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Report:

COOLING SELECTIVE SURFACES

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CHAPTER ONE

INTRODUCTION

This report summarises the principal issues concerning the use of high solar reflectance (low solar absorbtance), high infrared emittance coatings - referred to in this report as selective surfaces - for minimising solar heat gain into buildings (from domestic to commercial to industrial) and thus substantially reducing energy consumption for cooling purposes or, indeed, eliminating the need for air conditioning. This resultant reduction in electricity consumption, in turn means that less greenhouse gases are emitted into the atmosphere[1]. A report produced by FARIMA[2] illustrates this environmental problem -

"carbon dioxide emissions generated by summer cooling through use of electric air conditioning are about five times as great as for winter heating, which in Victoria is predominantly by natural gas".

One would expect this figure to increase considerably in other areas of Australia as the majority of the rest of Australia has a much warmer climate and thus far greater cooling needs than Victoria. The report [2] further states,

"the Greenhouse paper predicts rising summer temperatures which will thus add to this summer electrical load for domestic air conditioning".

Increased global concerns and awareness of the intensified Greenhouse Effect requires a mix of remedial solutions, from simple, short-term measures to more complex, long-term solutions.

Coating the exterior of buildings (walls and roof) with a selective surface could be one of the simplest, cost-effective and immediate solutions to reducing electricity bills and subsequently reducing greenhouse gas emissions in Australia's hot climate. The potential for export earnings is sizeable given the global warming problem.

The following gives a review of the physics of selective surfaces in Chapter 2. In Chapter 3 a brief history of the concept of "R-values" as applied to bulk insulations and Australian Standard AS2627.1[3] is given. Incorporating selective surfaces into existing, accepted air conditioning cooling load calculations is discussed in Chapter 4. Estimates of energy savings are also included. This work is concluded in Chapter 5, which also reviews current research in the field of reducing air conditioning electricity consumption by the use of selective surfaces.

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[1] For every kWhr of electricity saved, 1.2kg less of CO_2 gases are produced[1].

CHAPTER TWO

PHYSICS OF SELECTIVE SURFACES

A summary of the primary factors used to characterise selective surfaces is given. These factors are illustrated by describing a roof surface[2] in analogy with a flat-plate solar collector [4]. Two new parameters are introduced, the "Relative Cooling Index"[5] and the "Surface Cooling Factor" so that the performance of different surface coatings can be readily compared. The reader is referred to the work of Paul Berdahl[6] (an internationally recognised expert on energy and the environment) for an excellent overview of the subject.

The traditional approach to the analysis of radiative transfer between the exterior skin of a building and the radiant environment emphasises the mean solar absorbtance α and the mean thermal (long-wave infrared) emittance ε. However, as noted by Berdahl[6], these parameters represent a considerable simplification. For a comprehensive picture, one requires the complete characterisation of the reflectance ρ and transmittance τ of the building surface as a function of (most importantly) wavelength, direction and light polarisation. The absorbtance (and thus emittance[3]) can be deduced from ρ and τ by

$$\alpha + \rho + \tau = 1 \qquad \text{Equation 2.1}$$

The majority of selective surfaces are used to selectively reflect or absorb light by discriminating on the basis of wavelength. The important spectral (wavelength) ranges are for sunlight, 0.3 - 2.5 μm, and 300 K environmental thermal radiation, 4 - 40 μm.

2.1 Radiative Cooling

Radiative cooling at infrared wavelengths occurs because the ordinary thermal radiation emitted by a surface is not completely balanced by the corresponding emission by the atmosphere, especially in the "atmospheric window" located between 8 and 13 μm. An optimal selective surface[4] can have a net radiative loss (cooling) of 120 W/m^2 at ambient temperature[7]. Typically, this cooling is in the 60 - 100 W/m^2 range[6]. This should be compared with the Perth 12 hour average global irradiance on a horizontal plane G, averaged over the "summer" months of December to March of 606 W/m^2[8]. Thus, a surface facing the sky experiencing this imbalance of outgoing and incoming thermal radiation, cools below the ambient air temperature at night. Higher day-time temperatures result in an even larger imbalance. However, the absorbed solar light is usually so intense that the surface becomes warmer than the ambient air during most of the day. Radiative cooling is the phenomenon that keeps

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[2] For simplicity, only roof surfaces are described in this section. The concepts are directly applicable to any exterior surface.

