The efficient collection and long term storage of solar energy in the UK, using air as the working fluid

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The efficient collection and long term storage of solar energy in the UK, using air as the working fluid

Thesis submitted for the degree of Doctor of Philosophy in Energy Research at the Open University, September 1984

Volume 2

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Nomenclature
Chapter 2

$A_C$  Collector area (m$^2$)
$A_S$  Storage tank surface area (m$^2$)
$c$  Appropriate specific heat (J Kg$^{-1}$ °C$^{-1}$)
$c_p$  Volume heat capacity at constant pressure (J Kg$^{-1}$ °C$^{-1}$)
$C_h$  Initial capital expenditure per house (£)
$E_T$  Total (accumulated sum) of the radiation falling over a time period of one month on an inclined surface which is above the threshold radiation (J m$^{-2}$)
$f$  Differential fuel inflation
$F_h$  Fuel cost per year per house (£)
$F_R$  Collector/heat-exchanger efficiency factor
$F'$  Collector efficiency factor
$i$  Discount rate
$I_{th}$  Threshold solar irradiance (W m$^{-2}$)
$K_h$  Repeated capital expenditure per house (£)
$L$  Monthly total heating demand for space heating and hot water (J)
$L_s$  Energy lost from storage tank during the month (J)
$MC$  Storage heat capacity (J °C$^{-1}$)
$N$  Lifetime of hardware (years)
$n$  Number of years
$P_{VC_h}$  Present value cost per house
$Q$  Heat energy (J)
$Q_N$  Net heat transferred to storage during the month (J)
$Q_T$  Solar energy collected during the month (J)
$R_h$  Running costs per year per house (£)
$s$  Pebble shape factor
$T_a$  Ambient temperature (°C)
$T_{at}$  Ambient temperature averaged over periods when the radiation level is above the threshold (°C)
$T_g$  Monthly average ground temperature (°C)
$T_s$  Store temperature (°C)
$ar{T}_s$  Monthly average store temperature (°C)
$T_{so}$  Store temperature at the beginning of the month (°C)
\( \Delta T \)  Temperature change (°C)

\( t_m \)  Total number of seconds in a month

\( t_t \)  Total number of seconds collector is in operation in month, i.e. when radiation level is above threshold

\( U_L \)  Collector overall loss coefficient (W m\(^{-2}\) °C\(^{-1}\))

\( U_S \)  Storage tank heat loss coefficient (W m\(^{-2}\) °C\(^{-1}\))

\( V \)  Volume (m\(^3\))

\( \rho \)  Density (kg m\(^{-3}\))

\( \overline{(\tau \alpha)} \)  Monthly average transmittance-absorptance product
Nomenclature
Chapter 3

\( A_C \)  Collector area (m²)
\( F_R \)  Collector heat-exchanger efficiency factor
\( f \)  Fraction of monthly total demand met by solar energy
\( H_T \)  Monthly average daily radiation incident on the collector surface per unit area (Jm⁻²)
\( L \)  Monthly total heating demand for space heating and hot water (J)
\( N \)  Days in month
\( T_a \)  Monthly average ambient temperature (°C)
\( T_{\text{ref}} \)  An empirically derived reference temperature (100° C)
\( t_m \)  Total number of seconds in a month
\( U_L \)  Collector overall loss coefficient (Wm⁻² °C⁻¹)
\( \tau \alpha \)  Monthly average transmittance-absorptance product
**Nomenclature**

**Chapter 4**

A  Aperture area, or transparent frontal area of collector (m²)

Cₚ  Specific heat of transfer fluid at constant pressure (Jkg⁻¹ °C⁻¹)

Dₜ  Characteristic length (m)

F'  Absorber plate (or collector) efficiency factor

Fₚ  Collector heat removal factor

g  Acceleration of gravity (ms⁻²)

h₁  Convective heat transfer coefficient, duct top to heat transfer fluid (Wm⁻² °C⁻¹)

h₂  Convective heat transfer coefficient, duct base to heat transfer fluid (Wm⁻² °C⁻¹)

hᵣ  Radiative heat transfer coefficient (Wm⁻² °C⁻¹)

hₖ  Wind heat transfer coefficient (Wm⁻² °C⁻¹)

H  Duct height (m)

I  Equivalent normal solar irradiance (Wm⁻²)

k  Thermal conductivity (Wm⁻¹ °C⁻¹)

L  Collector length (m)

m  Mass flow rate of transfer fluid (Kg s⁻¹)

Nu  Nusselt number

Pr  Prandtl number

Qu  Energy per unit time, useful (W)

Ra  Rayleigh number

Re  Reynolds number

T₁  Duct top, temperature (°C)

T₂  Duct base, temperature (°C)

Tₐ  Ambient air-temperature (°C)

Tₖ  Cover temperature (°C)

Tₑ  Exit fluid temperature (°C)

Tᵢ  Inlet fluid temperature (°C)

Tₘ  Mean fluid temperature (Tₑ + Tᵢ)/2 (°C)

Tₚ  Average absorber temperature (°C)

Uₘ  Bottom loss heat transfer coefficient (Wm⁻² °C⁻¹)

Uₑ  Edge loss heat transfer coefficient (Wm⁻² °C⁻¹)

Uₗ  Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)
$U_t$ Top loss heat transfer coefficient (Wm$^{-2} \cdot ^\circ C^{-1}$)

$V$ Wind velocity (ms$^{-1}$)

$W$ Collector width (m)

$x$ Insulation thickness (m)

$\alpha$ Absorptance of the collector absorber surface for solar radiation

$\beta$ Volume thermal expansion coefficient (K$^{-1}$)

$\epsilon_c$ Cover emissivity

$\epsilon_p$ Absorber plate emissivity

$\eta$ Efficiency

$\mu$ Absolute (dynamic) coefficient of viscosity (Kg m$^{-1} \cdot$ s$^{-1}$)

$\rho$ Density (Kgm$^{-3}$)

$\tau$ Transmittance of the solar collector

($\tau \alpha$) The product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance

$\sigma$ Stefan-Boltzmann constant
Nomenclature

Chapter 5

A  Aperture area, or transparent frontal area for collector (m$^2$)

$A_c$  Collector area (m$^2$)

$c_p$  Volume heat capacity at constant pressure (J/Kg$^{-1}$°C$^{-1}$)

$P'$  Absorber plate (or collector) efficiency factor

$P''$  Collector flow factor

$P_1$  Correction factor for partial shading of the collector

$P_2$  Correction factor for variation of $\tau_a$ with the angle of incidence

$P_3$  Correction factor for variation in optical properties from normal for diffuse irradiance

$P_R$  Collector heat removal factor

$h_w$  Wind heat transfer coefficient (W/m$^2$°C$^{-1}$)

