HEAT AND LIGHT TRANSMISSION PERFORMANCE OF MEMBRANE STRUCTURES

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SUMMARY:

Studies of the thermal performance of fabric structures have been restricted and limited to certain aspects. The designer of the building must be aware of the total performance which includes air temperature, mean radiant temperature, air movement and humidity within the space as well as the illumination level. These variables are influenced by the properties of the fabric, the configuration of the fabric, the thermal mass of the building, particularly the floor, heat gains from other sources, the form of air conditioning system and external conditions. The highly complex nature of the thermal performance has been simplified and modelled but from a rather restricted outlook of the fabric supplier. Further work is required although a simplified approach generally achieves an acceptable design which is probably conservativ

PREAMBLE:

The development of the fabric roof has been carried out by enthusiasts with greater emphasis on the aesthetics compared to the environmental conditions under the roof. Conditions within the initial installation must have been, however, satisfactory, and perhaps better than anticipated. Little analytical environmental study seems to have been generated by early installations.

The thermal equilibrium set up within the enclosing envelope is very dependent on the season with more severe conditions to overcome in the winter. The form and materials of the building play a significant role in preventing excessive temperature variations in the space under the membrane.

The energy consumption is a vital factor in assessing the total performance of a building. In the U.S.A various States have introduced Codes based on ASHRAE Standards, mainly 90-75. The Standard is somewhat limited as it considers elements of the building rather than the building as a whole. In Northern States double layer fabric roofs have been developed but these are not justified in Australia at the present cost of energy with perhaps the exception of Tasmania.

THERMAL EQUILIBRIUM

Heat flows through the fabric by three mechanisms :

1. Solar radiation.
2. Low temperature radiation.
3. Convection.

The amount of solar radiation entering the building is dependent on the reflectance and transmittance of the material. Reflectance values range from 65% to 80%, an average value being 73%. Transmittance values range from 5% to 20%. 14% to 18% of solar radiation is absorbed with approximately half of this being released at a high level into the space. The overall effect is to obtain a shading co-efficient of between 0.12 and 0.18, the shading co efficient being the ratio of the amount of solar energy entering the enclosure divided by that entering through clear 3mm glass. However, allowing that the radiant proportion does not directly enter the occupied zone, the effective SC is between 0.08 and 0.14. i.e. the proportion of the solar radiant which causes a temperature rise of the air within the space.

For the transmitted portion to cause a rise of air temperature it must first be absorbed by surface and then released by convection to the air. If the structure is one containing a considerable mass, then a high proportion will not be released but will be stored in the structure to probably be eventually released at night. This, of course, is called passive solar heating.

Due to the high spaces, stratification, if allowed to occur will result in very little heat entering in Summer through convection as the air under the fabric will be hotter than the outside air. The overall result is that summer loads are not excessive and are somewhat balanced by the reduced need for artificial lighting.

In winter, however, the situation is different in cold, cloudy weather. Although some radiation still exists the fabric reflects most of this and heat is lost by convection, natural convection on the inside and either natural or forced convection depending on the velocity of the wind on the outside. A further factor is that high spaces result in stratification, thus increasing the temperature difference over the fabric. The conductance of the fabric in winter is between 6.5 and 7.5 W/m^2K. Also, the area of the fabric roof is between 15% and 30% greater than that of the floor. Hence, in cold climates without solar radiation, heat losses can become unacceptably high. As the roof surface temperature is low, it also lowers the mean radiant temperature of the surroundings requiring high temperatures for maintaining comfort conditions.

BUILDING SERVICES:

There are two sets of conditions to be taken into consideration for design of the air conditioning to be provided to maintain comfort conditions:

1. Summer conditions.
2. Winter conditions.

In Summer it is of benefit to allow the air to stratify and to thus allow some of the heat absorbed to collect at high level with some venting of this air at the top of roof through an adjustable opening. Air should therefore, be supplied at a low level and arranged to avoid entering the upper layers. In most structures the occupied zone is at or near the floor. If cooling is required at upper levels it should be arranged to be restricted to the occupied areas and supplied in such a way as to cause the least disturbance to the hot stratus.