[3] For an opaque surface, Kirchhoff's law states that the wavelength-dependent emittance is equal to the absorbtance.

[4] One designed to primarily emit (and thus also absorb) thermal radiation for wavelengths in the atmospheric window and reflect (not absorb) radiation outside this window.

the planet at its life-promoting low temperature and it is also responsible for phenomena such as dew and frost formation on plants. This day-time cooling effect can be maximised (or at least the heating minimised) by opaque coatings with high solar reflectance ρ_{sol} (that is, low solar absorbtance α_{sol}) and high infrared emittance, especially in the atmospheric window, ε_{8-13}. For example, a selective surface such as SOLARCOAT[14] can reduce the solar heat absorbed on a horizontal roof in Perth to about 91 W/m^2 (c.f. the global irradiance of 606 W/m^2), averaged over the 12 hours of sunlight. Comparing this with the typical radiative cooling power of 60 - 100 W/m^2, partial day-time cooling is a real phenomenon. It has been demonstrated that these coatings can significantly reduce energy use for cooling [5,6,9,15].

2.2 Roof Heat Gain

To illustrate the parameters used to describe the *average* radiant energy exchange between the exterior surface of a building and the environment, a roof is presented in analogy with a flat-plate solar collector[4]. Thus, using similar terminology, the heat flux into the roofing materials q/A (W/m^2) is given by

$$q/A = S - ((T_r - T_a)/R_L) \qquad \text{Equation 2.2.1}$$

where, A is the area of the roof (m^2).

S is the solar radiation absorbed by the roof surface, given by

$$S = \alpha_{sol}\, G_T \qquad \text{Equation 2.2.2}$$

where, G_T is the total solar radiation impinging on the roof and α_{sol} is the solar absorbtance of the roof.

R_L is the “loss resistance” of the roof surface ((m^{2}K)/W);
T_r is the roof mean temperature (K); and
T_a is the outdoor ambient temperature (K).

R_L is usually approximated by

$$R_L = 1/(h_c + h_r) = 1/h_o \qquad \text{Equation 2.2.3}$$

where h_c is the convection heat transfer coefficient;
h_r is the radiation heat transfer coefficient; and
$h_o = h_c + h_r$ is the total outside surface conductance (W/(m^{2}K)).

h_c is dependent on surface texture and wind velocity. The “rougher” the surface texture and the higher the wind velocity, the greater the value of h_c[5].

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[5] See, for example, Figure 1, Chapter 22 of 1993 ASHRAE Handbook-Fundamentals [10]. For “summer conditions” (wind velocity of 12 km/hr) h_c increases by about 30% for a stucco surface compared with a glossy flat surface.

h_r can be estimated by

$$h_r = \varepsilon_r \sigma (T_r^2 + T^2_{sky})(T_r + T_{sky}) (T_r - T_{sky})/(T_r - T_a) \quad \text{Equation 2.2.4a}$$

$$= \varepsilon_r \sigma (T_r^4 - T_{sky}^4)/(T_r - T_a) \quad \text{Equation 2.2.4b}$$

where ε_r is the *average* infrared emittance of the roof. A closer approximation would be to use the emittance measured in the 8 - 13 μm atmospheric window, $\varepsilon_{8-13.}$ σ is the Stefan-Boltzmann constant, equal to 5.6697×10^{-8} W/(m^{2}K^4).

T_{sky} is the "sky temperature", a parameter used for characterising the radiative heat transfer between horizontal nonspectral emitting surfaces and the sky. That is, radiative cooling effect is accounted for by the approximation of T_{sky}, which is a function of atmospheric water vapour, the amount of cloud cover and air temperature, with the lowest sky temperatures (and thus maximum radiative cooling) occurring under an arid, cloudless sky - as is the case over a large proportion of the Australian continent.

