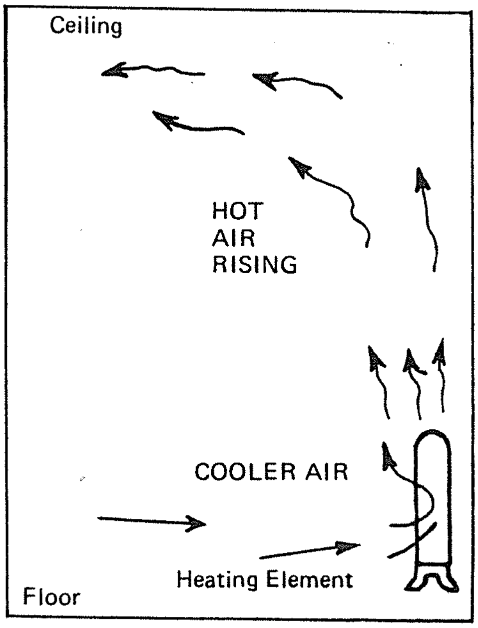


FIG. 3.4

From the foregoing it will be clear that heat is transferred from place to place in gases and liquids by convection.

(c) Radiation

The best example of this phenomenon is the radiation of heat from the sun. The sun emits electromagnetic waves which come to the earth through space (a virtual vacuum) at the speed of light (300 000 km/s). This emission from the sun contains electromagnetic waves of various wave lengths:—

(i) Ultra Violet: 0·01 to 0·39 μm (causes sunburn)
(ii) Visible Light: 0·39 to 0·76 μm (visible)
(iii) Infra-red: 0·76 to 100 μm (felt as warmth)

In a similar way a white hot bar of iron emits visible light plus radiant heat which can be felt from a distance. As the bar cools the colour changes to red —then darker and darker till it is black. But even though visible light is no longer emitted the heat radiated is still considerable and can serve as a warning that the bar has a high temperature. Radiant heat is independent of visible light, and depends on the **absolute temperature** of the emitting body. Heat radiates from one body to another through a vacuum or through air, and travels at the speed of light.

An examination of the curves of "black-body radiations" for varying temperatures shows that in the consideration of the heating and cooling of building interiors, radiations with wave lengths shorter than 5 μm are not significant, refer Fig. 3.5.

