*2 Technology of Solar Cooking

*2.1 Introduction

In the typical operation of a solar cooker, *solar radiation* arrives at the cooker location, where it is often *reflected* off a reflecting surface and directed through a transparent cover where some radiation is absorbed and reflected away but most is *transmitted* through, where it is *absorbed* by a surface which gets hot and *transfers heat* to the food. Simultaneously, heat is lost to the surrounding atmosphere. However, the heat loss may be minimized by thermal *insulation*.

The items italicized (radiation, reflection, transmission, absorption, heat transfer, insulation) represent important processes involved with cookers. A brief discussion of the technical issues underlying these processes follows.

*2.2 Some fundamentals of solar radiation

It is interesting to consider that the source of all solar energy, the sun, is a massive sphere 1.4 million kilometers (0.87 million miles) in diameter, and 150 million km (93 million miles) from the earth. From a point on the earth to the opposite edges of the solar disk is an angle of only about a half a degree. Even though the solar rays spread out radially from the sun in all directions, the earth-sun distance is so great that the rays hitting the earth are considered to be parallel.

The surface of the sun is about 5500 °C (9900 °F). At its core, about only 3 % of its total volume, it is about 10 million °C (18 million °F) because of a continuous nuclear reaction (fusion) converting hydrogen into helium. The sun is approximately 80% hydrogen and 18 % helium, and it is consuming hydrogen at a rate of 4 million tons per second. There is no worry about the depletion of its hydrogen fuel, however; 10 million years from now only 1 % of its present hydrogen fuel will be consumed.

From the sun, the earth is but a tiny spot in the cosmos, and therefore receives only one billionth of the sun's total radiation. This radiation, or solar power reaching the earth (outside its layer of atmosphere, or *extraterrestrial*) is about 1.7×10^{14} kilowatts (or 4×10^{15} kilowatt hours per day). In terms of power per area, called solar *flux* (e.g., watts per square meter, W/m^2), the earth outside of the atmosphere receives a flux of about 1353 W/m^2, which is called the *solar constant*. Actually this radiation flux changes several percent over the course of a year because of small changes in the earth-sun distance.

A solar cooker at any location on the earth of course does not have a power input of 1353 W/m^2 with which to cook food. Solar flux hitting a horizontal surface on the surface of the earth is much less than the extraterrestrial solar flux because of

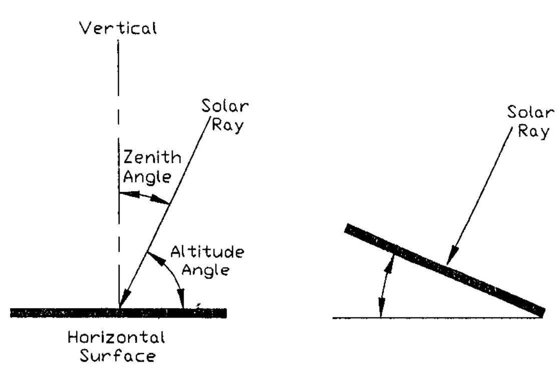
absorption and scattering by the atmosphere
time of day
latitude of location
date of the year
altitude of location
meteorological conditions

These effects are briefly discussed below.

Absorption of radiation by the atmosphere. As the solar radiation passes through the atmosphere, some is absorbed and scattered by atmospheric substances such as ozone, oxygen, water, and dust. When solar rays pass through the atmosphere perpendicularly (when the sun is overhead), the solar flux is reduced by around 15 to 30%, depending on time of year.

The reduction of solar flux by the atmosphere causes the solar flux reaching a horizontal surface on the earth to be composed of two parts. The direct solar flux, sometimes called *beam* radiation, representing the part that does not get absorbed or scattered by the atmosphere, is radiation coming in parallel rays from the direction of the sun. The *diffuse* part of the flux comes from all angles and can be around 5 to 15 % of the direct flux on a clear day.. On a day that is very cloudy and the sun cannot be seen, all the sunlight that is seen is diffuse. Solar cookers are designed and operated for the most part by consideration of the direct solar flux, nevertheless the diffuse part is present, but insufficient to power a cooker.

Time of day. The earth rotates, causing the relative position of the sun to vary from sunrise to sunset, and making the altitude angle, α, vary from zero at sunrise to a maximum at solar noon, and again to zero at sunset. Altitude angle is the angle between the horizontal and the sun, while zenith angle is the angle between the vertical and the sun; consequently altitude angle plus zenith angle is 90° . Altitude angle affects the radiation on a horizontal surface from two important effects. When altitude angle is less than 90°, the horizontal surface area is not "aimed" at the sun, so the solar rays hit at an angle. The solar flux received by the surface is then reduced by the sine of the angle α, compared to a surface facing the sun. For example, as shown in the figure, when the altitude angle is 60°, the sin α effect amounts to sin 60° = 0.87, or 87%. The solar flux on a horizontal surface would



Altitude and Zenith angles. Surface at the right is tilted by the Zenith angle to give maximum solar flux on the surface.

then have only 87 % of the flux on a surface tilted toward the sun. To face the sun, the horizontal surface must be tilted an amount equal to the zenith angle, which is 90° minus 60° altitude angle, or 30°. When the altitude angle is much less, the effect of the horizontal surface not facing the sun is even greater. For example, when altitude angle is 25°, the horizontal surface receives only 42% of the flux received by a surface perpendicular (*normal*) to the sun's rays, or tilted 65° from the horizontal.

The second effect comes from the fact that when the sun is not directly overhead, the rays must pass through more distance of atmospheric layer to reach the ground, resulting in more atmospheric attenuation. For example, when altitude angle is 30°, the longer path through the atmosphere results in another 15% or so reduction in solar flux compared to overhead sun. Note, the reduction in flux caused by the surface not aimed at the sun can be corrected by tilting the surface so that the solar rays hit the surface perpendicularly, as shown at the right of the figure above.

Solar time is measured from *solar noon*, when the observer's earth meridian passes under the sun. In other words, solar noon is when the sun is directly south (north) in the northern (southern) hemisphere. Within any time zone, at some longitude, the difference between solar time and local clock time can be calculated or measured by observing at what time the sun is directly south.