To minimise summer cooling energy consumption in buildings due to solar heat gain through the roof (and walls), one requires to minimise q/A in Equation 2.2.1. This can be achieved by minimising S, (Equation 2.2.2) the solar radiation absorbed by the roof surface and also by minimising R_L (Equation 2.2.3) the roof surface loss resistance. That is, we desire as much heat to be carried away from the top of the roof as possible. This runs contrary to the conventional understanding of the concept of thermal resistance "R-values"- "the higher the R-value, the better the situation". This issue is further discussed in Chapter 3.

Both S and R_L are "controllable" quantities directly related to the surface properties of the roof. G_T, the total solar radiation impinging on the roof is partially controllable in the sense that judicious orientation of the roof can minimise G_T - particularly in southern latitudes in the Southern Hemisphere (specifically referring to Australia). This controllability diminishes as the building is located in more northern latitudes. G_T can also be minimised by direct shading by, for example, large trees. However, the simplest and most practical way of minimising solar heat gain from the exterior skin of a building is to select a coating with a low value of α_{sol} (Eqn 2.2.2) and a large value of ε_r (Eqn 2.2.4), or preferably, ε_{8-13} (it is assumed that h_c remains relatively constant before and after coating). In this respect, it is possible to define the ratio ε/α[6], the "Surface Cooling Factor" (SCF), as a figure of merit to characterise exterior surface coatings.

The higher the SCF, the greater is the ability of the coating to minimise solar heating effects and thus the greater the potential to reduce energy use for cooling. Table 1 gives examples of the SCF for various surface finishes.

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[6] Here the subscripts have been omitted with the understanding that in practical terms, it is usually always the solar absorbtance and the infrared emittance that is measured.

Material	ε	α	SCF = ε/α	Reference
Solarcoat	>0.95[7]	0.15	6.33-6.67	[11,12]
Conventional White Paint	0.90	0.20	4.50	[6]
Off-white Paint	0.90	0.25	3.60	[12]
Green Paint	0.90	0.54	1.67	[12]
Red Paint	0.90	0.80	1.12	[12]
Dark Concrete	0.90	0.85	1.06	[13]
Galvanised Steel	0.30	0.29	1.03	[12,13]
Black Paint	0.90	0.90	1.00	[12,13]
Black Chrome[8]	0.09	0.95	0.0947	[4,13]

Table 1. The Surface Cooling Factor (SCF) of typical materials. The higher the SCF, the cooler the surface.

From Table 1, it is evident that specially designed selective coatings such as SOLARCOAT[14] are significantly more effective at keeping a surface cool, compared to conventional materials. SOLARCOAT is about 30% better in this respect, than conventional white paint. Compared to galvanised steel, SOLARCOAT is about 84% better.

Another method for characterising the surface cooling properties of coatings, referred to as the "Relative Cooling Index" (RCI) has been suggested by Rosenfeld et al.[5]. In this technique, a horizontal surface coated with a particular material is exposed to sunlight and the midday ambient air and surface temperature is recorded. The temperature rise between surface and ambient air temperature, ΔT_{s-a} is used to rate different surfaces. For highly absorptive (high α) surfaces, such as black paint, ΔT_{s-a} was recorded to be as high as 50°C, while for less absorptive (low α) surfaces, such as white acrylic paint pigmented with titanium dioxide, ΔT_{s-a} was about 10°C. The RCI for white paint was arbitrarily set to 100% while black paint was rated with an RCI of 0%. On this scale, SOLARCOAT would be expected to have an RCI of about 108%[9].

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[7] Measured at a wavelength of approximately 10 μm, that is, within the atmospheric window. All the other values of εin the table are *averages* over the thermal spectrum.

[8] Black Chrome is used to coat the surface of solar water heater collectors. Hence, the extremely low SCF - the surface is specifically used to heat rather than cool. This materials is a heating selective surface.

[9] Based on ΔT_{s-a}= 7°C, which is 30% lower than that measured for white paint, ΔT_{s-a} = 10°C.

