IMPROVING THE THERMAL PERFORMANCE OF A LIGHT-WEIGHT METAL ROOF IN HOT CLIMATES

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ABSTRACT

Corrugated Galvanized Steel (CGS) sheets are widely used for low-cost roof construction in hot regions. Due to the intense solar radiation, long exposure to the sun's rays, and its high thermal conductivity, the CGS sheet transmits heat indoors which creates an uncomfortable environment. Based on principles of thermodynamics, different light-weight CGS roofs that use common techniques to reduce the heat penetration are evaluated. A method that assesses the improved thermal performance and life-cycle cost of these systems is applied. Various cost-effective CGS roofs are suggested.

RESUME

Les panneaux cannelés d'acier galvanizé (CGS) sont souvent utilisés dans les pays au climat chaud pour la construction de toiture à coût economique. L'intense radiation solaire, la longue exposition des toiture aux rayons du soleil, et la haute conductivité thermale de ceux-ci, provoquent l'émission de chaleur à l'interior du bâtiment, créant ainsi un environnement hasardeux. En se basant sur les principes de la thermodynamique, des toitures légères avec panneaux CGS qui utilizent des techniques simples pour limiter l'admission de la chaleur sont evaluées. Une méthode estimant la performance thermale améliorée et le coût du cycle de vie de ces systèmes est appliquée. Divers toitures avec panneaux CGS de coût efficacité sont suggérées.

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CHAPTER I

INTRODUCTION

1. Outline of the problem

A most successful component in low-cost housing has been the roof made of Corrugated Galvanized Steel (CGS) sheet. Since its introduction at the beginning of this century, its use has become very popular. The CGS sheet has great number of advantages as a roofing material in low-cost housing: it protects well from rain; its high strength and flexibility make it resistant to earthquake damage; finally, it is easy to transport, handle, and install. Besides these technical advantages, the CGS sheet's general acceptability stems from social grounds as this material seems to represent modernism and progress. The low-cost dweller believes this and uses this component attempting to integrate himself to a progressive social group.

CGS sheets have been widely used in so-called hot regions, considered to be those where the annual mean temperature is (+)20°C, and extend in a strip along the equator. Latin and South America, the major part of Africa, Middle East, and Asia are found in these regions. CGS roofs are found in different types of hot areas. For instance, in the hot arid northern Sudan the popularity of CGS sheets, makes them a common replacement for the traditional mud roof system.[1] In tropical Central America, this component is replacing the clay tile roof.[2] Most of the world's population live in the hot regions, and for these people the main advantage of CGS sheet has always been its low-cost. Regardless of all these advantages, this component possesses a severe drawback: excessive heat transmission.

In a house located in a hot region the roof is the main source of heat transmission, because of its long exposure to the sun's rays. This phenomenon is especially exacerbated when the roofing material has a high thermal conductivity, as is the case with steel. As an example of this phenomenon, the data of an experimental study conducted in northern Sudan, is illustrative.[3] This investigation examined several types of roof construction. Two of these roofs were CGS sheet with different surface finishing and interior conditions. Figure 1 shows the average hourly temperatures of the exterior roof surface, of plain CGS sheet. The bold line shows the temperature of the external air in the shade, and the dashed line the outside surface temperature of the roof. The maximum temperature of the former was 44°C, while that of the roof's outside surface was 74.5°C.

The significance of the increase in the temperature of the exterior roof surface is its effect upon the internal air temperature of the house. Since the CGS sheets are thin, the

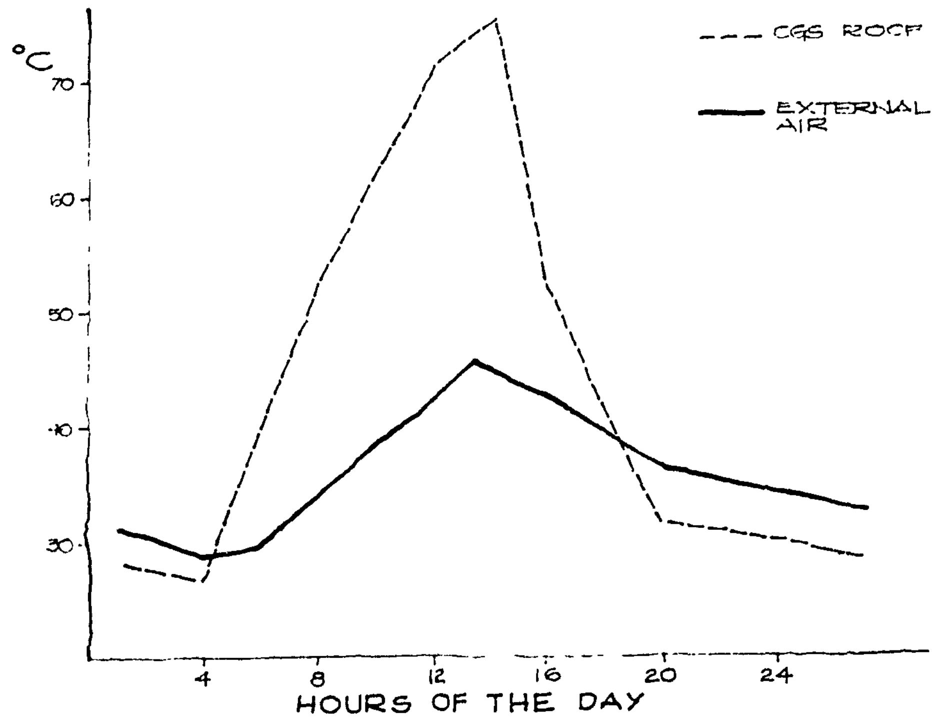

Figure 1. Average hourly temperature of the outside surface of a CGS roof.
After Mukhtar, 1980, 412.

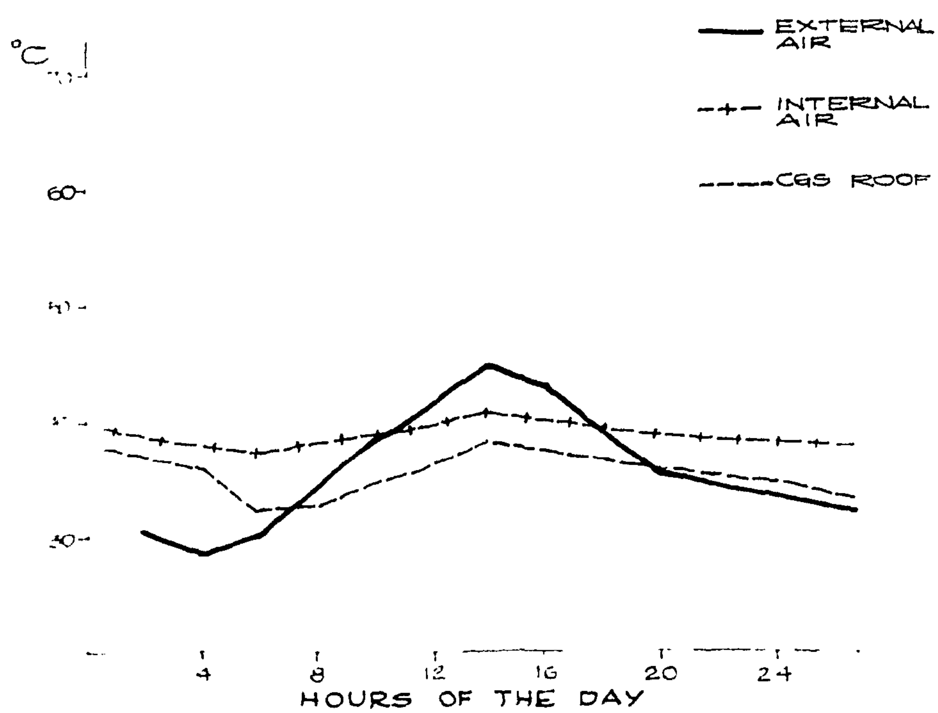

Figure 2. Average hourly temperature of the inner ceiling surface of a CGS roof with ventilated roof space.
After Mukhtar, 1980, 413.

temperature of the inner surface is almost the same as the outside surface temperature, i.e. 74.5°C. As the metal sheets' temperature rise, they radiate heat indoors, creating an uncomfortable and even hazardous micro-environment.

Some scholars have suggested that a well-maintained CGS roof with a well ventilated ceiling space and a light-weight ceiling is the ideal low-cost roof for the warm humid tropics.[4] Others have pointed out that a roof with a light-coloured exterior surface, can avoid the negative effects of heat build-up.[5] Another researcher has stated that adding small amounts of insulation to the roof construction, can keep the indoor ceiling temperature at acceptable levels during hot dry summer days.[6]

Repeatedly in the literature of low-cost housing it is mentioned that there is a need for a cheap roof with better thermal performance. This problem has been approached in several ways. The field study carried out in northern Sudan is an example. In order to reduce the effect of the CGS roof's overheating on the internal temperature, a ceiling of fiberboard (15 mm) was added. Measurements of the underside ceiling surface temperature and the internal air were taken, and it was found that the maximum temperature of the internal air (41°C) exceeded the maximum of the lower ceiling surface (38°C). The dash-cross line in Figure 2 shows the air temperature of the interior air, and the dashed-dot line shows that of the lower roof surface. The bold line represents the temperature of the external air whose maximum was 44°C. The aforesaid points suggest that although reduction of heat penetration has been accomplished, further decrease of the inner roof surface temperature is required. It also shows that reduction of heat penetration through a CGS roof can be accomplished by relatively simple devices.

This thesis has two main purposes: 1) to investigate heat gain through the roof by understanding the principles that govern this phenomenon; and, 2) to improve the thermal performance of the CGS roof through the evaluation of simple techniques that minimize the temperature difference between the interior and the exterior. This will be achieved by using inexpensive materials with suitable thermal properties, so that the owner-builder can improve the roof using the minimum amount of money, simple tools, and no special skills.

This thesis is organized as follows. The second chapter describes the method of evaluating the thermal performance of roofs. The third chapter examines the commonly practised techniques for protecting the roof against heat gain. Each technique is analyzed in terms of the principles of thermodynamics. Based on this analysis, this section develops a variety of alternative light-weight CGS roofs, and ends with an assessment of their thermal performance. The fourth chapter describes the life-cycle cost technique, and analyzes the improved roofs. The final chapter presents an evaluation of these systems in terms of the effect on the interior thermal conditions.

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CHAPTER II

METHODOLOGY

1. Introduction

Due to its high thermal conductivity, its long exposure to the sun's rays, its orientation, and its interaction with other climatological factors, CGS roofs are a source of excessive heat in low-cost housing. It is the intention of this section to describe the method utilized to improve the thermal performance of CGS roofs. The chapter focuses on the procedure of calculating heat transmission under steady-state conditions. Understanding this issue requires a knowledge of the principles which govern the behaviour of heat, and an explanation of heat transmission through the roof. These two aspects are presented below. The research method is explained at the end of this chapter.

2. The basic principles

The first law of thermodynamics states that energy cannot be created or destroyed, it can only be converted from one form to another. The second law of thermodynamics establishes that heat transfer can only take place in one direction: from a higher temperature to a lower temperature state.[1] Heat moves from a hotter to a cooler body in three forms: **conduction**, **convection**, and **radiation**. Heat transfer by conduction occurs when there is direct contact between one body and a hotter one. Convective heat transfer is the process where heat moves from the body's surface to a fluid, most commonly air. Heat exchange by radiation -also called thermal radiation- refers to the wavelengths of the radiation spectrum. It is heat that can not be seen, but can be felt as one gets closer to the radiant matter. It is important to remember that the magnitude of heat flow by radiation depends on the temperature of both surfaces -radiating and receiving- and on the surfaces' properties of **absorptivity** (a), and **emissivity** (e). The emissivity of a surface at normal temperatures ($10^{\circ}C$-$38^{\circ}C$) is not necessarily the same as its absorptivity.[2] From Table 1 it can be observed that dull copper, aluminum, or galvanized steel absorb an amount between 40%-65% of solar radiation, but they emit 20%-30% of radiant heat.

The phenomenon of heat transmission through the roof is explained as follows. The total amount of solar radiation that the roof absorbs is transformed into heat which moves through the material by conduction, increasing the temperature of the roof. A portion of this heat is transmitted by convection (i.e. through air movement), both to the outside and to the inside roof surface. The remaining part of the heat will be eventually radiated indoors. This phenomenon is represented in Figure 3.

Surface	Emissivity or Thermal Absorptivity at 10–38 °C (50–100 °F)	Absorptivity for Solar Radiation
Black nonmetallic surfaces	0.90–0.98	0.85–0.98
Red brick, concrete, and stone, dark paints	0.85–0.95	0.65–0.80
Yellow brick and stone	0.85–0.95	0.95–0.70
White brick, tile, paint, whitewash	0.85–0.95	0.30–0.50
Window glass	0.90–0.95	Transparent
Gilt, bronze, or bright aluminum paint	0.40–0.60	0.30–0.50
Dull copper, aluminum, galvanized steel	0.20–0.30	0.40–0.65
Polished copper	0.02–0.05	0.30–0.50
Highly polished aluminum	0.02–0.04	0.10–0.40

Table 1. Average emissivities and absorptivities for some common building surfaces. Hassan, 1986, 18.

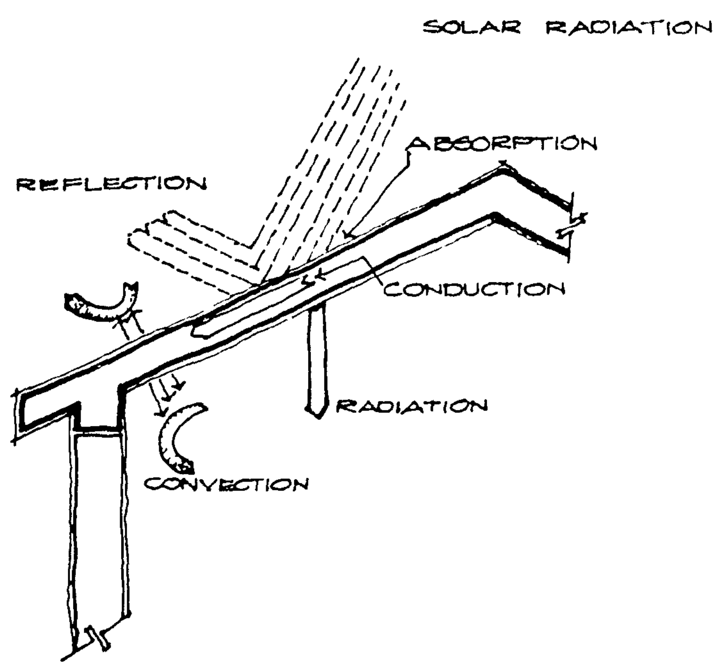

Figure 3. The phenomenon of heat transmission through the roof.

Absorptivity is a dimensionless factor denoting the proportion of solar radiation incident on the surface of a material. Since every material absorbs and reflects solar radiation, **reflectivity** denotes the component that is reflected. **Thermal conductivity** is defined as the transmission of heat by conduction only, i.e. by contact of a warmer surface with a cooler one. The thermal conductivity of building materials ranges from 0.02 m^2 degrees C/W (expanded polystyrene) to 200 m^2 degrees C/W (aluminum sheet). As the thermal conductivity of a material depends mainly on its density and its heat capacity, it is generally acknowledged that light-weight materials have a low thermal conductivity, whereas heavy-weight materials possess high thermal conductivity.[3]

3. Research Method

A suitable approach to the optimization of the performance of a building component, (i.e. a roof system), is quantitative analysis. This is a particularly appropriate method when a common measure of its cost and its benefit can be found. While the common measure is often money, the benefits achieved can also be social and environmental.[4] However, for the purpose of this research the common measure will be cost, and the benefit will be the reduction of heat gain through the roof.

Quantitative analysis is a three step operation, each step involving the application of a specific technique. The first step requires the calculation of the inner roof surface temperature. This is accomplished by calculating the heat transmission. The second step involves the calculation of the life-cycle cost of the roof system. The last step analyses the thermal performance of the roof in terms of its life-cycle cost. The following part of this study explains the main concepts of the analytical procedure utilized to improve the thermal performance of the CGS roof. The chapter ends with a brief explanation of the life-cycle cost technique.

3.1 First step: the analytical calculation of heat transmission under steady-state conditions

The analytical method used to calculate the temperature on the under-side of the roof, involves three steps: first, the calculation of the **Sol-air** or **equivalent outdoor temperature**, second the estimation of the roof's **thermal resistance**, and finally the measurement of **heat gain.**

The **Sol-air** or **equivalent outdoor temperature** is the temperature of the outdoor air in contact with the roof, which combines the heating effect of radiation falling on the roof with the heat loss to the surroundings.[5] When the exterior roof surface is exposed to solar radiation, its temperature is higher than the outdoor air on the shade. The roof exchange heat with the environment by convection and radiation, and therefore the net heat gain through the roof is the difference between the absorbed solar radiation and the heat loss to the surroundings.

The **thermal resistance** (R) of a material is its capacity to resist heat flow. This concept differs from the **thermal resistivity** (r), in that the former expresses the capacity of opposition to heat flow of a specific thickness of a certain material, while the latter refers to a 1 m thickness of the same material. Thermal resistance is expressed in $m^{2o}C/W$; the power unit Watt indicates the time of unit heat delayed.[6] The concept of **heat gain** refers to the amount of heat flow from the exterior surface of a roof to the inside surface of the same element. The quantity of heat flowing through the roof in unit time is defined as rate of heat flow or rate of thermal transmission. Its expression in metric units is given by W/m^2.

3.2 Second step: the life-cycle cost technique

In low-cost housing cost, obviously, plays a decisive role. The second step analyzes the roof in terms of life-cycle cost. Life-cycle cost is useful in assessing the economic impact of improvements on the roof system. This technique establishes that present costs are not equivalent to future costs, and permits one to determine the total amount of money it will be necessary to invest during the life term of the roof system. In order to accomplish this, two procedures can be followed: the Total Present Worth routine or the Equivalent Annual Cost procedure.[7]

Since initial cost represents a crucial aspect in low-cost roofing, it is more suitable to apply the Total Present Worth cost process, which will provide an approximate idea of the future value of an amount invested at present. The procedure follows two steps: the first requires the calculation of the capital costs or non-recurring costs; the second involves the assessment of the future or recurring costs such as maintenance, repairs, and replacement.

3.3 Third step: cost-benefit analysis

The last step examines the relationship between the thermal performance and the life-cycle cost of the alternative roofs. This is achieved through the cost-benefit analysis technique. This technique considers that both thermal performance and low cost are determinants for the improvement of the CGS roof, and it chooses from several alternatives those which provides best thermal performance with the least cost.

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CHAPTER III

ROOFS AND HEAT PROTECTION

1. Introduction

In a hot climate the chief requirement that a roof has to satisfy is protection against heat. Traditionally, people have used several common techniques to protect the roof against heat gain. These have emerged in accordance with climatic conditions, dependent on the availability of different building materials. These commonly used solutions need to be scientifically studied and further improved to make them compatible with actual requirements.[1] This chapter examines the common techniques used to protect the roof against heat gain. Each technique is explained in terms of principles of thermodynamics with data of experimental methods. A wide spectrum of improved light-weight CGS roof systems is developed. The chapter ends with an assessment of the thermal performance of these improved roof systems.

2. Common techniques

With regard to thermal protection roofs have been classified as light-weight and heavy-weight.[2] Experts have pointed out that a light-weight structure which does not store heat is appropriate in hot-humid conditions. They note that materials such as tiles, sheets of asbestos-cement, or aluminum are desirable. Studies carried out in hot-humid regions have suggested that a light-weight structure, with a low-weight insulating material on the exterior can provide the same heat flow during the day as would be provided by a heavy structure. This rule does not necessarily apply to hot-dry regions, since heavy roofs are predominant in those areas as they delay the required time for the heat to flow indoors.[3]

For both types of roofs, the amount of heat absorbed depends on its surface qualities -mainly colour- and its thermal resistance. While heat moves by conduction, convection and radiation, the reduction of heat flow can be accomplished in three different ways: with reflective, resistive and/or retarding insulation.[4] Thus, the basic techniques of protecting the roof against heat gain can be categorized as 1) techniques that reduce heat absorption and, 2) techniques that reduce actual heat flow. The analysis of these ideas is organized according to Table 2.

2.1 Surface qualities

A simple technique that is widely used to protect roofs against solar radiation is to paint them white. It is well known that the reflectivity of a surface increases with the lightness of its colour. In experimental studies conducted

Category	Technique	Mechanism
Reduction of Heat Absorption	Surface qualities	Reflective
	Shading	Retarding
Reduction of Heat flow	Additional mass	Retarding
	Ceiling	Resistive
	Attic ventilation	Resistive
	Ceiling insulation	Resistive
	Foil	Reflective

Table 2. Techniques and mechanism of protecting roofs against heat gain.