$I$  Equivalent normal solar irradiance (W/m$^2$)

$I_b$  Direct solar irradiance in plane of collector (W/m$^2$)

$I_d$  Diffuse solar irradiance in plane of collector (W/m$^2$)

$I_m$  Measured total solar irradiation incident upon the aperture plane of the collector (W/m$^2$)

$m$  Mass flow rate of transfer fluid (Kg s$^{-1}$)

$m_t$  Mass flow rate of leak (Kg s$^{-1}$)

$M$  Fluid capacity of collector (Kg)

$(mc)_e$  Effective heat capacity of collector (J °C$^{-1}$)

$q$  Output power per unit aperture area conveyed by the heat transfer fluid (W/m$^2$)

$Qu$  Energy per unit time, useful (W)

$(Qu)_t$  Energy per unit time under transient conditions (W)

$r$  Correlation coefficient

$t$  Time (s)

$T_a$  Ambient air temperature (°C)

$T_b$  Average back plate temperature (°C)

$T_e$  Exit fluid temperature (°C)

$T_f$  Average temperature of the fluid in the collector (°C)

$T_i$  Inlet fluid temperature (°C)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{in}$</td>
<td>Measured fluid inlet temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Mean fluid temperature ($T_e + T_i)/2$ ($^\circ$C)</td>
</tr>
<tr>
<td>$T_p$</td>
<td>Absorber plate temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Mean absorber temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{sky}$</td>
<td>Equivalent black body sky temperature ($^\circ$C)</td>
</tr>
<tr>
<td>$T^*$</td>
<td>Reduced temperature $(T_i - T_a)/I$ ($m^2 \cdot ^\circ$C w$^{-1}$)</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Collector overall heat transfer (loss) coefficient ($Wm^{-2} \cdot ^\circ$C$^{-1}$)</td>
</tr>
<tr>
<td>$V$</td>
<td>Wind velocity ($ms^{-1}$)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
</tr>
<tr>
<td>$\tau_\alpha$</td>
<td>Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>Collector time constant under flow conditions (s)</td>
</tr>
<tr>
<td>$\tau_d$</td>
<td>Cut off time (s)</td>
</tr>
<tr>
<td>$(\tau_\alpha)_e$</td>
<td>Effective transmittance absorptance product</td>
</tr>
<tr>
<td>$(\tau_\alpha)_n$</td>
<td>Product of the absorptance and transmittance for normal irradiance</td>
</tr>
<tr>
<td>$\Delta T^*$</td>
<td>Time increment</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of incidence; degrees from normal</td>
</tr>
</tbody>
</table>
Nomenclature

Chapter 6

\( P_R \) Collector heat removal factor

\( h_{p-c} \) Convection coefficient between absorber plate and cover (Wm\(^{-2}\cdot\text{C}^{-1}\))

\( h_{rp-c} \) Radiation coefficient between absorber plate and cover (Wm\(^{-2}\cdot\text{C}^{-1}\))

\( h_{rc-a} \) Radiation coefficient from the cover to sky (Wm\(^{-2}\cdot\text{C}^{-1}\))

\( h_w \) Wind heat transfer coefficient. (Wm\(^{-2}\cdot\text{C}^{-1}\))

\( I \) Equivalent normal solar irradiance (Wm\(^{-2}\))

\( I_{\text{th}} \) Threshold solar irradiance (Wm\(^{-2}\))

\( T_a \) Ambient air temperature (°C)

\( T_i \) Inlet fluid temperature (°C)

\( U \) Collector heat loss coefficient \( P'U_L \) (Wm\(^{-2}\cdot\text{C}^{-1}\))

\( U_L \) Collector overall heat transfer (loss) coefficient (Wm\(^{-2}\cdot\text{C}^{-1}\))

\( \varepsilon_t \) Thermal emissivity

\( \eta \) Efficiency steady state

\( \bar{\eta} \) Daily averaged efficiency

\( \eta_o \) Zero loss collector efficiency, \( P'(\alpha \tau) \)

\( \tau_s \) Solar transmissivity

\((\tau\alpha)\) Product of the absorptance and transmittance for normal irradiance
Nomenclature

Chapter 7

A  Aspect ratio or area of main heater
a  Accommodation coefficient
\( \bar{c} \)  Average velocity of molecules (m s\(^{-1}\))
c\(_p\)  Specific heat at constant pressure (J Kg\(^{-1}\) °C\(^{-1}\))
c\(_v\)  Specific heat at constant volume (J Kg\(^{-1}\) °C\(^{-1}\))
d  Molecular diameter (m)
D\(_h\)  Hydraulic diameter (m)
g  Acceleration of gravity (m s\(^{-2}\))
Gr  Grashof number
h  Combined heat transfer coefficient from absorber to cover (W m\(^{-2}\) °C\(^{-1}\))
h\('\)  Heat transfer coefficient of material of known conductivity (W m\(^{-2}\) °C\(^{-1}\))
h\(_b\)  Heat transfer coefficient for flow across panel wall (W m\(^{-2}\) °C\(^{-1}\))
h\(_c\)  Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (W m\(^{-2}\) °C\(^{-1}\))
h\(_p\)  Heat transfer coefficient for flow across panel (W m\(^{-2}\) °C\(^{-1}\))
h\(_r\)  Heat transfer coefficient for flow across the inside of the panel due to radiation (W m\(^{-2}\) °C\(^{-1}\))
h\(_s\)  Heat transfer coefficient for flow across standard insulation (W m\(^{-2}\) °C\(^{-1}\))
k  Thermal conductivity (W m\(^{-1}\) °C\(^{-1}\))
L  Linear dimension (m)
m  Wall molecule mass (Kg)
m\('\)  Gas molecule mass (Kg)
M  Mass of one mole (kg mol\(^{-1}\))
N\(_A\)  Avogadro's number
Nu  Nusselt number
p  Gas pressure (Nm\(^{-2}\))
P\(_c\)  Critical pressure when \( R_a = R_a c \)
Pr  Prandtl number
q  Power dissipated in central heater (W)
\( Q \) 
Energy per unit time, rate of heat supply to main heater (W)

\( Q_p \) 
Rate of heat supply to panel from main heater (W)

\( r \) 
Specific gas constant (R/M)

\( R \) 
Gas constant

\( Ra \) 
Rayleigh number

\( Ra_c \) 
Critical Rayleigh number, for \( Ra < Ra_c \) no convection, \( Nu = 1 \)

\( Re \) 
Reynolds number

\( s \) 
Absorber plate to cover separation (m)

\( t \) 
Panel wall thickness (m)

\( T \) 
Average of plate and cover temperature (°C)

