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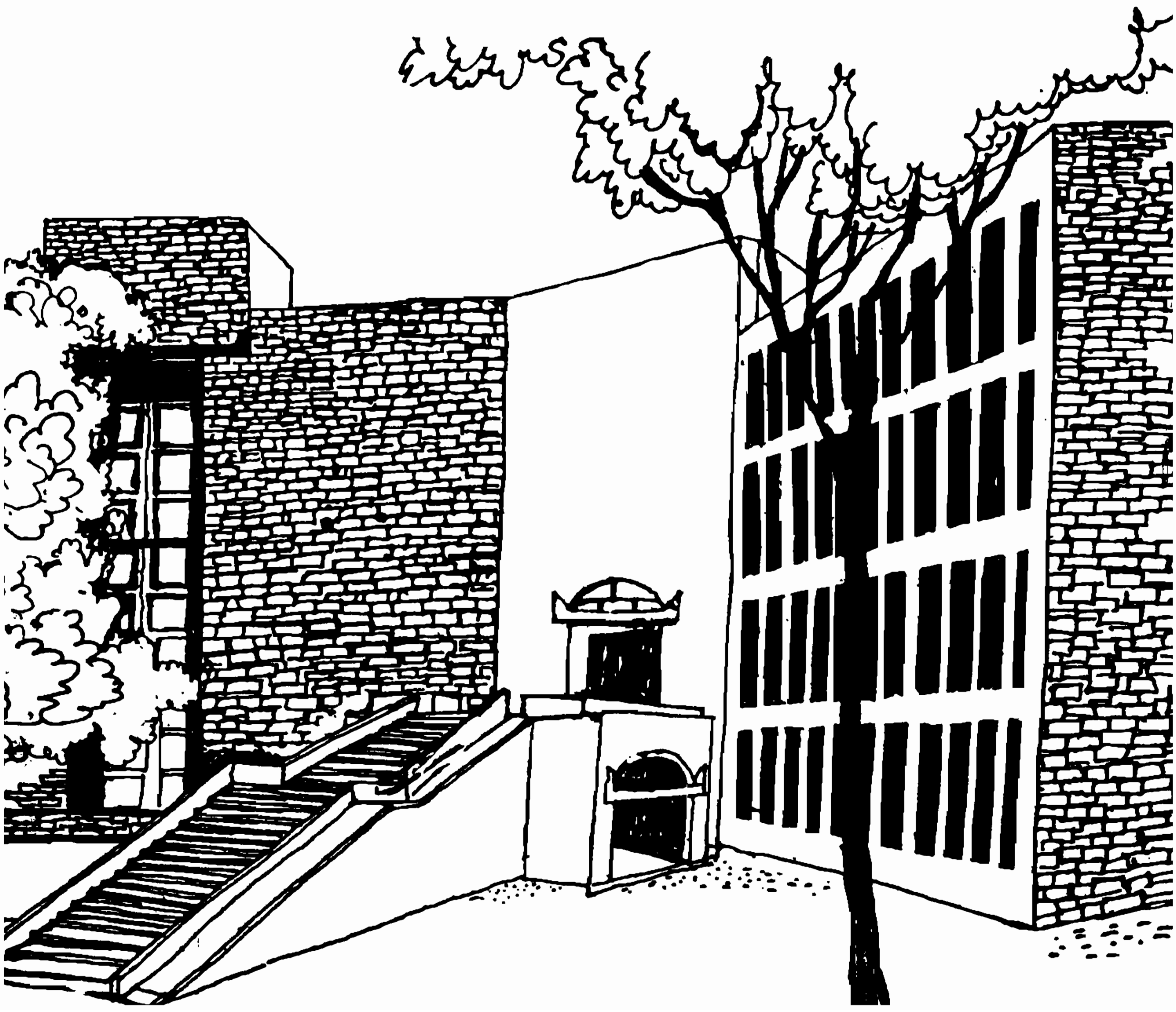

ESTIMATING STRENGTH OF ELECTRICAL BACK-UP FOR BOX SOLAR COOKER USING SIMULATION

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Abstract

In this paper we use simulation to estimate the strength of back-up needed in Ahmedabad region to make the box cooker usable throughout the year. A lumped parameter model is made of double glazed cooker marketed in Gujarat. Its performance is simulated using climatic data of Ahmedabad during August, when insolation is the lowest. Simulations are done on an empty cooker, placed on horizontal surface at 8 A.M. Plate and cover temperatures are tracked till 4 P.M. at interval of less than a minute. Unassisted cooker will fail to be of use in August, because plate temperature rises very slowly and does not reach 120°C, considered necessary. A back-up of 50 W is found necessary to make the cooker perform satisfactorily in August, and hence in other months. This will keep the cooker essentially a slow cooking solar device as it is.