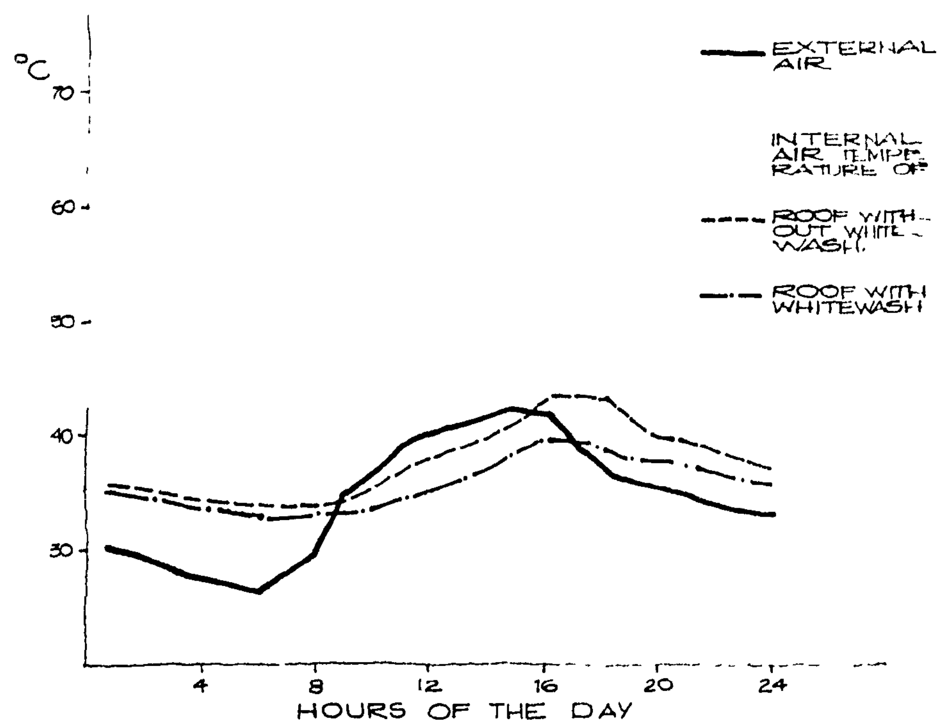

Figure 4. The effect of whitewash on a concrete roof slab.
After Mukhtar, 1980, 418-421.

in northern Sudan, the effect of whitewash applied on the external surface of a bare concrete roof slab was studied. It was observed that the temperature of the external surface and of the internal air improved notably. Figure 4 shows this result; the bold line is the external air temperature, and the dash/dot line shows the internal air temperature of the roof slab without whitewash; the broken line indicates the temperature of the whitewashed slab, which was lower than the external air temperature.

The utility of white paint has also been tested on CGS roofs. In Figure 5 the dash/dot line represents the internal air temperature of the unpainted roof, and the broken line the temperature of the painted roof; the bold line shows the external temperature. One can observe that the roof painted white accomplished a reduction of 5 degrees C in comparison with the unpainted roof. Nevertheless, the inside temperatures of both roof types was greater than the external air.

2.2 Shading

The main function of a shading device is to reduce solar radiation and incorporate a layer of natural insulating material: air. These devices can be fixed, adjustable, or retractable.[5] A common shading device is shown in Figure 6. It shows a shaded iron sheet roof, also known as double roof.

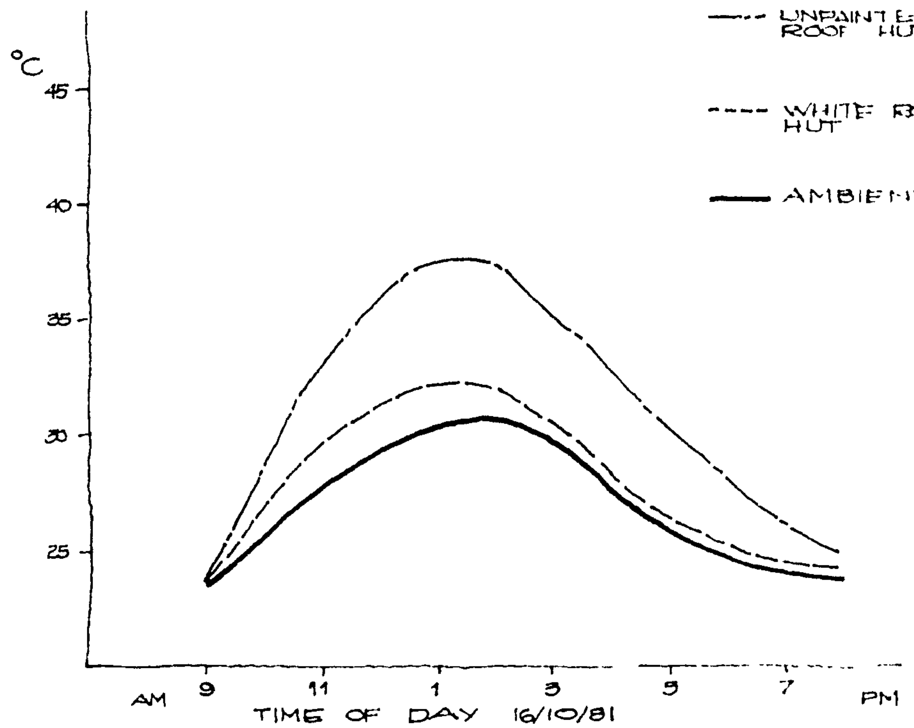

Figure 5. Temperature inside model huts roofed with painted and unpainted CGS roofs.
After Nason, 1985, vol 28: 1, 3.

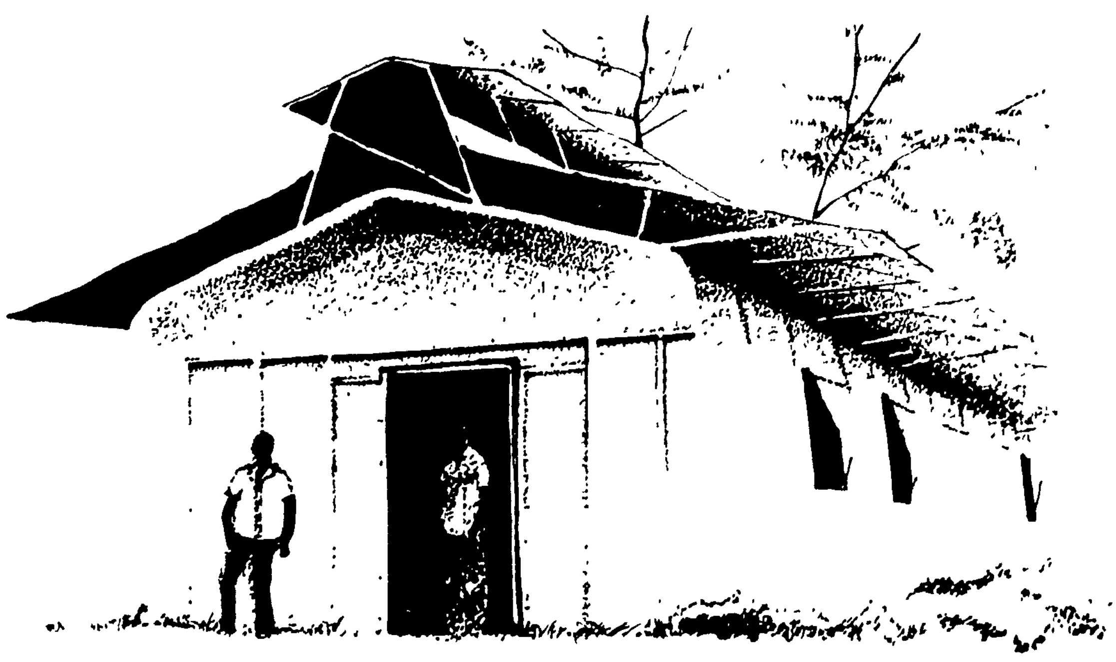

Figure 6. Double roof with iron sheets in Cambodia.
After Lippsmeier, 1969, 53.

CGS sheets are commonly used as shading device in Sudan. Their success in improving the thermal performance of a bare concrete slab was assessed in the investigation mentioned earlier. While the temperature of the inner roof surface was 37°C, it was 7 degrees below the exterior air in the shade. Figure 7 shows the average temperature of the lower roof surface of the shaded slab; the bold line represents the temperature of the external air.

One cheap and practical shading material which has been tested is a reed panel on bamboo frames. In another study, the effectiveness of the panels was assessed through comparison with the internal air temperature and the temperature of the ceiling without shading. It was found that while the shaded ceiling temperature closely matched the internal air (both reached about 40°C as maximum temperature), the temperature of the ceiling without shading was almost 45°C. The ceiling temperature of the shaded slab was below the external air temperature by 2 degrees.[6]

2.3 Additional mass

Another common technique to protect the house against heat gain consists of placing additional material over the roof. An illustration of this idea is the roof of a haveli (a type of communal house in India). This roof type consists of a timber beam structure which supports three layers of

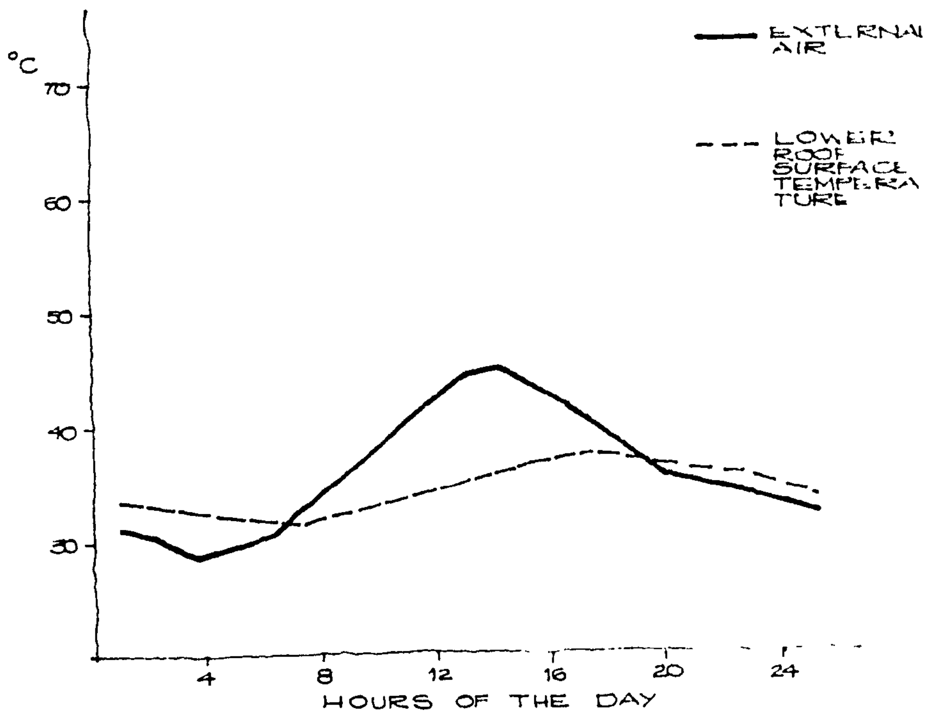

Figure 7. The thermal performance of a concrete slab shaded with CGS sheet.
After Mukhtar, 1980, 416.

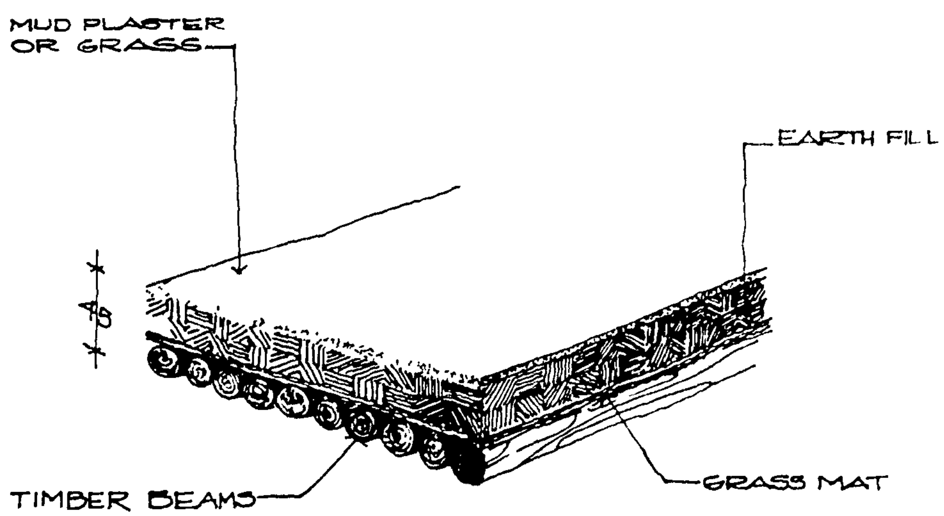

Figure 8. Scheme of a <u>Haveli's</u> roof.
After Gupta, 1985, vol 28: 3.

materials: a thin layer of grass mat, a thick layer of earth fill and a layer of mud plaster. The roof is sometimes finished with whitewash (Figure 8).

2.4 Ceiling

The use of a ceiling to provide reduction of heat flow is very common. The thermal function of the ceiling is to reduce heat flow by convection. To accomplish this it is necessary to use light-weight materials of low density.[7] Different experiments performed in warm-humid regions have shown that a roof without a ceiling does not provide adequate heat protection. These studies also showed that many types of materials offer acceptable indoor thermal conditions.[8] The ceiling, besides being a barrier to heat flow, provides a space under the roof which can incorporate three different devices: attic ventilation, ceiling insulation, and foil.

2.5 Attic ventilation

A ventilated attic space is critical as a means to reduce heat flow. Following the experimental investigation carried out in Sudan, it was found that a roof constructed with CGS sheets, and fiberboard ceiling -with ventilated and unventilated roof space- achieved similar reduction of the underside ceiling temperature. On the other hand, several scientific studies of roofs with and without ventilated attic spaces have shown a difference in temperature reduction.[9]

A possible explanation of this discrepancy is the effect of the ventilation rate. When the ventilation of the roof space is provided by natural means, the rate of ventilation may fluctuate and heat removed can vary considerably. Therefore, the success of roof ventilation depends on continuous air movement.[10] The key to this success is to increase the difference of the height of the vent openings, as the air introduced by this means is proportional to the vertical distance between them and the indoor-outdoor temperature.[11]

The ventilation of the attic space by natural means is provided by the so-called chimney effect. This is achieved when two openings are provided at different heights forming a difference of pressure; while the warm air (gathered at the underside of the roof) escapes through the upper vents, the cool air flows in by the lower apertures. To enhance air circulation, gable louvers at each end are commonly used as well. Figure 9 shows this mechanism. There are some negative side effects of ventilated roofs. One of these is condensation at the surface of the metal sheets. To prevent this a layer of some insulating material over the roof is of a great help.[12]

2.6 Ceiling insulation

It is broadly acknowledged that ceiling insulation

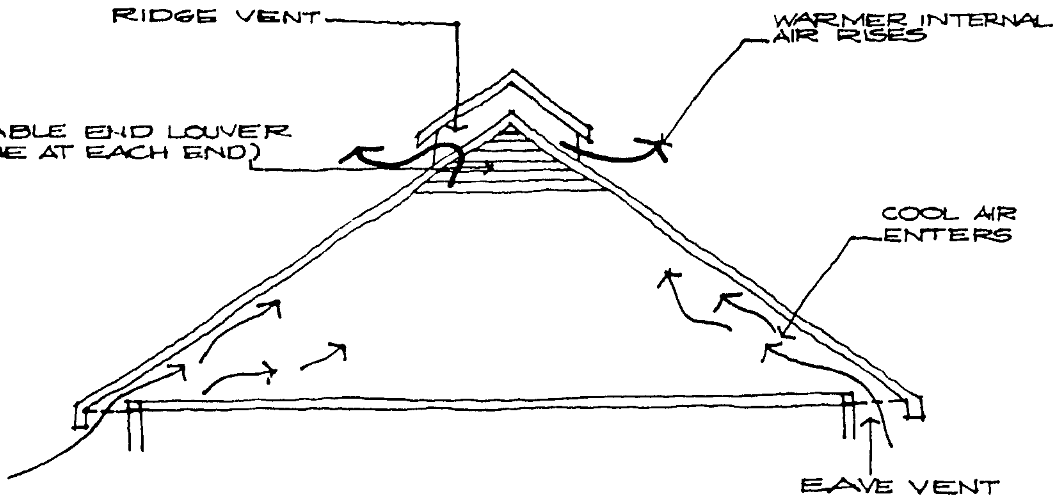

Figure 9. Ventilation of attic spaces by stack effect.
After Egan, 1975, 60.

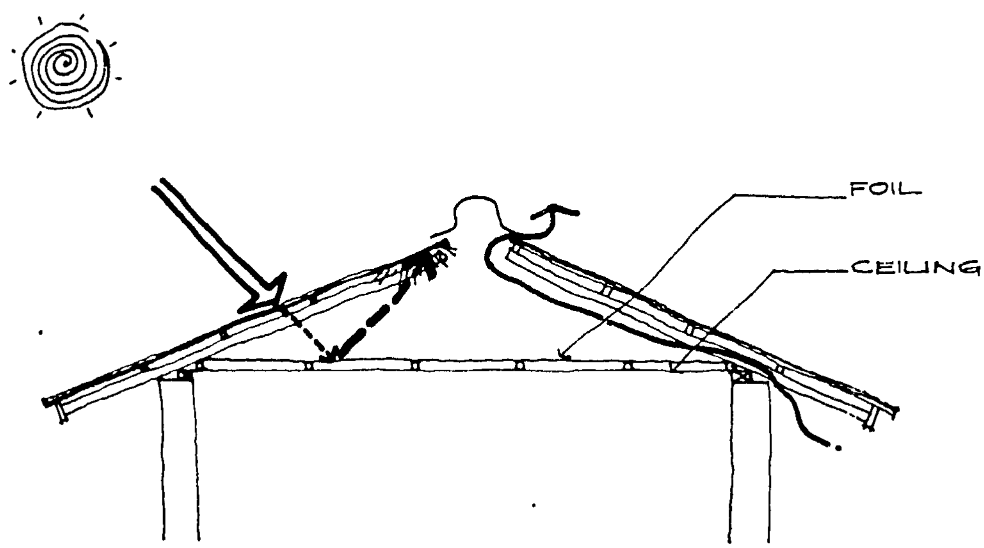

Figure 10. The effect of reflective foil on the underside roof surface.

offers a great opportunity to reduce heat transmission through the roof. Field studies have shown that ceiling insulation in a light-weight metal roof can maintain the indoor temperature at an acceptable level.[13] The effectiveness of this technique was tested in Australia using model huts roofed with CGS sheets. A plasterboard ceiling (100 mm thick) was insulated with rock-wool batts. The reduction of heat transmission was found to be considerable. When the maximum external air temperature reached 31.5°C, the maximum internal recorded temperature was 32.5°C.[14]

It is important to mention that the insulation value of a roof construction is given by the combined roof-ceiling insulating value. As the ceiling itself usually has little resistance value, the roof-ceiling resistance depends to a great extent on the amount and type of the ceiling insulation. It has been suggested that the incorporation of 250 mm of mineral wool insulation into a corrugated galvanized iron roof with a fibrous-plaster ceiling, can provide acceptable thermal resistance in the hot-dry climate of Australia.[15] It is true, however, that this kind of insulation is relatively expensive.

While the roof-ceiling insulating value is determined by the **thermal resistance** (R-value), it is often defined by the **U-value** or **thermal transmittance.** The U-value from air to air is simply defined as 1/R. Thus, for the hot-dry climate of Australia, it has been suggested a roof-ceiling value of 1.08 W/m^2 degrees C should be the minimum standard.[16] For hot-humid climates the agreement among researchers is a roof-ceiling U-value of 0.8 W/m^2 degrees C.[17]

2.7 Foil

Heat transmission from the underside of the roof takes place by convection and by long-wave radiation, therefore, a material with low absorptivity and low emissivity is recommended above the ceiling to reduce the heat flow. Experimental results indicate that the effect of this mechanism is significant. A roof without insulation but with a metal foil produced a temperature reduction indoors of an additional 1.5°C.[18]

In order to achieve maximum efficiency it is necessary to consider three aspects of the foil. First, it should not be in contact with other materials on its warm side because conduction will take place and the insulating effect would be lost. Second, as dust accumulation on the foil increases emissivity, it is more useful to place the foil facing downward. This reduces dust accumulation and heat emmission indoors. Third, the roof layer facing the foil will be heated considerably owing to reradiation emitted by the foil, unless a well ventilated roof space is provided.[19] Figure 10 shows these phenomena. The dot line arrow represents the long wave radiation reflected by the foil striking the underside of the roof, and the bold line shows the air moving through the ventilated roof space.

3. Improved CGS roof systems

A wide range of improved CGS roof systems was developed considering the principles that govern the phenomenon of heat exchange, and the techniques used to protect the roofs against heat penetration. These systems reduce solar radiation and heat conduction of the roof assembly by passive means. The goal of these improved roof systems is to reduce the temperature difference between the lower roof surface and that of the external air.