CHAPTER THREE

R-VALUES AND AS2627.1

The question of how selective surfaces relate to the "R-value" rating of bulk insulations (usually of the "batt"-type) is often raised. Hopefully, these misunderstandings will be rectified in this chapter. Also of concern is that (to the author's knowledge) no Australian Standard yet exists to characterise and compare the quality of selective surfaces for cooling purposes.

The original Australian Standard AS2627.1 - Thermal Insulation of Roof/Ceiling in Dwellings which Require Heating was published in 1983[3a]. The standard was prepared by a Committee BD/58 represented on which were all associations concerned in the manufacture and sale of thermal insulation of the so-called batt-type. As the title suggested, AS2627.1 was exclusively concerned with the costs of heating dwellings and under what condition the usage of batts could be justified. It listed the main towns in Australia and suggested the minimum additional insulation required for various types of roofs, to provide adequate comfort in dwellings during winter/cold weather. In the preface was stated the following:

"Serious effort has been made to avoid a dogmatic (or authoritative) approach";

"......recommendations should be supported by the rationale upon which they were made";

"This standard recommends the thermal resistance of insulation that can be justified financially in the roof/ceiling element of dwellings that are heated. It is intended to be a practical guide to the reduction of heat losses through the roof/ceiling element.";

"It does not attempt to cover situations where summer comfort is the major consideration.".

It was not until 1993 that it was acknowledged that summer comfort was the dominant consideration in the majority of Australia. AS2627.1[3b] was modified to incorporate a cost justification for using batt-type insulation in hot/summer conditions. However, one should strongly heed the implications of the following statement made in AS2627.1 - 1993:

"It is recognised that there are many additional measures which can be taken to minimise energy use, such as increased thermal mass, double glazing, correct orientation and shading (the appropriate measures for a particular building will depend on the climate)".

Clearly, only thoughtful design of all building elements will truly result in an energy efficient building.

Of importance in this report is that AS2627.1-1993 takes no account of selective surfaces for summer cooling calculations. In fact, "Calculations were made for horizontal and vertical surfaces with a solar absorptance of 0.8 (80%)".

This should be compared with the value of 0.15 (15%) for a selective surface such as SOLARCOAT (see Table 1). That is, a SOLARCOAT coated building would absorb 81% less solar heat than the equivalent building as specified in AS2627.1-1993. Furthermore, the effect of selective thermal emittance is also not evaluated in AS2627.1 - 1993.

A batt and a selective surface are two entirely different things and cannot be compared on any meaningful basis whatsoever. Mass type insulation retards heat flow, whereas selective surfaces impede heat flow. It would be misleading to attempt to characterise a selective surface by an equivalent R-value, the conventional method for characterising bulk insulations, as this thermal resistance is based purely on the thermal conductivity of the material [15].

Chapter 2 introduced the SCF and the RCI as two possible methods of characterising the cooling (or heating) effects of surfaces. Importantly, engineers and architects should be aware that no single element is the panacea for all building energy efficiency issues. All components must be considered in an overall systems approach. Simple, practical elements such as selective surfaces offer substantial benefits in reducing cooling energy consumption. In the proceeding chapter, a technique for incorporating selective surfaces into air conditioning cooling load calculations is presented.

CHAPTER FOUR

INCORPORATING SELECTIVE SURFACES INTO AIR CONDITIONING COOLING LOAD CALCULATIONS AND ENERGY SAVINGS

As discussed in the previous chapter, it is not possible to characterise a selective surface by an idealised R-value for the purpose of determining summer comfort levels in a building or to determine the size of a cooling air conditioning system. Engineers and architects require simplified techniques for modelling the behaviour of selective surfaces so that they can be readily incorporated into cooling load calculations. This can be achieved by using the concept of the "Sol-Air Temperature"[10]. Only a brief review is given here, the reader is referred to the ASHRAE Handbook - Fundamentals, Chapter 26[10] for a more extensive discussion of the subject.