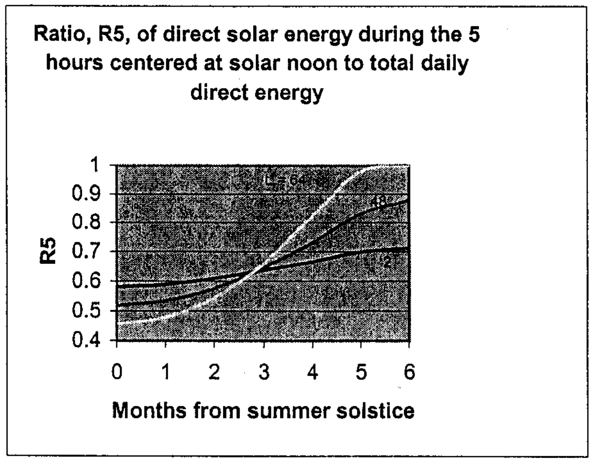
Latitude on the earth. North and south positions on the earth are measured by latitude angle, L, going from -90° at the south pole, to zero at the equator, to +90°at the north pole. Horizontal surfaces at different latitudes at any given time have different solar altitude angles, which affect the solar flux on the surface. In the region of the earth between L = +23.5° and –23.5° (the torrid zone), the sun can be directly overhead ($\alpha = 90°$) at noon for certain times of the year. North of latitude 23.5° or south of latitude –23.5° the sun is never directly overhead.

Date of the year. The axis of the earth's rotation is tilted about 23.5° with respect to the plane of revolution around the sun. In one revolution around the sun (one year) the angle of solar rays to a horizontal surface changes. The summer solstice (approximately June 21 for northern and December 21 for the southern hemisphere) is the day when the noon sun has greatest altitude (outside of the torrid zone), and is the day with longest time of sunlight.

Altitude of location. Higher altitudes on the earth have a thinner layer of atmosphere for solar rays to travel through, so other things being equal, less of the extraterrestrial solar flux would be absorbed and scattered before hitting a surface on the ground, and the flux at ground level would be higher for higher elevations. For the first few kilometers of increasing elevation above sea level, the solar flux increases about 190 W/m^2 for every kilometer [ref: Meinel]

Meteorological conditions. All of the above influences on solar power can be fairly accurately calculated or known, however at any location and time, local meteorological conditions (clouds, dust, rain) have a great effect on solar power available for cooking. Fortunately, measurement stations have been placed at many places around the world, as well as in satellites, and have measured daily solar radiation and provided a data base. [For example, The Atmospheric Sciences Data Center (ASDC) at NASA Langley Research Center, http://eosweb.larc.nasa.gov/sse/] Often solar radiation data is presented as a total solar energy per unit area for one day, expressed in units such as kilowatt hours per m^2 per day or mega joules per m^2 per day, or similar units. The solar cook is more interested in solar power, kW per m^2, that would likely be available during the hours of the day when cooking is done, not a daily average. Taking, for example, the five hours centered at solar noon, the total direct solar energy received in those five hours can be calculated [using hourly data from Hsieh, J.S., Solar Energy Engineering, Prentice Hall, 1986] as a fraction of the daily total direct radiation. This fraction depends on latitude and month and is shown in the graph below. Here the period of five hours is arbitrarily taken as representative as the most likely time period for solar cooking.

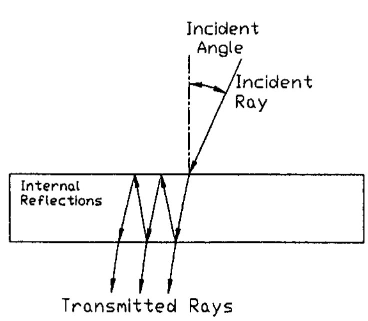
For example, the ASDC data for Ahmadabad, India (latitude L = 23°) for August, 1993 (two months from summer solstice) gives a solar energy of around 6 kWh per m^2 per day. From the figure we find R_5 = 0.6, so about 0.6 of this energy occurs in the five hours between 9:30 AM and 2:30 PM (solar time). The *average* solar flux for the five hour period is then 0.6 times 6 kW h/m^2 per day divided by 5 hours, resulting in 720 W/m^2.
Use of historical solar data is only an indication of what solar flux might be encountered in the future.



*2.3 Solar radiation through transparent covers

Many solar collector devices, including solar cookers, often have a transparent cover which transmits solar radiation into the device to become absorbed at a surface. The purpose of the cover is to lessen the heat loss from the cooker by enclosing hot air and preventing the escape of thermal radiation from inside the cooker, yet still allow a solar radiation input to the cooker. Not every cooker needs a cover, as for example a concentrator cooker could direct a sufficiently high flux directly to a pot without an intervening cover material. Not all of the solar flux hitting a transparent cover gets through the cover because of two effects, (1) internal absorption of radiation within the cover material, and (2), multiple refractions (bending) and reflections of the radiation as it meets the interface between the air and the cover material, both on the outside and inside air/cover interfaces. Both of these effects depend on the angle that the radiation hits the cover. The fraction of the incoming solar flux that gets through the cover is called *transmittance*, τ, (sometimes *transmissibility*). The ideal value of τ would be 1, when all of the radiation transmits through the cover.

As radiation passes through the cover material, some of it is absorbed and transformed into heat. Internal absorption depends on a property of the cover material, called the *extinction coefficient* (units of cm^{-1}, e.g.). Absorbed radiation depends on the total



distance traveled through the cover material, as well as the extinction coefficient.

When radiation travels from one medium (e.g., air) to another (e.g., glass) at some angle of incidence, there is a complicated series of reflections and refractions (bending) at each interface. At each of the multiple reflections, some radiation comes back toward the incident radiation and therefore does not get transmitted and some radiation goes through the cover to the cooker. The physical property governing this phenomenon is the index of refraction (air = 1.0). Since the multiple reflections between the inner and outer interfaces of the cover also are accompanied by travel through the material, internal absorption acts to reduce the total radiation transmitted.