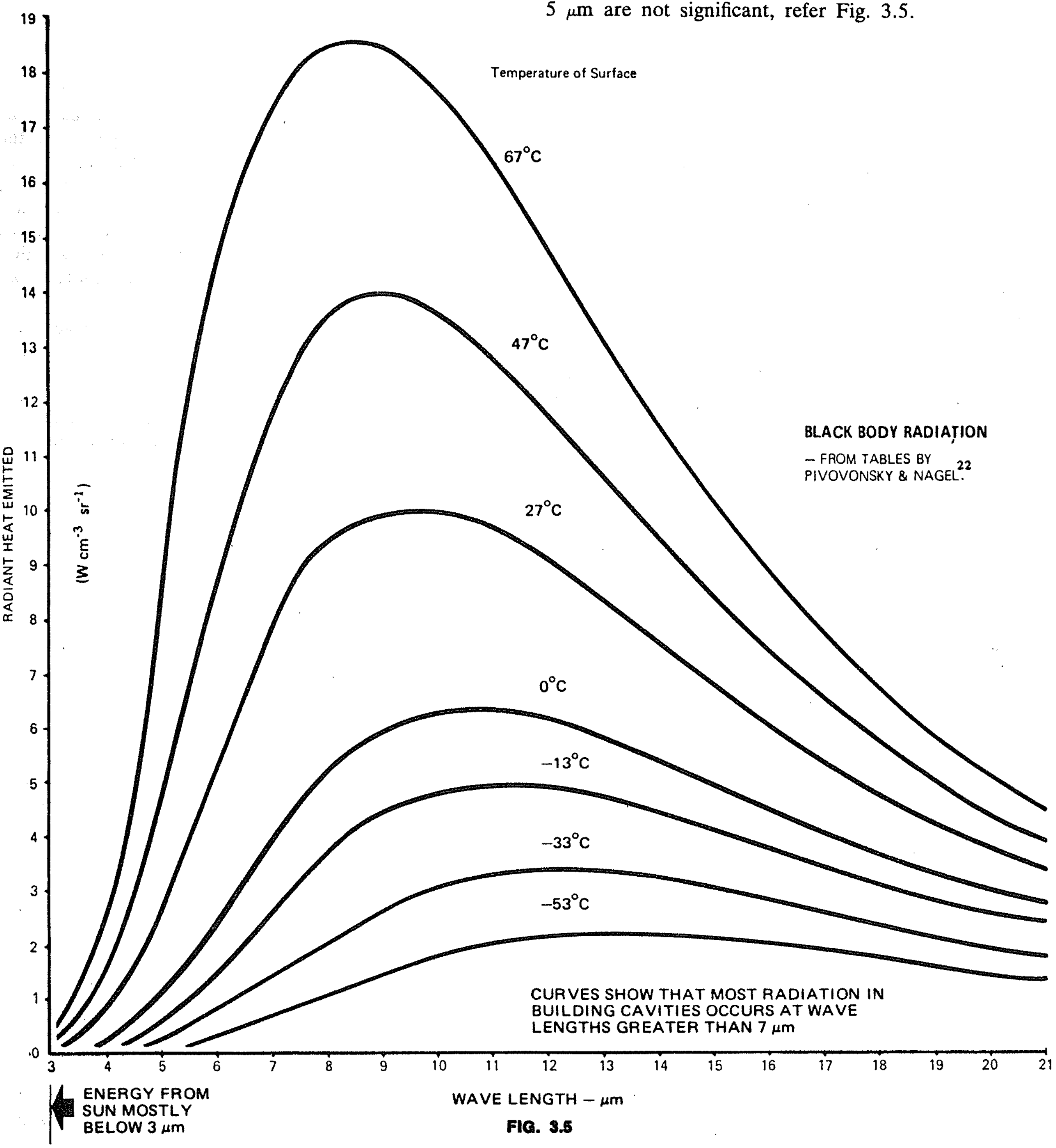


FIG. 3.5

4. INSULATION

It has been seen that some materials conduct heat more rapidly than others. Those that have a high rate of heat transference are called CONDUCTORS, whereas those that have a low rate of heat transference are called INSULATORS.

4.1 Thermal Conductivity (k)

(Refers to unit thickness)

The thermal **conductivity** (k) of a homogeneous material specifies its rate of transference of heat. If a material has a "k" value of 1, it means that a 1 m cube of the material will transmit heat at the rate of 1 watt for every degree of temperature difference between opposite faces. Its conductivity would be written as 1 W/(m.K), (Refer to Fig. 4.1) and this would be unit conductivity.

A conductivity value can not be given for an air space since its effect on heat flow is not directly proportional to its thickness. Variations in direction of heat flow, the position of the air space (i.e. vertical, horizontal, etc.), and such things as mean temperatures have differing effects. Refer to Table 4.1 for conductance and resistance values of air spaces.

4.2 Thermal Conductance (C)

(Refers to any thickness of a material or structural component such as a wall.)

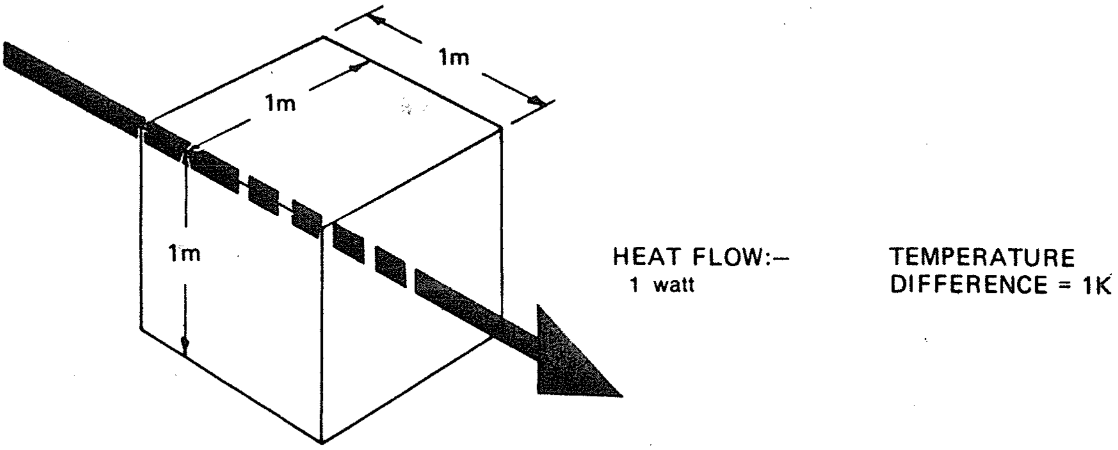
"THERMAL CONDUCTANCE IS THE THERMAL TRANSMISSION THROUGH UNIT AREA OF A STRUCTURAL COMPONENT OR OF A STRUCTURE (E.G. A WALL CONSISTING OF BRICKS, THERMAL INSULATION, CAVITIES, ETC.) PER UNIT TEMPERATURE DIFFERENCE BETWEEN THE HOT AND COLD FACES (UNIT; W/(m^2.K))."