In winter, stratification increases the heat loss but unlike summer, it should be avoided. If the air is introduced at high temperature, i.e. high difference between the supply air and room air, stratification will be encouraged due to the buoyant forces. Cooling consideration in summer requires that the air be supplied at low level. The buoyancy forces will then cause the air jet to fall. In winter, the buoyancy will cause the jet to rise and may result in inadequate distribution and encourage stratification with higher heat losses. In order for the jet of air to traverse the space, high velocities may be needed. These will cause draughts when cooling is required.

Stratification may also cause natural circulation to be set up in the building causing down draughts particularly, under high glazed walls. One method of overcoming some of these difficulties in winter is to provide supplementary radiant heating, probably most conveniently arranged as floor coils either off peak electric or hot water.

Radiant heating allows the supply air temperature to be reduced by providing a portion of the heating. It also increases the mean radiant temperature of the surroundings so that somewhat lower air temperature can be accepted.

COMPLEXITY OF CALCULATION OF SOLAR GAIN:

Solar tables are available which will enable the calculation of solar radiation incident on a flat surface at any one angle to the horizontal. In the case of the fabric roof there are an infinite number of infinitesmal flat surfaces forming the curved surface. To obtain the total quantity of solar radiation incident on the fabric roof requires integration over the entire surface. As the process of heat transfer is not steady state, to obtain a strict analytical solution the above integration must be carried out at equal time intervals (½ or 1 hour) over the duration of solar radiation. A further complication is that some self shading of the fabric roof occurs. The radiant exchanges must, of course, be combined with convection and conduction.

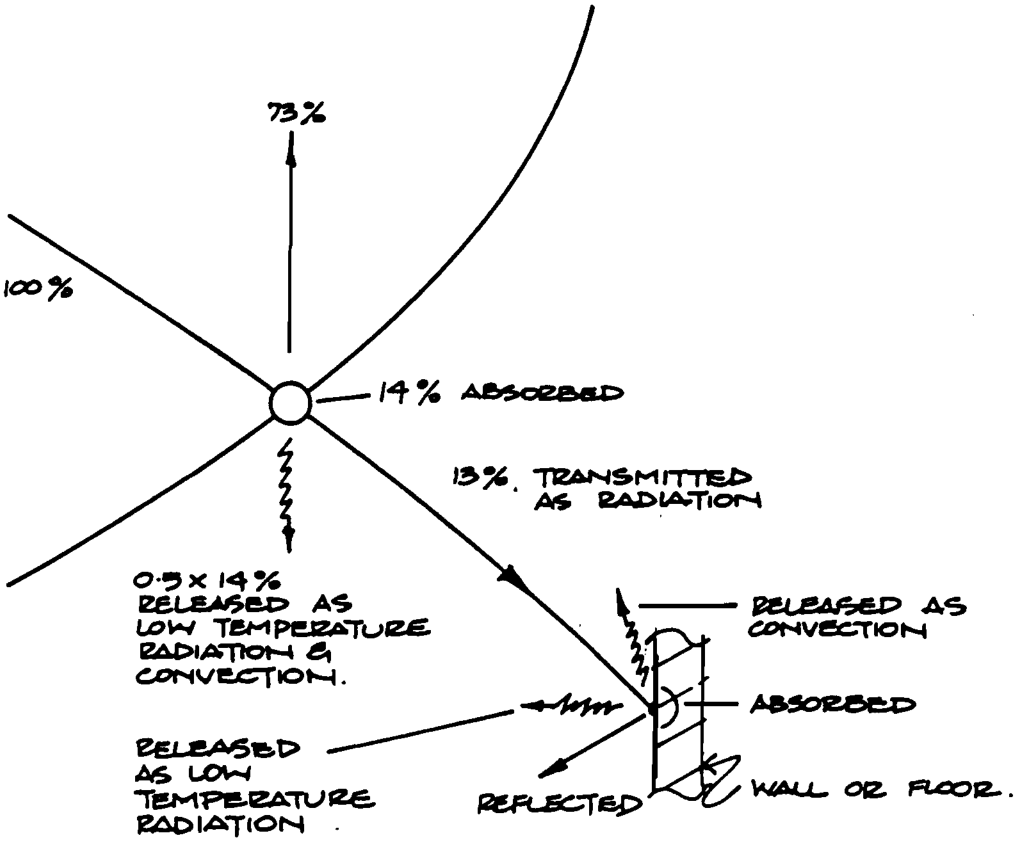
Some useful results can be obtained by simplification of the amount of solar radiation entering the air envelope from two perpendicular planes.

