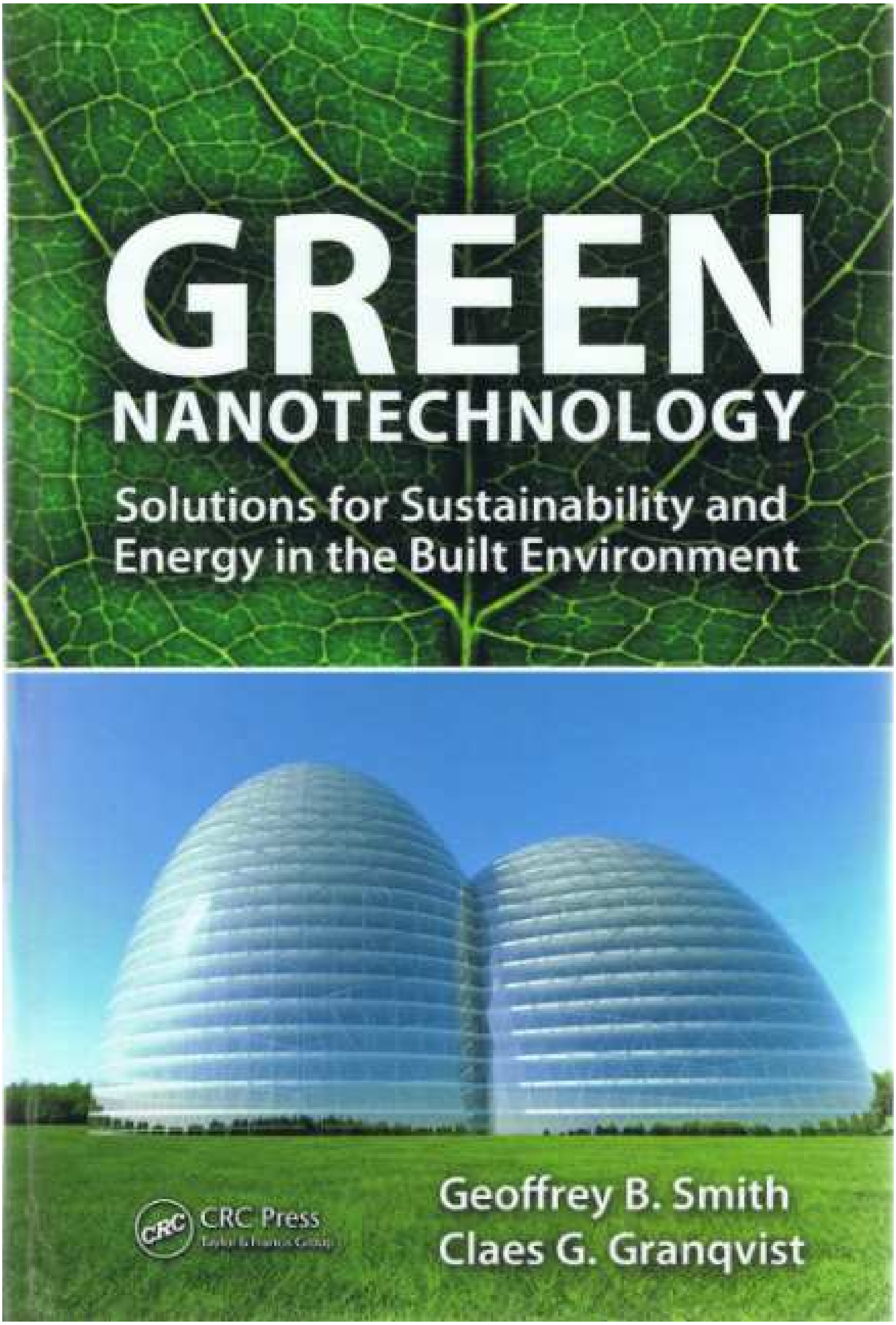

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AN EXTRACT WITH PERMISSION OF THE AUTHOR.

are high. However, among all current options, it is even more energy efficient and financially attractive to spread the load over time and use conventional power stations at night for cooling. Chillers work more efficiently at night, and one can further reduce demand by using supplementary night sky cooling. A number of state-of-the-art air conditioning systems cool glycol-water mixtures to near ice temperature overnight and then use the stored cold fluid the next day in various ways such as to cool overhead beams. The cooled thermal mass of the building can involve using interior walls or floors, columns or beams filled with chilled water-glycol, or suitably located phase change materials. The latter can be micro-encapsulated waxes. Greater use of night cooling with conventional compressors plus storage is thus to be encouraged. This also opens the way for hybrid operation with advanced night sky cooling systems. These do not seem to have been considered before, but have much to offer. They will reduce compressor power needs and also pump much of the exhaust heat into space instead of into nearby air. Such hybrid systems are well suited to both large buildings and to homes. The sky cooling devices introduced in Section 7.4 may also be applicable in homes for collecting and storing cold fluid overnight to fully supply cooling needs the next day. The implication is that if cooling loads in homes are not too high—which presumes good design—these systems could completely eliminate the need for electrically powered cooling, apart from a small amount of power for fans or pumps.