\( T_1 \) 
Inside panel temperature nearest to cold plate (°C)

\( T_2 \) 
Inside panel temperature nearest to main heater (°C)

\( T_g \) 
Guard ring temperature (°C)

\( T_i \) 
Temperature of main heater, also fluid inlet temperature (°C)

\( T_0 \) 
Temperature of cold plates (°C)

\( \alpha \) 
Thermal diffusivity (m² s⁻¹)

\( \beta \) 
Thermal volume expansion coefficient (= 1/T for a perfect gas), (K⁻¹)

\( \gamma \) 
\( \frac{C_p}{C_V} \)

\( \Delta \theta \) 
Hot plate temperature unbalance (\( T_i - T_g \)), (°C)

\( \Delta T \) 
Temperature difference across panel (°C)

\( \varepsilon_1 \) 
Emissivity of surface at temperature \( T_1 \) (°C)

\( \varepsilon_2 \) 
Emissivity of surface at temperature \( T_2 \) (°C)

\( \mu \) 
Viscosity (Pa s)

\( \nu \) 
Kinematic viscosity (\( \mu/\rho \)) (Pa s m³ Kg⁻¹)

\( \rho \) 
Density (Kg m⁻³)

\( \sigma \) 
Stefan-Boltzmann constant (Wm⁻² K⁻⁴)

\( \lambda \) 
Mean free path (m)
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[18] Duffie, J.A. and Beckman, W.A.

[19] Larson, D.C.
TABLE 2.1 Energy input by fuel and sector in Petajoules for U.K. low grade heat needs (≤80°C) for 1976 and 2025 as predicted by Leach [1]

<table>
<thead>
<tr>
<th>Sector</th>
<th>Fuel</th>
<th>Total 1976</th>
<th>Total 2025</th>
</tr>
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<tr>
<td></td>
<td>Solid</td>
<td>Liquid</td>
<td>Gas</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space and Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>1976</td>
<td>-</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Engineering and other metal trades</td>
<td>1976</td>
<td>17.2</td>
<td>71.4</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>32.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Chemical &amp; Allied Trades</td>
<td>1976</td>
<td>0.8</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Food, Drink &amp; Tobacco</td>
<td>1976</td>
<td>3.2</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Textiles, Leather &amp; Clothing</td>
<td>1976</td>
<td>5.1</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.6</td>
<td>4.2</td>
</tr>
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<td>Paper, Printing &amp; Stationary</td>
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<td>1.9</td>
<td>5.4</td>
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<td></td>
<td>2025</td>
<td>1.7</td>
<td>0.3</td>
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<td>Building Materials</td>
<td>1976</td>
<td>0.9</td>
<td>4.6</td>
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<td></td>
<td>2025</td>
<td>1.9</td>
<td>1.2</td>
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<td>Other trades</td>
<td>1976</td>
<td>7.8</td>
<td>61.2</td>
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<td></td>
<td>2025</td>
<td>19.5</td>
<td>14.2</td>
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<td>Process</td>
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<td>Agricultural</td>
<td>1976</td>
<td>0.9</td>
<td>22.1</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td></td>
<td>-</td>
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<tr>
<td>Domestic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space</td>
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<td></td>
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<tr>
<td>Water</td>
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<td>Space</td>
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<td></td>
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<tr>
<td>Water</td>
<td></td>
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<tr>
<td>TOTAL</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substance</td>
<td>Comments</td>
<td>Density $\rho$/Kg m$^{-3} \times 10^3$</td>
<td>Specific heat capacity $C_p$/JK$^{-1}$ Kg$^{-1} \times 10^3$</td>
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<tr>
<td>----------------------------</td>
<td>-----------------------------------------------</td>
<td>----------------------------------------</td>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td>Chabazitic tuff</td>
<td>Common beolite in Italy</td>
<td>1.4</td>
<td>1.09</td>
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<tr>
<td>Water</td>
<td></td>
<td>1.0</td>
<td>4.19</td>
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<tr>
<td>Iron shot</td>
<td></td>
<td>7.86</td>
<td>0.54</td>
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<td>Scrap Iron</td>
<td>Zero voids</td>
<td>7.90</td>
<td>0.53</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>7.9</td>
<td>0.5</td>
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<tr>
<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids</td>
<td>5.16</td>
<td>0.75</td>
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<td>Fe$_2$O$_3$</td>
<td></td>
<td>5.20</td>
<td>0.75</td>
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<tr>
<td>Wet earth</td>
<td></td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Water and salt (brine)</td>
<td></td>
<td>1.2</td>
<td>3.0</td>
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<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td></td>
<td>4.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Scrap Aluminium</td>
<td>Zero voids</td>
<td>2.74</td>
<td>0.963</td>
</tr>
<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td>2.4</td>
<td>-18</td>
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<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td>2.3</td>
<td>-10</td>
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<td>Oils</td>
<td>Cracking occurs at high temp.</td>
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<td>MgCO$_3$·6H$_2$O</td>
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<td>MgCO$_3$</td>
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<td>0.84</td>
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<tr>
<td>Concrete</td>
<td>Zero voids</td>
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<td>1.13</td>
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<tr>
<td>Stone</td>
<td>Zero voids</td>
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<td>0.88</td>
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<td>Bulk Density</td>
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<td>---------</td>
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<td>----------</td>
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<tr>
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<td>2.74</td>
<td>0.92</td>
<td>88</td>
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<td>0.75</td>
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<td>Granite</td>
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<td>0.796</td>
<td>89</td>
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<td>Sulphur Liquid</td>
<td>2.1</td>
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<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
<td>83</td>
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<td>0.8</td>
<td>88</td>
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<td>Brick</td>
<td>2.23</td>
<td>0.84</td>
<td>89</td>
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<td>Paraffin Oil</td>
<td>0.8</td>
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<td>Olive Oil</td>
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<td>2.0</td>
<td>99</td>
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<td>93</td>
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<td>0.9</td>
<td>89</td>
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<td>Sulphur</td>
<td>2.1</td>
<td>0.7</td>
<td>90</td>
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<tr>
<td>Sodium</td>
<td>0.95</td>
<td>0.963</td>
<td>77</td>
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<tr>
<td>Mitec</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td>Draw salt</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
<td>94</td>
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<td>Store</td>
<td></td>
<td>Collector</td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>-------</td>
<td>-------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>length</td>
<td>280 m</td>
<td>area</td>
<td>2,900 m²</td>
</tr>
<tr>
<td>width</td>
<td>10 m</td>
<td>heat transfer factor (F_R)</td>
<td>0.9</td>
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<tr>
<td>height</td>
<td>4 m</td>
<td>overall heat loss coefficient</td>
<td>1.0 Wm⁻² °C⁻¹</td>
</tr>
<tr>
<td>volume</td>
<td>11200 m³</td>
<td>optical efficiency averaged</td>
<td>0.8</td>
</tr>
<tr>
<td>storage material pebbles, density</td>
<td>1600 kg m⁻³</td>
<td>over useful incident angles (\tau_a)</td>
<td></td>
</tr>
<tr>
<td>storage material pebbles; specific heat capacity</td>
<td>837 J kg⁻¹°C⁻¹</td>
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<td></td>
</tr>
<tr>
<td>store insulation; thickness</td>
<td>0.6 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>store insulation; thermal conductivity</td>
<td>0.036 Wm⁻² °C⁻¹</td>
<td></td>
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<tr>
<td>Item</td>
<td>Description</td>
<td>Energy Input</td>
<td>Cost Per Unit</td>
</tr>
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<td>------</td>
<td>--------------------------------------------------</td>
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<td>---------------</td>
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<tr>
<td>1800</td>
<td>Energy input in cost but not in on-site construction</td>
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<td></td>
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<tr>
<td>500</td>
<td>Fuel and ducting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16800</td>
<td>Insulation without backup</td>
<td>7 C(\text{m}^3)</td>
<td>222 C(\text{tonne})</td>
</tr>
<tr>
<td>1200</td>
<td>Insulation section</td>
<td>69 C(\text{m}^3)</td>
<td>222 C(\text{tonne})</td>
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<td>155</td>
<td>Glass fibre</td>
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<td>2470</td>
<td>Concrete sections</td>
<td></td>
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<td>3750</td>
<td>Concrete - concrete</td>
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<td>6520</td>
<td>Concrete - asphalt</td>
<td></td>
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<td>103</td>
<td>Packing</td>
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<td>2340</td>
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<td>577</td>
<td>Packing</td>
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<tr>
<td>39</td>
<td>Base - hardcore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>880</td>
<td>Base - hardcore</td>
<td></td>
<td></td>
</tr>
<tr>
<td>118</td>
<td>Excavation and site</td>
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</tbody>
</table>