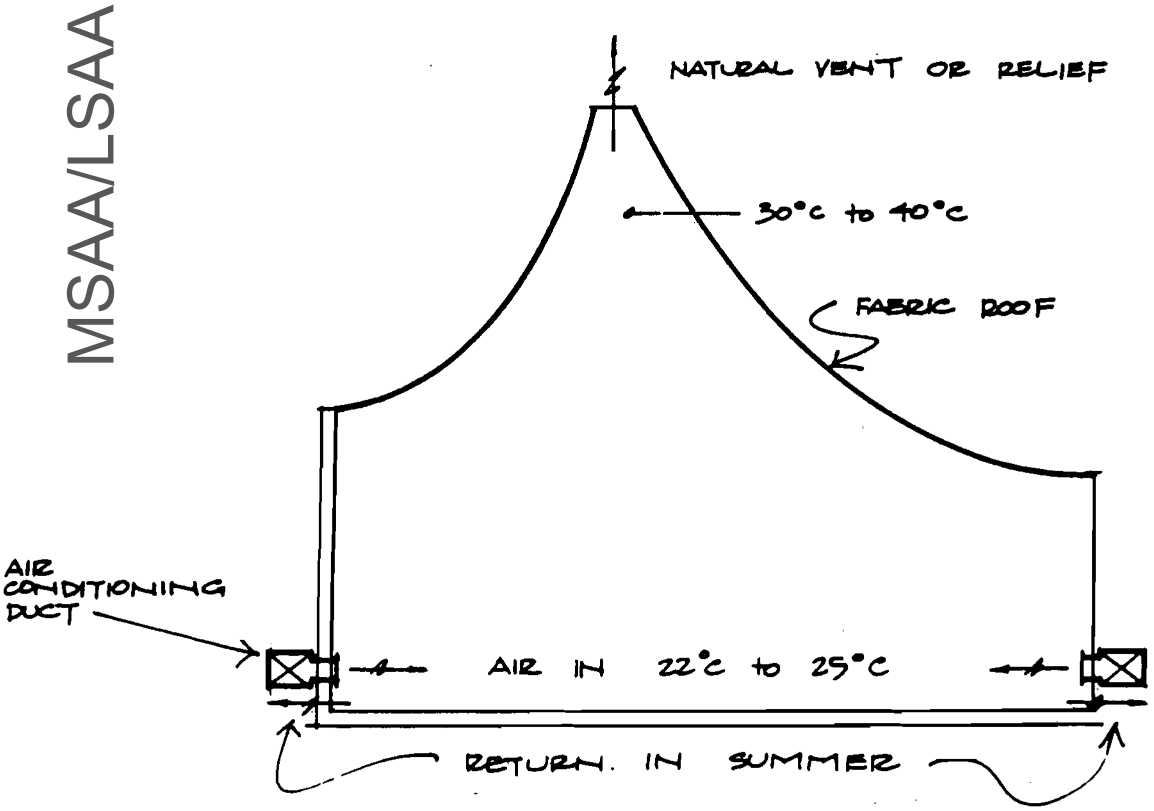
1. A horizontal plane defined by the edges of the roof.
2. A vertical triangular plane which always faces the sun.