If the thickness in Fig. 4.1 were halved the rate at which heat would be transferred from one face to the other would also be halved. However since time is of unit duration in a conductance value the conductance will now be doubled to 2W/m^{2}K. For a thickness other than 1 m or for a non-homogeneous structure the term CONDUCTANCE (C) is used. In such cases the thickness of the component or components making up the structure must be stated.

4.3 Heat Storage Capacity

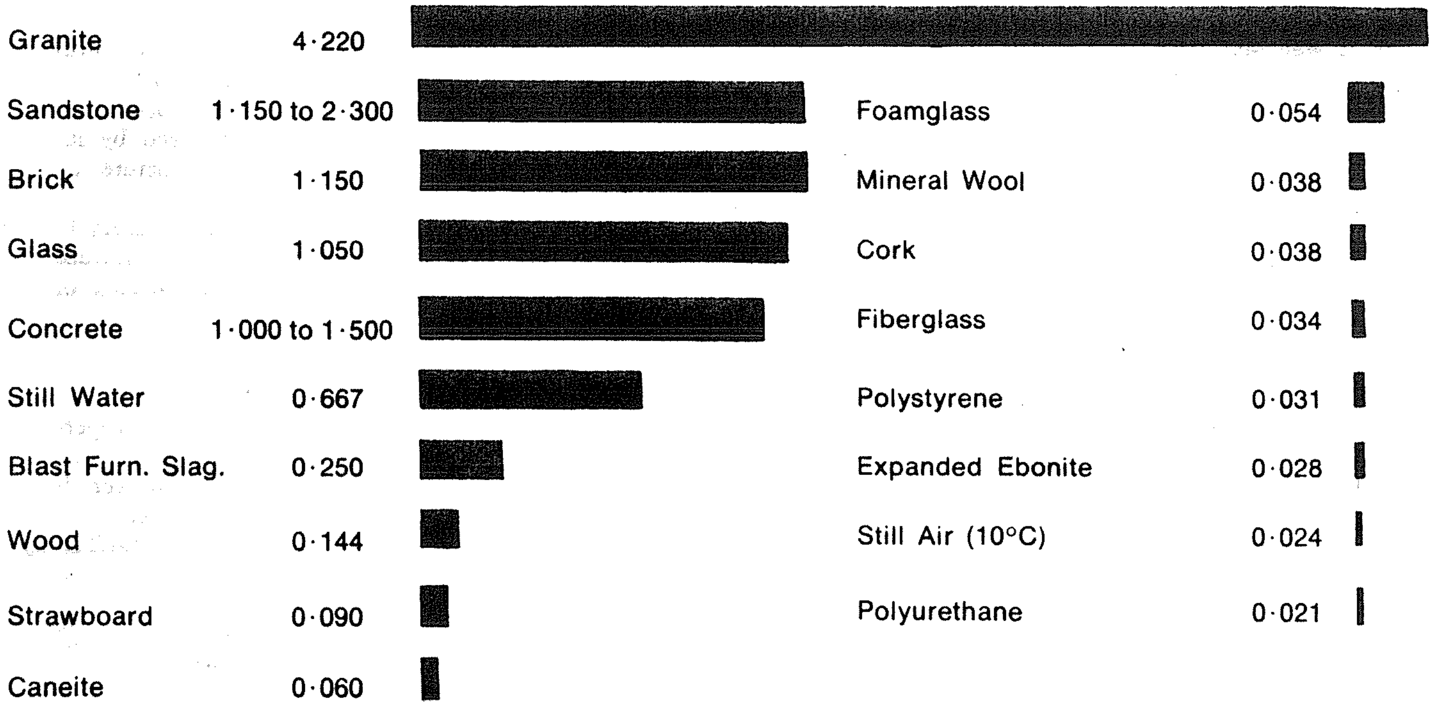
Where two insulating materials have the same "k" value, the one with the lowest heat capacity is the most desirable whenever intermittent heating and/or cooling is necessary. This is because less energy is required for heating or cooling the insulation. Similarly in warm humid climates with relatively small diurnal fluctuations in air temperature, the lighter insulation will cool down more quickly thus taking more rapid advantage of any drops in temperature.