TABLE 2.4: Inventory, energy and economics of Prometheus (as described in Table 2.3)
TABLE 2.5 Present value of the costs per house of 3 space
and water heating systems, $N = 45$ years, $n_1 = 15$ years, $n_2 = 30$ years. Domestic space and water
heating requirement = $27.5$ G J/yr, costs in £ 1980.

<table>
<thead>
<tr>
<th></th>
<th>Prometheus</th>
<th>Gas</th>
<th>Electricity (Economy 7)</th>
</tr>
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<tr>
<td>$C_h/£$</td>
<td>5700</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>$K_h/£$</td>
<td>0</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>$F_h/£ \text{ yr}^{-1}$</td>
<td>18</td>
<td>117</td>
<td>146</td>
</tr>
<tr>
<td>$R_h/£ \text{ yr}^{-1}$</td>
<td>11</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>

$i = 0.05$ \quad $f = 0.04$ \quad 6600 \quad 6000 \quad 6300

$PVC_h$ $i = 0$ \quad $f = 0.04$ \quad 8500 \quad 17800 \quad 20200

$i = 0$ \quad $f = 0.02$ \quad 7500 \quad 11700 \quad 12500
TABLE 2.6 Costs and inventory of various interseasonal solar heating systems modelled along with the cost, collector area and storage volume required to provide 27.5 GJ per annum.

<table>
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<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector type</td>
<td>Flat plate selective</td>
<td>Evacuated tube collector</td>
<td>Concentrating collector</td>
<td>High performance evacuated</td>
</tr>
<tr>
<td>Collector area /m²</td>
<td>2100</td>
<td>4600</td>
<td>14000</td>
<td>2800</td>
</tr>
<tr>
<td>Storage volume /m³</td>
<td>7500</td>
<td>17700</td>
<td>38500</td>
<td>11200</td>
</tr>
<tr>
<td>Insulation thickness/m</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
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<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
<td>130-30</td>
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<tr>
<td>Number of houses heated by system</td>
<td>50</td>
<td>300</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Energy consumption GJ/annum per house</td>
<td>32.4</td>
<td>25</td>
<td>54</td>
<td>27.5</td>
</tr>
<tr>
<td>Cost of collectors £1980/m²</td>
<td>60</td>
<td>64</td>
<td>64</td>
<td>72</td>
</tr>
<tr>
<td>Cost of store £1980/m³</td>
<td>16</td>
<td>11</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Collector area/Storage volume (m²/m³)</td>
<td>0.28</td>
<td>0.26</td>
<td>0.36</td>
<td>0.25</td>
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<tr>
<td>Total system capital cost £1980</td>
<td>322900</td>
<td>659000</td>
<td>1740000</td>
<td>570000</td>
</tr>
<tr>
<td>Collector area required to heat type A5 house (27.5 GJ/annum)/m²</td>
<td>35.7</td>
<td>16.9</td>
<td>17.8</td>
<td>28</td>
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<tr>
<td>Storage volume required for type A5 house /m³</td>
<td>127</td>
<td>65</td>
<td>49</td>
<td>112</td>
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<tr>
<td>Cost per A5 house/£1980</td>
<td>5480</td>
<td>2416</td>
<td>2215</td>
<td>5700</td>
</tr>
</tbody>
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[ ] Chapter 2 reference numbers
<table>
<thead>
<tr>
<th>Store temperature rise/$^\circ$C</th>
<th>Cost/£1982 per KWh recovered energy seasonal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tank 80</td>
<td>0.28 - 0.39</td>
</tr>
<tr>
<td>Pit storage 50</td>
<td>0.19 - 0.30</td>
</tr>
<tr>
<td>Rock cavern 70</td>
<td>0.11 - 0.21</td>
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<tr>
<td>Storage in clay 12</td>
<td>0.07 - 0.13</td>
</tr>
<tr>
<td>Multiple well systems in rock</td>
<td>0.07 - 0.12</td>
</tr>
<tr>
<td>Aquifers 15</td>
<td>0.025 - 0.08</td>
</tr>
<tr>
<td>Prometheus (pebble bed,</td>
<td></td>
</tr>
<tr>
<td>using data from Table 2.6)</td>
<td>100 0.43</td>
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### TABLE 2.8 Summary of domestic communal interseasonal storage systems