To develop these low-cost CGS roof systems two points were considered. First, the definition of appropriate materials for each one of the techniques studied. Second, these techniques and materials were combined to form fifty-seven roof systems. Table 3 shows these materials and techniques and the basic data to carry out the heat gain calculation. Figure 11 shows four improved CGS roof systems. Other alternative roofs are schematized in Figure 12. The whole list of improved CGS roofs is presented below.

Improved CGS roofs:

1. Unpainted Corrugated Galvanized Steel (CGS).
2. CGS with two coats of white acrylic paint on its exterior surface.

DESCRIPTION	RESISTIVITY r m^2degC/W	REFLECTIVITY (solar radiaion)%	EMISSIVITY e %
LIGHT-WEIGHT METAL ROOF Corrugated Galvanized Steel sheet (0.8 mm).	0.0187	35	20
SURFACE QUALITIES White acrylic paint.	-	70	90
Whitewash.	-	85	90
SHADING Jute canvas.	22.37	79	90
Cane panels.	-	-	-
ADDITIONAL MASS Earth (dry and packed).	1.33	30	41
Straw (board).	10.75	40	95
Light-weight polymer concrete	5.26	60	90
Entortado (mortar sand-cement lime over light-weight aggregate).	1.96	60	90
CEILING Particleboard.	7.38	-	90
Jute.	22.37	-	90
Cane panels.	-	-	-
Straw.	10.75	-	90
Aluminum Foil.	-	-	0.5

Table 3. Properties of low-cost materials used to improve the thermal performance of CGS roofs. After ASHRAE, 1977, 22.13-22.17 and Evans, 1980, 157-158.

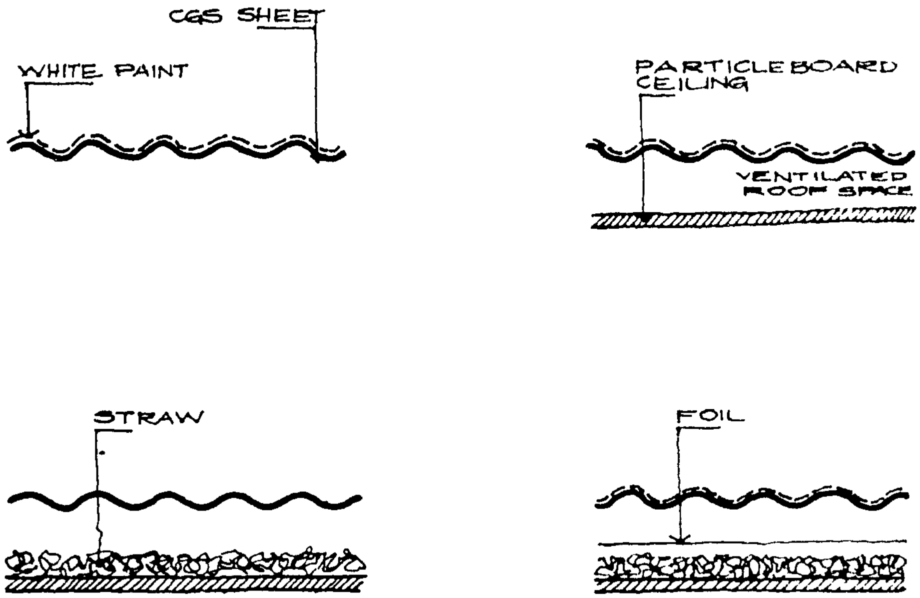

Figure 11. Four thermally-improved CGS roof systems.

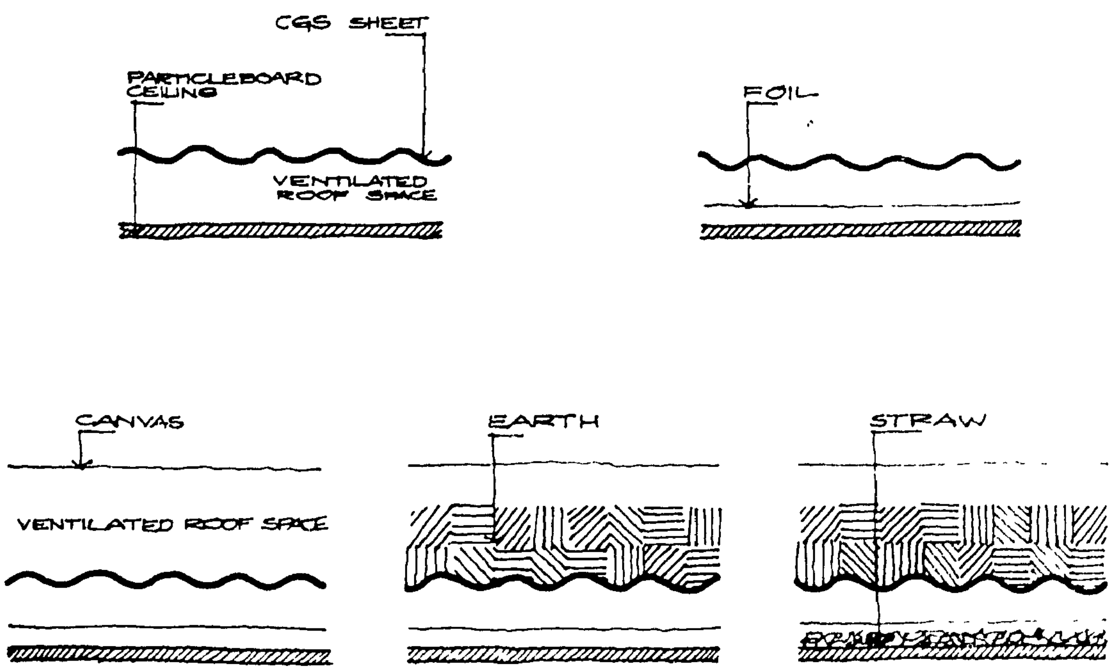

Figure 12. Alternative improved CCS roof systems.

3. CGS roof with two coats of whitewash on its exterior surface.

4. Unpainted CGS with jute canvas shading(0.105 mm) above the roof.

5. Unpainted CGS double roof with ventilated roof (150 mm).

6. CGS with a layer of earth (304 mm).

7. CGS with a layer of straw (500 mm).

8. CGS with a layer of light-weight polymer concrete (225 mm).

9. CGS with a layer of light-weigth aggregate (304 mm) and mortar sand-cement-lime (12.7 mm).

10. Unpainted CGS with particleboard ceiling (12.7 mm) and ventilated roof space (150 mm).

11. Unpainted CGS with particleboard ceiling (12.7 mm) and unventilated roof space.

12. Unpainted CGS with jute ceiling (0.105 mm) and ventilated roof space (150 mm).

13. Unpainted CGS with particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

14. Unpainted CGS with particleboard ceiling (12.7 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

15. Unpainted CGS with particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

16. CGS with whitewash, and earth (304 mm).

17. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

18. CGS with two coats of white acrylic paint, jute ceiling (0.105 mm), and ventilated roof space (150 mm).

19. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), straw (50 mm) over

the ceiling, and ventilated roof space (100 mm).

20. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

21. CGS roof with two coats of white acrylic paint, jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

22. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

23. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

24. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (150 mm).

25. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

26. CGS with two coats of whitewash, jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

27. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (150 mm).

28. Unpainted CGS with jute canvas shading (0.105 mm) and earth (304 mm) over the roof.

29. Unpainted CGS with jute canvas shading (0.105 mm) and straw (500 mm) thick over the roof.

30. Unpainted CGS with jute canvas shading (0.105 mm) and light-weight polymer concrete (225 mm) over the roof.

31. Unpainted CGS with jute canvas shading (0.105 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

32. Unpainted CGS with jute canvas shading (0.105 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

33. Unpainted CGS double roof with straw (500 mm) over the lower layer. (33)

34. CGS with earth (304 mm), jute ceiling (0.105 mm) and ventilated roof space (150 mm).

35. CGS with earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (150 mm).

36. CGS with earth (304 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

37. CGS with earth (304 mm), jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

38. CGS with straw (500 mm), particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

39. CGS with straw (500 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

40. CGS with lightweight polymer concrete (225 mm), particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

41. CGS roof with light-weight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

42. CGS with straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

43. CGS with straw (500 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

44. CGS with straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

45. CGS with straw (500 mm), jute ceiling (0.105 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

46. CGS with lightweight polymer concrete (225 mm), jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

47. CGS with lightweight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

48. CGS with lightweight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

49. CGS with whitewash, earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

50. CGS with whitewash, lightweight polymer concrete (225 mm), jute ceiling (0.105 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

51. CGS with whitewash, earth (304 mm), particleboard ceiling (12.7 mm) thick, straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (150 mm).

52. CGS with whitewash, lightweight polymer concrete (225 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

53. CGS with whitewash, lightweight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), particleboard ceiling (12.7 mm), straw (50 m), aluminum foil facing downward, and ventilated roof space (150 mm).

54. CGS with shading canvas (0.105 mm), earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

55. CGS with shading canvas (0.105 mm), straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

56. CGS with shading canvas (0.105 mm), earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

57. CGS with shading canvas (0.105 mm), straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

4. The thermal performance of improved CGS roofs

The analytical method of heat transmission under steady state conditions takes into account the roof's outside surface reflectivity and its thermal resistance. As stated earlier, the method is a three step process: calculation of the **Sol-air** temperature, assessment of the roof system's **thermal resistance**, and finally the calculation of the lower roof surface temperature or **heat gain.**

To carry out these calculations, an inclined (10°) CGS roof located in the city of Monterrey, Mexico, at 25°40' N - 100°48' W, elevation of 527.91 m is assumed. The air temperature outside is 35°C. The climate prevailing can be considered hot-dry type. Calculations are developed for June 21 at noon. An illustration of the heat gain calculations is presented in Appendix A at the end of this document. The results of these calculation are shown below.

ROOF No.	TEMPERATURE OF THE INNER ROOF SURFACE (degrees centigrades)
1	56.43
2	40.82
3	39.36
4	38.13
5	37.87
6	46.31
7	36.94
8	39.86
9	36.87
10	39.47
11	43.29
12	40.05
13	37.74
14	37.09

15	36.59
16	35.58
17	36.48
18	36.72
19	35.79
20	35.68
21	35.73
22	35.47
23	36.03
24	35.58
25	35.48
26	35.51
27	35.33
28	37.04
29	35.40
30	36.26
31	36.08
32	35.56
33	37.87
34	38.27
35	36.98
36	36.68
37	36.75
38	35.69
39	35.73
40	36.62
41	35.71
42	35.64
43	35.64
44	35.57
45	35.40
46	36.13
47	36.32
48	35.52
49	35.43
50	35.27
51	35.28
52	35.21
53	35.18
54	35.50
55	35.14
56	35.35
57	35.13

It is interesting to note that the calculations of heat gain through a roof of low heat capacity under steady state conditions result in a slightly higher temperature value than it is in actual performance.[20]

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C H A P T E R IV

LIFE-CYCLE COST ANALYSIS OF IMPROVED CGS ROOFS

1. Introduction

In the preceding chapter the thermal performance of fifty seven improved CGS roofs was assessed based on principles of thermodynamics. This process is the first step in the analysis. The second step requires obtaining the life-cycle cost of each alternative. The main intention of this chapter is to analyze the relationship between the life-cycle cost and the thermal behaviour of the improved roofs. The chapter is organized as follows: first, the theory of life-cycle costing is briefly explained and an example is provided; second, a graph that correlates the roof systems' thermal performance with their life-cycle cost is developed; third, the roofs are analyzed sequentially from the cheapest to the most expensive. The focus is on those roofs that provide the best thermal performance with the least cost, that is to say, the systems which are the most cost-effective.

2. Life-cycle costing

Life-cycle costing is a technique considered a useful tool for decision-making when the concern is a choice among several options. The technique takes into account the main factors that determine the cost of a building component throughout its useful life. Life-cycle costing assumes that "today's money" is not equivalent to "tomorrow's money", in other words, to afford a certain amount in 20 years, it is necessary to "invest" today a sum that will depends on current and future interest rates.[1]

The main cost factors involved in a roof are the initial capital investment, maintenance, repair and replacement, and salvage. Each one of these costs is affected by other factors. Maintenance (a "tomorrow" expense), is necessary in order to maintain the performance of a roof. This periodic work will require the investment of human and monetary resources. More important, the amount spent will depend on the frequency of maintenance -the more often the maintenance, the bigger the invested amount. Furthermore, if the initial capital investment was possible by means of loans and financing charges, its repayment could be a continuing cost as well.[2]

It is here that the life-cycle cost technique is of great help. It is possible to assess the actual amount of a future investment by bringing its value to a Present Worth. This type of measure calculates the future value of all costs due to periodic work, (i.e. maintenance) by means of coefficients related to the interest rate and the life span of the roof system. This future value is then brought to a

Present Worth and summed to the initial capital investment cost to obtain the Total Present Worth.

2.1 Assumptions

The interest rate utilized in this study has been chosen as 15 percent. This figure is very small in comparison with the actual rates in the location considered, but for the purpose of this study this rate can at least illustrate the application of the technique. There are two aspects related to the matter of the interest rate that it is necessary to note. "First, the higher the interest rate, the less worthwhile it is to try to avoid future expenses by increasing initial costs. Second, analyses with very short life-cycles and a high interest rate require the greatest accuracy".[3] For this project it is assumed the CGS sheet has a useful life of 20 years, which is used as the life-cycle period. The roof structure consists of common purlins and rafters spaced 1.2 and 1.0 m on centre (see Figure 13).

The costs to be considered for the purpose of this investigation are the initial capital investment cost, repair and replacement, maintenance and salvage costs. Labour is excluded as it is considered that the roof assembly erection is by the owner-user himself. The material cost of earth and is assumed to be nil. Lightweight polymer concrete is established as 30 percent cheaper than lightweight aggregate

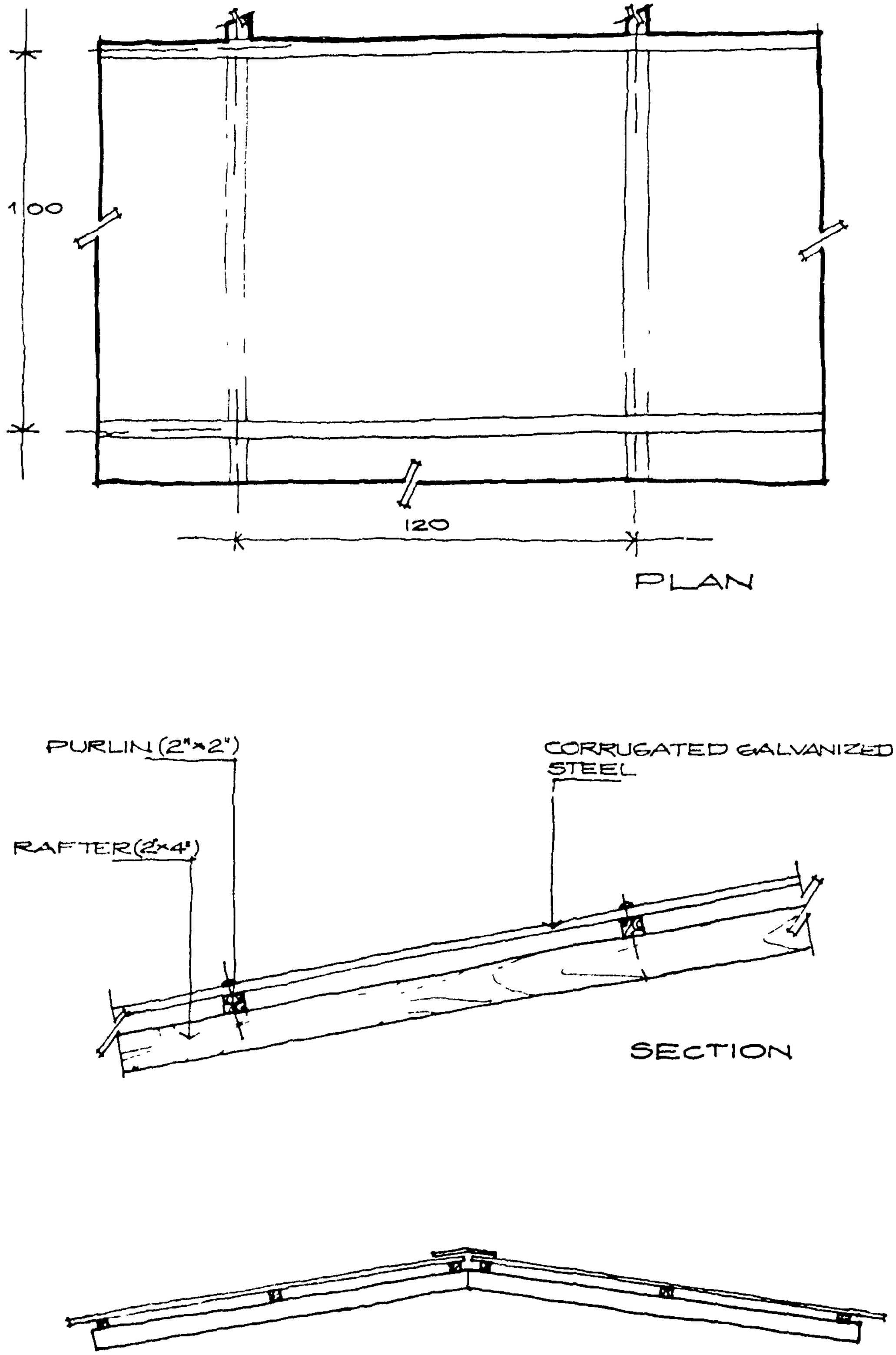


Figure 13. CGS roof over purlins and rafters.

with sand-cement-lime.

Regarding maintenance, the assumptions depend on the specific material. For instance, whitewash needs to be renewed every year, while acrylic paint renewal is every five years; with respect to repairs and replacement similar considerations are established. It is considered that a jute ceiling can last as long as particleboard, therefore the replacement time is the same in both cases. On the other hand, when the jute is utilized as a shading device on the exterior, it has to be replaced more often (as it is more exposed to climatic elements). As far as the salvage cost is concerned, it is assumed the CGS sheets have a 2 percent recovery cost after 20 years of performance. All the other materials forming the roof assembly are considered not to have salvage value.

It is important to emphasize that as the cost of building materials vary from place to place every study must consider the costs in the specific area being studied. An example of this material cost variation is that of the CGS sheet in the city of Monterrey, Mexico. In the south area of the city the cost of a 0.8 mm sheet (including shipping) is US$ 42.17/m^2, in the north this material costs US$ 31.17 /m^2. Figure 14 shows the material costs used in this research.

TECHNIQUE & MATERIAL	COST/M^2
LIGHT-WEIGHT METAL ROOF	
Corrugated Galvanized Steel sheets (0.8 mm).	US$ 42.17
Supporting structure.	4.14

	46.31
SURFACE QUALITIES	
White acrylic paint.	1.83
Whitewash (quicklime-water-salt).	0.54
SHADING	
Jute canvas.	3.64
Cane Panels.	-
Double roof of CGS sheets (0.8 mm).	88.48
ADDITIONAL MASS	
Earth (dry and packed).	-
Straw.	-
Light-weight polymer concrete.	10.96
<u>Entortado</u> (mortar sand-cement-lime over light-weight aggregate)	13.04
CEILING	
Particleboard 1.27 cm thick.	4.53
Jute.	3.64
Cane Panels.	-
Straw.	-
Aluminum foil.	0.45

Figure 14. Material's costs for life-cycle cost analysis.

2.2 Calculation of life-cycle cost

In order to carry out the life-cycle cost analysis, the process described by the American Institute of Architects in Life-cycle Cost Analysis for Architects, is applied.[4] For each one of the alternative roof systems the same life span of 20 years and an interest rate of 15 percent are assumed. The life-cycle cost of the basic roof system No.1, (i.e. unpainted CGS sheets) is shown in Figure 15. The calculation involves the following procedure. In the "Year" column is written the time when the cost will occur. The initial cost of the CGS sheet along with the supporting structure is recorded in the column of "Non-recurring costs". The refixing cost is entered in the "Repairs/replacement" row. Its future value is obtained by means of the UPW coefficient (see Table 4; the coefficients for years 10 and 20 are underlined in this table). The Future Value is brought to a Present Worth with the use of the SPW coefficient. As there are neither replacement nor maintenance costs for this basic roof system, the last step is to include the salvage value of the CGS sheet. This value is recorded with a negative sign (-), to indicate that this cost is not added to the other costs.

To calculate the life-cycle cost of the other systems, maintenance and replacement are included, and for each one of the roof assemblies the same format is utilized. The initial

1. Unpainted Corrugated Galvanized Steel (CGS).					
DISCOUNT RATE: 15 percent	NONRECURRING COSTS			RECURRING COSTS	
LIFE-CYCLE: 20 yrs.	Year	Amount	Total Present Worth x SPW = PW	Years	Total Present Worth x UPW = PW
INITIAL CAPITAL INVESTMENT COSTS CGS roof No.1	0	46.31	46.31		0
MAINTENANCE COSTS					
REPAIRS/REPLACEMENT CGS roof No.1	10	0.93	0.23		0
SALVAGE COSTS CGS roof No.1	20	4.63	-0.28		0
TOTAL PRESENT WORTH			46.26		

Figure 15. Life-cycle cost of basic CGS roof.