Keywords: Box cooker simulation, electrical back-up

Need for a Back-up

Box solar cooker (cooker for short) was launched in Gujarat in the late seventies. Gujarat could be rated as a region of high potential for cookers, characterized as it is by high insolation, high ambient temperatures, low cloud cover, and widespread shortage of fuel-wood. However, the total number of cookers sold till the year 1994 was only about 35,000 units, and sales appeared to be levelling off. This suggested that further improvements may now be needed.

A survey was, therefore, carried out in and around Ahmedabad city to identify new features users may desire and equally importantly, be willing to pay for. Conjoint analysis of feedback from actual and potential users revealed three features that may significantly enhance the acceptability--provision of back-up source, doneness indicator, and stainless steel vessels (Naik and Sharan [1]). These findings led us to begin developing cooker with new features, in particular with an electrical back-up. Though, it is not quite desirable that electricity be used for such purposes as cooking, we hope, provision of back-up will lead to fuller use of cookers.

Cookers with electrical back-up are indeed available in the market. Some of these have back-up sources of 500 W or even more. Intuitively, this appears unnecessarily high at least for Gujarat. This is shown by the work of Patel and Patel [2], who determined experimentally that strength of about 125 W was adequate. Their work was done in the month of April at Vallabh Vidyanagar (Gujarat). We have not come across any published analytical procedure by which source strength could be estimated for a given region. It was therefore decided to develop one.

Procedure reported in this paper was devised specially, in order to retain the cooker essentially as a solar device, with back-up just sufficient to help it achieve cooking temperatures in periods when insolation as well as ambient temperatures become low in Ahmedabad region. A lumped parameter model of heat transfer processes in a double glazed cooker is made. Reflector, though commonly provided in cookers, has been excluded. This has been done in order to get a conservative value of back-up strength. Simulations are done using climatic data of Ahmedabad and parameters of cooker approved by Gujarat Energy Development Agency (GEDA).

Heat Transfer Processes

A list of symbols is given below.

Let

I_h	Insolation (global) on horizontal surface (W/m^2)
T_p, T_{c1}, T_{c2}, T_a, T_s	Temperatures of absorber plate, glass covers, ambient air and sky (°K)
α_p, e_p	Absorptivity and emissivity of plate, dimensionless
α_{c1}, α_{c2}, e_{c1}, e_{c2}	Absorptivity and emissivity of glass covers, dimensionless
τ	Transmissivity (solar) of glass, dimensionless
$(\tau\alpha_p)_e$	Transmissivity-absorptivity product effective for two-cover system
$(mc)_p$,	Heat capacity of absorber plate (J/°K)
$(mc)_{c1}$, $(mc)_{c2}$	Heat capacity of glass covers (J/°K)
h_{pc1}	Convective heat transfer coefficient between plate and first cover (W/m^2K)

h_{c1c2}	Convective heat transfer coefficient between first and second cover (W/m^2K)
h_w	Convective heat transfer coefficient between top cover and atmosphere (W/m^2K)
U_b, U_s	Bottom and side loss coefficient (W/m^2K)
σ	Stefan-Boltzman constant (W/m^2-$°K^4$)
F_{p-c1}	View factor from plate to first cover, dimensionless
F_{c1-c2}	View factor from first to second cover, dimensionless
A_p, A_{c1}, A_{c2}, A_b, A_s	Areas of absorber plate, glass covers, bottom and side (m^2)
k	Thermal conductivity of insulation (W/m°K)
d	Thickness of insulation (m)
N_u, R_a	Nusselt and Rayleigh numbers, dimensionless
T	Time
V	Wind speed (m/s)

Figure 1 gives a schematic cross section of a typical cooker.