<table>
<thead>
<tr>
<th>Name</th>
<th>Location of Store/or Centre of Study</th>
<th>Design Study or Constructed</th>
<th>Storage Material</th>
<th>Number of Houses Per Store</th>
<th>% of Annual House Heating Supplied by System</th>
<th>Cost Per House £</th>
</tr>
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<tbody>
<tr>
<td>Lambovos, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td></td>
<td>27 000</td>
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<tr>
<td>Inglestad, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td></td>
<td>19 320</td>
</tr>
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<td>Studsvik, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>400</td>
<td>93</td>
<td></td>
<td>5 150</td>
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<tr>
<td>Lyckebo, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>500</td>
<td>100</td>
<td></td>
<td>10 500</td>
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<tr>
<td>Arizona, USA</td>
<td>Design Study</td>
<td>Water</td>
<td>250</td>
<td>100</td>
<td></td>
<td>3 012</td>
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<tr>
<td>Northampton, USA</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>10 000</td>
<td>100</td>
<td></td>
<td>6 000</td>
</tr>
<tr>
<td>Sussex, UK</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>100</td>
<td>100</td>
<td></td>
<td>10 000</td>
</tr>
<tr>
<td>City University, London, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>100</td>
<td>78</td>
<td></td>
<td>4 000</td>
</tr>
<tr>
<td>ERR, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td></td>
<td>2 416</td>
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<tr>
<td>PCL, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>50</td>
<td>100</td>
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<td>5 480</td>
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<td>Component</td>
<td>Variable</td>
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<tr>
<td></td>
<td>Area $A$ ($m^2$)</td>
<td>U-value ($Wm^{-2}°C^{-1}$)</td>
<td>UA ($W°C^{-1}$)</td>
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<tr>
<td>Wall</td>
<td>88.5</td>
<td>1.0</td>
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<tr>
<td>Roof</td>
<td>48.6</td>
<td>0.6</td>
<td>29.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>48.6</td>
<td>0.5</td>
<td>24.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>15.0</td>
<td>5.5</td>
<td>82.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fabric specific loss</td>
<td></td>
<td>224$W°C^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td>80$W°C^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td>304$W°C^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 3.2  Average weather data (1969-1977) for Kew, London, Latitude 51°N

<table>
<thead>
<tr>
<th>Month</th>
<th>Days in month</th>
<th>Solar radiation on a South-facing vertical surface (KWh/m²/month)</th>
<th>Solar radiation on a South-facing surface 30° to horizontal (KWh/m²/month)</th>
<th>Ambient Temperature (°C)</th>
<th>Degree days baseline 15.5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>31</td>
<td>28</td>
<td>25.2</td>
<td>5.2</td>
<td>346</td>
</tr>
<tr>
<td>Feb</td>
<td>28</td>
<td>42</td>
<td>45</td>
<td>4.6</td>
<td>304</td>
</tr>
<tr>
<td>March</td>
<td>31</td>
<td>74</td>
<td>91</td>
<td>5.7</td>
<td>282</td>
</tr>
<tr>
<td>April</td>
<td>30</td>
<td>75</td>
<td>115</td>
<td>8.2</td>
<td>197</td>
</tr>
<tr>
<td>May</td>
<td>31</td>
<td>87</td>
<td>146</td>
<td>11.8</td>
<td>113</td>
</tr>
<tr>
<td>June</td>
<td>30</td>
<td>90</td>
<td>166</td>
<td>14.9</td>
<td>-</td>
</tr>
<tr>
<td>July</td>
<td>31</td>
<td>84</td>
<td>150</td>
<td>17.2</td>
<td>-</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>78</td>
<td>123</td>
<td>16.8</td>
<td>-</td>
</tr>
<tr>
<td>Sept</td>
<td>30</td>
<td>72</td>
<td>95</td>
<td>13.9</td>
<td>56</td>
</tr>
<tr>
<td>Oct</td>
<td>31</td>
<td>59</td>
<td>66</td>
<td>10.8</td>
<td>132</td>
</tr>
<tr>
<td>Nov</td>
<td>30</td>
<td>39</td>
<td>37</td>
<td>6.7</td>
<td>256</td>
</tr>
<tr>
<td>Dec</td>
<td>31</td>
<td>25</td>
<td>22</td>
<td>5.3</td>
<td>333</td>
</tr>
<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss (W°C⁻¹)</td>
<td>Net annual space and water heating demand (GJ)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-----------------</td>
<td>-----------------------------------</td>
<td>---------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
<td>304</td>
<td>41.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
<td>304</td>
<td>40.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>291</td>
<td>39.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
<td>291</td>
<td>33.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>A4 + extra layer of glazing (i.e. double)</td>
<td>255</td>
<td>33.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>251</td>
<td>27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>186</td>
<td>23.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>182</td>
<td>22.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>182</td>
<td>19.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>A9 + extra layer of glazing (i.e. triple)</td>
<td>177</td>
<td>16.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>A10 + cavity increased to 200 mm</td>
<td>150</td>
<td>16.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component</td>
<td>Area $A$ ($m^2$)</td>
<td>$U$-value $(Wm^{-2}°C^{-1})$</td>
<td>$UA$ $(W°C^{-1})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-----------------</td>
<td>-----------------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>73.9</td>
<td>1.0</td>
<td>73.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>41.2</td>
<td>0.6</td>
<td>24.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>41.2</td>
<td>0.5</td>
<td>20.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>13.3</td>
<td>5.5</td>
<td>73.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fabric spec. loss</td>
<td></td>
<td></td>
<td>192 $W°C^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventilation spec. loss</td>
<td></td>
<td></td>
<td>68 $W°C^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total house spec. loss</td>
<td></td>
<td></td>
<td>260 $W°C^{-1}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3.5 Thermal Characteristics of existing houses with different levels of retrofitted insulation.