4.1 Sol-Air Temperature

The primary weather-related variable influencing the cooling load for a building is solar radiation. It is possible to define an equivalent outdoor air temperature that, in the absence of all radiation changes, gives the same rate of heat entry into a surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air. This temperature is defined as the sol-air temperature. Following [10](Chapter 26), the heat balance at a sunlit surface gives the heat flux into the surface q/A (W/m^2) as

$$q/A = \alpha G_T - h_o(T_s - T_a) - \varepsilon\Delta R \qquad \text{Equation 4.1.1}$$

A, G_T, α, h_o, T_a and ε are as previously defined in Section 2.2, except that now Equation 4.1.1 is applicable to any sunlit surface at temperature T_s(K).[10]

In Equation 4.1.1, the radiative cooling phenomenon has been explicitly defined by introducing the term ΔR(W/m^2) - the difference between the infrared radiation incident on the surface from the sky and surroundings and radiation emitted by a blackbody at outdoor ambient air temperature T_a (see Sections 2.1 and 2.2). From Section 2.1, ΔR is between 60 and 100 W/m^2, depending on atmospheric conditions.

Assuming the rate of heat transfer can be expressed in terms of the sol-air temperature T_e(K), then

$$q/A = h_o\,(T_e - T_s) \qquad \text{Equation 4.1.2}$$

and from Equations 4.1.1 and 4.1.2

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[10] Note the similarity between Equations 4.1.1 and 2.2.1. The difference arises from separating the radiative cooling term (the T_{sky} approximation) and the radiation term between the surface and ambient air at temperature T_a in Equation 2.2.4. Thus, the h_r component of h_o (Eqn 2.2.3) in Equation 4.1.1 looks like $h_r = \varepsilon\sigma(T_s^2 + T_a^2)(T_s + T_a)$ - cf Equation 2.2.4. h_o is commonly assumed to be 17 $W/(m^2K)$.

$$T_e = T_a + (\alpha G_T/h_o)-(\varepsilon\Delta R/h_o) \qquad \text{Equation 4.1.3a}$$

or

$$T_e = T_a + [\alpha G_T - \varepsilon\Delta R]/h_o \qquad \text{Equation 4.1.3b}$$

It is clear that a selective surface with a high SCF (see Table 1, that is, a material with high ε and low α) will minimise T_e. Also note that a given selective surface will be more effective at reducing T_e in an arid, cloudless climate, as compared to a humid, cloudy climate (assuming that G_T remains unchanged) since ΔR would (in general) be greater in the former climate. More research is necessary to characterise ΔR in Australia.

4.2 Cooling Load Calculations and Energy Savings

Two space cooling load calculation techniques have been developed (and are in current usage) which use T_e to represent outdoor conditions - the Transfer Function Method (TFM) and the Total Equivalent Temperature Differential (TETD) method (see Chapter 26 in [10])[11]. A discussion of these techniques is beyond the scope of this report. However, it will suffice to say that in both methods, the total heat gain through exterior walls (and doors) and roofs is modelled to be directly proportional to T_e. Hence, reducing T_e results in a reduced heat gain, which can significantly reduce cooling energy consumption.

A typical example of a single-family detached house will illustrate these energy (and cost) savings. The floor plan and construction details of the house are given in Appendix 1. The outdoor design conditions are almost identical to those of Perth: 36°C 2.5% dry-bulb, daily range of 12°C and 23°C 2.5% wet-bulb (Chapter 24 in [10]). Also, the climatic conditions would be expected to be similar given Perth's latitude of 32°S (c.f. 36°N). It will be assumed that the cooling equipment operates for the 12 sunlight hours per day (c.f. 24hr/day recommended in Chapter 25[10] for residential buildings) for the 4 "summer" months of December to March (120 days). The 12 sunlight hour average conditions are T_a = 24.9°C and G_T = 606W/m^2 (on a horizontal plane, as will be assumed for the roof)[8]. It will also be assumed that ΔR is about 63W/m^2 for a horizontal surface and $\Delta R = 0$ for a vertical surface (see discussion in Chapter 26[10]). As mentioned in footnote 10, h_o = 17 W/(m^{2}K). Furthermore, it will be assumed that the original dwelling has exterior surfaces with $\alpha = 0.8$ and $\varepsilon = 0.9$, a SCF of 1.12, (as specified by AS2627.1[3b]. Note that [10] actually uses α =0.88).