15%

FACTOR	SCA single compound amount	SPW single present worth	UCA uniform compound amount	UPW uniform present worth	UCR uniform capital recovery	USF uniform sinking fund	GRADIENT present worth gradient	uniform annual gradient
GIVEN	P	F	A	A	P	F		
FIND	F	P	F	P	A	A		
YEAR								
1	1 150	8696	1 000	0 870	1 150	1 000		
2	1 322	7561	2 150	1 626	6151	4651	0 756	4561
3	1 521	6575	3 472	2 283	4380	2880	2 071	9071
4	1 749	5718	4 993	2 855	3503	2003	3 786	1 326
5	2 011	4972	6 742	3 352	2983	1483	5 775	1 723
6	2 313	4323	8 754	3 784	2642	1142	7 937	2 097
7	2 660	3759	11 07	4 160	2404	0904	10 19	2 450
8	3 059	3269	13 73	4 487	2229	0729	12 48	2 781
9	3 518	2843	16 79	4 772	2096	0596	14 76	3 092
10	4 046	2472	20 30	5 019	1993	0493	16 98	3 383
11	4 652	2149	24 35	5 234	1911	0411	19 13	3 655
12	5 350	1869	29 00	5 421	1845	0345	21 19	3 908
13	6 153	1625	34 35	5 583	1791	0291	23 13	4 144
14	7 076	1413	40 51	5 724	1747	0247	24 97	4 362
15	8 137	1229	47 58	5 847	1710	0210	26 69	4 565
16	9 358	1069	55 72	5 954	1680	0180	28 30	4 752
17	10 76	0929	65 08	6 047	1654	0154	29 78	4 925
18	12 38	0808	75 84	6 128	1632	0132	31 16	5 084
19	14 23	0703	88 21	6 198	1613	0113	32 41	5 231
20	16 37	0611	102 4	6 259	1598	0098	33 58	5 365
21	18 82	0531	118 8	6 312	1584	0084	34 65	5 488
22	21 65	0462	137 6	6 359	1573	0073	35 62	5 601
23	24 89	0402	159 3	6 399	1563	0063	36 50	5 704
24	28 63	0349	184 2	6 434	1554	0054	37 30	5 798
25	32 92	0304	212 8	6 464	1547	0047	38 03	5 883
30	66 21	0151	431 7	6 566	1523	0023	40 75	6 207
35	133 2	0075	881 2	6 617	1511	0011	42 36	6 402
40	267 9	0037	1779	6 642	1506	0006	43 28	6 517
45	538 8	0019	3585	6 654	1503	0003	43 81	6 583
50	1083	0009	7218	6 661	1501	0001	44 10	6 621

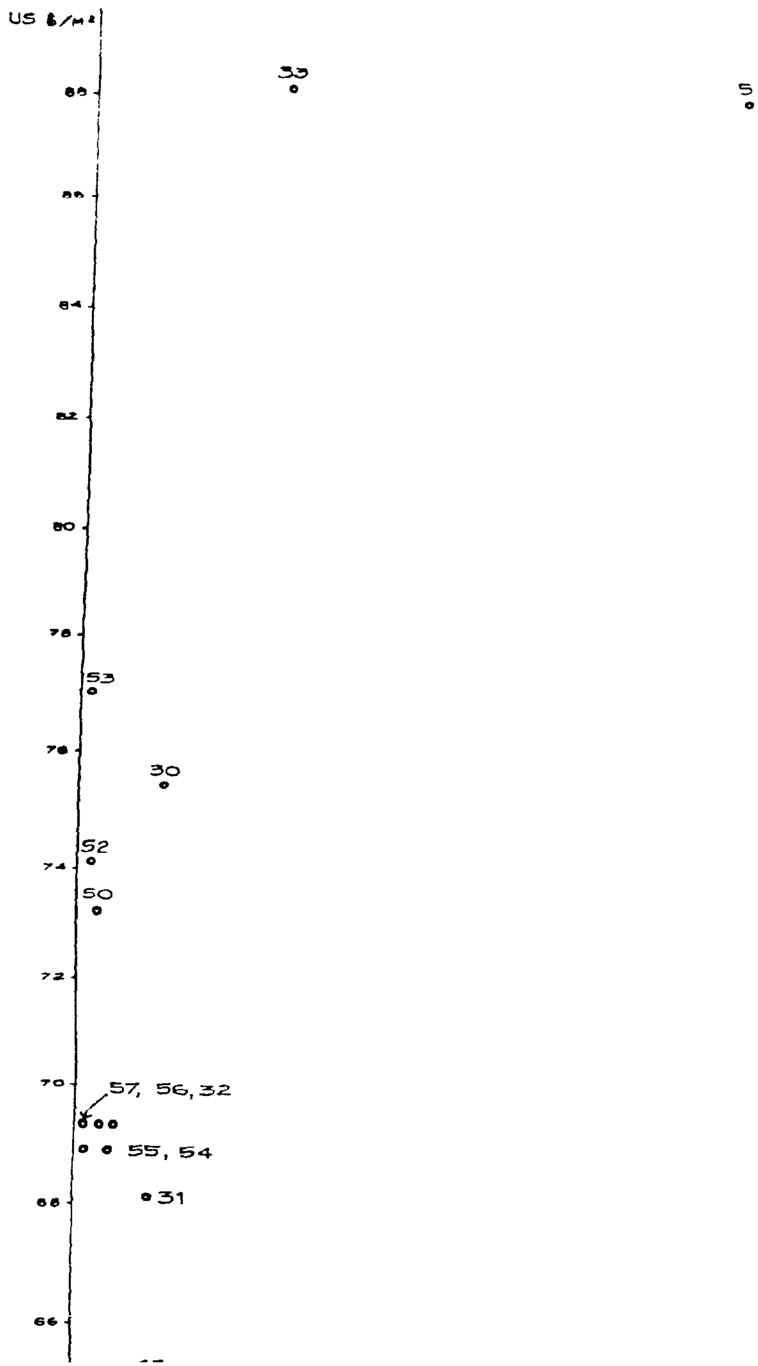
Table 4. Coefficients of Interest rate. American Institute of Architects, 1977, 39.

cost of the item requiring maintenance is projected into the future using the corresponding UPW coefficient. This Future Value is brought to a Present Worth through the same procedure, and summed to the preceding life-cycle cost of the basic system to obtain the final cost. Following this process the life-cycle cost of the fifty-seven CGS roofs was obtained. The results of these calculations are shown in Appendix B.

The following section examines the life-cycle costs with regard to the thermal performance of each roof. It compares the systems that exhibit similar behaviour (i.e. a similar amount of heat transmission) and cost. It will be of particular interest to identify any patterns that the graphic analysis provides.

3. Cost-Benefit Analysis

In the graphic analysis the life-cycle cost of the fifty-seven improved roofs are plotted as a function of their thermal behaviour (see Figure 16). The temperature on the underside of the ceiling is represented on the horizontal axis in degrees C, whereas the life-cycle costs are expressed on the vertical axis in US $\$/m^2$. From this data two main features appear: the overall cost-benefit curve, and the different groups or clusters of improved roofs.


US $/M²
84
82
80
74
72
70
66
33
5
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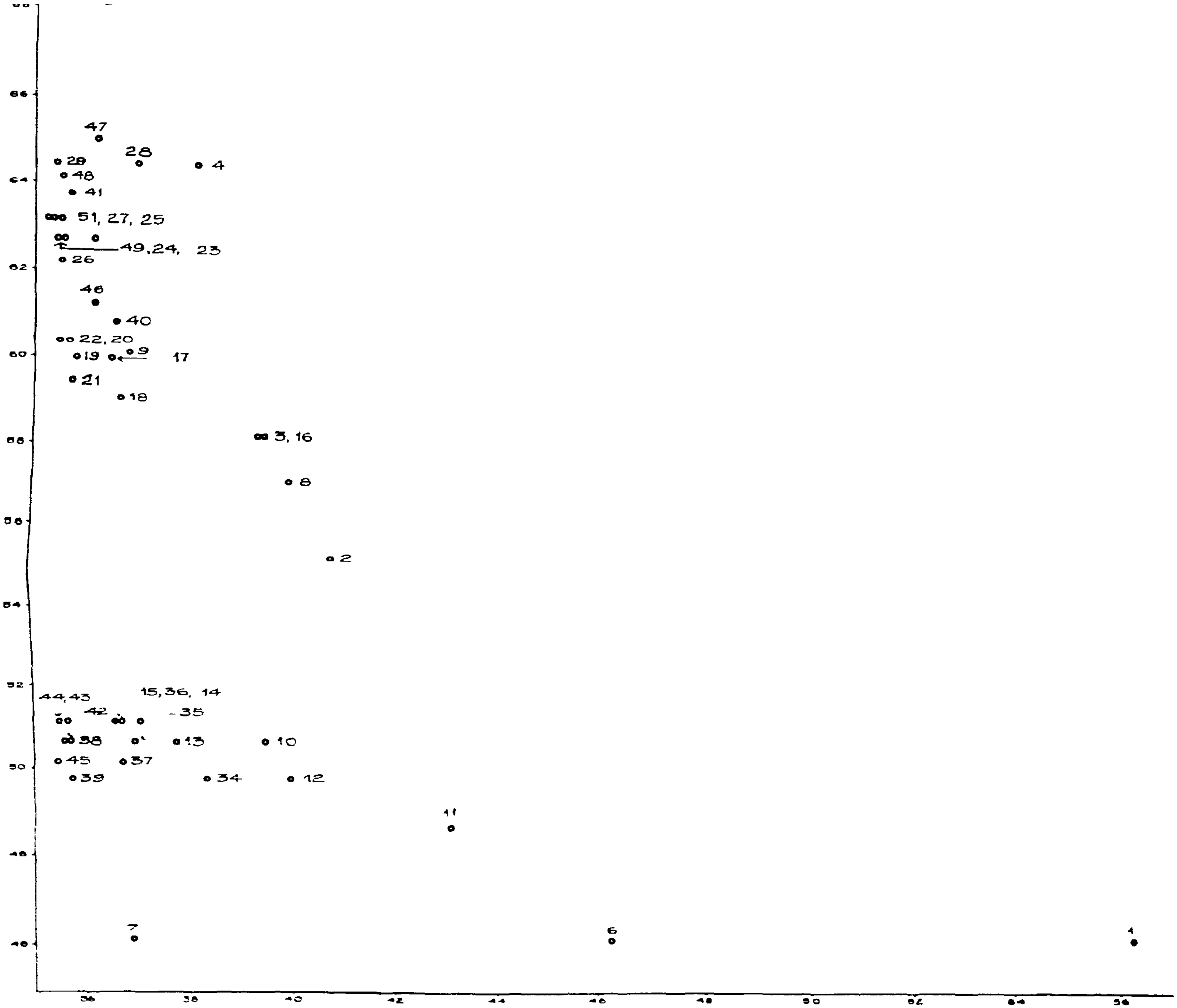
57, 56, 32
55, 54
31



INNER ROOF SURFACE TEMPERATURE GRAPHED AGAINST LIFE-CYCLE COST OF 57 THERMALLY-IMPROVED CGS ROOFS

FIGURE 16. GRAPH OF COST-BENEFIT

The cost-benefit curve represents the relationship between improved thermal performance and increased cost. Of particular importance is the shape of the curve. Figure 17 is useful to better explain this issue. It shows three different possible shapes of a relationship between two variables. The figure at the top shows a possible curve indicating a high negative correlation. In this case it is very expensive to achieve large improvements, moreover, the improvement is minimum and the investment high. The figure in the middle shows a different curve that illustrates a consistent negative relationship between reduced temperature and increased cost. That is to say better performance increases directly as more money is invested in improvements.

A different curve is shown at the bottom of Figure 17. It indicates a low negative relationship, suggesting a decreasing benefit as cost increases. On the other hand, the curve also suggests that significant benefits can be initially achieved with low investments. The shape suggests that the optimum improvement occurs where the curve changes direction; beyond this point temperature reduction is small and cost increases large, in other words, the improvement achieved does not justify the additional investment. This is the cost-benefit curve that resulted from the present study.

Groups of roofs are formed when several systems cluster close to the curve. These groups have similar thermal

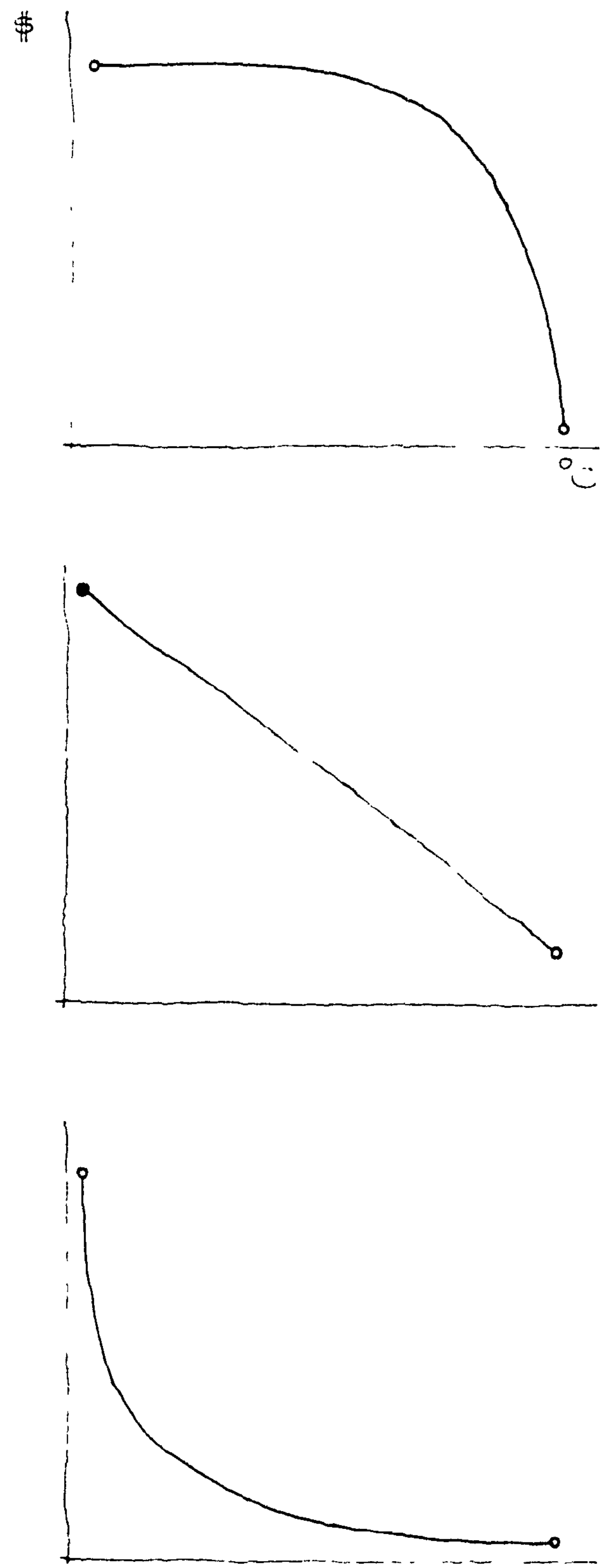


Figure 17. Graphs of negative correlation.

performance, that is to say they reduce the heat gain in the same amount. On the other hand, they can differ in cost. The improved roofs with the least cost, are found at the bottom of the graph. These are the systems that accomplish a notable improvement with a low investment. Conversely, some roofs seem to separate from the curve and disperse. Some separate only in the vertical direction whereas other disperse in both directions. They possess unusual behaviour. An examination of these grouping and type of roofs concludes this section.

3.1 Groupings of improved CGS roofs

At the bottom of the graph appear the two cheapest roofs: No.6 (earth over the CGS sheets) and No.7 (straw on top of the CGS sheets). Although the thermal behaviour of No.6 is not remarkable, the reduction of heat transmission is nevertheless significant, moreover, it is achieved without increasing cost. Likewise, straw's good insulation properties determine the excellent thermal performance of No.7. The very low cost of straw makes this roof cheaper - by far- to the other alternatives. Its thermal performance is comparable to that of roofs No.37 (earth on top, jute ceiling, foil), No.36 (earth on top, particleboard ceiling, foil) and No.15 (particleboard ceiling with straw, foil), however as it is cheaper, is considerably more cost-effective.

The first grouping appears in the bottom left of the graph, where the curve starts to move upwards. The group is formed by roofs No.39 (straw on top the roof, jute ceiling), No.45 (straw, jute ceiling, foil), No.38 (straw, particleboard ceiling), No.42 (straw, particleboard ceiling with straw), No.43 (straw, particleboard ceiling, foil), and roof No.44 (straw, particleboard ceiling with straw, foil). Roof No.45 achieves the greatest thermal improvement mainly due to the combined effect of light-weight straw on top and the jute ceiling. This system performs better than No.39 - the cheapest of this group- owing to the use of foil. They are both extremely cost-effective. Roof No.45, which performs slightly better than No.39 (with a minimum additional investment -aluminum foil), is the most cost-effective of all.

To examine better this group Figure 18, which is an enlargement of Graph , is useful. In this figure, it is evident that roof No.45 is thermally and economically superior to Nos.42, 38, 43, and 34. System No.39, although it does not provide the best thermal performance, is far cheaper than the others, and is also effective. This suggests that it is more useful to have a jute ceiling and foil in combination with straw on top, than an insulated particleboard ceiling combined with straw on top of the roof.

It is interesting to observe the behaviour of roofs

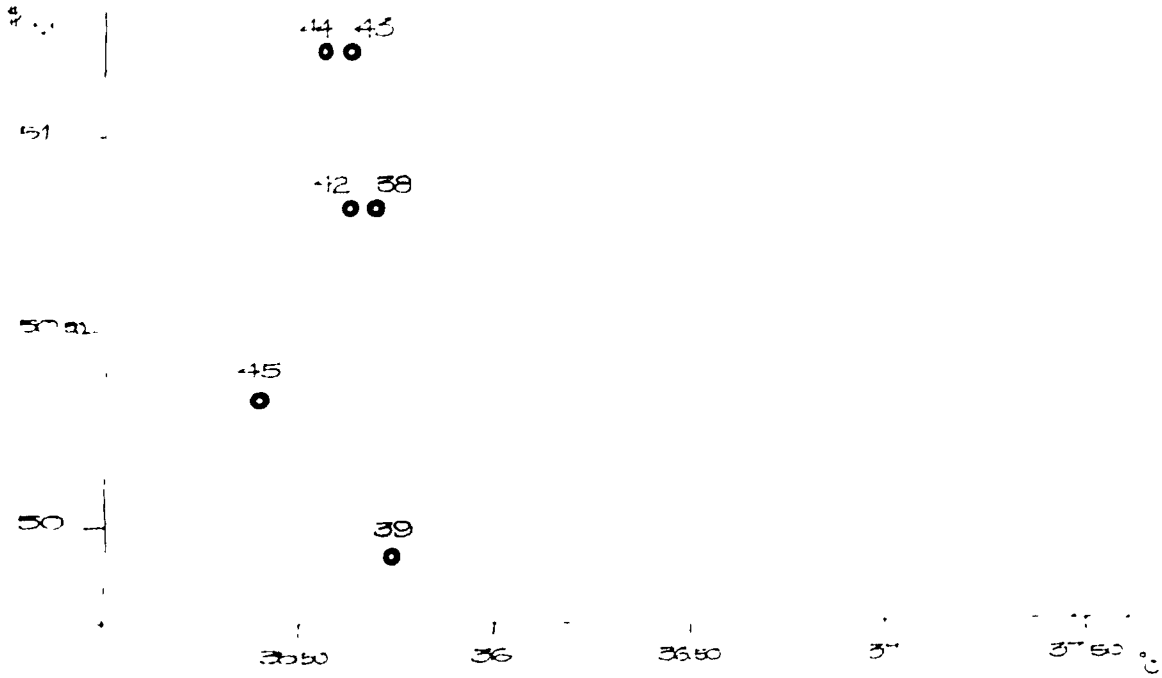


Figure 18. The most cost-effective CGS roofs.