<table>
<thead>
<tr>
<th>House type</th>
<th>Insulation level</th>
<th>Total house specific loss ($W^0C^{-1}$)</th>
<th>Net annual space water heating demand (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0</td>
<td>Basic (average UK housing stock)</td>
<td>260</td>
<td>34.9</td>
</tr>
<tr>
<td>B1</td>
<td>B0 + 50 mm of loft insulation (100 mm total)</td>
<td>249</td>
<td>33.1</td>
</tr>
<tr>
<td>B2</td>
<td>B1 + fibre-fill cavity (50 mm)</td>
<td>219</td>
<td>28.3</td>
</tr>
<tr>
<td>B3</td>
<td>B2 + 50 mm of loft insulation (150 mm total)</td>
<td>215</td>
<td>27.7</td>
</tr>
<tr>
<td>B4</td>
<td>B3 + extra layer of glazing (i.e. double)</td>
<td>182</td>
<td>23.1</td>
</tr>
<tr>
<td>B5</td>
<td>B4 + extra layer of glazing (i.e. triple)</td>
<td>170</td>
<td>21.7</td>
</tr>
<tr>
<td>B6</td>
<td>B5 + 100 mm external wall insulation</td>
<td>156</td>
<td>19.6</td>
</tr>
<tr>
<td>Test No.</td>
<td>Date</td>
<td>Day/night</td>
<td>Air temp. at inlet (°C)</td>
</tr>
<tr>
<td>---------</td>
<td>------------</td>
<td>-----------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>1</td>
<td>21/6/83</td>
<td>1334-1354</td>
<td>51.1</td>
</tr>
<tr>
<td>2</td>
<td>25/6/83</td>
<td>1344-1443</td>
<td>82.5</td>
</tr>
<tr>
<td>3</td>
<td>26/6/83</td>
<td>1123-1132</td>
<td>79.1</td>
</tr>
<tr>
<td>4</td>
<td>5/7/83</td>
<td>1132-1200</td>
<td>84.3</td>
</tr>
<tr>
<td>5</td>
<td>19/8/83</td>
<td>1325-1344</td>
<td>75.1</td>
</tr>
<tr>
<td>6</td>
<td>19/8/83</td>
<td>1209-1218</td>
<td>60.1</td>
</tr>
<tr>
<td>7</td>
<td>19/8/83</td>
<td>1343-1352</td>
<td>69.1</td>
</tr>
<tr>
<td>8</td>
<td>19/8/83</td>
<td>1430-1439</td>
<td>79.7</td>
</tr>
<tr>
<td>9</td>
<td>18/8/83</td>
<td>1142-1511</td>
<td>69.1</td>
</tr>
<tr>
<td>Test No.</td>
<td>20°C</td>
<td>25°C</td>
<td>30°C</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>1.62</td>
<td>1.61</td>
<td>1.60</td>
</tr>
<tr>
<td>2</td>
<td>1.72</td>
<td>1.70</td>
<td>1.69</td>
</tr>
<tr>
<td>3</td>
<td>1.82</td>
<td>1.80</td>
<td>1.79</td>
</tr>
<tr>
<td>4</td>
<td>1.92</td>
<td>1.90</td>
<td>1.89</td>
</tr>
<tr>
<td>5</td>
<td>2.02</td>
<td>2.00</td>
<td>1.99</td>
</tr>
</tbody>
</table>

Table 5.2(b) Results of steady state testing of structured polycarbonate collector.
### TABLE 5.3 Collector configuration modelled for transient analysis by RRDCT.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector length (along flow)</td>
<td>4.00 m</td>
</tr>
<tr>
<td>Collector width</td>
<td>1.00 m</td>
</tr>
<tr>
<td>Cover to plate spacing</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Rear Duct gap</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Back insulation dry glass fibre</td>
<td>0.10 m</td>
</tr>
<tr>
<td>Edge insulation dry glass fibre</td>
<td>0.05 m</td>
</tr>
<tr>
<td>Material of plate and duct-back</td>
<td>duraluminium HS 15 TB</td>
</tr>
<tr>
<td>Plate absorbtance</td>
<td>0.95 at $\theta = 0$ falling slightly as $\theta$ increases</td>
</tr>
<tr>
<td>Emissivity of upper surface of the plate (diffuse)</td>
<td>0.10</td>
</tr>
<tr>
<td>Emissivity of duct surface (diffuse)</td>
<td>0.91</td>
</tr>
<tr>
<td>Emissivity of cover (diffuse)</td>
<td>0.85</td>
</tr>
<tr>
<td>Cover polycarbonate thickness</td>
<td>2.00 mm</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0.06 kg s(^{-1})</td>
</tr>
<tr>
<td>Thickness of plate and of duct-back DY1</td>
<td>0.2 mm</td>
</tr>
<tr>
<td></td>
<td>DY2 0.5 mm</td>
</tr>
<tr>
<td></td>
<td>DY3 1.0 mm</td>
</tr>
<tr>
<td></td>
<td>DY4 2.0 mm</td>
</tr>
<tr>
<td></td>
<td>DY5 5.0 mm</td>
</tr>
</tbody>
</table>

### TABLE 5.4 Results of transient and steady state testing with multi node model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Steady state</th>
<th>Transient 0.5mm (DY2)</th>
<th>Transient 2mm (DY4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta t$/min</td>
<td>-</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>$N$</td>
<td>-</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>$\tau_c$/min</td>
<td>-</td>
<td>2.8</td>
<td>9.7</td>
</tr>
<tr>
<td>$F_{RUL}$/$Wm^{-2}K^{-1}$</td>
<td>2.83*</td>
<td>2.768</td>
<td>2.604</td>
</tr>
<tr>
<td>$F_{R\alpha}$</td>
<td>0.683</td>
<td>0.585</td>
<td>0.569</td>
</tr>
<tr>
<td>$KF_{R\alpha}$</td>
<td>0.683</td>
<td>0.706</td>
<td>0.686</td>
</tr>
<tr>
<td>$\hat{\sigma} F_{RUL}$</td>
<td>-</td>
<td>0.012</td>
<td>0.036</td>
</tr>
<tr>
<td>$\hat{\sigma} F_{R\alpha}$</td>
<td>-</td>
<td>0.0008</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

$K = \text{correction factor for equivalent normal direct radiation} = \frac{(\tau_0)_{\text{direct}}}{(\tau_0)_{\text{diffuse}}} = \frac{0.830}{0.688} = 1.206$

$\ast = \text{at low fluid inlet temperatures}$
<table>
<thead>
<tr>
<th>n</th>
<th>F_R (10^4 k_n)</th>
<th>( \alpha_F (10^4 k_n) )</th>
<th>n/( \tau^* )</th>
<th>( \tau^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.433800115133</td>
<td>0.017945235996</td>
<td>0.558117255249</td>
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<td>0.61749143134</td>
<td>0.007</td>
<td>0.61423738287</td>
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<td>0.48568243941</td>
<td>0.005</td>
<td>0.48568243941</td>
<td>0.005</td>
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<tr>
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<td>0.48974307916</td>
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<td>0.508166425486</td>
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<tr>
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<td>1.10433967528</td>
<td>0.011</td>
<td>0.56992090468</td>
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<tr>
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<td>0.86668243941</td>
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<tr>
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<td>0.005</td>
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<td>0.035</td>
<td>0.15437285763</td>
<td>0.013</td>
</tr>
<tr>
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<td>0.201872198707</td>
<td>0.035</td>
<td>0.27312120016</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>0.28496045234</td>
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<td>0.546242420031</td>
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</tr>
<tr>
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<td>0.43368903049</td>
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<td>0.43368903049</td>
<td>0.026</td>
</tr>
<tr>
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<td>0.29687080452</td>
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<td>0.27312120016</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>0.415619232632</td>
<td>0.021</td>
<td>0.498743079159</td>
<td>0.029</td>
</tr>
<tr>
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<td>0.415619232632</td>
<td>0.029</td>
<td>0.403744397415</td>
<td>0.026</td>
</tr>
<tr>
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<td>0.403744397415</td>
<td>0.026</td>
<td>0.403744397415</td>
<td>0.026</td>
</tr>
</tbody>
</table>