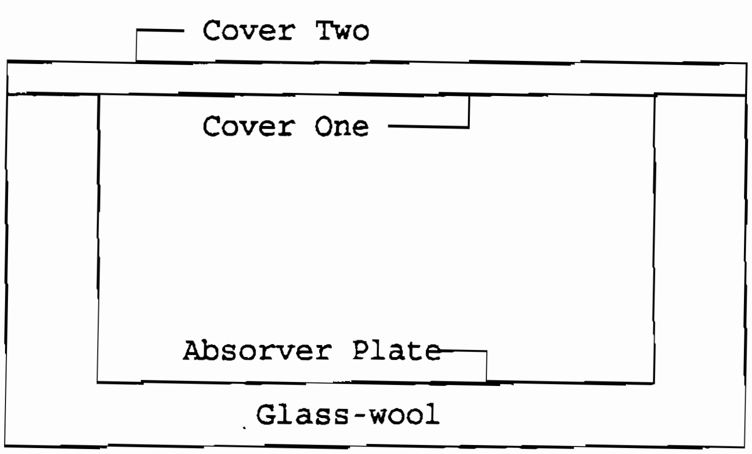

Figure 1: Schematic Section of Double-glazed Cooker

Heat balance on plate

$$(mc)_p \frac{dT_p}{dt} = A_p(\tau\alpha)_e I_h - \frac{\sigma\left(T_p^4 - T_{c1}^4\right)}{\left(\frac{1-e_p}{e_p A_p} + \frac{1}{F_{p-c1} A_p} + \frac{1-e_{c1}}{e_{c1} A_{c1}}\right)} - A_p h_{pc1}\left(T_p - T_{c1}\right) - A_b U_b\left(T_p - T_a\right) - A_s U_s\left(T_p - T_a\right) \quad (1)$$

First term on the right is heat gain by plate by absorption of radiation coming through two-cover system. second heat loss through radiation back to the first cover, third heat loss to first cover by convection, fourth heat loss through bottom and fifth heat loss through sides by conduction. For radiative transfer from plate to first cover, these two surfaces are treated as aligned rectangles of finite dimension.

First Cover

$$(mc)_{c1} \frac{dT_{c1}}{dt} = A_{c1}\tau\alpha_{c1} I_h + \frac{\sigma\left(T_p^4 - T_{c1}^4\right)}{\left(\frac{1-e_p}{e_p A_p} + \frac{1}{F_{p-c1} A_p} + \frac{1-e_{c1}}{e_{c1} A_{c1}}\right)} + A_p h_{pc1}\left(T_p - T_{c1}\right) - A_{c1} h_{c1c2}\left(T_{c1} - T_{c2}\right) - \frac{\sigma\left(T_{c1}^4 - T_{c2}^4\right)}{\left(\frac{1-e_{c1}}{e_{c1} A_{c1}} + \frac{1}{F_{c1-c2} A_{c1}} + \frac{1-e_{c2}}{e_{c2} A_{c2}}\right)} \quad (2)$$

First term on the right is heat gain by absorption of radiation passing through second cover, second heat gain through radiation from plate, third heat gain from plate by convection, fourth heat loss to top cover by convection, and fifth heat loss to top cover by radiation.

Second Cover

$$(mc)_{c2} \frac{dT_{c2}}{dt} = A_{c2}\alpha_{c2} I_h + \frac{\sigma\left(T_{c1}^4 - T_{c2}^4\right)}{\left(\frac{1-e_{c1}}{e_{c1} A_{c1}} + \frac{1}{F_{c1-c2} A_{c1}} + \frac{1-e_{c2}}{e_{c2} A_{c2}}\right)} + A_{c2} h_{c1c2}\left(T_{c1} - T_{c2}\right) - A_{c2} e_{c2}\,\sigma\left(T_{c2}^4 - T_s^4\right) - A_{c2} h_w\left(T_{c2} - T_a\right) \quad (3)$$

First term on the right is heat absorbed by second cover from sun, second heat gain by radiation from first cover, third heat gain by convection from first cover, fourth heat loss to atmosphere by radiation and fifth heat loss to surroundings by convection.

Specifications of Cooker

Specifications of cooker approved by GEDA are given below [3].

Weight (kg)	12.5	**Insulation thickness**
Outer dimension (cm)	52 X 52 X 15	Bottom (cm) 5
Casing material	Aluminium sheet	Side (cm) 5
Glass covers		(Material: Glass-wool)
- Second cover (cm)	47 X 47 X 0.30	
- First cover (cm)	43.5 X 43.5 X 0.30	
Gap between covers (cm)	2	
Absorber tray (cm)	44 X 44 X 8	
- Plate thickness (mm)	1	

Heat Transfer Coefficients

Estimates of the convective heat transfer coefficient between the plate and first glass cover, first and second glass cover was made using Holland's correlation [4].