On the other hand, in climates with large daily variations in outdoor air temperature and solar radiation intensity, there is merit in having an insulation which has a high heat capacity or "thermal inertia" thus adding to the flywheel effect of the constructional mass which tends to iron out peak differences in temperature.



ILLUSTRATING UNIT CONDUCTIVITY

FIG. 4.1



Note:—These values can vary depending on the density and moisture content of the material.

TYPICAL CONDUCTIVITIES ("k" VALUES) (W/(m.K))

FIG. 4.2

4.4 Thermal Resistivity — $r = \frac{1}{k}$

(For a 1 m thickness)

Thermal Resistivity is defined as "THE RECIPROCAL OF THERMAL CONDUCTIVITY"[6].

4.5 Thermal Resistance — $R = \frac{1}{C}$

(For any thickness)

The thermal resistance of a structure is "the reciprocal of its thermal conductance". It refers to the thermal resistance (Heat Resistance Units) of any section or assembly of building components and is particularly useful in computing the overall transfer rate of a building section. The method is to calculate the resistance of each individual section of the wall and then to **add** the resistances to get the TOTAL RESISTANCE.

In carrying out such calculations the resistance of the air films on the inside and the outside of the building must be taken into account, because these comparatively motionless layers of air adjacent to the solid wall sections offer appreciable resistance to the flow of heat. The values of these resistances depend on the air velocity and their reciprocals are known as "SURFACE CONDUCTANCE COEFFICIENTS" (f). Refer to Table 4.3 for surface resistances for still and moving air.

4.6 Surface Conductance Coefficients

The C value for the thin layers of air on either side of a building section are designated:—

f_i = inside surface conductance coefficient (still air).

f_o = outside surface conductance coefficient (moving air).

The units of f_i and f_o are the same as for C, i.e., W/(m^2.K).

4.7 The 'U' Value—"Coefficient of Thermal Transmittance"

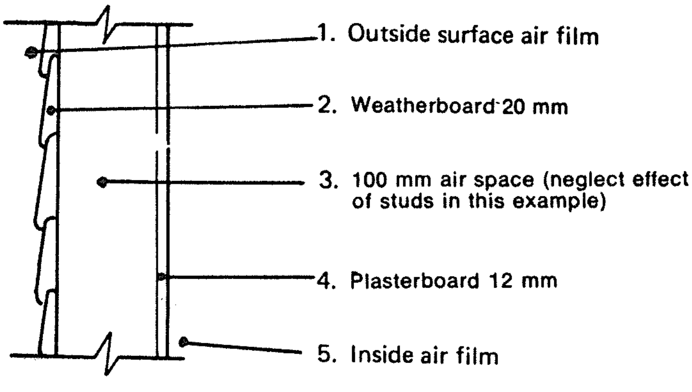
The "U" value is similar to C and has the same units—W/(m^2.K). The term is a measure of the heat transferred through complete building components, such as a wall, INCLUDING the outside and inside air films. The 'U' value is determined by taking the reciprocal of the total resistance of a building section,

$$\text{i.e., } U = \frac{1}{\text{TOTAL R}}.$$

In calculating 'U' values, AIR SPACES (including attic spaces which have a significant resistance) must be taken into account. The method of determining the thermal resistance of air spaces is covered in a later section.