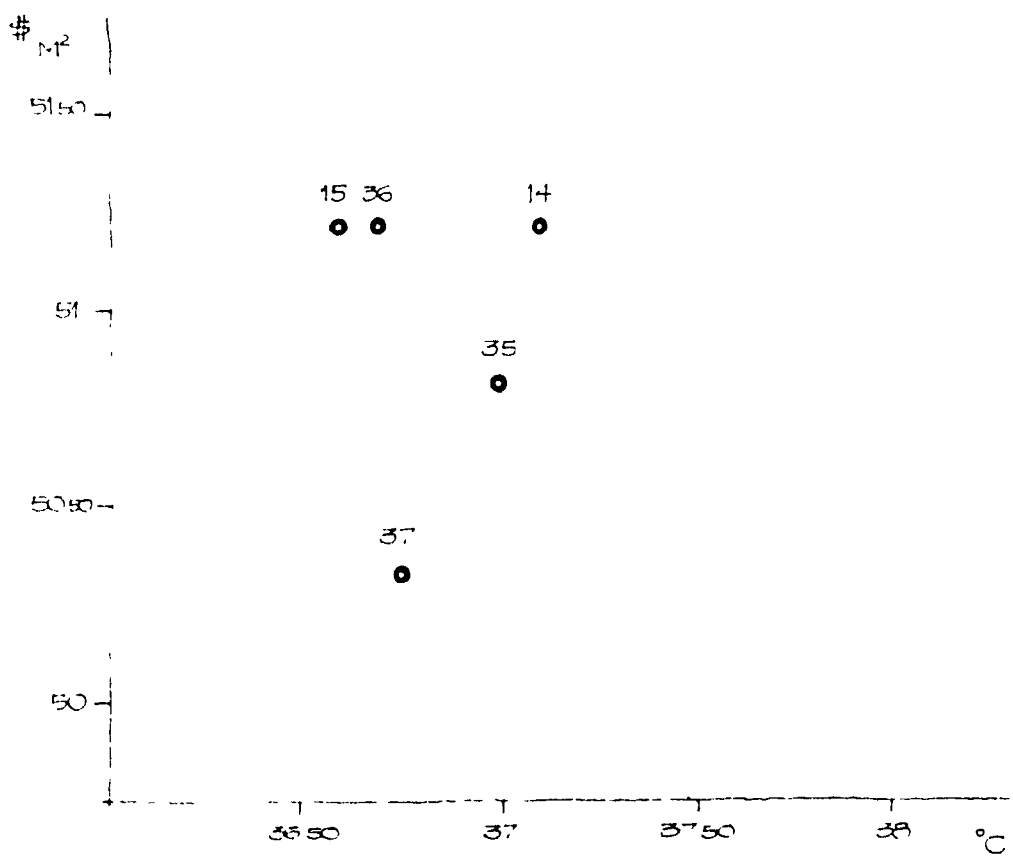


Figure 19. Groups of roofs with earth and ventilated ceiling.

Nos.42 and 43. While both produce the same thermal performance [35.64°C], the former costs less, as the cost of straw was assumed to be nil. This suggests that straw ceiling-insulation is more cost-effective than foil. However, the behaviour of No.44 shows that foil in combination with ceiling insulation, provides an economical thermal improvement. It is also important to remember that all these roofs have as common element 500 mm of straw on the top.

Five roofs clustered close to the previous group are: No.37 (earth, jute ceiling, foil), No.35 (earth, particleboard ceiling with straw) No.14 (particleboard, foil), No.36 (earth, particleboard, foil), and No.15 (particleboard with straw, foil) (see Figure 19). The superiority of No.37 over Nos.35, and 14, underlines the efficacy of jute as a ceiling. A comparison of roof No.37 with No.36 also support the efficacy of jute -while the thermal performance of both is almost the same, the former is cheaper. This emphasizes the efficacy of ceilings and the usefulness of earth. Roof No.15, which is thermally better than all these, indicates that particleboard as a ceiling is also useful. Comparing this roof with No.14, one can realize that its better thermal performance is mainly due to the use of straw as ceiling insulation. That is why roof No.15 is the more cost-effective of this group.

Following the cost-benefit curve upwards, between US$ 59/m^2 and US$ 60/m^2 another group appears. Four roof systems form this group: No.21 (white paint, jute ceiling, foil), No.19 (white paint, particleboard ceiling with straw), No.20 (white paint, particleboard ceiling, foil), and No.22 (painted white, particleboard ceiling with straw, foil). Roof No.22 performs better than the others due to the use of ceiling insulation and foil. Roof No.21 -the cheapest- achieves the same improvement as roofs Nos.19 and 20. While this underlines the usefulness of jute ceilings, the similar behaviour of Nos.19 and 20 suggests that reflective foil alone is not as effective when the roof is painted.

A comparison between roof No.21 and roof No.39 (the best of the preceding group), indicates that whereas both achieve the same thermal performance (35.73°C), the difference in cost is extreme. The former is much more expensive than the latter (owing to maintenance costs), and suggests that the white paint on roof No.21 may not be necessary. The importance of this comparison is that it generally confirms what the shape of the curve suggests -that benefit decreases as cost increases.

Slightly more expensive than this group, at US$ 63/m^2, is another group of six roofs. This group can be better studied by means of Figure 20. It shows that roof No.26 (whitewash, jute ceiling, foil) is the cheapest, which is

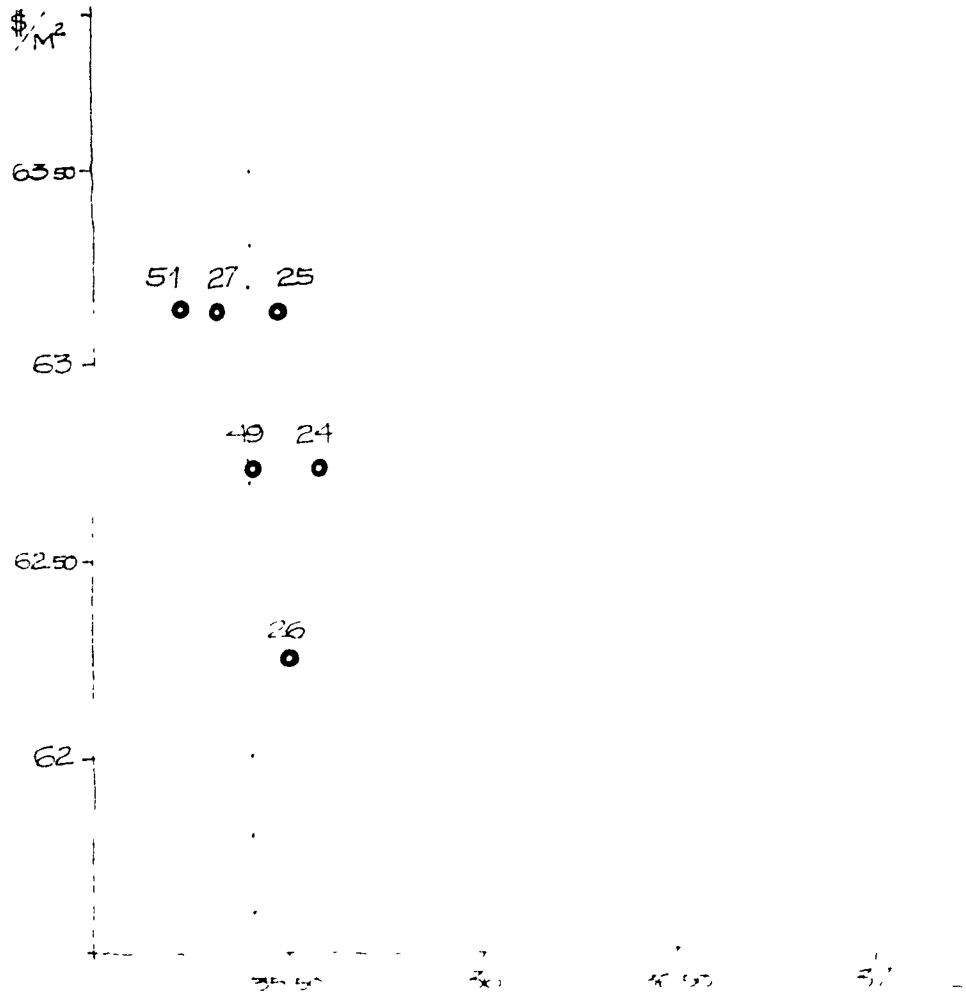


Figure 20. Group of whitewashed CGS roofs.

followed by No.24 (whitewash, particleboard ceiling with straw), No.49 (whitewashed earth, particleboard ceiling with straw), No.25 (whitewash, particleboard, foil), No.27 (whitewash, particleboard ceiling with straw, foil), and No.51 (whitewash, earth, particleboard ceiling with straw, foil). Roof No.51 performs better than No.27 due to the use of earth, although the improvement is very small. Similarly, No.49 performs slightly better than No.24 owing to the use of earth, but the difference in improvement is bigger than in the preceding comparison. This points out that above a certain amount of insulation, reduction of heat penetration is more difficult to achieve.

The thermal behaviour of roofs No.25 and No.26 is interesting. The former is more expensive than the latter owing to the use of a particleboard ceili ¸, but the thermal performance of both is similar; clearly, jute as a ceiling is more cost-effective than particleboard. The behaviour of roofs No.26 and No.24 also confirms this, as the former is cheaper and transmits less heat. Likewise, it is also correct to say that straw insulation and foil provide similar thermal improvement.

The roofs in this grouping show the same pattern as those of the previous category. This is due to the common techniques used: whitewash or paint, ceilings, insulation, and foil. They tend to be more expensive owing to the maintenance costs of whitewash. It appears, then, that white acrylic paint is more cost-effective than whitewash since roof No.26 [35.51°C-$62.25/m^2] is more expensive than roof No.21 [35.73°C-$59.49/m^2].

Three roofs are separate from this group. They are No.41 (aggregate with mortar, jute ceiling) No.48 (aggregate with mortar, jute ceiling, foil), and No.29 (shaded, straw on top). The better behaviour of No.29 suggests than jute canvas and the ventilated roof space are less effective in the reduction of heat penetration. Similarly, the thermal performance of the two former systems underlines the utility of ceilings, and suggests that aggregate with mortar may not be necessary. In point of fact this also suggests that unless a minimum amount of insulation is provided a reduction of heat is difficult to achieve.

At the top of the curved portion of the graph, five roof systems form a group. Roof No.54 (canvas shade, earth, particleboard ceiling with straw), and roof No.55 (canvas shade, straw over the roof, particleboard with straw) are the cheaper of this group. Roofs No.32 (canvas shade, particleboard ceiling, foil), No.56 (canvas shade, earth, particleboard ceiling with straw, foil), and No.57 (canvas shade, straw over the roof, particleboard ceiling with straw, foil) are slightly more expensive than the preceding two due to the use of foil. The small difference of performance between them suggests that in this type of assembly the usefulness of foil is not significant.

The roofs with straw on top, (Nos.55 and 57), achieve the best thermal performance -roof No.57 actually achieves the best thermal performance among all the fifty-seven systems examined. This is so because straw is thermally superior to earth as insulation. The noticeable difference in thermal performance of roofs No.55 and No.32 illustrates the efficiency of straw. In addition, the behaviour of all these suggests that the thermal improvement due to a shading device is not worth the extra investment.

Four roofs are scattered along the vertical axis. They are roofs No.50 (whitewash, concrete, jute ceiling, foil), No.52 (whitewash, concrete, particleboard ceiling with straw, foil), No.53 (aggregate with whitewashed mortar, particleboard ceiling with straw, foil), and No.30 (canvas shade, concrete). The interior temperature of the former three is almost equal to the exterior temperature in the shade. In terms of usefulness, roof No.50 (the cheapest), is far better than roofs No.53 and No.52. This emphasizes the utility of jute as a ceiling and, on the other hand, points out that concrete with whitewash has limited usefulness. Moreover, roofs No.53 and No.52, suggest that the efficiency of a ceiling insulated with straw and foil is not significant. The behaviour of No.30 indicates the limited value of shaded roofs: they do not perform better, and are extremely expensive.

Two "unusual" roofs are No.33 (two layers of CGS with straw on the lower) and No.5 (two layers of CGS). The better performance of the former is obviously due to the straw. The poor thermal behaviour of the latter underlines the unsuitability of CGS sheets as shading devices; they transmit more heat, and reduce the efficiency of ventilation of the roof space. Below No.33 is found an apparently unusual system -No.4 (shaded with jute). The reflectivity of jute and the incorporation of a ventilated roof space, produce an acceptable thermal improvement, however the high cost (due to maintenance) reduces the overall cost-effectiveness.

Other roofs that are a suitable examples of peculiar behaviour are roofs No.3 (whitewash), No.16 (whitewash, earth), No.8 (lightweight concrete on top), and No.2 (white acrylic paint). These systems are rather expensive, although their thermal performance is acceptable. Roof No.3 and No.16 achieve a better thermal improvement, due to the high reflectivity of whitewash, unfortunately, their high cost offset this positive characteristic. Roof No.16 suggests, besides, that the thermal improvement reduces when whitewash is applied on earth. Altogether, it appears that white paint is more cost-effective than whitewash, since this material is cheaper in the long term. This underlines the negative effect of maintenance: a very cheap material such as whitewash can become expensive in the longer term. On the other hand, if one compares these roofs with the shaded roof (No.4), it is evident that the former are more cost-effective since the better thermal performance of the shaded roof is offset by its higher cost. This accentuates the fact that significant improvements are possible with minimum investments provided the improvements will not incur high maintenance costs in the future.

4. Summary

This analysis has suggested that in the improvements studied benefit decreases as cost increases. This cost-benefit analysis has also suggested that significant improvements are possible with minimum investments. It has indicated that until a certain minimum amount of insulation is provided, increased benefit is difficult to achieve. The most cost-effective roof comprises straw on top, a jute ceiling, reflective foil, and ventilated roof space, (No.45). Another effective roof system is a layer of straw on top, jute ceiling and ventilated roof space (No.39). The roof which provides the greatest thermal benefit with the least investment simply has straw on top (No.7). On the other hand, the roof system that achieves the best thermal performance has straw over the sheets, insulated ceiling, reflective foil, shading canvas (No.57). The most expensive systems are the CGS double roof (No.5), and the CGS double roof with straw on the lower roof's layer (No.33). The roof with only earth (No.6), is the cheapest of all, with the less thermal improvement.

This analysis has demonstrated the importance of placing additional materials on top of the roof, especially lightweight insulating materials. This can be done economically using straw. Equally important is the use of earth on top of the roof, although its thermal properties are not as effective as that of straw. It would be correct to say that the very low cost of these techniques makes them both suitable for low-cost housing.

This examination has indicated that ceilings and ventilated spaces provide important thermal improvements with a small amount of investment. Jute as a ceiling material is extremely effective, as the reduction of heat is significant and its cost is low. A ceiling of particleboard is another effective device, especially as its incorporation creates the conditions for further improvement by using two additional techniques: insulation, and foil. This study has shown that 50 mm of a cheap material such as straw, gives significant thermal and economical improvements. The provision of aluminum foil is also useful. Its effectiveness is greater when it is used in combination with a very lightweight ceiling and a lightweight material over the roof (roofs No.45 and 43). However, when this device is used in a roof painted white in conjunction with ceiling insulation, the additional benefit is almost nil.

Surprisingly, this study indicates that painting the roof surface white is not a cost-effective strategy. The thermal improvement that whitewash or paint provide is offset by the increased cost due to their maintenance. Those systems which comprised a ceiling with insulation and foil achieved -with less cost- the same thermal improvement as white-painted roofs.

One of the most commonly used improvements, concrete over the roof, is offset by its high cost. This type of roof can be improved with a lightweight ceiling that incorporates a ventilated roof space, although the high cost makes it not worth the extra investment. Finally, this analysis, has made evident the fact that shaded roof or double roofs are not cost-effective solutions, for while the thermal performance may be acceptable, their cost is too high.

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C H A P T E R V

AN EVALUATION OF IMPROVED CGS ROOFS

1. Introduction

The main intention of this thesis is to evaluate quantitatively the improved CGS roofs in terms of the effect on the interior thermal conditions of dwellings. In the preceding chapter the fifty-seven improved CGS roofs were evaluated from an overall benefit point of view. This chapter reviews the improved CGS roofs in terms of a thermal performance standard, and an acceptable cost. The examination is according to the improvement techniques utilized. The chapter first explains the criteria of evaluation and defines the cost the owner-builder can afford. Second, it reviews the groupings of inappropriate CGS roofs. Third, the chapter looks at the appropriate (or cost-effective) systems, emphasizing the techniques used. The chapter concludes suggesting the roofs that may be the most useful for the owner-builder.

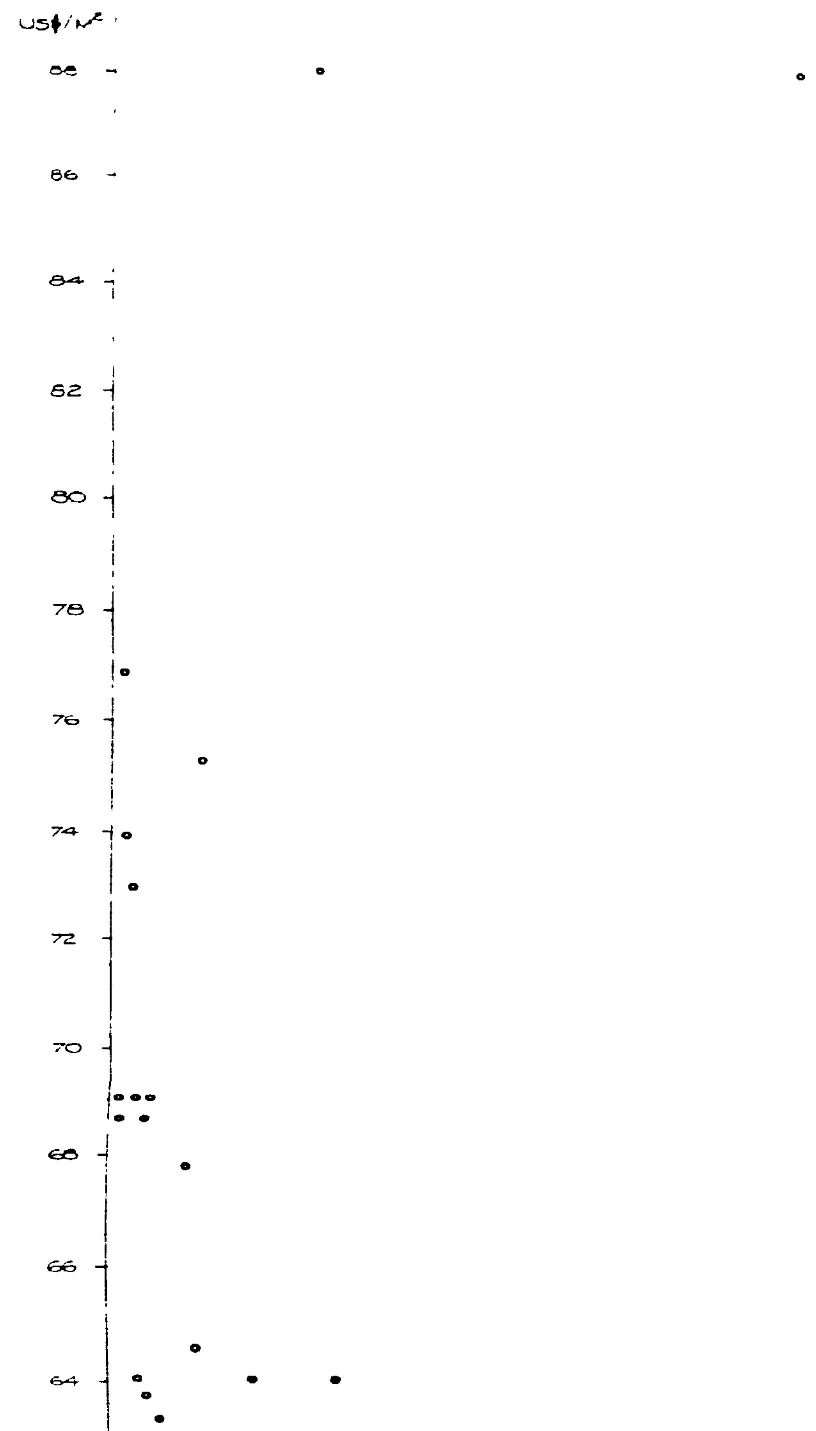
2. The Criteria

The suitability of a thermally-improved roof will ultimately be evaluated by the user. This evaluation will, in turn, depend on personal physiological needs and on the specific type of climate. Most researchers agree that in order to be thermally-acceptable the inner roof surface temperature "should not exceed by 4.5 degrees C that of the ambient air temperature".[1-2] In the case of this study, it would be 35°C + 4.5, or 39.5°C.

Since better performance of low-cost roofing is a function of both benefit and cost, it is necessary to define the cost that the owner-user can afford. In this thesis it is assumed that 15 percent above the cost of a plain CGS roof is the maximum acceptable cost of an improvement. Plotting the cost as a function of the maximum temperature, against the standard of thermal performance (39.5°C), defines the area that encloses the systems that are thermally acceptable and can be afforded by the low-income user. Besides these appropriate systems, two other categories of improvements appear on the graph: cool but too expensive and inexpensive but too hot (see Figure 21).