$$N_u = 1 + 1.44\left[1 - \frac{1708}{R_a}\right]^{+} + \left[\left(\frac{R_a}{5830}\right)^{1/3} - 1\right]^{+}$$

$$h = \frac{N_u\, k}{d}$$

Exponent (+) indicates that only positive values of the quantity in brackets is to be used, set to zero, if negative. As stated, for the radiative transfer from plate to glass cover, the two surfaces have been treated as aligned rectangular opaque and diffuse. Treating the glass cover as opaque simplifies the computation without introducing significant error since the transmissivity of glass in the infrared range is very small. Convective heat transfer coefficient from second cover to atmosphere is obtained by following relation. Wind speed has been taken to be 1 m/s.

$$h_v = 5.7 + 3.8\, V$$

Parameters used in Simulation

$(mc)_p$	829 J/°K (m = 894 g; c = 0.927 J/g°K)
$(mc)_{c1}$	1225 J/°K (m = 1532 g; c = 0.8 J/g°K)
$(mc)_{c2}$	1431 J/°K (m = 1789 g; c = 0.8 J/g°K)
A_p	0.1936 m^2 (44 X 44 cm)
A_{c1}	0.1892 m^2 (43.5 X 43.5 cm)
A_{c2}	0.2209 m^2 (47 X 47 cm)
A_b	0.1936 m^2
A_s	0.1408 m^2 (4 [44 X 8 cm])
τ_g	0.85 (τ_{c1}, τ_{c2} = τ_g)
α_g	0.08 (α_{c1}, α_{c2} = α_g)
e_g	0.88 (e_{c1}, e_{c2} = e_g)
α_p	0.93
e_p	0.93
$(\tau\alpha)_e$	0.806 (for two-cover system, from Duffie and Beckman, p.231, equation 6.9.10)
σ	5.669 X 10^{-8} W/m^2°K^4
h_{pc1}	2.1 W/m^2°K
h_{c1c2}	4.12 W/m^2°K
h_w	9.5 W/m^2°K
U_b	1.04 W/m^2°K
U_s	1.04 W/m^2°K
F_{pc1}	0.72 (from catalogue)
F_{c1c2}	1 (from catalogue)
k	0.052 W/m°K (glass wool)
d	5 cm (side and bottom equal)

Climatic Data of Ahmedabad

Solar radiation in Ahmedabad reaches its lowest in August. We therefore selected August for determination of back-up strength. Data of ambient temperature and global radiation on horizontal surface was taken from Mani **[5]**. This data was converted into Fourier series shown below **[6]**. Respective Fourier coefficients are shown in **tables 1 and 2**. **Figures** 2 and 3 show Fourier representation graphically.

$$T_a = A_0 + \sum_{m=1}^{n} \left(A_m \operatorname{Cos}(m \frac{\pi}{12} t) + B_m \operatorname{Sin}(m \frac{\pi}{12} t) \right)$$

$$I_h = A_0 + \sum_{m=1}^{n} \left(A_m \operatorname{Cos}(m \frac{\pi}{12} t) + B_m \operatorname{Sin}(m \frac{\pi}{12} t) \right)$$

where
- t — time in hours, midnight being the origin
- A_m, B_m — Fourier coefficients with units of quantity on left-hand side
- n — number of harmonics

Table 1
Fourier Coefficients for Air Temperature Series: AHMEDABAD

	n	0	1	2	3	4	5	6
August	A	28.03	-1.12	0.12	0.02	0.03	0.01	-0.03
	B		-2.07	0.50	0.06	-0.10	-0.03	0.04

Table 2
Fourier Coefficients for Global Solar Radiation Series: AHMEDABAD

	n	0	1	2	3	4	5	6
August	A	185.88	-287.54	117.54	-2.73	-17.17	0.91	3.58
	B		-45.99	40.92	-5.92	-9.38	0.55	5.17