The table at the right gives the effective transmittance for some cover materials, for the case when the incident radiation is perpendicular to the cover. White glass, with low iron content, has less internal absorption than ordinary glass. The plastic films have higher extinction coefficients than glass, but the film thick nesses used are usually much less than glass thickness, so the energy absorbed in the thin plastic film may be less than for thicker glass. The fraction of the energy absorbed in the cover material is not a total loss because the heat generated in the cover acts to reduce the heat loss through the cover.

Material	Thickness	Transmittance
Window Glass	0.32 cm(1/8 in.)	0.83
White Glass	0.32 cm(1/8 in.)	0.91
Polyethylene	0.025 cm(0.01 in.)	0.88
Polyethylene	0.013 cm(0.005 in.)	0.90
Mylar	0.025 cm(0.01 in.)	0.84
Teflon	0.025 cm(0.01 in.)	0.95

Transmittance is a function of the wavelength of the radiation, and the above discussion and table refer to wavelengths corresponding to solar radiation. The issue is more complicated for incident radiation that is at an incident angle greater than zero, i.e., not perpendicular to the cover surface. For incident angles up to about 55°, the transmittance is not much different from perpendicular incidence, but at angles greater than this, the transmittance drops drastically. This effect may be observed by shining a flashlight through a window as the incident angle is slowly increased. At large incident angles, the light beam does not penetrate. A transparent cover may be coated with a different transparent material that has an index of refraction between the values for air and the cover. Such a coating is an *antireflection coating* and may increase the transmittance.

In addition to solar radiation passing through the cover, on its way to a pot or absorber, there is so-called *thermal* radiation (also called *infrared*) passing from inside the cooker back out into the atmosphere. Thermal radiation is generated by the objects (pot, absorber, etc) inside the cooker and is characterized by the temperature of those objects and a property *emissivity* (ranging from near zero to near 1) which characterizes how well those objects emit radiation. A perfect emitter, called a "black body" has an emissivity of 1. As an example of thermal radiation, consider an object at 100 °C with emissivity of 1.0. The surface of the object would radiate flux at a rate 1100 W/m^2. For an object at 100 °C with low emissivity of 0.05 (corresponding to polished aluminum, e.g.), the flux would be 55 W/m^2. These not insignificant flux values for thermal radiation show that the transmittance for thermal radiation should be low so as to "trap" the thermal radiation inside the cooker.

An ideal cover material would have a low transmittance for thermal radiation as well as high transmittance for solar radiation. Even though all radiation is spread over all wavelengths from very short to very long, most of the energy of a radiating body has a range of wavelengths wherein most of the energy of radiation lies. For example, solar radiation has about 70% of its energy in the range of wavelengths 0.3 to 1.0 micrometers, while thermal radiation for a body at 100 °C has about 60% of its energy in the range 5 to 14 micrometers (microns). Because of this disparity in wavelengths corresponding to most energy, cover materials can have different transmittance for solar radiation than for thermal radiation. Low transmittance for thermal radiation (long wavelengths) and high transmittance for solar radiation (shorter wavelengths) is sometimes termed the *greenhouse* effect. (However a real greenhouse works by the cover acting as an air trap, keeping the heated air inside the greenhouse.)

The transmittance of many plastic materials is greatly dependent on wavelength of radiation, and the graph of transmittance versus wavelength has peaks and valleys from radiation from interactions with the complex molecular structure. The table at right gives a rough average for the average transmittance of several materials for the range of wavelengths of thermal radiation.

Material	Thickness (mm)	Thermal Transmittance
Glass	0.71	0
Plexiglass	1.5	0
Fiberglass	1	0
Polycarbonate	1.2	0.01
Polyethylene	0.13	0.7
Polypropylene	0.13	0.6
Tedlar	0.5	0.4
Mylar	0.13	0.1
Kapton	0.13	0.1

*2.4 Thermal Insulation

The schematic diagram of a box cooker at the right [figure not done yet]is a good system to examine the role of thermal insulation. In any cooker, input power (radiation) enters and as the cooker gets hotter than the surrounding environment, heat power is lost because of the temperature difference. Cooking occurs faster or at higher temperatures if the heat loss is lessened. Wall heat loss represents heat transfer through a material by virtue of a temperature difference between the inside (cooking volume) and the outside (surroundings). For the following discussion, the temperature difference is called ΔT, and the rate of heat loss is Q_{loss} (e.g., watts). The cooker wall area contributing to heat loss is A_c.

The heat loss rate is simply described as

$$Q_{loss} = A_c \ \Delta T / R \quad \text{or} \quad Q_{loss} = U A_c \ \Delta T$$

The quantity R is *thermal resistance* (°C per W/m^2, e.g.), and its reciprocal U = 1/R is called the *conductance* (W/m^2 per °C, e.g.) both of which are in use in the literature. Thermal resistance may be thought of as the ratio of temperature difference across the wall to the heat flux (W/m^2, e.g.) through the wall. Note that a lower area A_c would decrease Q_{loss}, but the surface area of the cooker may be determined by required size volume, etc. ΔT is fixed by cooking temperature and ambient temperature and is not easily controllable. Therefore a construction of wall material with high thermal resistance (low conductance) is called for. The thermal resistance of a material, such as the wall of a box cooker, arises from the thickness of the wall and the materials making up the wall. The thicker the wall, the more resistance to heat flow. The material property that governs the ability of a material to conduct heat is the *thermal conductivity*, k (watt/m °C, e/g.) The table at right gives typical values of thermal conductivity for various materials. The thermal resistance, R, as defined above for any of the materials listed in the table is the thickness of that material divided by the thermal conductivity. These are representative values only, as actual values depend on how tightly packed is the material, actual composition, etc. Metals have high conductivity and are conductors, not insulators. Aluminum metal for example has a thermal conductivity of about 200 W/m °C, depending on the alloy.