Example—the calculation of the 'U' value of a wall section.

a) Uninsulated



AN UNINSULATED STUD-FRAME WEATHERBOARD WALL.
FIG. 4.3

Consider the wall section shown in Fig. 4.3. The 'U' value is determined in the following manner:

Calculation Winter mean temp. 10°C T.D. 17K	k	C	R
1. Outside surface air film	—	—	·044
2. Weatherboard 20 mm	·144	7·25	·138
3. 100 mm Air space (resistance taken from data given later in paper)	—	—	·165
4. Plasterboard 12 mm	·173	14·42	·069
5. Inside air film	—	—	·120
(Heat resistance units) TOTAL			0·536

$$U = \frac{1}{\text{Total R}} = \frac{1}{0{\cdot}536} = 1{\cdot}87\ \text{W/(m}^2\text{.K)}$$

To decrease the 'U' value of the above wall section, the "R" value of the 100 mm air space must be increased by using insulation.

4.8 An Analysis of Heat Flow Across an Air Space

It is obvious that if insulation is used in the wall of Fig. 4.3 it must be placed in the air space. Heat will cross this space by three distinct methods. For a vertical uninsulated air space bounded by normal building materials such as wood and gypsumboard, the approximate proportions of the modes of heat transfer are:

Radiation	70%
Convection	25%
Conduction	5%

This can be demonstrated by an analytical method[7].

It can be seen that radiation poses by far the greatest problem as it is responsible for 70% of the heat transferred through the wall air space. In the case of heat flow through ceilings, the situation is similar, as under summer conditions 87% or more of the downward heat flow is by radiation. If radiation can be controlled the overall heat flow can be reduced considerably. The heat flow can also be reduced by increasing the thermal resistance of the structure by installing mass insulation in the air space.

In order to control radiation it is first necessary to understand how heat is transferred from one surface to another by radiation. This involves a knowledge of the nature of radiation from a surface.

4.9 "Black Body" Radiation

A "black body" is a theoretical body with properties such that it will absorb all radiation falling on its surface, reflecting and transmitting none. However, it does emit radiation depending on its absolute temperature T, in accordance with the STEFAN-BOLTZMANN law—

$$q = \sigma A T^4$$

where q = quantity of heat (J)
σ = Stefan-Boltzmann constant
A = Surface area
T = temperature, °K

4.10 Emissivity

Emissivity (e) is defined as:

> "THE RATIO OF THE THERMAL RADIATION FROM UNIT AREA OF A SURFACE TO THE RADIATION FROM UNIT AREA OF A FULL EMITTER (BLACK BODY) AT THE SAME TEMPERATURE"[6].

The emissivity of aluminium foil is 0·05 at temperatures of surfaces in building spaces, e.g., attics, habitable rooms, etc. This means that the material "emits" only 5% of the amount of heat that a black body would emit if it were at the same temperature.

Most building materials such as wood and tiles have an emissivity of 0·90. The surface of mass insulants also has an emissivity of approximately 0·90, i.e., their surface emits 90% of the amount of heat which would be emitted by a black body at the same temperature.

4.11 Reflectivity

Reflectivity (r) is defined as:

> "THE RATIO OF THE AMOUNT OF THERMAL RADIATION REFLECTED FROM A SURFACE TO THAT WHICH FALLS ON ITS SURFACE".

Aluminium foil has the high reflectivity of 0·95, i.e., it reflects 95% of the incident thermal radiation, whereas the surface of most building materials and the surfaces of mass insulants have low thermal reflectivities —usually about 0·10.