An even greater simplication would be to consider the surface area of the roof as a flat plane. The area of this flat plane would be between 15% and 30% greater than the floor area below depending on the configuration of the roof.

Even with either simplification the non-steady nature of the flow of heat into the space must be taken into account. As the heat enters the air enclosure by three processes

1. Direct transmission.
2. Convection from the surface.
3. Low temperature radiation from the surface.


73%
100%
14% ABSORBED
13%. TRANSMITTED AS RADIATION
0.5 x 14% RELEASED AS LOW TEMPERATURE RADIATION & CONVECTION.
RELEASED AS CONVECTION
ABSORBED
RELEASED AS LOW TEMPERATURE RADIATION.
REFLECTED
WALL OR FLOOR.


NATURAL VENT OR RELIEF
30°c to 40°c
FABRIC ROOF
AIR CONDITIONING DUCT
AIR IN 22°c to 25°c
RETURN. IN SUMMER

predictions are complex, particularly predicting how much of 1. (the transmitted proportion) will enter the air in the space in the occupied zone after it has undergone absorption by the internal surfaces.

SIMPLE COMPARISON BETWEEN INSULATED ROOF AND FABRIC ROOF

It is interesting to compare the approximate heat gains per square metre of

1. Steel deck roof with 75mm of mineral wool and plaster ceiling
2. A fabric roof with a transmittance of 0.1 and a reflectance of .75

under the following conditions -

1. Outside air temperature 35°C
2. Inside air temperature 25°C
3. Incidental solar radiation 900 W/m^2.
4. Lighting load 40W/m^2 (incancescent) for steel deck roof.

Heat gain through steel deck roof = UA ΔT (equivalent).
= .5 x 1 x 35
= 17 W/m^2

Heat gain by lighting = 40 W/m^2
Total gain = 57 W/m^2

Heat gain through fabric = area ratio x shading x solar
co-efficient radiatio
intensit
= 1.2 x .1 x 900
= 108 W/m^2

Heat gain by lighting = 0
Total gain = 108 W/m^2.

Hence, there is a difference of 50 W/m^2. However, the flow of heat to the area is less, due to the absorption of a portion of the heat the structure. This is particularly so on a large building. Doubling the dimensions of the roof results in eight times the volume and a very much increased available mass for storage and later release of heat.

If it is accepted that the real difference is in the order of 35 W/m^2. then it will have the following effect on the air conditioning system:

$$\text{Increase in air flow} = \frac{35}{1.2 \times 10} - 2.9\ L/S/m^2$$

The additional capital cost of the air conditioning system will be in the order of \$30 per m^2,

i.e. A steel deck roof \$110/m^2 of floor.
A fabric roof \$140/m^2 of floor.

In winter the simplified comparison can be made :

$$\text{Steel deck} = .6 \times 1 \times (20-5)$$
$$= 9\ W/m^2$$

$$\text{Fabric roof} = 7 \times 1.2 \times (28-5)$$
$$= 193\ W/m^2$$

Due to the natural lighting the amount of electrical energy input can be reduced by 40 W/m^2. The energy can be supplied by a cheaper fuel or with a low electrical input by a heat pump.

It is suggested that some of this heat be provided by radiant heat from the floor. Between 100 and 120 W/m^2 can be provided by floor heating, thus leaving say 80 W/m^2 to be provided by air from the heating system. This ought to enable the air to be supplied at a temperature of 30°C or below to reduce stratification and excessive losses.

REDUCING THE LOAD

As both heating and cooling loads are greater than well insulated roof some consideration should be given to ways of reducing this. The following are possible approaches :

1. To allow the air temperature in the space to vary or swing thus making maximum use of the thermal capacity of the structure.
2. To provide radiant heating to allow lower air temperatures by increasing the mean radiant temperature.