Material	Thermal Conductivity W/m C
Air	0.03
Foam, Polyurethane	0.03
Fiberglass	0.04
Corkboard	0.04
Wool Felt	0.05
Cotton	0.06
Sawdust	0.06
Paper	0.18
Wood	0.1-0.2
Sand	0.3
Plaster	0.5
Glass	0.8
Dry Soil	1
concrete	1.04

Materials with low conductivities are often porous in nature, with air in the pores, meaning that the low conductivity of air is partly responsible for the low conductivity of the porous material. A wall may be constructed with an inner and an outer sheet of rigid material, with an air space between. If the air space is made as large as, say 10 cm. (0.1 m), the resulting R value would be less than that obtained by dividing conductivity of air in the table above by the thickness of 0.1 m., because of air currents in the space. Naturally occurring air currents in the space assists in transferring heat, effectively reducing the thermal resistance over the case of a stagnant air space. A smaller air space would inhibit the air circulation, but of course then the thickness is less also. The thickness of air gap which gives the most resistance depends on the wall orientation, overall size, and temperatures, and is typically 1 to 2 cm. for small cookers. In order to inhibit air circulation in a thicker air space, the space between the rigid sheets can be filled with a porous low conductivity filler material that inhibits the air circulation. Walls of cookers have been constructed with filler materials of straw, crumpled newspaper, cardboard sheets, and many other readily available porous materials. [ref: Pejack]

In addition to heat conduction through the wall, there is also thermal radiation through the wall material when the material is porous. Reflective surfaces inhibit the radiation transfer, and cooker insulated walls are often lined with aluminum foil for this purpose.

*2.5 Solar absorption

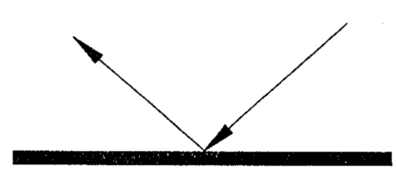
In order to get heat, or temperature rise of food in a cooker, solar radiation must at some point become absorbed by a surface. When radiation hits an opaque surface, some of the energy is reflected back, and some is absorbed. The absorbed radiation manifests as a heat input at the surface. The fraction of the incident radiation that is absorbed is termed *absorptance*, α (sometimes called *absorptivity*). The absorptance of surfaces depends on the wavelength of the radiation, and therefore absorptance for solar radiation (short wavelengths) is different from absorptance for thermal radiation (longer wavelengths). For an absorber surface, such as the food pot in a cooker, it is desired to have a high value of absorptance, say 0.9 and above. If the surface absorptance is very low, say 0.1, the surface would in effect be a reflector. The absorptance depends not only on the surface material, but its surface finish and oxidation as well. Recalling that any surface emits its own thermal radiation, depending on its temperature and emissivity, it makes sense that the temperature of an absorbing surface depends not only on its solar absorptance but also the emissivity of that surface for thermal radiation. That is to say, a surface that absorbs solar radiation well and emits thermal radiation poorly will get hotter than a surface with the same solar absorptance but higher emissivity, ε, for its thermal radiation. Hence, the ratio of α to ε is indicative of the relative temperature of surfaces exposed to solar radiation. The table at right [ref: Mills, Cengel] gives the solar absorptance, α, and ratio of *solar* absorptance to *thermal* emissivity, a/ε for some surfaces encountered in solar applications.

Surfaces that tend to get hot in the sun, those with high values of a/ε, are called *selective surfaces*. The reader may have noticed that the surface of a black car (α/ε =1.) feels hotter in the sun than a white car (α/ε = 0.3). A surface treatment applied to an absorber surface to make it selective will result in a higher net radiation input. The selectivity of the surface may degrade with time and wear.

Surface	Absorptance α	α/ε
Black chrome deposited on aluminum or steel	0.94-0.97	5.-10.
Black nickel deposited on steel	0.9	6.
Black paints	0.90-0.98	1.
Stainless steel, sandblasted	0.85	2.
Stainless steel, dull	0.5	2.4
Titanium, oxidized	0.8	4.
Copper, oxidized black	0.9	6.
Concrete	0.6	0.8
Aluminum, anodized	0.14	0.2
Aluminum, polished	0.1	3.

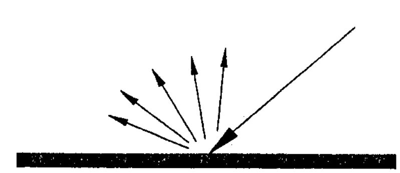
*2.6 Reflection

The direct solar rays, or beam radiation, coming from the direction of the sun comprise most of the solar energy on days when one would be solar cooking. The smaller fraction of solar energy, as discussed earlier, is the diffuse radiation caused by scattering of sunlight in the atmosphere. In the present discussion we consider only the direct solar radiation.



Specular Reflection

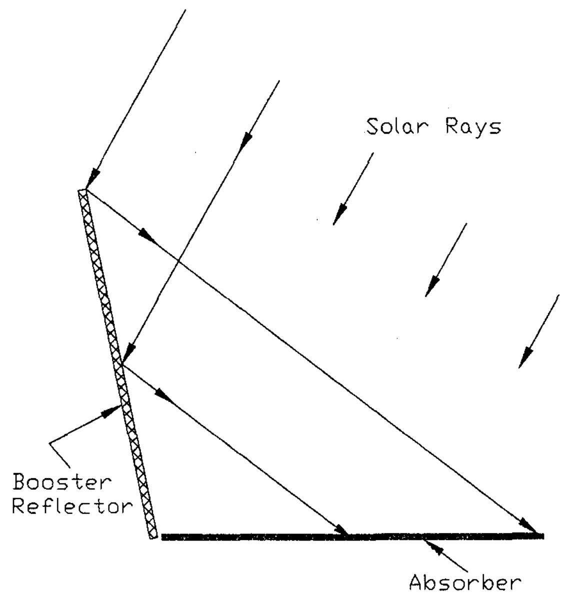
Reflectors are used in cookers to increase the amount of radiation flux to an absorber surface or food pot. When radiation strikes a reflecting surface, some of the reflected radiation will still be beam radiation, directed at an angle such that the reflected ray has the same angle with the