Other sources of natural cooling also need to be considered in buildings, including natural ventilation, cool underground soil, and evaporative cooling. In some parts of the world, snow and ice can be accumulated during the winter and used for cooling during the summer. But ultimately these sources still pump heat or water vapor into the local environment, just as electrically powered cooling does. Night sky cooling avoids this.

7.3 HIGH-ALBEDO PAINTS FOR COOL BUILDINGS

The thermal performance of facades and roofs in buildings is a key to determine the need for heating or cooling energy and for the thermal comfort of the occupants. The improvement potential is huge, and it has been estimated that retrofitting of facades and roofs to make them more thermally efficient can reduce today's (2010) demand for heating and cooling by 50 to 60% [14]. The need for action is urgent, particularly in warm countries undergoing rapid development, since improved liv- ing standards tend to rapidly accelerate the use of electrically powered air conditioning [4]. Increased use of air conditioning in cars and other forms of transport also emphasizes the need for better control of solar heat gains. Both coatings and insulation materials are of importance for improving the energy efficiency.

Chapters 4 and 5 demonstrated that windows and luminaires are significant elements for the facade’s impact on the internal energy demand. These are important for the building’s apertures but, of course, the opaque parts of the building envelope matter very much, too, and, as we will discuss here, new types of paints have much to offer and can be as significant as good thermal insulation. Furthermore, as explained earlier in this chapter, improved roof coatings can contribute substantially to raising the urban albedo and hence offset large amounts of added CO_2, as well as contribute to demand savings and create nicer microclimates.

For a given color of the paint, different combinations of selective coatings and insulation may yield the same overall improvement of the thermal performance of a wall or roof of a building in a given geo- graphic location. Therefore, the final decision of what paint to actually use will come down to relative costs, availability of the different options, aesthetic appeal, ease of application and installation, and whether the building is under construction or being retrofitted. Routine maintenance of painted surfaces may provide an opportunity for easy improvement in performance once the technologies and approaches we address here become more widely available or lower in cost. The number of white and colored paint products being marketed as "solar” or "sun reflecting” has increased greatly in recent times as people are becoming more interested in green technology and aware that solar and thermal control can yield large energy savings.

7.3.1 How Cool Can a Solar Exposed Root Get?

A surface having a neutral color can range from very bright white with A_{sol} ~ 10%, through dull white and light gray with A_{sol} between 40 and 60%, to near black with A_{sol}, ~ 90%. So, whitish-looking surfaces are not necessarily very good solar reflectors and may absorb as much as half of the incident solar energy in some cases. Also, dull white solar irradiated surfaces with A_{sol} = 50% can get hot and yield significant internal heat transfer to whatever is thermally connected to such a surface.

It is not uncommon that roofs reach 60°C to 75°C under clear skies, so it is easily realized that roofs should have high solar reflectance combined with high thermal emittance, at least for warm and hot climates. The high emittance not only helps keep down daytime temperatures on roofs and walls but allows the roof, and often the interior and building mass, to cool to a temperature a few degrees below that of the ambient at night. With highly solar reflecting roofs and walls it can take some time after sunrise to overcome the stored coolness. This type of spectral selectivity minimizes solar heat gain and maximizes emitted radiation and hence is the exact reverse of what is needed for the efficient solar thermal collectors discussed in Section 6.1; the ideal spectrum for the surfaces of present interest was introduced in Section 2.9.

Normal metal roofing is neither strongly solar reflecting nor strongly thermally emitting, so it has far from ideal properties. A well-known treatment for roofs involves coatings that are heavily pigmented with TiO_2 microparticles. This pigment has a high refractive index so the paints backscatter strongly and hence reflect the solar heat, and suit- able additional constituents can render them efficient thermal radiators. A variety of such high-performance basic white paints are available. Further inorganic and other additives can improve them optically and thermally and sometimes also enhance their long-term durability; such improvements can be especially important for roofs, given their high solar exposures and large temperature changes.