3. Inappropriate systems

While most of the expensive systems meet the thermal performance standard, their cost ranges widely. For example, the cost of a double roof is \$US 89/m^2 whereas paint and lightweight concrete are between \$US 55 and \$US 58/m^2. Besides being too expensive, double roofs of CGS do not


US$/M²
88
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80
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72
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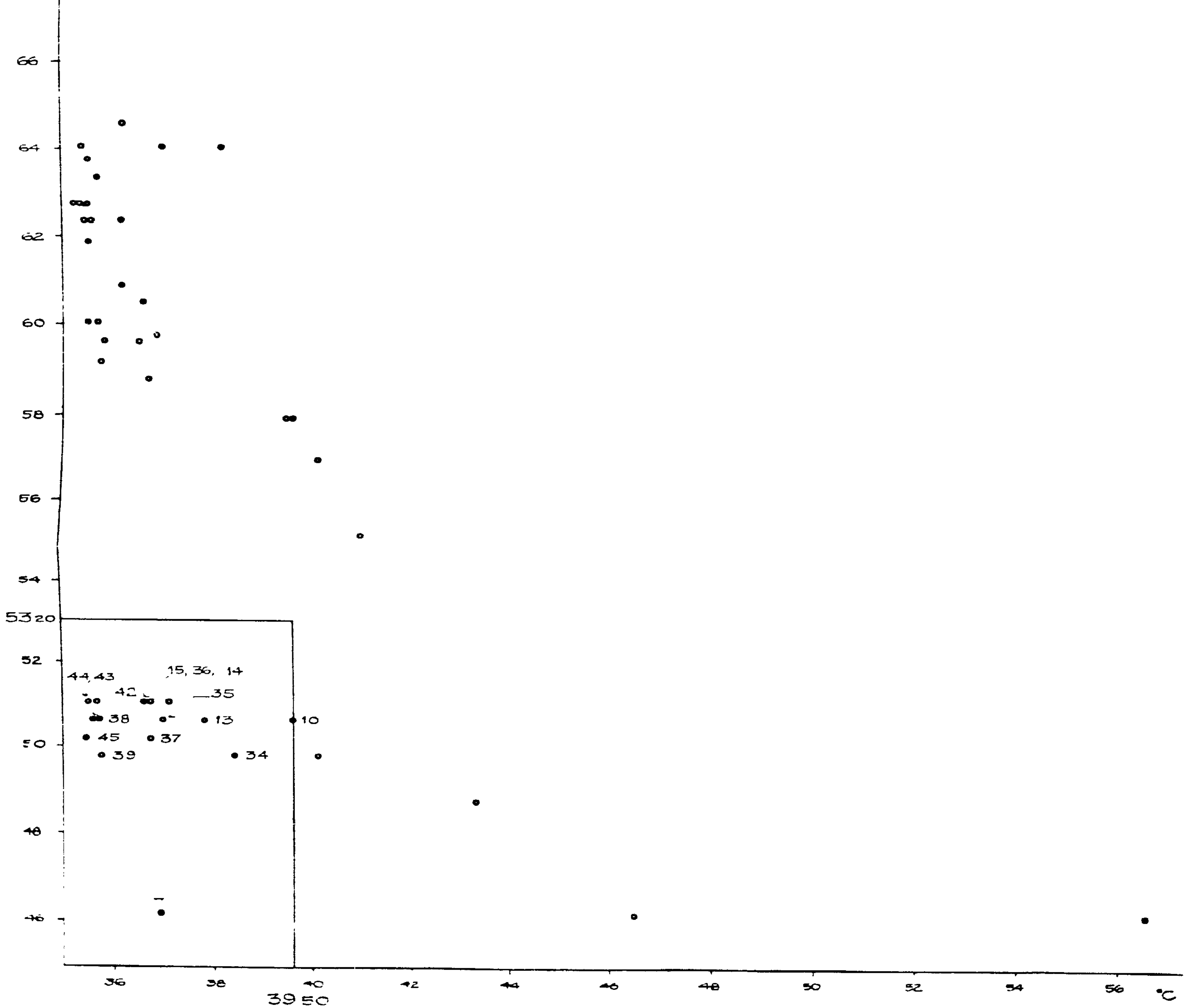

FIGURE 21 A THERMAL PERFORMANCE STANDARD PLOTTED AGAINST AN ACCEPTABLE COST

meet the standard of thermal performance. A double roof with lightweight material in the lower layer is also too expensive, although it reaches the required degree of temperature reduction. It is evident that CGS as a double roof is unsuitable, and it stresses the effectiveness of straw as an insulating material.

The expensive systems that meet the standard of thermal performance almost reach the temperature of the exterior air in the shade. The most expensive of these, costing between \$US 73/m^2 and \$US 77/m^2, include light colour paint (whitewash), additional mass, ventilated ceiling, ceiling insulation, and foil. Unfortunately, their high cost, caused by the initial investment for the additional material and the maintenance costs of painting, places them out of the reach of the owner-builder.

Slightly less expensive although with similar lower roof surface temperatures, are five improvements comprising shading, additional thermal mass over the roof, ventilated ceilings, ceiling insulation, and foil. The maintenance costs of the shading devices raise the life-cycle cost of these systems. This confirms the earlier suggestion that shading is not cost-effective. On the other hand, it is true that the remarkable thermal performance of these roofs is produced by the techniques of additional material, ventilated ceilings, ceiling insulation, and foil.

Other inappropriate systems with notable thermal performance cost about \$US 63/m^2. They include light colour paint (whitewash), ventilated ceilings, ceiling insulation, and foil. Their good thermal performance is the result of the combined effect of all these techniques. The efficacy of paint is limited, and it is precisely the maintenance of this technique that contribute to its high cost.

Slightly less expensive than the previous systems and also achieving the standard of thermal behaviour are five other roofs (paint, ventilated ceilings, ceiling insulation and/or foil). These are less expensive than the preceding because acrylic paint needs less maintenance than whitewash. It is important to remember, however, that the difference in heat reduction between them is almost minimal, although whitewash possesses higher reflectivity than white paint.

Among the inappropriate systems, four have unusual thermal behaviour as they are both expensive and thermally unacceptable. These are CGS with whitewash, CGS with whitewash and earth, CGS with additional mass on top, and CGS with paint. The two former are unacceptable due to the high cost of maintaining the whitewash, although they almost achieve the temperature standard. The latter two besides being expensive, do not sufficiently reduce heat transmission. This stresses again that the use of materials of high heat capacity over the roof, and whitewash on the exterior surface are not appropriate to improve the thermal performance of the roof. This fact is striking since these improvements are frequently reported.[3]

Four of the inexpensive systems do not meet the standard of thermal performance. They are CGS with additional mass (earth), CGS with an unventilated ceiling, and CGS with a ventilated ceiling. The system with earth on top does not achieve enough reduction of heat penetration because earth is not an effective insulating material.

The roof with an unventilated ceiling is also cheap, but it falls far below the acceptable standard of thermal performance. In contrast, the systems with ventilated ceilings almost reach the required temperature reduction. In fact, the one with a ventilated particleboard ceiling is on the edge of the acceptable area. It can be concluded that an unventilated ceiling is not an appropriate technique, whereas ventilated ceilings need additional improvements to reach the required standard of thermal performance.

4. Appropriate systems

Fourteen systems fall within the area formed by the standards of thermal performance and acceptable cost. The range of cost of these systems is not large and the difference in heat reduction is likewise small, though perceptible. The list below shows these roofs.

CGS with straw (500 mm), ventilated particleboard ceiling (12.7 mm), straw ceiling insulation (50 mm), foil. (No. 44)

CGS with straw (500 mm), ventilated particleboard ceiling (12.7 mm), foil. (No. 43)

CGS with straw (500 mm), ventilated particleboard ceiling (12.7 mm), straw ceiling insulation (50 mm). (No. 42)

CGS with straw (500 mm), ventilated particleboard ceiling (12.7 mm). (No. 38)

CGS with straw (500 mm), ventilated jute ceiling, foil. (No. 45)

CGS with straw (500 mm), ventilated jute ceiling. (No. 39)

Unpainted CGS with ventilated particleboard ceiling (12.7 mm), straw ceiling insulation (50 mm), foil. (No. 15)

CGS with earth (304 mm), ventilated particleboard ceiling (12.7 mm), foil. (No. 36)

Unpainted CGS with ventilated particleboard ceiling (12.7 mm), foil. (No. 14)

CGS with earth (304 mm), ventilated particleboard ceiling (12.7 mm), straw ceiling insulation (50 mm). (No. 35)

CGS with earth (304 mm), ventilated jute ceiling (0.105 mm), foil. (No. 37)

CGS with straw (500 mm) on top. (No. 7)

Unpainted CGS with ventilated particleboard ceiling, straw ceiling insulation (50 mm). (No. 13)

CGS with earth (304 mm), ventilated jute ceiling (0.105 mm). (No. 34)

CGS with ventilated particleboard ceiling. (No. 10)

These systems suggest that additional thermal mass over the roof, ventilated ceilings, ceiling insulation, and foil are all appropriate techniques to improve the thermal performance of a CGS roof. They also confirm the usefulness of earth.

To sum up, fourteen of the appropriate roofs utilize ventilated ceilings, and eleven of them use additional mass on top of the roof. Six systems include foil, whereas five roofs utilize ceiling insulation. It is possible to say, then, that of seven different techniques studied in this thesis, five are appropriate to improve the thermal performance of the CGS roof. The two inappropriate techniques are painting the exterior surface, and shading the roof.

5. Conclusion

Corrugated galvanized steel sheet is one of the most successful construction components in low-cost housing. Its broad use has increased in hot regions due to its affordability and ease of erection. However, a major disadvantage of this element is excessive heat transmission; overheating of the CGS roof is an important problem because it creates an uncomfortable interior environment. This determines a two fold problem: an improved CGS roof that is both thermally suitable, and inexpensive.

To overcome the problem of overheating it is necessary to identify appropriate techniques and methods that suit the context of low-cost housing. The method used in this research compares the life-cycle cost of simple improvements with the roofs' thermal performance. The analysis indicates that five improvement techniques are cost-effective: additional thermal mass over the roof, ventilated ceilings, ceiling insulation, and foil. Of these, additional thermal mass over the roof appears to be the most cost-effective. The maximum thermal improvement achieved by a roof with straw on top, was almost equal to the shaded outside air temperature. There are no studies that have experimentally confirmed this calculation. This fact, and the encouraging results, suggest interesting areas for future research.

It must be recognized that a disadvantage of straw as additional mass over the roof is that is flammable and can not support loads. Fire retardant coatings, stabilized mud, plaster sand-cement-lime, or mortar gravel-lime-cement could overcome these disadvantages.[4-5] Although not addressed by this thesis, these improvements likewise suggests interesting areas of research.

Besides additional thermal mass, other cost-effective techniques are ventilated ceilings, ceiling insulation and foil. The cost-benefit analysis demonstrates that these can improve the thermal performance of a CGS roof with a small increase in cost. Three important examples of this are jute used for a ventilated ceiling, straw as ceiling insulation, and aluminum foil. The effectiveness of jute suggests that research should focus on this as a low-cost thermal improvement to the CGS roof. Studies into the effectiveness of strawboard and cane panels as ceilings, could lead to further improvement of this technique.

An important argument related to ventilated roof spaces is that their appropriateness increases with the addition of ceiling insulation.[6] Although an apparent drawback of ceiling insulation is its high cost, the present study suggests that it is possible to overcome with the use of a cheap lightweight material -such as straw- which do not require maintenance. Worthy of noticing is the fact that almost any amount of ceiling insulation is desirable, and that optimum insulation is achieved when it is equally distributed inside and outside the roof.[7-8]

With regard to foil, this study has shown that is a cost-effective technique. However, it must be remembered that dust accumulation is an important factor that can influence its thermal performance. It has been acknowledged that although the foil is facing downward, over time dust accumulation on the upper surface increases heat gain, reducing its effectiveness.[9-10] Field studies that examine the effect of dust accumulation on the thermal performance of foil could lead to a better understanding of the behaviour of this material.

This study also suggests that two techniques are not cost-effective: painting and shading the roof. Although the importance of using a light colour paint in the roof's exterior surface is stressed in several studies, the present research has shown that this technique can be a costly one. The reduction of heat gain is offset by the increase of costs due to maintenance. However, it is important to bear in mind that an appropriate coating surface is crucial to maintain or improve the thermal performance of a roof. Despite extensive research that has been conducted to improve the performance of paints, the influencing factors (climatological and environmental), are still difficult to overcome.[11] This suggests that future research should focus on improving the durability of paints and search for materials more resistant to these factors.

The present study has also shown that the usefulness of shading decreases owing to maintenance costs. Likewise, due to its high initial cost and poor thermal performance the double roof is not appropriate. This thesis suggests, however, that it could be improved by placing additional lightweight material both on the upper layer and on the lower layer of the roof.

For the owner-builder of a low-cost roof, the initial investment is the decisive matter. Hence, the cheapest alternative will always be his first choice. Of the fourteen appropriate systems the following have the lowest initial cost:

Roof No.	Description	Initial Cost
7	CGS with straw (500 mm) on top.	$US 46.26/m^2
39	CGS with straw (500 mm), jute ceiling (0.105 mm).	$US 49.95/m^2
34	CGS with earth (304 mm), jute ceiling (0.105 mm).	$US 49.95/m^2
45	CGS with straw (500 mm), jute ceiling (0.105 mm), foil.	$US 50.35/m^2
37	CGS with earth (304 mm), jute ceiling (0.105 mm), foil.	$US 50.35/m^2
42	CGS with straw (500 mm), particleboard ceiling (12.5 mm), straw ceiling insulation (50 mm).	$US 50.84/m^2
38	CGS with straw (500 mm), particleboard ceiling (12.5 mm).	$US 50.84/m^2
35	CGS with earth (304 mm), particleboard ceiling (12.5 mm), straw ceiling insulation (50 mm).	$US 50.84/m^2
13	Unpainted CGS with particleboard ceiling (12.5 mm), straw ceiling insulation (50 mm).	$US 50.84/m^2
10	Unpainted CGS with particleboard ceiling (12.5 mm).	$US 50.84/m^2

Table 5. Cost-effective CGS roofs with low initial cost.

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APPENDIX A

HEAT GAIN CALCULATIONS

To illustrate the three step process of the analytical calculations of heat gain under steady state conditions, the thermal performance of the basic roof is presented below.

The first step is to stablish the **Sol-air** or **equivalent outdoor temperature** as expressed in the formula:

$$O_e = O_o + \frac{a\ I}{h_c + h_r} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ (1)$$

where O_e = Sol-air temperature, °C

O_o = Outdoor temperature, °C

a = Absorptivity of the roofing material

I = Intensity of solar radiation, W/m^2

h_c = Convective surface coefficient, W/m^2 degrees C

h_r = Radiation surface coefficient, W/m^2 degrees C

The intensity of solar radiation can be obtained from values recorded in tables. In this study it was calculated according to the process of the ASHRAE; the value obtained was 995.64 W/m^2.[1] The convective surface coefficient (h_c) is given by the formula:

$$h_c = 5.8 + 4.1v$$

where v is the wind velocity. Considering a wind velocity of 5.029 m/s h_c is:

$$h_c = 5.8 + 4.1(5.029)$$

$$= 26.41 \ W/m^2 \ ^oC.$$

The radiation coefficient (h_r) depends on the emissivity of the specific material. For the CGS sheet the emissivity is 0.20, therefore:

$$h_r = 5.7 \ e$$

$$h_r = 5.7(0.20)$$

$$= 1.14 \ W/m^2$$

Thus, the Sol-air temperature is:

$$O_e = 35 + \frac{(0.65) \times (995.64)}{26.42 + 1.14}$$

$$= \mathbf{58.48^oC}$$

Once this parameter has been obtained, the **thermal resistance** of the roof is assessed. This requires the knowledge of the factors R_{so}, (resistance of outside surface) and R_{si} (resistance of inner surface). It is important to notice the factor R_{si} differs from R_{so}, owing to the h_{co} value. The h_{co} value for surfaces not in contact with the external air is a constant given by 1.5 W/m2·2

Thus, R_{so} and R_{si} are obtained by:

$$R_{so} = \frac{1}{h_c + h_r}$$

$$= \frac{1}{26.42 + 1.14}$$

$$= 0.0362 \ m^2 \text{ degrees C/W.}$$

and R_{si} is:

$$R_{si} = \frac{1}{h_c + h_r}$$

$$= \frac{1}{1.5 + 1.14}$$

$$= 0.3787 \text{ m}^2 \text{ degrees C/W.}$$

Therefore, the total thermal resistance from air to air is:

$$R_t = R_{so} + R_{aa} + R_c + R_{si} \quad \text{m}^2 \text{ degreesC/W.} \quad . \; . \; . \; . \; . (2)$$

where R_{aa} is the resistance of the roof assembly as:

$$R_{aa} = (l \times r + l_1 \times r_1 + \ldots \; ln \times r_n) \text{ m}^2 \text{ degrees C/W.} \quad . \; . (3)$$

where l = thickness of the exterior roof layer, in m

l_1 = thickness of next layer of the roof, in m

l_n = thickness of subsequent layers of the roof, in m

r = resistivity of the exterior roof layer, in m^2 degrees C/W

r_1 = resistivity of next layer of the roof, in m^2 degrees C/W

r_n = resistivity of subsequent layers of the roof, in m^2 degrees C/W.

Values of thermal resistivity are obtained from tables. For the plain CGS roof (sheet 0.8 mm), R_{aa} is:

$$R_{aa} = l \times r \quad (\text{m}^2 \text{ degrees C/W})$$

$$R_{aa} = 0.00008 \times 0.01\dot{8}7 \text{ m}^2 \text{ degrees C/W}$$

$$R_{aa} = 0.00001 \text{ m}^2 \text{ degrees C/W}$$

Since there is not roof cavity, R_c is not integrated. Thus, R_t is:

$$R_t = (0.0362 + 0.00001 + o.3787) \text{ m}^2 \text{ degrees C/W}$$

$$R_t = 0.4149 \text{ m}^2 \text{ degrees C/W.}$$

Finally, the calculation of the inner roof surface temperature O_{si}, or **heat gain** is the development of the formula:

$$O_{si} = O_e - \frac{(R_t - R_{si})}{R_{si}} (O_e - O_o)\ ^{o}C. \ldots \ldots (4)$$

$$O_{si} = 58.48 - \frac{(0.4149 - 0.3787)}{0.4149} (58.48 - 35)$$

$$O_{si} = \mathbf{56.43^{o}C}$$

When a roof assembly includes a ventilated attic or ventilated roof space, the **effective resistance** and the thermal resistance of the ceiling must be included. Therefore, the total thermal resistance R_t is:

$R_t = R_{so} + R_{aa} + R_c + R_{si}$ (m^2 degrees C/W). . . . . . . (2)

where R_{aa} includes the resistance of the ceiling, R_c is the resistance of the ventilated roof space, and R_{si} is the inner roof surface coefficient at the ceiling level. As an example, the thermal performance or heat gain of the unpainted CGS sheets roof with ventilated roof space and particleboard ceiling is presented below. The first step or Sol-air temperature value is equal to the preceding, since the conditions of the exterior roof surface are the same.

Thus the resistance R_{aa} is the sum of the resistances of:

resistance of CGS sheet = 0.00001 m^2 degrees C/W

resistance of particleboard ceiling
1.27 cm is: 0.0127 x 7.38 = 0.0936 m^2 degrees C/W

R_{aa} = 0.0936 m^2 degrees C/W

The **effective resistance** of the roof space R_c is obtained from Table 6.[3] As the data is provided in imperial units, the following values appear in that system. The required conversion to metric units is carried out eventually. Thus,

Ventilation air temperature (35°C) 95°F = 90

Sol-air (58.48°C) 137.26°F = 140

Natural ventilation = 20 : 3.1,

Since the ventilation air temperature must be similar to 95°F, it is required to interpolate:

Ventilation air temperature = 100

Sol-air = 140

Natural ventilation = 20 : 2.7, then

3.1 (-) 2.7 = 0.4. Therefore, 0.4/2 = 0.2 leads to:

$$2.7 + 0.2 = 2.9 \text{ (hr ft}^2\text{F)/Btu or}$$

$$3.1 - 0.2 = 2.9 \text{ (hr ft}^2\text{F)/Btu.}$$

Converting to metric units: 2.9 x 1.761102 E-01 = 0.5107 m^2 degrees C.