Diffuse Reflection

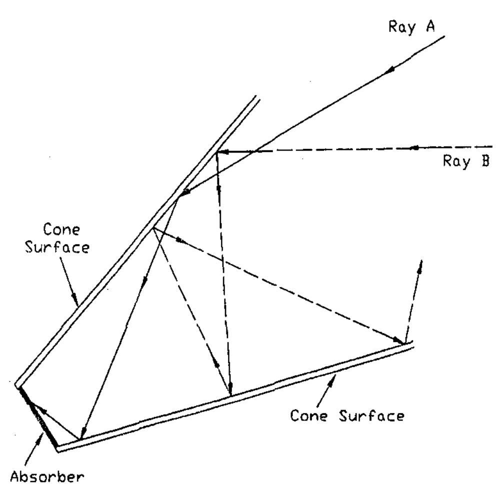
perpendicular to the surface as the incident ray. In other words, the angle of incidence is equal to the angle of reflection, and this is sometimes called *specular* reflection. For a "mirror" reflector most of the incident beam reflects as specular reflection. Any image in the incident radiation is preserved in the reflection. For a non-mirror like reflector, the reflected rays are distributed over many angles, and the reflection is called *diffuse*. The surface appears "matte", and an image is not preserved in the reflection. Specular and diffuse reflections are illustrated in the figure. In both cases, some small fraction of the incident flux may not be reflected at all. The reflectance of a surface may be defined as the fraction of the incident flux that is reflected as both beam and diffuse (*total reflectance*), or may be defined also as the fraction of the incident beam that is reflected as beam radiation only (specular). Generally, a good reflector would have a high total reflectance (over 90%) and generally be mostly specular rather than diffuse. In the following discussion, we consider only the specular or beam reflection.

Plane, or flat reflectors are the simplest type of reflector and when optimized, that is, adjusted for certain angles, can maximize the flux arriving at a target. The total flux arriving at the target is increased, or "boosted" by the booster reflectors over and above the flux received with no reflectors. The flux hitting the absorber (or cover) with booster reflectors divided by the flux without reflectors is called the *concentration ratio*. The diagram at right shows a booster reflector that is angled with respect to the solar rays at the angle so that the maximum amount of solar power is reflected to the absorber. As the angle of the solar ray changes, the booster would have to be adjusted to continue to reflect the maximum solar power to the absorber. The booster reflector and absorber shown has a concentration ratio of about 1.6, assuming the reflectance of the booster is nearly 1. That means the absorber is receiving 60% more radiation than it would without the booster.



Booster reflector set at angle to maximize flux to a horizontal absorber or window.

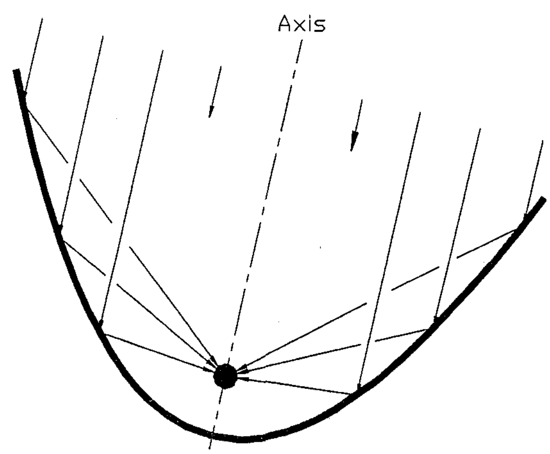
Conical reflectors have the useful property called *developable*, that is, a conical surface can be made from a flat surface without distorting the surface when folding into a cone. (A sheet of paper can be folded into a cone surface without wrinkling or tearing the



Cone concentrator. Ray A (solid line) hits the absorber. Ray B (dashed line) is turned back.

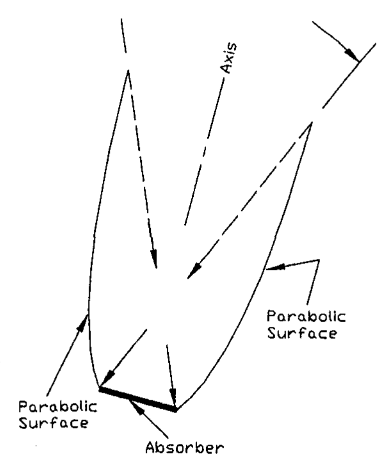
paper, and illustrates the developable property of a cone.) Not all of the solar rays entering the cone opening (*aperture*) hit the target absorber. The included angle of the cone, incident angle of solar rays, size of the aperture, size of target, and fraction of solar flux hitting the target are all geometrically related. The diagram shows two rays A and B at different angles with respect to the cone axis (cone centerline). Ray A is nearly parallel to the axis and is reflected inside the cone and hits the absorber. Ray B is not nearly parallel to the axis and the diagram shows that after several internal reflections, the ray is turned back without hitting the absorber.
The developable property and simplicity of the cone and the achieving of some concentration have been exploited in some cookers.

A parabolic reflector in the true sense is a surface made by either revolving a parabolic curve around its axis or by moving a parabolic curve perpendicular to its plane resulting in a "*parabolic trough*". Either case is shown in the figure. When the incident rays and parabolic axis are parallel, all the reflected rays hit a point in the case of a paraboloid of revolution (so-called three dimensional parabolic reflector), or a line in the case of a trough (two dimensional parabolic reflector). The point or the line is called the *focus* of the parabola. Note that the parabolic trough is developable. If the surface is not tracked so that the axis is not always parallel to the solar rays, the target becomes not a point or a line but a finite volume. For a cooker, if the target volume is the absorber or pot, the situation of the rays not concentrating at a point or line may be satisfactory or even desirable. Large concentration ratios associated with parabolic reflectors result in intense flux at the focus that may be harmful to human skin or eyes, or burn pots. Generally parabolic surfaces are turned *(tracked)* so that the solar rays are parallel to the axis or nearly so. When the axis of the parabolic reflector is not aligned with the solar rays, the concentration ratio is significantly reduced. Parabolic surfaces have been approximated by slats or narrow strips of reflector surface.



Parabolic reflector. All rays entering parallel to the axis reflect to the focus.