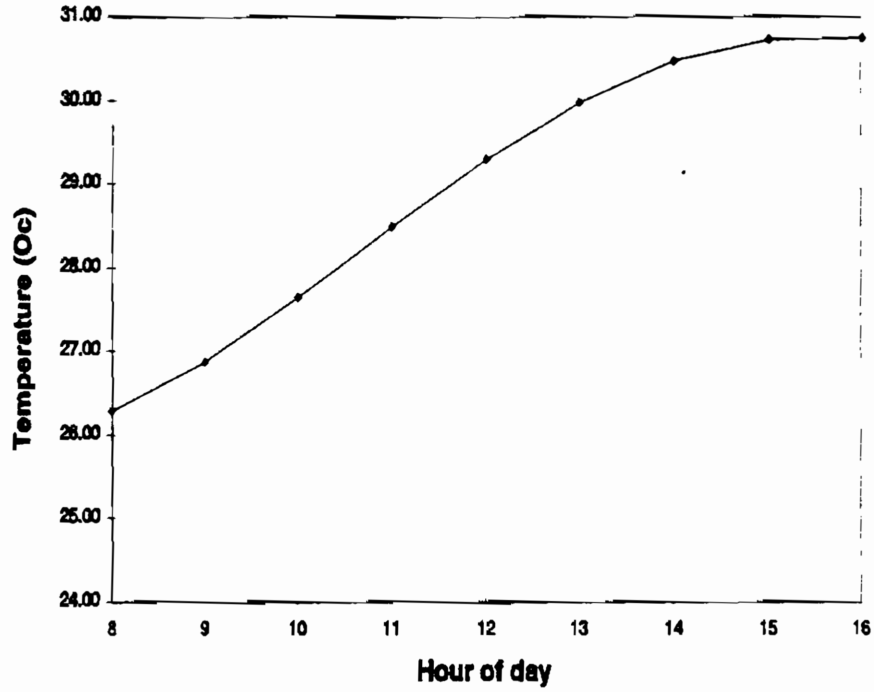

Figure 2: Ambient temperature at Ahmedabad (August)

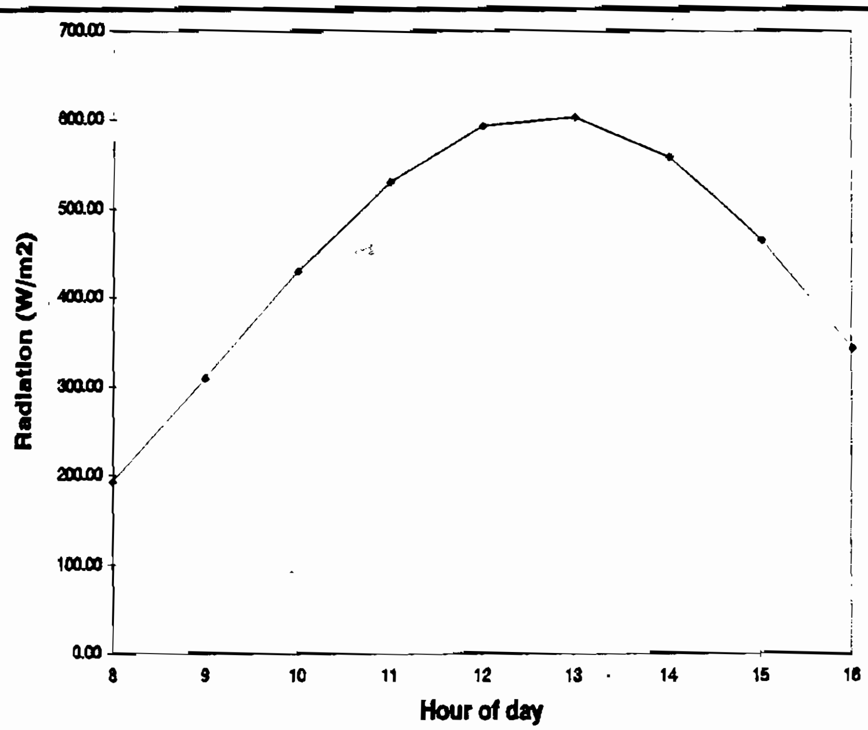

Figure 3 - Global solar radiation at Ahmedabad (August)

Simulation: Required Strength of Back-up

An empty cooker, with all its components at temperature equal to that of the ambient air, is placed outdoors on horizontal surface at 8:00 A.M. **Equations 1, 2 and 3** are integrated numerically to yield plate and cover temperatures, as the day advances. Simulations were done in DYNAMO, a continuous systems simulation package. Integration was done using Euler method with interval of integration as 0.01 hrs.

Figure-4 shows the temperature and time graph of the plate on an average day in August. Note the maximum temperature achieved is only 119°C. Moreover, this temperature is reached only after 12 noon, leaving very little time to do the cooking. A good cooker is expected to produce stagnation temperature upwards of 120°C, considered necessary for satisfactory performance. This result corresponds well with feedback we received from cooker users in Ahmedabad, who stated that during this part of the year the cooker fails to work satisfactorily.