The last value to obtain is the resistance of the inner roof surface R_{si}. As it was mentioned earlier the convective

PART A. NONREFLECTIVE SURFACES

Ventilation Air Temp., F	Sol-Air[d] Temp., F	No Ventilation		Natural Ventilation		Power Ventilation[e]			
		Ventilation Rate, cfm/ft²							
		0		0.1[b]		0.5		1.0	
		1/U Ceiling Resistance, R[c]							
		10	20	10	20	10	20	10	20
	120	1.9	1.9	2.8	3.4	6.3	9.3	9.6	16
80	140	1.9	1.9	2.8	3.5	6.5	10	9.8	17
	160	1.9	1.9	2.8	3.6	6.7	11	10	18
	120	1.9	1.9	2.5	2.8	4.6	6.7	6.1	10
90	140	1.9	1.9	2.6	3.1	5.2	7.9	7.6	12
	160	1.9	1.9	2.7	3.4	5.8	9.0	8.5	14
	120	1.9	1.9	2.2	2.3	3.3	4.4	4.0	6.0
100	140	1.9	1.9	2.4	2.7	4.2	6.1	5.8	8.7
	160	1.9	1.9	2.6	3.2	5.0	7.6	7.2	11
PART B. REFLECTIVE SURFACES[f]									
	120	6.5	6.5	8.1	8.8	13	17	17	25
80	140	6.5	6.5	8.2	9.0	14	18	18	26
	160	6.5	6.5	8.3	9.2	15	18	19	27
	120	6.5	6.5	7.5	8.0	10	13	12	17
90	140	6.5	6.5	7.7	8.3	12	15	14	20
	160	6.5	6.5	7.9	8.6	13	16	16	22
	120	6.5	6.5	7.0	7.4	8.0	10	8.5	12
100	140	6.5	6.5	7.3	7.8	10	12	11	15
	160	6.5	6.5	7.6	8.2	11	14	13	18

Table 6. Effective Resistance of Ventilated Attics. Summer Conditions.
ASHRAE, 1977, 22.23.

surface coefficient h_c, is the constant 1.5 W/m^2C. The radiation surface coefficient h_r is the product of 5.7e. The e value corresponds to the emissivity of the particleboard ceiling, therefore:

$$h_r = 5.7(0.90)$$

$$= 5.13.$$ Then R_{si} is:

$$R_{si} = \frac{1}{1.5 + 5.13}$$

$$= 0.1508 \text{ m}^2 \text{ degrees C/W}$$

From formula (2) the total thermal resistance R_t is the sum:

$$R_{so} = 0.0362 \text{ m}^2 \text{ degrees C/W}$$

$$R_{aa} = 0.0936 \text{ m}^2 \text{ degrees C/W}$$

$$R_c = 0.5107 \text{ m}^2 \text{ degrees C/W}$$

$$R_{si} = 0.1508 \text{ m}^2 \text{ degrees C/W}$$

$$R_t = 0.7913 \text{ m}^2 \text{ degrees C/W}$$

Thus, it is possible to calculate the inner roof surface temperature or heat gain of the unpainted CGS roof with particleboard ceiling 1.25 cm thick, and ventilated roof space as in formula (4):

$$O_{si} = 58.48 \frac{(0.7913 - 0.1508)}{0.7913}(58.48-35)$$

$$= 58.48 - (0.8094)(23.48)$$

$$= \mathbf{39.47^{\circ}C}$$

The calculations of the whole CGS roofs are presented in Appendix B. These calculations were done with a hand calculator model TI-32 solar.

E N D N O T E S

1. ASHRAE. Handbook of Fundamentals, New York: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. 1977.

2. Szokolay, S. V. Environmental Science Handbook for Architects and Builders, New York: John Wiley and Sons, 1980, 256.

3. ASHRAE, 1977, 22.23.

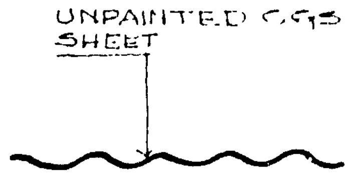
APPENDIX B

HEAT GAIN AND LIFE-CYCLE COST CALCULATIONS RESULTS

1. Unpainted Corrugated Galvanized Steel (CGS).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	35
R_{so}	0.0362	
R_{si}	0.3787	
R_T =	0.4149	



U=2.41 W/m^2 deg C   Inner roof surface temperature: 56.43°C

Life-Cycle Cost.

Interest Rate: 15 percent

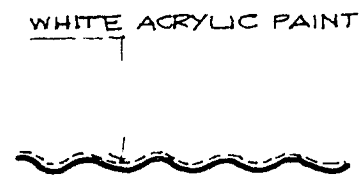
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	46.26
Total					46.26

2. CGS with two coats of white acrylic paint on its exterior surface.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Paint	-	70
R_{so}	0.0316	
R_{si}	0.3787	
R_T	0.4104	



U=2.43 W/m^2 deg C Inner roof surface temperature: 40.82°C

Life-Cycle Cost.

Interest rate: 15 percent

Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Paint	1.83	7.33			
Total					55.42

3. CGS roof with two coats of whitewash on its exterior surface.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Whitewash	-	85
R_{so}	0.0316	
R_{si}	0.3787	
$R_{T=}$	0.4104	

$U=2.43\ W/m^2$ Inner roof surface temperature: 39.36°C

Life-Cycle Cost.

Interest Rate: 15 percent

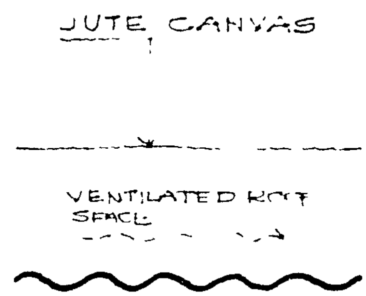
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(−)0.28	
White-wash	0.54	11.39			
Total					58.19

4. Unpainted CGS with jute (0.105 mm) canvas shading.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0317	
Effective Resistance	0.3874	
R_{si}	0.3787	
R_T =	0.8001	



U=0.80 W/m^2 deg C   Inner roof surface temperature: 38.13°C

Life-Cycle Cost.

Interest rate: 15 percent

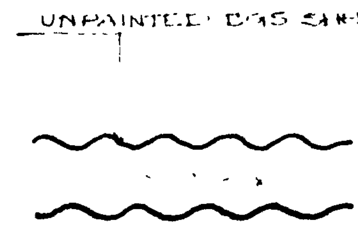
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Total					64.50

5. Unpainted CGS double roof with ventilated roof (150 mm) space.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	35
R_{so}	0.0362	
Effective Resistance	0.5107	
CGS	0.00001	
R_{s1}	0.3787	
R_T =	0.9256	



U= 1.08 W/m^2 deg C   Inner roof surface temperature: 44.60°C

Life-Cycle Cost.

Interest rate: 15 percent

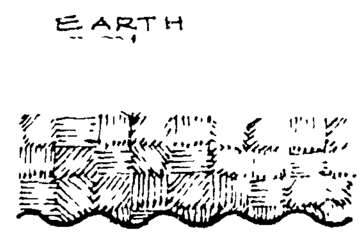
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
CGS 2nd	42.17		0.018	(-)0.26	
Total					88.19

6. CGS with a layer of earth (304 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Earth	0.4064	30
R_{so}	0.0314	
R_{si}	0.3787	
R_T =	0.8165	



U =1.22 W/m^2 deg C   Inner roof surface temperature:46.31°C

Life-Cycle Cost.

Interest rate: 15 percent

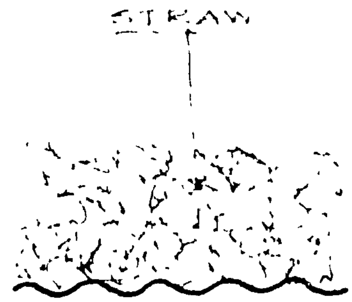
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Earth	-				
Total					46.26

7. CGS with a layer of straw (500 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Straw	5.375	40
R_{so}	0.0314	
R_{si}	0.3787	
R_T =	5.7864	



U=0.17 W/m^2 deg C Inner roof surface temperature: 36.94°C

Life-Cycle Cost.

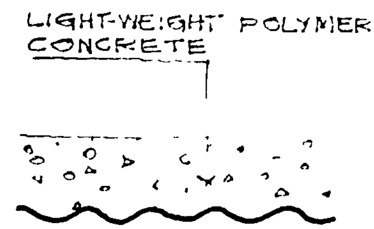
Interest rate: 15 percent

Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Straw	-				
Total					46.26

8. CGS with a layer of light-weight polymer concrete (225 mm).

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Concrete	1.1842	60
R_{so}	0.0316	
R_{si}	0.3787	
R_T =	1.5945	



U=0.62 W/m^2 deg c Inner roof surface temperature: 39.86°C

Life-Cycle Cost.

Interest rate: 15 percent

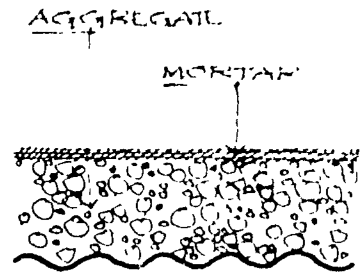
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Concrete	10.96				
Total					57.22

9. CGS with light-weigth aggregate (304 mm) and mortar sand-cement-lime (12.7 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Mortar	0.0091	60
R_{so}	0.0362	
Aggregate	1.8175	
R_{si}	0.3787	
R_T =	2.237	



U=0.44 W/m^2 deg C Inner roof surface temperature: 36.87°C

Life-Cycle Cost.

Interest rate: 15 percent

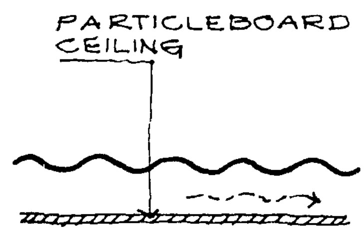
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
<u>Entor-tado</u>	13.04		0.80		
Total					<u>60.10</u>

10. Unpainted CGS with particleboard ceiling (12.7 mm) and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	35
R_{so}	0.0362	
Effective Resistance	0.5107	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	0.7913	



U=1.26 W/m^2 deg C   Inner roof surface temperature: 39.47°C

Life-Cycle Cost.

Interest rate: 15 percent

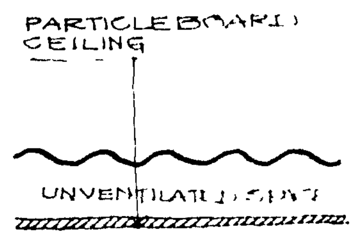
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/m^2
		Maintenance	Repairs	Salvage Value	
CGS	46.3[illegible]		0.23	(-)0.28	
Particleboard	4.53		0.02		
Total					50.81

11. Unpainted CGS with particleboard ceiling (12.7 mm) and unventilated roof space.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	35
R_{so}	0.0362	
Resistance Unventilated space	0.3346	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	0.4644	



U=2.15 W/m^2 deg C Inner roof surface temperature: 43.29°C

Life-Cycle Cost.

Interest rate: 15 percent

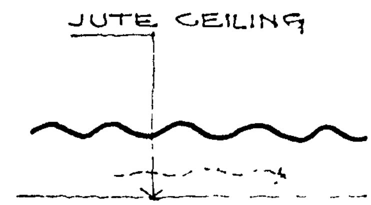
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	43.99		0.22	(-)0.28	
Particleboard	4.53		0.02		
Total					48.48

12. Unpainted CGS with jute ceiling (0.105 mm) and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	35
R_{so}	0.0362	
Effective Resistance	0.5107	
Jute	0.0023	
R_{si}	0.1508	
R_T =	0.7000	



$U=1.42\ W/m^2$ deg C Inner roof surface temperature: 40.05°C

Life-Cycle Cost.

Interest rate: 15 percent

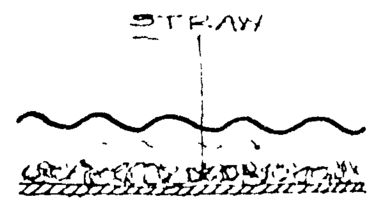
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64		0.018		
Total					49.92

13. Unpainted CGS with particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	35
R_{so}	0.0362	
Effective Resistance	0.4755	
Straw	0.5376	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.2937	



U=0.77 W/m^2 deg C   Inner roof surface temperature: 37.74°C

Life-Cycle Cost.

Interest rate: 15 percent

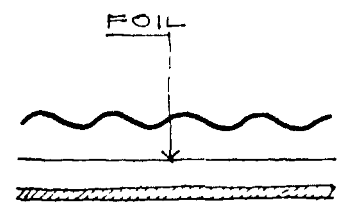
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Parti-cleboard	4.53		0.02		
Straw	-				
Total					50.81

14. Unpainted CGS with particleboard ceiling (12.7 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
R_{so}	0.0362	
Effective Resistance	1.4088	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.6894	



U=0.59 W/m^2 deg C Inner roof surface temperature: 37.09°C

Life-Cycle Cost.

Interest rate: 15 percent

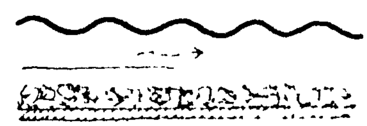
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Particleboard	4.53		0.02		
Aluminum Foil	0.40		0.008		
Total					51.22

15. Unpainted CGS with particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	35
R_{so}	0.0362	
Effective Resistance	1.4088	
Straw	0.5376	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	2.2270	



U=0.44 W/m^2 deg C Inner roof surface temperature: 36.59°C

Life-Cycle Cost.

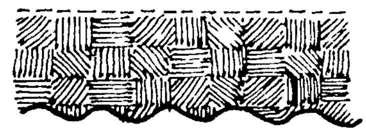
Interest rate: 15 percent
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth \$US/m^2
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Parti-cleboard	4.53		0.02		
Aluminum Foil	0.40		0.008		
Straw	-				
Total					51.22

16. CGS with whitewash, and earth (304 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Earth	0.4064	whitew. 85
R_{so}	0.0319	
R_{si}	0.3787	
R_T =	0.8171	



U=1.22 W/m^2 deg C   Inner roof surface temperature: 39.38°C

Life-Cycle Cost.

Interest rate: 15 percent

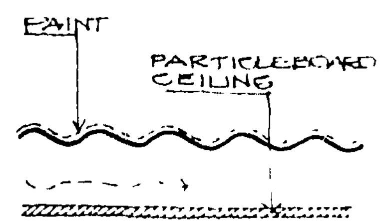
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Earth	-				
Total					58.19

17. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm) and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	paint 70
R_{so}	0.0316	
Effective Resistance	0.3874	
Particleb.	0.0936	
R_{si}	0.1579	
R_T =	0.6706	



U=1.49 W/m^2 deg C Inner roof surface temperature: 36.48°C

Life-Cycle Cost.

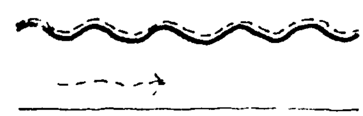
Interest rate: 15 percent
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth: Maintenance	Present Worth: Repairs	Present Worth: Salvage Value	Total Present Worth $US/$m^2$
CGS	46.31		0.23	(-)0.28	
Paint	1.83	7.33			
Particleboard	4.53		0.02		
Total					59.97

18. CGS with two coats of white acrylic paint, jute ceiling (0.105 mm) and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	paint 70
R_{so}	0.0316	
Effective Resistance	0.3874	
Jute	0.0023	
R_{si}	0.1579	
R_T =	0.5793	



U=1.73 W/m^2 deg C Inner roof surface temperature: 36.72°C

Life-Cycle Cost.

Interest rate: 15 percent

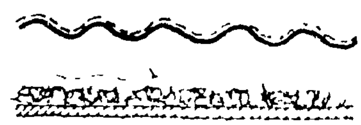
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
Paint	1.83	7.33			
Jute	3.64		0.018		
Total					59.08

19. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	paint 70
R_{so}	0.0316	
Effective Resistance	0.3874	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.201	



U=0.83 W/m^2 deg C   Inner roof surface temperature: 35.79°C

Life-Cycle Cost.

Interest rate: 15 percent

Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth \$US/m^2
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Paint	1.83	7.33			
Particleboard	4.53		0.02		
Total					59.97

20. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	paint 70
R_{so}		
Effective Resistance	1.1799	
Particleb.	0.0936	
R_{si}	0.1579	
R_T =	1.4631	

U=0.68 W/m^2 deg C   Inner roof surface temperature: 35.68°C

Life-Cycle Cost.

Interest rate: 15 percent

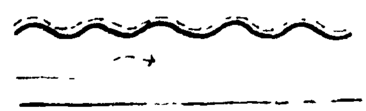
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Paint	1.83	7.33			
Aluminum Foil	0.40		0.008		
Particleboard	4.53		0.02		
Total					60.38

21. CGS roof with two coats of white acrylic paint, jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	paint 70
R_{so}	0.0316	
Effective Resistance	1.1799	
Jute	0.0023	
R_{si}	0.1579	
R_T =	1.3718	



U=0.72 W/m^2 deg C   Inner roof surface temperature: 35.73°C

Life-Cycle Cost.

Interest rate: 15 percent

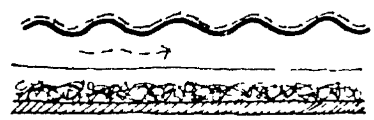
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Paint	1.83	7.33			
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					59.49

22. CGS with two coats of white acrylic paint, particleboard ceiling (12.7 mm), straw (50 mm), aluminum foil facing downward, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	paint 70
R_{so}	0.0362	
Effective Resistance	1.1799	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1588	
R_T =	1.9935	



U=0.50 W/m^2 deg C Inner roof surface temperature: 35.47°C

Life-Cycle Cost.

Interest rate: 15 percent

Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
Paint	1.83	7.33			
Straw	-				
Aluminum Foil	0.40		0.008		
Particleboard	4.53		0.02		
Total					60.38

23. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	whitew. 85
R_{so}	0.0316	
Effective Resistance	0.4138	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	0.6899	

U=1.44 W/m^2 deg C   Inner roof surface temperature: 36.03°C

Life-Cycle Cost.

Interest rate: 15 percent

Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Parti-cleboard	4.53		0.02		
Total					62.72

24. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	whitew. 85
R_{so}	0.0316	
Effective Resistance	0.4138	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.2274	

U=0.81 W/m^2 deg C   Inner roof surface temperature: 35.58°C

Life-Cycle Cost.

Interest rate: 15 percent

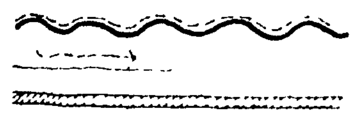
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Straw	-				
Parti-cleboard	4.53		0.02		
Total					62.74

25. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
R_{so}	0.0316	
Effective Resistance	1.2152	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.4913	



U=0.67 W/m^2 deg C   Inner roof surface temperature: 35.48°C

Life-Cycle Cost.

Interest rate: 15 percent

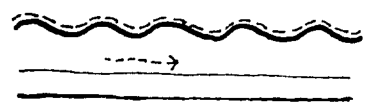
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Aluminum Foil	0.40		0.008		
Parti-cleboard	4.53		0.02		
Total					63.15

26. CGS with two coats of whitewash, jute ceiling (0.105 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	whitew. 85
R_{so}	0.0362	
Effective Resistance	1.2767	
Jute	0.0023	
R_{si}	0.1579	
R_T =	1.4686	



U=0.68 W/m^2 deg C   Inner roof surface temperature: 35.51°C

Life-Cycle Cost.

Interest rate: 15 percent

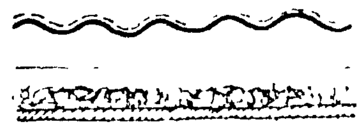
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
White-wash	0.54	11.39			
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					62.25

27. CGS with two coats of whitewash, particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	whitew. 85
R_{so}	0.0362	
Effective Resistance	1.3560	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	2.1696	



U=0.46 W/m^2 deg C   Inner roof surface temperature: 35.33°C

Life-Cycle Cost.

Interest rate: 15 percent

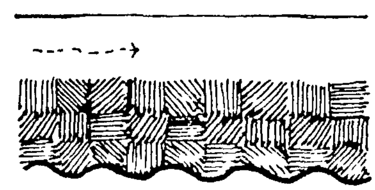
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Aluminum Foil	0.40		0.008		
Straw	-				
Particleboard	4.53		0.02		
Total					63.15

28. Unpainted CGS with jute canvas shading (0.105 mm), and earth (304 mm) over the roof.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Jute	0.0235	79
R_{so}	0.0317	
Effective Resistance	0.3874	
Earth	0.4064	
R_{si}	0.3787	
R_T =	1.2277	



U=0.81 W/m^2 deg C   Inner roof surface temperature: 37.04°C

Life-Cycle Cost.

Interest rate: 15 percent

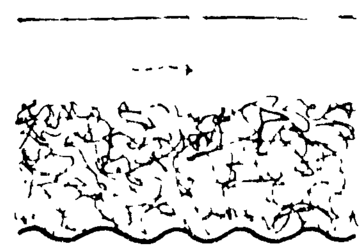
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Earth	-				
Total					64.50

29. Unpainted CGS with jute canvas shading (0.105 mm), and straw (500 mm) over the roof.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0362	
Effective Resistance	0.3874	
Straw	5.375	
R_{si}	0.3787	
R_T =	6.1751	



U=0.16 W/m^2 deg C Inner roof surface temperature: 35.40°C

Life-Cycle Cost.

Interest rate: 15 percent

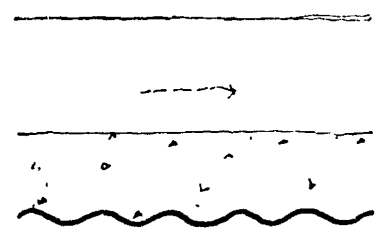
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Straw	-				
Total					64.50

30. Unpainted CGS with jute canvas shading (0.105 mm), light-weight polymer concrete (225 mm) over the roof.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0317	
Effective Resistance	0.3874	
Concrete	1.1842	
R_{si}	0.3787	
R_T =	1.9844	



U=0.50 W/m^2 deg C Inner roof surface temperature: 36.26°C

Life-Cycle Cost.