Interesting variations of parabolic surfaces are compound parabolic concentrators (CPC). A three dimensional CPC is made by inclining a parabola curve from its axis, then rotating the parabola about the concentrator axis (not parabola axis). A two



A compound parabolic concentrator (CPC). Rays entering within the acceptance angle are reflected to the absorber.

dimensional CPC is a trough where each side is a part of two parabolas, inclined to each other. The configuration shown at right depicts either case. The desirable characteristic of a CPC is that all solar rays entering the aperture that are within the direction of the acceptance angle will reflect to the absorber. When part of both branches of a parabola curve (e.g., left branch and right branch) are used in a CPC, the resulting surface has a "cusp". CPC reflectors have the property that when the incoming solar rays are not parallel to the CPC axis, but still within the acceptance angle of the CPC, all of the incoming rays reflect to the absorber, and the concentration ratio is not reduced. The simple parabolic reflector is required to have its axis be very nearly oriented parallel to the solar rays to achieve high concentration. CPC are a class of nonimaging reflectors because the image of the source of rays is not preserved on the target. Details of the geometry of CPC reflectors may be found in ref. [Welford & Winston].

*2.7 Energy balance and efficiency of solar cookers

A solar cooker is essentially an unsteady thermal device, unlike, for example a flat plate solar collector heating water. In a flat plate solar collector for hot water, the temperature of the cold water entering and hot water leaving are relatively constant; an efficiency can easily be defined as the rate of energy picked up by the circulating water divided by the power of the solar radiation falling on the collector area. Such an efficiency would be between 0 and 100%.

In the cooker, initially cold material (food and pot) begins to receive heat, and the temperature begins to rise. As time goes on, the rate of temperature rise slows, and eventually the temperature closely approaches a steady (constant) temperature. The cooker is kept at this temperature for an additional time sufficient to cook the food. When the solar flux varies during the heating up or cooking time periods, that contributes even more to the unsteady nature of the solar cooking process.

In the following discussion of the heat and temperatures in a cooker, the cooker is modeled with the following simplifying assumptions:

> The mass M being heated is characterized as having a uniform temperature T
>
> The heat loss from the cooker is equal to the temperature difference $\Delta T = (T - Ta)$ divided by the thermal resistance R of the cooker.
>
> Evaporation and associated energy loss is neglected.

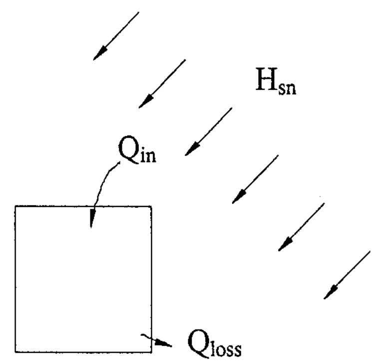
The following defined quantities are assumed constant:

H_{sn} = the solar flux (W/m^2) on a surface normal to the solar rays
A_i = the area of solar rays intercepted by the cooker
A_c = cooker area that is losing heat due to temperature difference between inside cooker and ambient
M = mass being heated
C_p = heat capacity (specific heat, kJ/kgC) of mass M
T_a = ambient temperature
R = thermal resistance $°Cm^2$/Watt of the cooker area Ac

Also the following symbols are defined as:

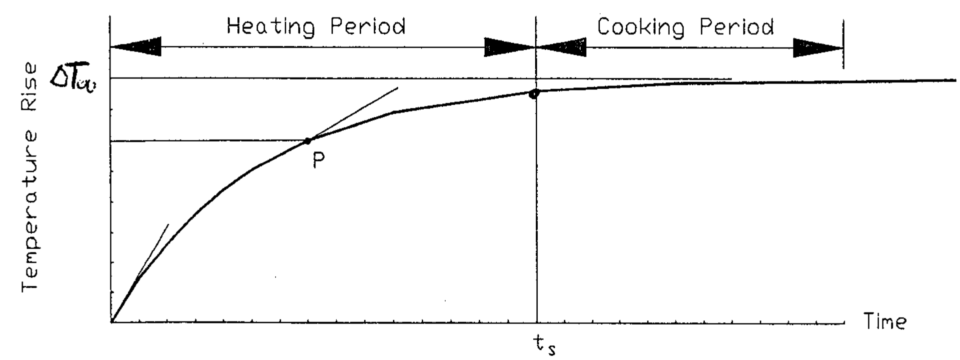
Q_{in} = heat rate into the mass being heated (watt, e.g.)
Q_{loss} = heat rate lost to ambient = $A_c \Delta T / R$ (watt, e.g.)

From an energy conservation standpoint, the difference between input power Q_{in} and power loss Q_{loss} goes into the mass M and produces a rate of temperature rise. If we take the assumption that at initial time the mass M has the same temperature as the ambient (surrounding) temperature Ta, then initially, the heat loss is zero. As the mass M heats up, the loss rate Q_{loss} increases until $Q_{loss} = Q_{in}$, and then the temperature will have practically reached the maximum steady temperature difference, ΔT_∞. During the heating up period then, the heat loss quantity increases from zero to a maximum value of Q_{in}. Based on the assumed model, the resulting graph of temperature difference ΔT plotted against time appears as shown below. The temperature difference ΔT approaches a maximum steady value of ΔT_∞ after a sufficiently long time, where



$$\Delta T_\infty = R\, \eta_o\, H_{sn}\, A_i / A_c$$

Since the heat rate into the mass M decreases with time as the heat loss rate increases, the maximum temperature ΔT_∞ is only gradually approached.



We can arbitrarily define a time t_s and a corresponding temperature ΔT_s where the mass M has reached 95% of its final temperature rise. (It may be recognized by some that the 95% of ΔT_∞ condition is compatible with the passage of three *time constants*.) The time period can then be conveniently thought of as a heating up period (of time period 3 times RMC_p/ A_c), and a subsequent cooking period at relatively constant temperature. When cooking food with appreciable water and evaporation (which this simplified model does not simulate), evaporation of water effectively fixes the maximum temperature at the boiling point of water (100 C at standard atmospheric pressure).