**TABLE 5.6** Data Output from 'TRANS' for SP collector, n = 1, in the format specified in Table F.6.1 of British Standard DD 77: 1982

DATA SETS ACCEPTED FOR ANALYSIS 80

<table>
<thead>
<tr>
<th>n/( \tau^* )</th>
<th>( \tau^* )</th>
</tr>
</thead>
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<tr>
<td>0.201872198707</td>
<td>0.035</td>
</tr>
<tr>
<td>0.28496045234</td>
<td>0.011</td>
</tr>
<tr>
<td>0.43368903049</td>
<td>0.026</td>
</tr>
<tr>
<td>0.474993408723</td>
<td>0.026</td>
</tr>
<tr>
<td>0.29687080452</td>
<td>0.016</td>
</tr>
<tr>
<td>0.415619232632</td>
<td>0.021</td>
</tr>
<tr>
<td>0.498743079159</td>
<td>0.029</td>
</tr>
<tr>
<td>0.415619232632</td>
<td>0.029</td>
</tr>
<tr>
<td>0.403744397415</td>
<td>0.026</td>
</tr>
</tbody>
</table>

POINTS ON THERMAL PERFORMANCE CHARACTERISTIC 80 FROM LEAST SQUARES FITS EACH WAY

MINIMUM ETA = 0.23543187816

MAXIMUM ETA = 0.71484616622

U = 7.33893217894

U = 13.9616808148
TABLE 5.8  Temperature distribution within DY1 collector (0.2mm thick plate and duct back) during ASHRAE steady state testing, $T_a = 293k$, $I = 700\text{wm}^{-2}$, Wind = 1m s$^{-1}$, $T_{sky} = 273k$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\bar{T}_p/k$</th>
<th>$\bar{T}_b/k$</th>
<th>$T_m/k$</th>
<th>$F_{RUL}$ (W m$^{-2}$ °C$^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{aveUL}$ (W m$^{-2}$ °C$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>332.73</td>
<td>333.01</td>
<td>322.1</td>
<td>317.86</td>
<td>2.762</td>
<td>.645</td>
<td>3.111</td>
</tr>
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<td>343</td>
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<td>396.94</td>
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<td>.095</td>
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<td>433.57</td>
<td>434.06</td>
<td>3.226</td>
<td>.037</td>
<td>3.564</td>
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TABLE 5.9  Temperature distribution and energy lost from DY1 collector (0.2mm thick plate and duct base) during zero radiation testing, $T_a = 293k$, $T_{wind} = 1m s^{-1}$, $T_{sky} = 273k$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\bar{T}_p/k$</th>
<th>$\bar{T}_b/k$</th>
<th>$T_m/k$</th>
<th>Energy lost per unit time per unit area (W m$^{-2}$ °C$^{-1}$)</th>
<th>$F_{RUL}$ (W m$^{-2}$ °C$^{-1}$)</th>
<th>$F_{aveUL}$ (W m$^{-2}$ °C$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>303</td>
<td>300.34</td>
<td>300.41</td>
<td>301.23</td>
<td>301.67</td>
<td>40.34</td>
<td>4.034</td>
<td>4.653</td>
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<td>333.32</td>
<td>333.79</td>
<td>336.20</td>
<td>338.16</td>
<td>146.66</td>
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<td>366.41</td>
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<td>266.50</td>
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<td>398.43</td>
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<td>406.34</td>
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<td>418.73</td>
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<td>3.439</td>
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<td>301.62</td>
<td>301.71</td>
<td>302.03</td>
<td>302.31</td>
<td>20.98</td>
<td>2.098</td>
<td>2.035</td>
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<td>*433</td>
<td>405.92</td>
<td>407.78</td>
<td>413.13</td>
<td>419.46</td>
<td>410.30</td>
<td>2.93</td>
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* $T_{sky} = 293k$
<table>
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<tr>
<th>Source</th>
<th>Temperature</th>
<th>Solar Intensity</th>
<th>Inlet Air Temperature</th>
<th>Collector Temperature</th>
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<tr>
<td>Indoor</td>
<td>7.77</td>
<td>77</td>
<td></td>
<td></td>
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<tr>
<td>Transient Steady-State</td>
<td>8.48</td>
<td>7.37</td>
<td></td>
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<tr>
<td>Transient</td>
<td>9.29</td>
<td>7</td>
<td></td>
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Structured Poly-carbonate Collector