Coatings with high solar reflectance and high thermal emittance, and related pigmented polymer foils, have been discussed over the years for both daytime use and for night sky cooling [15-18]. The best "cool" roof paints combine a hemispherical solar reflectance of ~90% with a blackbody thermal emittance of ~95%, and are able to maintain these characteristics for many years with only slight changes; these paints have a diffuse appearance, which is important since they do not produce glare. The same coating will be mentioned as an excellent candidate for day-night sky cooling in Section 7.4.

Glare can be disturbing, and there has been confusion on this issue, which may have prevented the uptake of coatings with low solar absorptance. In general, a highly diffuse but strongly reflective coating is much less of a problem for glare than a partly smooth but much darker coating (or even a plane glass sheet). In other words, glare from reflected solar light is a large problem for surfaces with a moderate specular component if they are viewed from a point to which the mirror component of the reflected beam is directed. And it is difficult not to look at that bright spot! A highly diffuse white surface, on the other hand, spreads the reflected energy into the whole outgoing hemisphere, so viewing from any one direction can be maintained with relative ease. Therefore, bright white paint rarely causes glare unless it has a semisheen or glossy ‘ surface, and a glossy black surface may cause more glare than a diffuse white one.

The practical energy savings of a coating with high solar reflectance and thermal emittance can be very large. Box 7.3 reports specific data for three different commercial buildings, demonstrating that the power for air conditioning can be decreased to a fraction of what is demanded with standard roofing, and that the average roof temperature can be decreased by 15°C to 20°C or even more.

BOX 7.3 PRACTICAL EXPERIENCE FOR BUILDINGS WITH "COOL" PAINTED ROOFS

Figure B7.3.1 shows power for air conditioning, measured during 1.5 years for two nearly identical supermarkets located in the same region and exposed to the same warm-to-hot climate [19]. When the standard finish was used, the power reached 40 to 45 MWh per month during several months. A "cool" paint had a dramatic effect and limited the power to between 15 and 22 MWh per month.

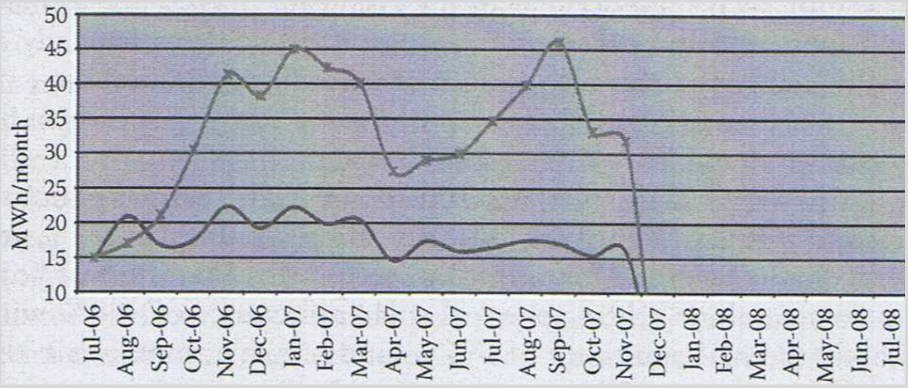

FIGURE B7.3.1 Air conditioning power usage in two almost identical nearby supermarkets near Brisbane, Australia, during a 1.5-year-long measurement campaign. Upper and lower curves refer to buildings having standard external finish and coated with "cool" paint, respectively. (From J. Bell et al., *Proceedings CD and Summary Book of the CIB International Conference on Smart and Sustainable Built Environment*, Brisbane, Australia, [November 19-21, 2003] [ISBN: 1-74107-040-6]; Paper T606.)

The huge energy savings observed in Figure B7.3.1 cannot all be attributed to direct reductions in heat gain. There are other benefits, too, which are related to two main influences, namely

- Significantly improved microclimate, especially just at and above the roof
- The “cool" coating’s ability to reach temperatures below those of the ambient overnight

The cooler microclimate can increase the efficiency of roof-mounted cooling units and/or provide cooler air-to-air exchange systems. The quantitative levels of power savings are dependent on the installation or the cooling unit and how it is operated, the way internal air exchange occurs, and the roof and ceiling insulation. The conclusion is that the very large savings evident from Figure B7.3.1 may not always occur, but at least half of the shown savings can be expected in most cases.

Figure B7.3.2 reports additional data demonstrating the large impact of a "cool" roof finish, here applied to a newspaper office/ production facility [20]. When a standard roof material was used, the temperature frequently reached 50°C to 70°C. Replacing this material with a "cool" white paint led to a very significant decrease in the roof temperature: the temperature difference was ~17°C on average and was exceptionally as large as ~25°C.