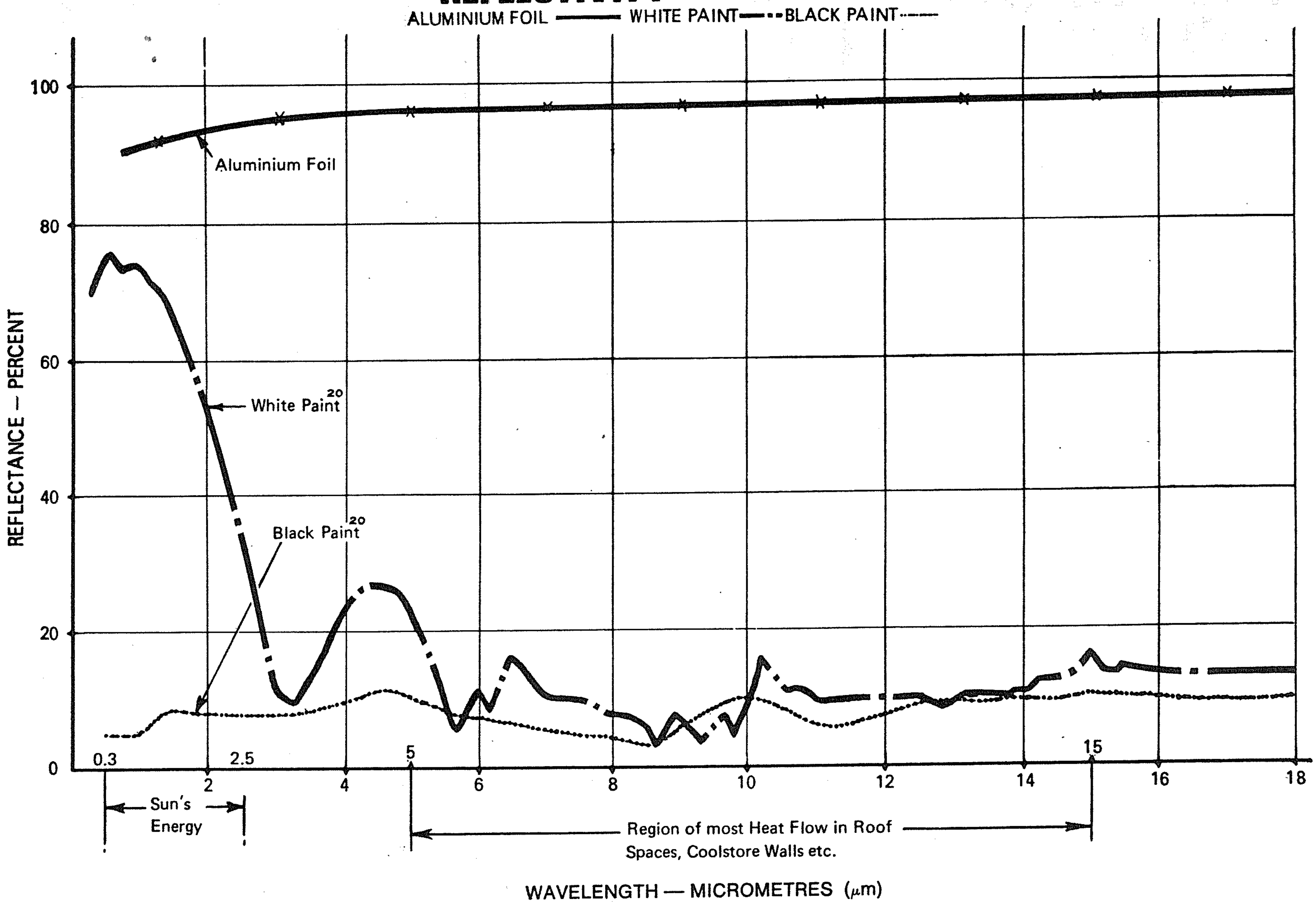
4.12 Wavelength

For any given wavelength;

emissivity (e) + reflectivity (r) = 1·00

Reflectivity of surfaces varies with the wavelength of the electromagnetic energy striking it.

REFLECTIVITY OF SURFACES



REFLECTIVITY OF SURFACES

FIG. 4.4

For example:

Polished Aluminium:—is a good reflector at all wavelengths.

White Paint:— is a good reflector of visible light and solar radiation but a poor reflector of room-temperature radiation.

Black Paint:— is a poor reflector at all wavelengths.

The wavelengths of significance from the point of view of thermal insulation are in the "low temperature" range of from 5 μm upwards, a range in which aluminium foil is an excellent reflector and both white and black paints are very poor reflectors. (Refer to figure 4.4.)

4.13 Roof Surface Temperatures

The temperature of a roof depends on:

(i) its surface reflectivity to the sun's energy,

(ii) the loss of heat by emission from its surface.

An aluminium roof may have the same reflectivity for solar radiation (say 0·80) as a white painted roof and yet because of its low emissivity of 0·11 for low temperature radiation compared with 0·90 for a painted roof, it can be deduced that the aluminium roof would be hotter than the white painted roof. This deduction is endorsed by the experimental results shown graphically in figure 4.5.