3. To use return air or relief air to "blanket" the roof.
4. To encourage stratification in summer and collect return air at low level.
5. To collect return air at high levels in winter (opposed to 4.)
6. If the heat loss is high then investigate double fabric roofs.

FURTHER WORK:

Some analysis of heat flows has been carried out by computer models but details of some of these are not readily available. The heat transfer with fabric roofed buildings is more complicated than buildings with conventional roofs. The basic mechanism of transfer and the means of predicting non steady heat flow are well established. Scope appears to exist for further analysis prediction and then verification by a testing programme.

Unfortunately, there is never sufficient time for the Engineer, Contractor or Owner to monitor existing buildings. Means of setting up monitoring programmes should be investigated.

NATURAL LIGHTING PERFORMANCE:

The illuminance prediction is similar to that of solar transmission. The level of illuminance in the horizontal plane depends on:

1. The external illuminance.
2. The light transmittance of the fabric.
3. The reflectance and absorption of the surfaces inside the building including the roof itself.

Of the light which enters the space some will be absorbed by the structure. The measure of this is called the co-efficient of utilization which equals:

$$\frac{\text{Total lumens on plane of utilization}}{\text{Total lumens from the fabric structures.}}$$

The values of the ratio vary from 0.3 to 0.6 depending on the building design and the location within the space.

Outside levels of illuminance vary from 5000 lux on cloudy days to 100,000 lux on sunny days with single fabrics of transmittance between .1 and .135, the inside levels would therefore be between 500 lux and 10,000 lux. These are very approximate guides.

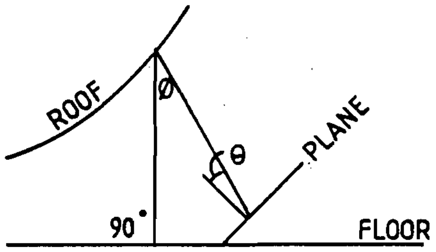
For a hypothetical overcast sky of 5500 lumens/(sq. metre) would give a level of 500 lux average with an inside single fabric roof.

The accurate calculation of lighting levels using the inverse square law

$$E = \frac{I\ (\phi)}{a^2}$$

E = illumination vector.

I(φ) = intensity in direction of the point P



For a horizontal plane $\theta = \phi$ and the illumination on the horizontal plane is

$$\frac{I(\phi)\ \cos^3 \phi}{m^2}$$

To integrate this over the floor for the entire fabric roof is a complex task. This will then provide the direct illumination only. The indirect will of course depend on the reflection from inner surfaces.

ARTIFICIAL LIGHTING:

As a rule the provision of artificial lighting for night use is necessary. Most fabric roofs cover areas with high ceilings. Difficulties of access and the lack of a suitable route for cables has resulted in indirect lighting with discharge or incandescent fittings being directed at the fabric. High levels of illuminance are not normally required so, although the co-efficient of utilization of this form of lighting is not high, the results are acceptable.

ENERGY CONSUMPTION:

Energy consumption has become one of the most important aspects of a building. Codes have been drawn up in an attempt to limit the amount of energy consumed. These however, are a narrow outlook, particularly when unusual buildings such as ones which have fabric roofs are considered. It is very easy to only predict the performance of the building under winter and summer design conditions. While these will determine the capital cost of the system, they do not establish how much energy will be used during the year. Only a thorough analysis of the building during the entire year will give an indication of this. The winter heat loss is considered under conditions of no solar radiation. During daylight hours some solar radiation will be present. The intensity of indirect is small when compared to direct but nevertheless, does contribute to the heat flow into the structure. In climates where the winter days are in the main sunny, solar radiation is sufficient to maintain comfort conditions. Attempts have been made to, in fact, utilize the solar radiation in a passive form. These have involved the use of a double fabric, the air being circulated through the space between the two fabrics.