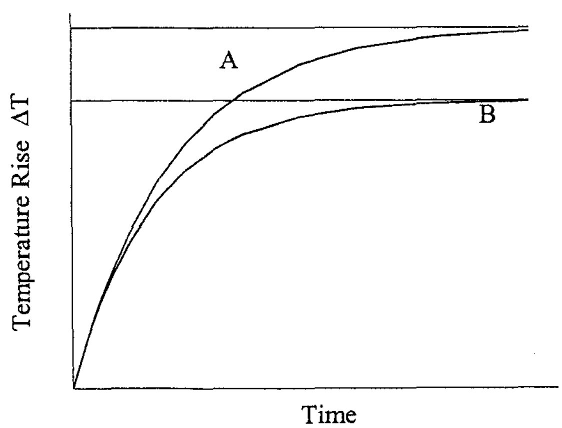
It is often convenient to characterize a system with an efficiency, similar to that mentioned above for a flat plate solar water heater. Efficiencies in general can be defined in several ways, and typically an efficiency compares actual performance with maximum possible performance. Efficiency in general then ranges from 0 to 100% with the desired value being as high as possible, consistent with constraints. Since A_i is the intercepted area of sunlight, at a solar flux of H_{sn}, then $A_i H_{sn}$ is the power input to the cooker.

Consider taking the ratio of net power received by the mass M, at any time, divided by the solar power input, as the basis for a definition of efficiency. During the cooking period, when ΔT is practically constant, the mass M is not receiving a net heat input, so efficiency would be zero by that definition. The solar radiation is only maintaining the heat loss, not heating the mass M further. The maximum heating rate occurs at initial time t = 0, and heat loss is zero then because the temperature of mass M and ambient temperature are the same ($\Delta T = 0$). Let us call this initial rate of temperature rise = Φ_0. An efficiency defined as the ratio of initial heat rate into the mass M divided by the intercepted solar power would be a measure of how well the cooker transfers the incoming solar radiation to the mass M, and would have a value between zero and 1. This ratio or efficiency can be called the *optical efficiency*, η_o. In terms of quantities defined above,

$$\eta_o = M\, C_p\, \Phi_0 / (H_{sn} A_i)$$

To measure the optical efficiency of a cooker, the temperature rise could be measured continuously to achieve a T versus time plot as shown. The slope of the curve at t = 0 is defined as Φ_0; then by knowing the mass M and its specific heat, the solar power, and the area of solar radiation intercepted, the optical efficiency can be obtained by the equation above.

The ability of a cooker to actually cook depends on the ability to conserve heat as it heats up (high thermal resistance, R) as well as having a good optical efficiency. For two cookers, identical except one having a high thermal resistance and the other a lower thermal resistance, the initial rate of heating Φ_0 will be the same, but the low resistance cooker will come to a lower final maximum temperature as shown in the curves at right.

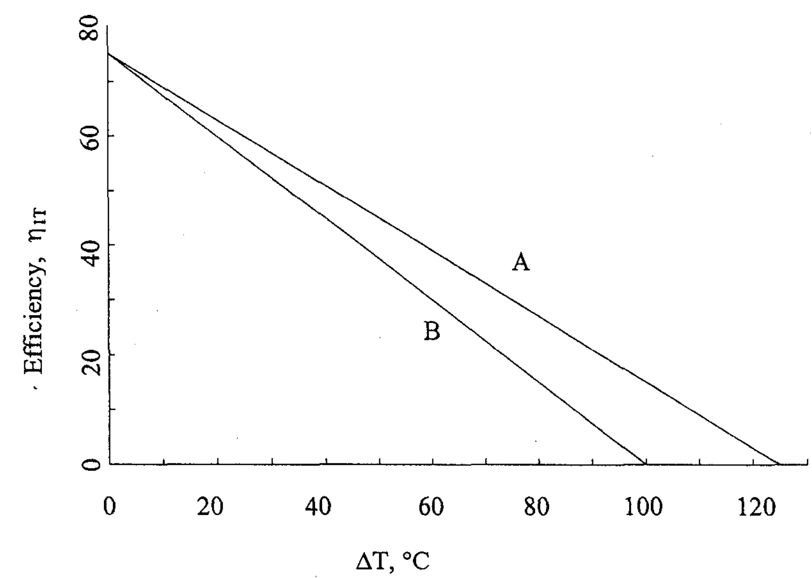


Temperature rise versus time for two cookers with identical conditions except thermal resistance. Cooker B has 0.8 of the thermal resistance of cooker A. The final ΔT of B is 0.8 that of A, but B reaches 95% of its final ΔT in 20% less time. Both curves have the same slope at zero time and therefore same optical efficiency.

In order to characterize the performance of a cooker in a way that measures its heat retention ability (thermal resistance), some value of temperature must be specified. In the graph of T versus time above, an arbitrary temperature rise of ΔT is out chosen. At this point on the curve, labeled point P, the heat rate is observed as being the slope of the curve at that point times the product of mass M and specific heat C_P. The heat rate at this temperature is less that the initial heat rate. Taking the ratio of this heat rate divided by the solar power intercepted by the cooker, the result is an efficiency, η_{1T}, based on a specific value of temperature rise. Subscript T indicates that the efficiency is specified as pertaining to a certain temperature rise. A cooker can then be characterized by an efficiency at any specific temperature rise ΔT as long as ΔT is less than ΔT_∞. The efficiency η_{1T} is given by

$$\eta_{1T} = \eta_o \exp(- A_c\, t / R\, M\, C_p) = [\, 1 - \Delta T/\Delta T_\infty]$$

If the efficiency is plotted against temperature rise, it will be equal to the optical efficiency at $\Delta T = 0$, and decrease to zero at the maximum temperature achieved, as shown. At $\Delta T = 100$ C, cooker A has an efficiency of 20%, meaning that at 100 C temperature rise it still is heating to higher temperature, while cooker B has a zero efficiency, meaning that it has reached its maximum temperature.



Efficiency η_{1T} versus ΔT for cookers A and B. At $\Delta T = 0$ both have efficiency equal to an assumed optical efficiency of 75%. At any ΔT, cooker A has a higher efficiency.

An efficiency η_{2T} could also be defined as the heating rate at any temperature rise divided by the initial heating rate, resulting in

$$\eta_{2T} = \exp(- A_c\, t / R\, M\, C_p) = \eta_{1T} / \eta_o$$

This efficiency η_{2T} then is an indication of ability to retain heat and is independent of optical efficiency, and ranges from 100% at initial time, decreasing to zero as ΔT_∞ is approached.