4.14 The Use of Aluminium Foil as an Insulator

Because of its high reflectivity and low emissivity, aluminium foil is an excellent insulating material if used in conjunction with an airspace where "low temperature" radiation is the principal mode of heat transfer.

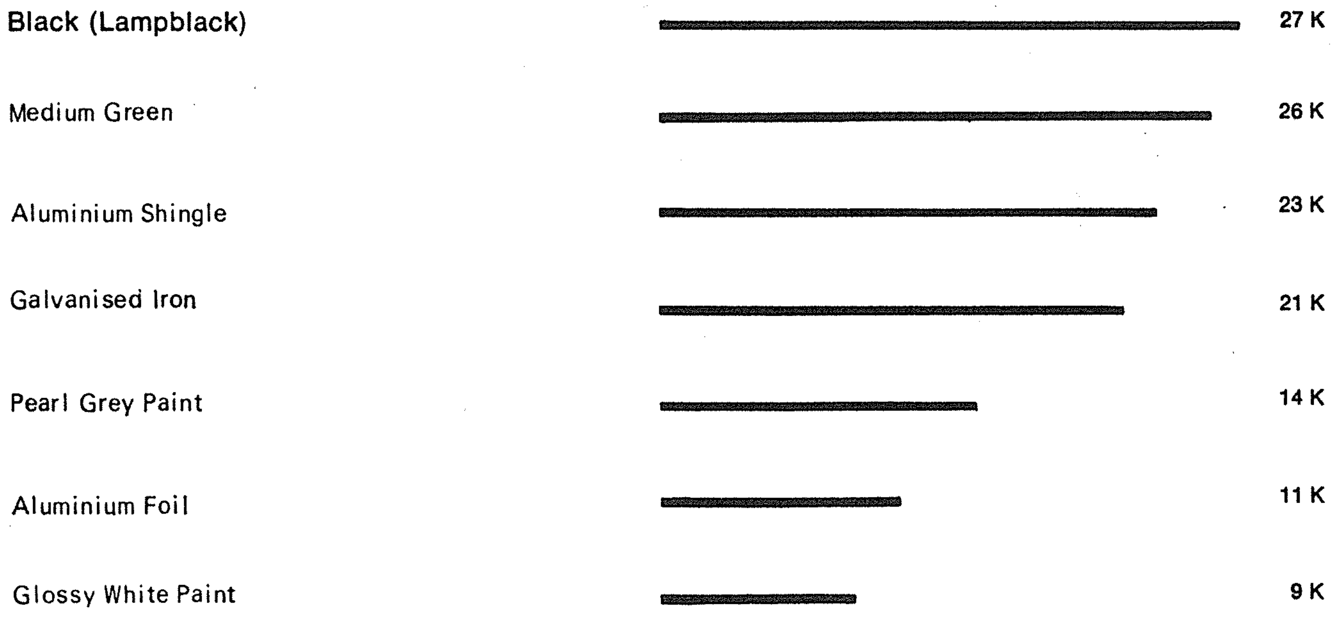
If aluminium foil is placed in the weatherboard wall of figure 4.3, the 'U' value becomes 1·2 W/(m^2.K), which represents a reduction in heat flow of 36%. The new arrangement is shown in figure 4.6.

The change in heat flow occurs because 95% of the radiant heat which passes across the air space from the outside to the inside is reflected. This has the effect of greatly increasing the resistance of the wall to heat flow.

If the heat flow were reversed, i.e., from inside to outside, the result would be the same as in this case the low 'emissivity' of the aluminium (0·5) would have the same effect in reducing the heat flow across the air space. The radiant energy emitted, because of the foil surface, is reduced by 95%.

4.15 Effect of Multiple Air Spaces

By installing double sided reflective insulation at the centre of the air space in Fig. 4.6 at the point marked 'X', **two** air spaces are created each with a polished aluminium surface, one being reflective and the other having a low emissivity. With this arrangement, the 'U' value is further reduced to 0·74 W/(m^2.K). This is a 60% reduction in heat flow compared with the uninsulated wall. (It should be noted that the thickness of the air spaces is important. This aspect of reflective insulation is discussed in a subsequent section.)



DAILY MEAN RISE IN TEMPERATURE (K) OF TEST PANELS EXPOSED TO SUN[21]
(30°, AUGUST, U.S.A.)

FIG. 4.5