The cooling energy, cost, and environmental savings will be calculated for the identical dwelling with the exterior coated with a selective surface such as SOLARCOAT: SCF = 6.33, $\varepsilon = 0.95$, $\alpha = 0.15$. These are calculated on the basis that

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[11] Data obtained by using the TFM on a group of applications considered representative have been used to generate Cooling Load Temperature Differential (CLTD) data as another technique for direct one-step calculation of cooling loads from heat gain through sunlit walls and roofs. Unfortunately, tabulated CLTD data is normally based on dark coloured ($\alpha = 0.88$) exterior surfaces (see Chapter 25 in [10]). AS2627.1 - 1993 assumes $\alpha = 0.8$.

the tabulated values of CLTD (see footnote 11 and Table 1, Chapter 25[10]) are reduced by the same proportion as the reduction in T_e before and after application of the selective surface. For example, using the given quantities, the sol-air temperature can be calculated for the original uncoated roof T_e^{uc} and for the coated roof T_e^{c} using Equation 4.1.3 (the roof is assumed to approximate a horizontal surface) giving T_e^{uc} = 50.1°C and T_e^{c} = 26.7°C. Thus, the SOLARCOAT coated roof will reduce T_e by 23.4°C or 47%.[12] It is therefore assumed that the CLTD for the roof will be reduced by an identical amount. On this basis, the cooling load due to heat gain through each exterior surface is re-calculated to take account of the selective surface. The final result is that the cooling load due to heat gain through all structural components (roof, walls, doors) is 1.16 kW for the SOLARCOAT coated house, compared with 2.06 kW for the original uncoated dwelling - a reduction of 0.9 kW or 44%. Similarly, the total sensible cooling load has been reduced to 5.51 kW by coating the building with SOLARCOAT, compared with 6.55 kW for the original uncoated building - a reduction of 16%. Significantly, this implies that the cooling air conditioning system capacity could be reduced by 16%, thus minimising the initial equipment investment.

Over the defined cooling period, one would expect a saving of 1296 kWhr in electricity consumption. At the current domestic price for electricity of 12.29c/kWhr, this corresponds to a saving of $159 per year.

Importantly, carbon dioxide (CO_2) emissions would be reduced by 1555 kg per year. As is evident, these savings are quite substantial for a single dwelling. The reductions in cooling power consumption and CO_2 emissions would be enormous when considering the whole of Australia's population. It is also noteworthy that for commercial/industrial applications an enhanced electricity cost saving would be expected since peak cooling power consumption would be significantly reduced by coating the building with a selective surface. For a complete economic analysis one should consider all factors which influence life-time cost including environmental cost (based on appropriate models).

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[12] The corresponding reductions in T_e are 21%, 35%, 27% and 34% for the N, E, S and W facing walls respectively.

CHAPTER FIVE

CONCLUSION

Practical experience with selective surfaces (of the SOLARCOAT-type) over the past 10 years both in Australia and abroad, in a multitude of applications, have verified the theoretical analysis presented in this report [15]. Most recently, a study supported by the U.S. Department of Energy was reported by Rosenfeld et al[5] on measures to mitigate the increasing "heat island" problem in American cities. The study specifically examined both the building- and city-scale effects of the urban surface on energy use and climate. Full-scale practical experiments revealed 20 - 40% direct energy savings (compare this with results presented in Chapter 4) by reducing the absorbtance[13]of a single building, and computer simulation indicated that the indirect effects of wide-scale absorbtance changes will nearly double the direct savings.

The use of selective surfaces would definitely enhance these savings. The findings were so conclusive that Rosenfeld et al [5] suggest government policy measures to implement "cool surfaces" (see p263 in [5] in Appendix 2). Due to the significance of this report, a copy is included in Appendix 2.