Without a full analysis of the entire year taking into account lighting, no definite statement can be made. In climates similar to Canberra, there appears to be an energy saving by the use of a fabric roof compared with a conventional one. In Melbourne, the energy input is probably slightly increased compared with a conventional roof, while we would suspect that the fabric roof would consume a good deal greater energy if it were used in Hobart. If the building is occupied at night, then of course, the fabric roof has a higher energy consumption. However, in climates similar to Brisbane there would appear to be a possible reduction of energy consumption compared to a normal insulated roof.

A popular concept to-day is the energy budget, i.e. how much energy the building ought to use in kW-Hr/m^2/year or MJ/m^2/year. These range from 400 MJ/m^2/year to 1000 MJ/m^2/year depending on the location, function of the building, hours of use and type of system. Energy consumption is a factor of influence but there are other equally important factors, some of which are difficult to quantify.

An example of target figures for Melbourne are MJ/m2/year:

	Office Building	Hospital
Cooling	120	450
Heating	200	500
Hot water service	5	180
Interior lights	160	350
Lifts	30	70
Ventilation system	50	200
	565	1750

If the heating and cooling energy usage were to be 30% greater for a fabric roof it would amount to .3 x 320 = 96MJ/m^2/year making a $\frac{96}{565} \times 100 = 17\%$ increase.

One factor influencing the consumption of energy is that spaces covered by fabric roofs often require high rates of outside air for ventilation. This incurrs higher consumption of both energy for heating and cooling irrespective of the form of roof. This air can be relieved through a vent in the top of the roof resulting in a blanketing effect.

CONCLUSION:

Fabric roofs have been used for shelter since man inhabited the earth. The recent developed roofs allow sufficient light to avoid artificial lighting in daytime. The amount of additional energy used as a result of the roof varies greatly from climate to climate. In some climates, in fact, less energy is used. This is contrary to the statement of some energy consultants.

The accurate analysis and prediction of energy transfer both heat and light is difficult although attempts have been made.

At this stage of development it would appear that there is a need to closely monitor existing buildings with fabric roofs and to compare the results to predictions.

It does not seem that the thermal performance, particularly for larger buildings with higher thermal use is a factor restricting their development.

In tropical areas cooling only will be required so provided the air is supplied at a low level and allowed to stratify, the use of the fabric roof should not result in increased energy consumption.

Comparative annual energy analysis for four different types of roofs at nineteen (19) different locations in U.S. cities is listed below. Results are obtained from a computer program. Los Angeles, New Orleans and Tampa are tropical or sub-tropical examples.

(ENERGY BUDGETS IN kBtu/sq. ft. - yr.)

CITY	Roof A	Roof B	Roof C	Roof D
Alburquerque	108	75	46	58
Atlanta	85	62	42	64
Boston	137	93	56	57
Chicago	143	98	58	58
Cincinnati	127	88	54	61
Fort Worth	85	63	45	69
Houston	74	57	45	73
Kansas City	133	92	57	65
Los Angeles	45	32	25	53
Memphis	95	69	48	68
New Orleans	75	58	44	71
New York	118	81	50	58
Phoenix	77	59	44	75
Portland, O.	115	77	44	51
Salt Lake City	149	100	59	59
San Jose	57	41	29	55
Seattle	124	82	45	49
Tampa	55	48	44	78
Washington. D.C.	114	79	50	63

ROOF A: Single layer fabric roof.
ROOF B: Double layer fabric roof.
ROOF C: Translucent insulated fabric roof.
ROOF D: Conventional insulated opaque roof.
Reference 3.

In hotter climates such as New Orleans, Tamper and Los Angeles the prediction clearly shows that the energy consumption will be equal or less than a conventional roof. As the climate becomes progressively colder the energy consumption rises making double layer and translucent insulated roofs necessary. Long periods of night operation where there is an absence of solar radiation may result in it being economically appropriate to use double layer roofs in Australia in cold weather.

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