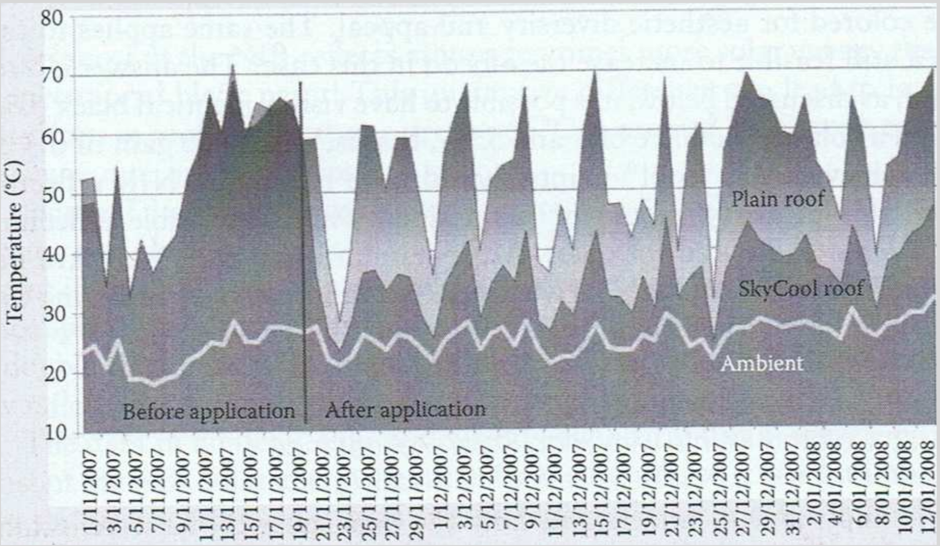

FIGURE B7.3.1 Maximum roof temperatures on a newspaper office/production facility in Sydney, Australia, during a 2.5-month-long measurement campaign. Data are shown for a standard plain roof, for a roof coated with "cool" white paint, and for the ambient. (From SkyCool Pty Ltd., Sydney, Australia [2007], private communication.)

A third example of the great benefits of “cool” paints is a 35,000 m^2 roof on the Melbourne Airport. This project also involved additional cooling at night by thermal storage in building elements and contents, whose thermal mass then reduced the warming on the following day. The project led to reductions in CO_2 emission exceeding 4,000 tons during 18 months.

The “cool" paints used on the supermarket, office/production facility, and airport discussed in Box 7.3 raised the roof albedo by some 0.4 to 0.5. The magnitude of the change makes it interesting to return to the discussion in Section 7.1 about the possibility of using increased urban albedos to offset CO_2 emissions on a global scale. As argued there, an overall change of the roof albedo by 0.25, together with a change of the road albedo of 0.15, would lead to an offset of these emissions by an amount corresponding to 11 years of expected increases. The conclusion then is that the "cool" paints can have a significant impact on the global CO_2 emissions if they are implemented in the urbanscape on a large enough scale.

The "cool" paints discussed above are visibly white. This is fine on shopping malls, supermarkets, warehouses, factories, airport terminals, some offices, and the like, but there are many roofs and walls that must be colored for aesthetic diversity and appeal. The same applies to cars. Is it still feasible to increase the albedo in this case? The answer is “yes" and, as discussed below, it is possible to have visibly identical black paints with a solar reflectance of 5 and 55%, that is, an albedo gain of 0.5 can be achieved. All "cool" paints should have maximum NIR reflection, and this property should be maintained while the visible reflectance is altered as desired for color. Most standard paints do not have high NIR reflectance, though, so we need to examine ways of achieving that. Various nanostructures are one option, as discussed below.

7.3.2 Colored Paints with High Solar Reflectance

It is important to understand how the hemispherical solar reflectance $R_{H,sol}$, can be divided into components for ultraviolet, luminous, and near-infrared reflectance. Using the data in Chapter 2, it can be found that

$$R_{H,sol} = 0.05\, R_{H,UV} + 0.43\, R_{H,lum} + 0.52\, R_{H,NIR} \tag{7.1}$$

that is, 52% of the reflectance is in the infrared. This shows that high solar reflectance can only be obtained if the NIR reflectance is very large. And if a distinct color is required, not just a pale one, then the luminous reflectance should be confined to a narrow band. The latter feature can be achieved with certain dyes, select pigments which may incorporate nanofeatures, and some nanoparticles.

The ideal colored "cool” paint for warm or hot climates would thus have, neglecting the UV, a maximum solar reflectance of $0.43R_{H,lum}$ + 0.52. Thus, a black paint with $R_{H,lum}$ ~ 0.05 could still have $R_{H,sol}$ as high as 0.55. But a conventional carbon black coating can achieve $R_{H,sol}$ ~ 0.06 at best. It then follows that a black roof, wall, or car body that