Unfortunately, widespread usage and acceptance of selective surfaces to minimise internal building temperatures and thus reduce cooling energy consumption in Australia has yet to be utilised to its full potential. What is even more discouraging is that Australia's climate is ideally suited to these materials. The reasons for this are many and complex. However, it is the author's belief that the primary reason for selective surfaces not being a fully accepted heat management tool is because of the lack of technical understanding and inappropriate marketing when the materials were first introduced. Terms such as "insulating paints" result in misleading, inappropriate perceptions and comparisons with bulk insulations. As demonstrated in this report, the science of selective surfaces and methods for modelling the performance when applied to buildings is well established.

The potential for selective surfaces to reduce cooling energy consumption and greenhouse gas emissions in Australia is enormous. Considering the world-wide concern for global warming, selective surfaces also could provide Australia with vital export earnings. It is essential that both state and Federal Governments support the necessary policy steps (discussed in [5], see Appendix 2) to fully implement selective surfaces. Timing is critical - ten years of practical experience should not be wasted!

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[13] The report[5] uses the term "albedo" which is equivalent to the solar reflectance. Increasing the albedo of an opaque surface is identical to decreasing the absorptance of that surface. See Equation 2.1.

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APPENDIX 1

This example is taken directly from [10] Chapter 25, example 1.

A single-family detached house (Figure A1) is located in a south-western state at 36°N latitude (in the United States).
Roof construction: Conventional roof-attic-ceiling combination, vented to remove moisture with 150 mm of fibrous batt insulation and vapor retardant (U = 0.28 $W/(m^2K)$.
Wall construction: Frame with 100 mm face brick, 90mm fibrous batt insulation, 20 mm polystyrene sheathing, and 13mm gypsum plaster board (U = 0.34 $W/(m^2K)$).
Floor construction: 100mm concrete slab on grade.
Fenestration: Clear double glass, 3mm thick, in and out. Assume closed, medium color venetian blinds. The window glass has a 600 mm overhang at the top.
Doors: Solid core flush with all-glass storm doors (U = 1.82 $W/(m^2K)$].
Outdoor design conditions: Temperature of 36°C dry bulb with a 13°C daily range and a humidity ratio of 0.0136 kg vapor/kg dry air (23.7°C wet bulb).
U-values for all external surfaces are based on a 3.4 m/s (12 km/h) wind velocity.
Indoor design conditions: Temperature of 24°C dry bulb and 50% rh.
Occupancy: Four persons, based on two for the master bedroom and one for each additional bedroom. Assign to the living room.
Appliances and lights: Assume 470 W for the kitchen, and assign 50% to the living room. Assume 470 W for the utility room, and assign 25% to the kitchen and 25% to the storage room.
The conditioning equipment is located in the garage, and the construction of the house is considered average.

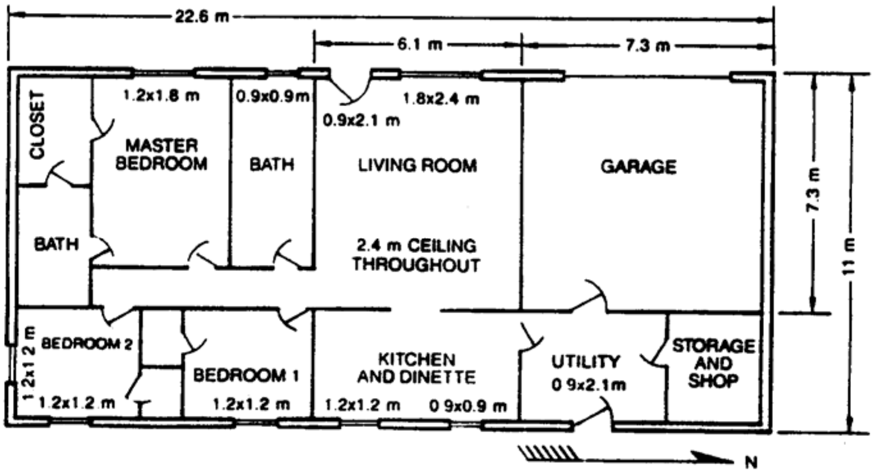

Figure A1: Floor plan of single-family detached house.