Two other figures of merit in use for cookers are F_1 and F_2 [Garg, 2 nd Conference, Balasubramaniam, 3 rd Conference]. If a cooker is set up with no mass M to be heated (*no load*), and allowed to come to a constant final temperature called the *stagnation temperature*, the temperature rise from ambient temperature to stagnation temperature divided by the solar flux on a *horizontal* surface is defined as the first figure of merit, F_1. Note that F_1 depends on the units used (e.g., °C m^2 per watt). Since at stagnation temperature all the heat input to the cooker is equal to the heat loss, figure of merit F_1 is proportional to the optical efficiency defined above times the cooker heat loss resistance, R.

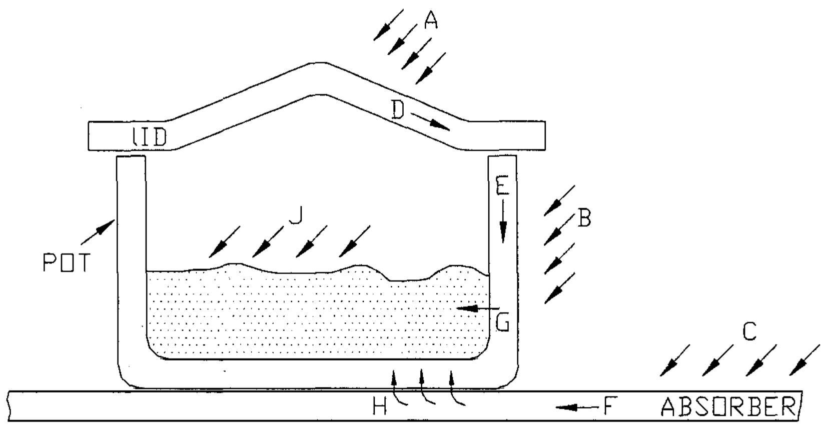
For the second figure of merit, F_2, the cooker is loaded with a known mass (pot, food) and the time required to heat from a specified lower temperature to a specified higher temperature is measured. F_2 (units of power, e.g., kW) is a measure of the heating power in that temperature range. Figure of merit F_2 is a measure of the cooker's ability to retain heat (high resistance or low conductance) as well as the optical efficiency. F_2 depends on the values of the lower and higher temperature differences used in the determination.

The various efficiencies and figures of merit discussed above may have a usefulness when comparing performance of different cookers, or evaluating design changes on a cooker. The ultimate merit of a cooker however is in achieving an adequate cooking temperature within a satisfactory time, with a useful mass. In evaluating the performance of, for example, an automobile, not only efficiency of fuel consumption (miles per gallon) is to be considered, but also many other factors such as cruising speed, top speed, fuel consumption with different loads, acceleration, cargo capacity, etc. are taken into account when determining the merit. Similarly with evaluating the merit of any cooker, the values of an efficiency or figure of merit must be consider along with satisfactory cooking performance for a range of food mass, solar flux, cooking time, cooker size and shape, structural integrity, and other factors.

*2.8 Cookware

In a pot being heated over a fire or electric hot plate, heat enters the bottom of the pot and conducts to the bottom of the food inside the pot. The sides and lid of the pot do not have a major role in heat transfer. Since the heat transfer is primarily through the bottom, sometimes the pot bottom is constructed in a way to facilitate heat transfer, such as being plated with high conductivity copper, or having small grooves.

In many solar cooking applications, the heat input is much different. A pot in a hypothetical solar heating environment is shown in the figure. Solar rays may be hitting the lid, becoming absorbed, and the heat then conducts along the lid at D, across the gap to the pot sides, then down the pot sides at E and to the food at G. In this mode, the thickness and conductivity of the pot material, and the thermal resistance of the lid-pot gap govern the heat transfer. High thermal conductivity of the pot and lid material and thick pots and lids contribute to good heat conduction from D to E to G. If there is not good thermal contact between lid and pot, this may contribute to a thermal resistance and inhibit conduction from lid to pot.



A cook pot. Solar rays may be absorbed at the lid at A, on the side at B, at an absorber plate at C, or in the case of a transparent lid, directly at the food at J. Heat conducts along the lid at D, down the pot wall at E, along the absorber at F and into the food at G and H.

When rays hit the sides of the pot at B and are absorbed, heat is conducted down the pot wall at E and into the food at G. Again, a good conducting pot wall helps the heat transfer. The thermal path from E to G in the wall is shorter than the case from lid at D to food at G, so heat transfer from solar rays at B to the food may be more effective than from solar rays at A to the food. The relative area of the intercepted rays at A and at B must also be considered, since the lid and sides of pot may be intercepting different amounts of solar energy. A question may be posed about the optimum height of a pot, above the level of the food. If the pot is tall, the conduction path length from lid to food is increased, inhibiting heat transfer. However, a tall pot offers more area at the sides for increased absorption at B. The optimum pot height would depend on the pot material, thickness, radiation flux, areas of lid and sides, and heat loss by air convection.

In some cases the pot may be sitting on an absorber surface which is absorbing radiation. This is the case for example in a box cooker when the bottom of the box is an absorber surface. In the figure, rays at C are absorbed and conduct horizontally in the absorber to H, then conduct into the pot. The absorber material must have sufficient thermal conductivity with sufficient thickness so that there is not much temperature drop along the absorber. The gap between pot and absorber should have good thermal contact so that it does not offer a conduction resistance to the heat transfer. The underside of the absorber should be an insulating surface to prevent heat loss downward.

In cases where the lid is transparent, radiation may pass directly to the food surface at J, eliminating the thermal resistance from D to E to F. Problems that may be encountered here would be water condensation on the inside of the lid which would interfere with solar transmittance of the lid. Another concept for a lid is the floating lid, directly on the food. Radiation would be absorbed on the lid and directly transferred to the food in contact below.

As discussed in the section on solar absorption earlier, the use of pot and lids with high absorptance is necessary. The net heat transferred to the pot may also be enhanced by pot and lid surfaces that are selective surfaces.

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