Let us assume now that the cooker has been provided with a back-up source of strength, S. It is assumed to be automatically turned on when the plate temperature falls below a given level, say, T_d and is off otherwise. Presence of such a feedback controlled back-up can be accounted for by adding the following term on right hand side of **Equation-1**.

$$S = \frac{W}{2} + \frac{W}{2}\,\mathrm{Sign}(T_d - T_p)$$

where W power of back-up source (watts)

T_d stagnation temperature desired, here 120°C

Sign signum function

With a source of 50 W, plate temperature reaches (120°C) by 9:30 A.M. (**figure-4**). Thus, a back-up of 50 W is adequate to make the present cooker usable through out the year in Ahmedabad region, during the hours solar cooking is presently done, in fact even a little earlier. We shall call this a **`all-days-of-year cooker'**.

Increasing the strength above 50 W helps only in extending the span of time during the day when stagnation temperature of 120°C can be achieved and maintained. For instance, a strength of 75 W (not shown) enables plate temperature to reach 120°C as early as 8:30 A.M. We can call this a **`all-hours-of-day cooker'**.

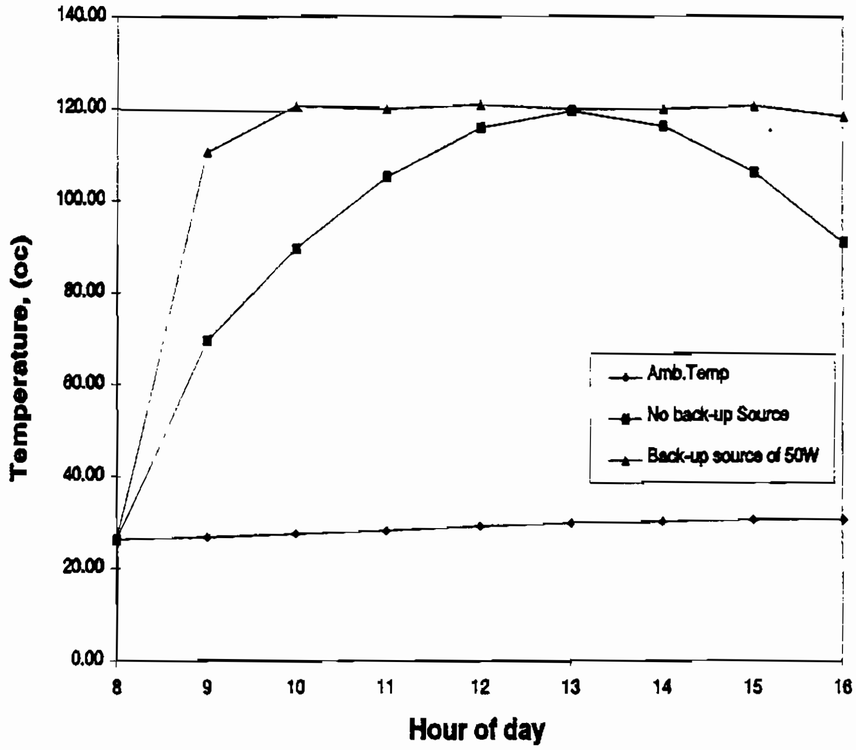

Figure 4 - Plate Temperature
(Simulated for Ahmedabad - August)

Table 3 Cooker Indoor	
Back-up Strength (W)	Max. Temperature Attained (°C)
100	120
150	155
200	185
300	235
400	275
500	313

Cooker Indoor

Simulations were also done with insolation reduced to zero ($I_h = 0$) and the ambient temperature set to a constant 26°C to mimic indoor conditions. **Table-3** shows the temperature achieved with source strength from 100 W to 500 W. It would require at least about 100 W to reach stagnation temperature of 120°C. A cooker with such a back-up source, can be called a fall back device.

Two points must be kept in view. First, above estimates are conservative inasmuch as reflect or has been excluded. On the other hand, these magnitudes are for the additional power made available, to the plate. Integrating a heating element to the plate will entail some loss which has not been included here.

Conclusion

It is obvious, that the strength of back-up required will differ from region to region. A little less apparent is the fact that it will also depend on whether the cooker is to be all-days-of-year device, **all-hours-of-day device** or also a (fall-back) indoor device for days when it is not possible to place it outdoors such as on rainy days.

Simulations suggest that a source of about 50 W can make the cooker all-days-of-year device around Ahmedabad. Increasing the strength to 75 W can enable the cooker to be used in the early mornings and late afternoons as well. Strength will need to be increased further to about 100-150 W to make it a fall-back device.

Back-up source of above magnitude will keep the cooker essentially a slow cooking solar device and not turn it into a fast electrical oven.

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