Interest rate: 15 percent

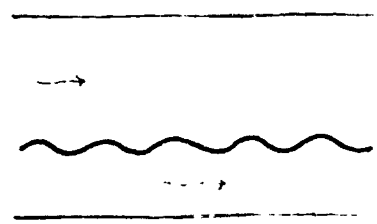
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth: Maintenance	Present Worth: Repairs	Present Worth: Salvage Value	Total Present Worth $US/$m^2$
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Concrete	10.96				
Total					75.46

31. Unpainted CGS with jute canvas shading (0.105 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0317	
Effective Resistance	0.3874	
Jute	0.0023	
R_{si}	0.1579	
R_T =	0.9691	



U=1.03 W/m^2 deg C   Inner roof surface temperature:36.08°C

Life-Cycle Cost.

Interest rate: 15 percent

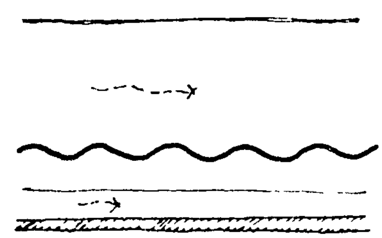
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Jute	3.64		0.018		
Total					68.16

32. Unpainted CGS with jute canvas shading (0.105 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0362	
Effective Resistance	0.3874	
Effective Resistance	1.1799	
Particleb.	0.0936	
R_{si}	0.1579	
R_T =	1.8529	



U=0.53 W/m^2 deg C   Inner roof surface temperature: 35.56°C

Life-Cycle Cost.

Interest rate: 15 percent

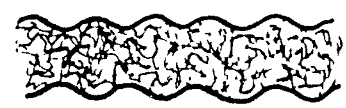
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(−)0.28	
Jute	3.64	14.60			
Aluminum Foil	0.40		0.008		
Particleboard	4.53		0.02		
Total					69.46

33. Unpainted CGS double roof with straw (250 mm) over the lower layer.

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	35
R_{so}	0.0362	
Straw	2.6875	
CGS	0.00001	
R_{si}	0.3787	
R_T =	3.1024	



U=0.32 W/m^2 deg C   Inner roof surface temperature: 37.87°C

Life-Cycle Cost.

Interest rate: 15 percent

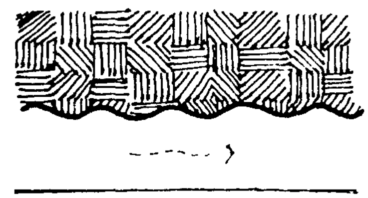
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Straw	-				
CGS 2nd layer	42.17		0.018	(-)0.26	
Total					88.19

34. CGS with earth (304 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Earth	0.4064	30
R_{so}	0.0319	
Effective Resistance	0.4754	
Jute	0.0023	
R_{si}	0.1579	
R_T =	1.0739	



U=0.93 W/m^2 deg C   Inner roof surface temperature:38.27°C

Life-Cycle Cost.

Interest rate: 15 percent

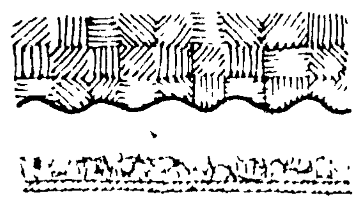
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Earth	-				
Jute	3.64		0.018		
Total					49.92

35. CGS with earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Earth	0.4064	30
R_{so}	0.0319	
Effective Resistance	0.4754	
Straw	0.5375	
Particleb.	0.09336	
R_{si}	0.3787	
R_T =	1.6956	



U=0.58 W/m^2 deg C   Inner roof surface temperature: 36.98°C

Life-Cycle Cost.

Interest rate: 15 percent

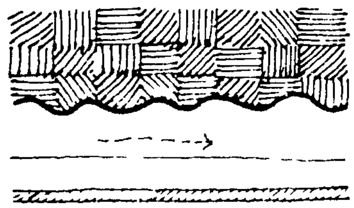
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Earth	-				
Straw	-				
Particleboard	4.53		0.02		
Total					50.81

36. CGS with earth (304 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Earth	0.4064	30
R_{so}	0.0314	
Effective Resistance	1.4089	
Particleb.	0.0936	
R_{si}	0.1579	
R_T =	2.0982	



U=0.47 W/m^2oC Inner roof surface temperature: 36.68°C

Life-Cycle Cost.

Interest rate: 15 percent

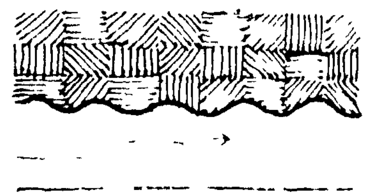
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(−)0.28	
Earth	–				
Aluminum Foil	0.40		0.008		
Parti-cleboard	4.53		0.02		
Total					51.22

37. CGS with earth (304 mm), jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Earth	0.4064	
R_{so}	0.0362	
Effective Resistance	1.4089	
Jute	0.0023	
R_{si}	0.3787	
R_T =	2.0066	



U=0.49 W/m^2oC Inner roof surface temperature: 36.75°C

Life-Cycle Cost.

Interest rate: 15 percent

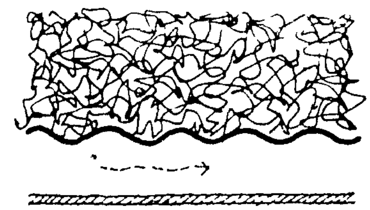
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/m^2
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Earth	-				
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					50.33

38. CGS with straw (500 mm), particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Straw	5.375	40
R_{so}	0.0314	
Effective Resistance	0.5459	
Particleb.	0.0936	
R_{si}	0.3787	
R_T =	6.4793	



U=0.14 W/m^2 deg C   Inner roof surface temperature: 35.69°C

Life-Cycle Cost.

Interest rate: 15 percent

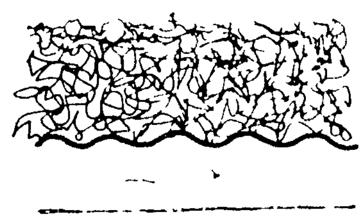
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
Straw	-				
Particleboard	4.53		0.02		
Total					51.31

39. CGS with straw (500 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Straw	5.370	40
R_{so}	0.314	
Effective Resistance	0.5459	
Jute	0.0023	
R_{si}	0.3787	
R_T =	6.3901	



U=0.15 W/m^2 deg C   Inner roof surface temperature: 35.73°C

Life-Cycle Cost.

Interest rate: 15 percent

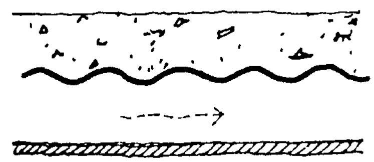
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/m^2
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Straw	-				
Jute	3.64		0.018		
Total					49.92

40. CGS with lightweight polymer concrete (225 mm), particleboard ceiling (12.7 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Concrete	1.1835	35
R_{so}	0.0316	
Effective Resistance	0.4402	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.8998	



U=0.52 W/m^2 deg C   Inner roof surface temperature: 36.62°C

Life-Cycle Cost.

Interest rate: 15 percent

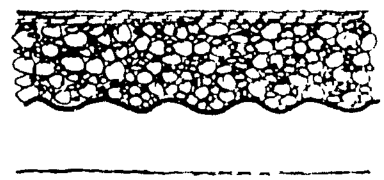
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Concrete	10.96				
Jute	3.64		0.018		
Total					60.88

41. CGS roof with light-weight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), jute ceiling (0.105 mm), and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Mortar	0.0091	60
Aggregate	1.8175	
R_{so}	0.0316	
Effective Resistance	0.4402	
Jute	0.0023	
R_{si}	0.1579	
R_T =	2.4587	



U=0.40 W/m^2 deg C   Inner roof surface temperature: 35.71°C

Life-Cycle Cost.

Interest rate: 15 percent

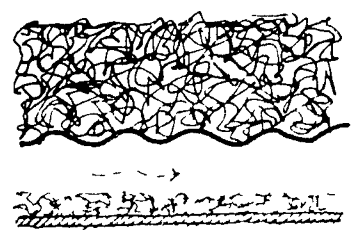
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Entorta-do	13.04		0.80		
Jute	3.64		0.018		
Total					63.76

42. CGS with straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Straw	5.375	40
R_{so}	0.0314	
Effective Resistance	0.5459	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	7.0168	



U=0.14 W/m^2 deg C Inner roof surface temperature: 35.64°C

Life-Cycle Cost.

Interest rate: 15 percent

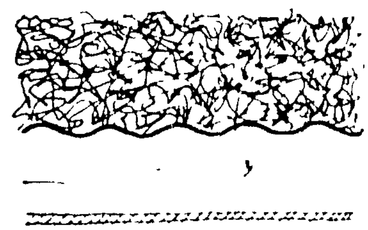
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Straw	-				
Straw	-				
Particleboard	4.53		0.02		
Total					50.81

43. CGS with straw (500 mm), particleboard ceiling (12.7 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Straw	5.37	
R_{so}	0.3140	
Effective Resistance	1.4300	
Particleb.	0.0936	
R_{si}	0.1579	
R_T =	7.3655	



U=0.13 W/m^2 deg C Inner roof surface temperature: 35.64°C

Life-Cycle Cost.

Interest rate: 15 percent

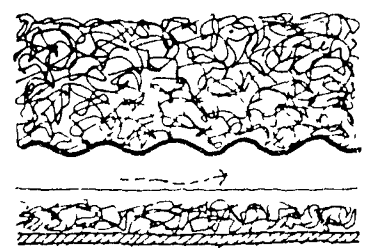
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(−)0.28	
Straw	-				
Aluminum Foil	0.40		0.008		
Straw	-				
Total					51.22

44. CGS with straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Straw	5.375	40
R_{so}	0.314	
Effective Resistance	1.4300	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	7.9009	



U=0.12 W/m^2 deg C Inner roof surface temperature:35.57°C

Life-Cycle Cost.

Interest rate: 15 percent

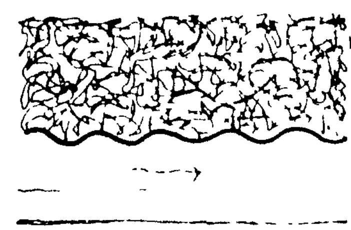
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Straw	-				
Aluminum Foil	0.40		0.008		
Straw	-				
Parti-cleboard	4.53		0.02		
Total					51.22

45. CGS with straw (500 mm), jute ceiling (0.105 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Straw	5.3700	40
R_{so}	0.3140	
Effective Resistance	1.4441	
Jute	0.0023	
R_{si}	0.1579	
R_T =	7.2884	



U=0.13 W/m^2 deg C   Inner roof surface temperature: 35.40°C

Life-Cycle Cost.

Interest rate: 15 percent

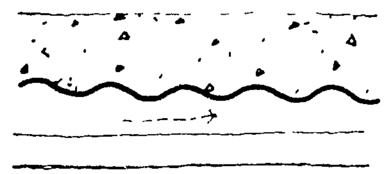
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
Straw	-				
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					50.33

46. CGS with lightweight polymer concrete (225 mm), jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Concrete	1.1835	35
R_{so}	0.0362	
Effective Resistance	1.3384	
Jute	0.0023	
R_{si}	0.1579	
R_T =	2.7137	



U=0.36 W/m^2 deg C Inner roof surface temperature: 36.13°C

Life-Cycle Cost.

Interest rate: 15 percent

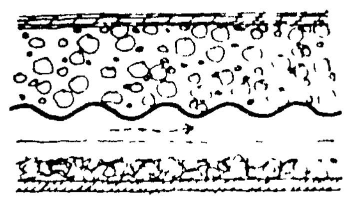
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth: Maintenance	Present Worth: Repairs	Present Worth: Salvage Value	Total Present Worth $US/$m^2$
CGS	46.31		0.23	(-)0.28	
Concrete	10.96				
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					61.29

47. CGS with lightweight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Mortar	0.0091	60
Aggregate	1.8175	
R_{so}	0.0316	
Effective Resistance	1.3560	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	3.9961	



U=0.25 W/m^2 deg C   Inner roof surface temperature: 36.32°C

Life-Cycle Cost.

Interest rate: 15 percent

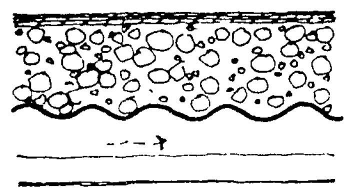
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/m^2
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
Entortado	13.04		0.80		
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					64.17

48. CGS with lightweight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), jute ceiling (0.105 mm), aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Mortar	0.0091	60
Aggregate	1.8175	
R_{so}	0.0316	
Effective Resistance	1.3384	
Jute	0.0023	
R_{si}	0.1579	
R_T =	3.3569	



U=0.29 W/m^2 deg C   Inner roof surface temperature: 35.52°C

Life-Cycle Cost.

Interest rate: 15 percent

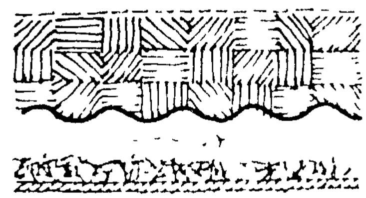
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
<u>Entortado</u>	13.04		0.80		
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					<u>61.29</u>

49. CGS with whitewash, earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Earth	0.4064	whitew. 85
R_{so}	0.0316	
Effective Resistance	0.4138	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.6338	



U=0.61 W/m^2 deg C Inner roof surface temperature: 35.43°C

Life-Cycle Cost.

Interest rate: 15 percent

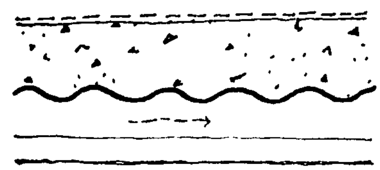
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Earth	-				
Straw	-				
Parti-cleboard	4.53		0.02		
Total					62.74

50. CGS with whitewash, lightweight polymer concrete (225 mm), jute ceiling (0.105 mm) aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Concrete	1.1835	whitew. 85
R_{so}	0.0316	
Effective Resistance	1.3560	
Jute	0.0023	
R_{si}	0.1579	
R_T =	2.7314	



U=0.36 W/m^2 deg C   Inner roof surface temperature: 35.27°C

Life-Cycle Cost.

Interest rate: 15 percent

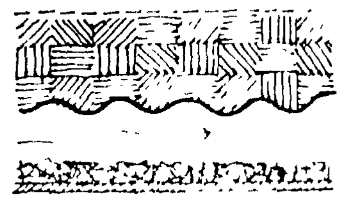
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Concrete	10.96				
Aluminum Foil	0.40		0.008		
Jute	3.64		0.018		
Total					73.22

51. CGS with whitewash, earth (304 mm), particleboard ceiling (12.7 mm) thick, straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Earth	0.4064	whitew. 85
R_{so}	0.0362	
Effective Resistance	1.3560	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.3787	
R_T =	2.576	



U=0.38 W/m^2 deg C Inner roof surface temperature: 35.28°C

Life-Cycle Cost.

Interest rate: 15 percent

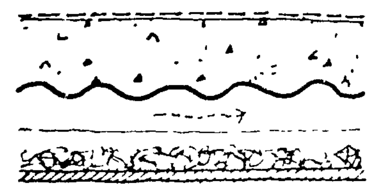
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
White-wash	0.54	11.39			
Earth	-				
Aluminum Foil	0.40		0.008		
Straw	-				
Parti-cleboard	4.53		0.02		
Total					63.15

52. CGS with whitewash, lightweight polymer concrete (225 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Concrete	1.1842	whitew. 85
R_{so}	0.0362	
Effective Resistance	1.3560	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	3.3538	



U=0.29 W/m^2 deg C   Inner roof surface temperature: 35.21°C

Life-Cycle Cost.

Interest rate: 15 percent

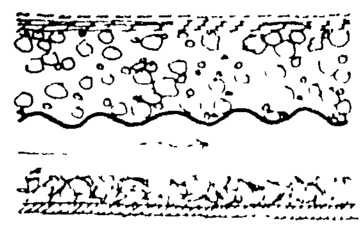
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-) 0.28	
White-wash	0.54	11.39			
Concrete	10.96				
Aluminum Foil	0.40		0.008		
Straw	-				
Particleboard	4.53		0.02		
Total					74.11

53. CGS with whitewash, lightweight aggregate (304 mm) with mortar sand-cement-lime (12.7 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (150 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Mortar	0.0091	whitew. 85
R_{so}	0.0362	
Aggregate	1.8175	
Effective Resistance	1.3560	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	3.9871	



U=0.25 W/m^2 deg C Inner roof surface temperature: 35.18°C

Life-Cycle Cost.

Interest rate: 15 percent

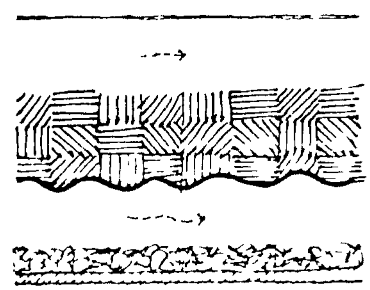
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth: Maintenance	Present Worth: Repairs	Present Worth: Salvage Value	Total Present Worth US/m^2
CGS	46.31		0.23	(-) 0.28	
White-wash	0.54	11.39			
<u>Entortado</u>	13.04		0.80		
Aluminum Foil	0.40		0.008		
Straw	-				
Particleboard	4.53		0.02		
Total					<u>76.99</u>

54. CGS with shading canvas (0.105 mm), earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflec-tivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0362	
Effective Resistance	0.3874	
Earth	0.4064	
Effective Resistance	0.3874	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.1508	
R_T =	1.9971	



U=0.50 W/m^2 deg C   Inner roof surface temperature: 35.50°C

Life-Cycle Cost.

Interest rate: 15 percent

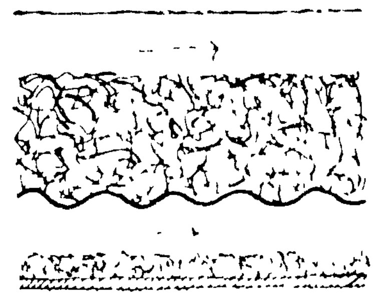
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Earth	-				
Straw	-				
Particleboard	4.53		0.02		
Total					69.05

55. CGS with shading canvas (0.105 mm), straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0362	
Effective Resistance	0.3874	
Straw	5.375	
Effective Resistance	0.3874	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.3787	
R_T =	6.9657	



U=0.14 W/m^2 deg C Inner roof surface temperature: 35.14°C

Life-Cycle Cost.

Interest rate: 15 percent

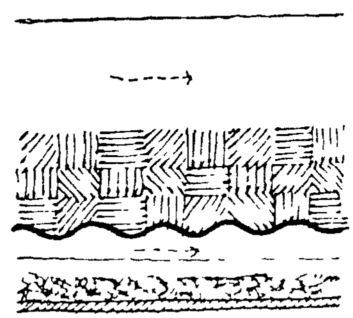
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Straw	-				
Straw	-				
Particleboard	4.53		0.02		
Total					69.05

56. CGS with shading canvas (0.105 mm), earth (304 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0362	
Effective Resistance	0.3874	
Earth	0.4064	
Effective Resistance	1.2328	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.3787	
R_T =	2.8425	



U=0.35 W/m^2 deg C   Inner roof surface temperature: 35.35°C

Life-Cycle Cost.

Interest rate: 15 percent

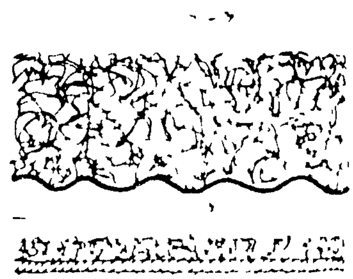
Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Earth	-				
Aluminum Foil	0.40		0.008		
Straw	-				
Particleboard	4.53		0.02		
Total					69.46

57. CGS with shading canvas, straw (500 mm), particleboard ceiling (12.7 mm), straw (50 mm) over the ceiling, aluminum foil facing downward, and ventilated roof space (100 mm).

Heat Gain

Element & Material	Thermal Resistance m^2 deg C/W	Reflectivity
CGS	0.00001	
Jute	0.0023	79
R_{so}	0.0362	
Effective Resistance	0.3874	
Straw	5.375	
Effective Resistance	1.2328	
Straw	0.5375	
Particleb.	0.0936	
R_{si}	0.3787	
R_T =	7.8111	



U=0.12 W/m^2 deg C   Inner roof surface temperature: 35.13°C

Life-Cycle Cost.

Interest rate: 15 percent

Life-cycle : 20 years

Material	Initial Capital Cost	Present Worth			Total Present Worth $US/$m^2$
		Maintenance	Repairs	Salvage Value	
CGS	46.31		0.23	(-)0.28	
Jute	3.64	14.60			
Straw	-				
Aluminum Foil	0.40		0.008		
Straw	-				
Particleboard	4.53		0.02		
Total					69.46

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