D.C. Hall Collector

<table>
<thead>
<tr>
<th>Test Method</th>
<th>P_U</th>
<th>P_W</th>
<th>T_WX</th>
<th>T_WY</th>
<th>( \text{IM}_{0} )</th>
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<td>Summary of collector testing results</td>
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TABLE 5.10
<table>
<thead>
<tr>
<th>Material</th>
<th>Reflective index (n)</th>
<th>Solar (0.2-4.0μm)</th>
<th>Infrared (3.0-500μm)</th>
<th>Expansion coefficient (°C⁻¹)</th>
<th>Temperature Limits (°C)</th>
<th>Weather-ability (comments)</th>
<th>Chemical Resistance (comments)</th>
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</thead>
<tbody>
<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
<td>125 mil</td>
<td>125 mil</td>
<td>7.98 x 10⁻⁶</td>
<td>120-130</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Plexiglass (Acrylic)</td>
<td>1.49</td>
<td>125 mil</td>
<td>125 mil</td>
<td>8.29 x 10⁻⁶</td>
<td>80-90</td>
<td>Average</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Teflon F.F.P. (Fluorocarbon)</td>
<td>1.343</td>
<td>5 mil</td>
<td>5 mil</td>
<td>12.55 x 10⁻⁶</td>
<td>200-220</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Tedlar P.V.F. (fluorocarbon)</td>
<td>1.46</td>
<td>4 mil</td>
<td>4 mil</td>
<td>5.95 x 10⁻⁶</td>
<td>110-170</td>
<td>Good to excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.64-1.67</td>
<td>5 mil</td>
<td>5 mil</td>
<td>2.00 x 10⁻⁵</td>
<td>150-200</td>
<td>Poor</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunlite (Fibre glass)</td>
<td>1.54</td>
<td>25 mil</td>
<td>25 mil</td>
<td>2.98 x 10⁻⁵</td>
<td>95-100</td>
<td>Fair to good</td>
<td>Good</td>
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<tr>
<td>Float glass (Glass)</td>
<td>1.518</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.21 x 10⁻⁶</td>
<td>230</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Temper glass (Glass)</td>
<td>1.518</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.21 x 10⁻⁶</td>
<td>230-250</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear limesheet glass (Low iron glass)</td>
<td>1.51</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.64 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear lime temper glass (Low iron glass)</td>
<td>1.51</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.64 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunade white crystal glass (0.01% iron glass)</td>
<td>1.50</td>
<td>125 mil</td>
<td>125 mil</td>
<td>10.00 x 10⁻⁶</td>
<td>200</td>
<td>Excellent</td>
<td>Good to excellent</td>
</tr>
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Source: Gary, H.P. 'Treatise on solar energy' Vol.1, A Wiley Interscience Publication, Chichester, 1982
<table>
<thead>
<tr>
<th>O.0</th>
<th>0.93</th>
<th>Computer (ratchin)</th>
<th>Supporting Reagent</th>
<th>Most Selective Path</th>
<th>Gradation Metal Catalyst Film</th>
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</thead>
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<tr>
<td>0.03 - 0.05</td>
<td>0.87</td>
<td>University of Sydney</td>
<td>Copper</td>
<td>Blue stainless steel</td>
<td></td>
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<tr>
<td>0.015</td>
<td>0.77</td>
<td>Skysor/MPD</td>
<td>Copper</td>
<td>Copper oxide</td>
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<tr>
<td>In-house</td>
<td>0.56</td>
<td>BUNPO</td>
<td>Stainless steel</td>
<td>Stainless steel</td>
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<tr>
<td>0.03 - 0.01</td>
<td>0.56</td>
<td>Sanyo</td>
<td>SS/Granges</td>
<td>Aluminum</td>
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<tr>
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<td>0.55</td>
<td>Phillips</td>
<td>SS/Granges</td>
<td>Aluminum</td>
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<tr>
<td>0.008 - 0.01</td>
<td>0.47</td>
<td>Maxerox/MPD</td>
<td>Conversion (CC)</td>
<td>ED</td>
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<td>0.46</td>
<td>Tabor Black</td>
<td>ED</td>
<td>Black nickel</td>
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<tr>
<td>0.016</td>
<td>0.46</td>
<td>Sumonese</td>
<td>ED</td>
<td>Black nickel</td>
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<tr>
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<td>0.46</td>
<td>Reactosol Tda.</td>
<td>ED</td>
<td>Black nickel</td>
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</tr>
<tr>
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<td>0.46</td>
<td>Surface/Coastrip</td>
<td>ED</td>
<td>Black nickel</td>
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</tr>
<tr>
<td>0.015 - 0.016</td>
<td>0.46</td>
<td>CIP</td>
<td>SS-Steel</td>
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<td>0.015 - 0.016</td>
<td>0.46</td>
<td>CIP</td>
<td>SS-Steel</td>
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<td>0.015 - 0.016</td>
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<td>CIP</td>
<td>SS-Steel</td>
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<td>0.015 - 0.016</td>
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<td>CIP</td>
<td>SS-Steel</td>
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**TABLE 6.2** Optimal Properties of Selective Absorber Surface Coatings
### Table 6.3  Key to collector variable features, used to obtain Figure 6.19

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Cover material: cover 1</td>
<td>Plate glass, thickness 6.0 mm</td>
</tr>
<tr>
<td>Cover 2</td>
<td>Polycarbonate, thickness 2.0 mm</td>
</tr>
<tr>
<td>Thickness of the plate</td>
<td></td>
</tr>
<tr>
<td>and of the duct-back:</td>
<td></td>
</tr>
<tr>
<td>DY1</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>DY2</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>DY3</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>DY4</td>
<td>2.0 mm</td>
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<tr>
<td>DY5</td>
<td>5.0 mm</td>
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<tr>
<td>Air flow in the rear-duct</td>
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<tr>
<td>Flow 0</td>
<td>Stagnation (M = 0)</td>
</tr>
<tr>
<td>Flow 1</td>
<td>All TI M = 0.0600 kg s⁻¹ (PON irrelevant)</td>
</tr>
<tr>
<td>Flow 2</td>
<td>TI = 303 K M = 0.0600 kg s⁻¹ PON = 128W</td>
</tr>
<tr>
<td>Flow 3</td>
<td>TI = 323 K M = 0.0562 kg s⁻¹ PON = 124W</td>
</tr>
<tr>
<td>Gas</td>
<td>Surface</td>
</tr>
<tr>
<td>-----</td>
<td>---------</td>
</tr>
<tr>
<td></td>
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<tr>
<td>Air</td>
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<tr>
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<td>N₂</td>
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<td>Pt.Black</td>
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<td>W</td>
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<td>CO₂</td>
<td>Pt.Bright</td>
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TABLE 7.2  Convection and conduction heat transfer coefficients for various gases at different temperatures as measured with guarded hot plate.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T_s/°C$</th>
<th>$T_i/°C$</th>
<th>$\frac{h_p}{(\text{Wm}^{-2}\text{°C}^{-1})}$</th>
<th>$\frac{Q}{A}/(\text{Nm}^{-2})$</th>
<th>$T_1/°C$</th>
<th>$T_2/°C$</th>
<th>$\frac{h_r}{(\text{Wm}^{-2}\text{°C}^{-1})}$</th>
<th>$h_c/\text{(Nm}^{-2}\text{°C}^{-1})$</th>
<th>$\Delta T/°C$</th>
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<tbody>
<tr>
<td>Air at atmospheric pressure</td>
<td>10</td>
<td>14</td>
<td>0.798</td>
<td>3.19</td>
<td>10.16</td>
<td>13.84</td>
<td>0.163</td>
<td>0.704</td>
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<tr>
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<td>20.7</td>
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<td>20.05</td>
<td>11.10</td>
<td>19.70</td>
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<td>2.193</td>
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<td>1.725</td>
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<td>1.915</td>
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<td>33.3</td>
<td>2.195</td>
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<td>30.80</td>
<td>0.180</td>
<td>2.632</td>
<td>17.8</td>
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<tr>
<td>Air, $p = 82$ torr</td>
<td>10.35</td>
<td>37.9</td>
<td>1.60</td>
<td>44.08</td>
<td>12.55</td>
<td>35.70</td>
<td>0.185</td>
<td>1.720</td>
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<td>1.621</td>
<td>46.12</td>
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<td>36.49</td>
<td>0.185</td>
<td>1.750</td>
<td>23.83</td>
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<td>Air, $p = 81$ torr</td>
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<td>43</td>
<td>1.567</td>
<td>51.24</td>
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<td>Air, $p = 71$ torr</td>
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<td>10.6</td>
<td>34.9</td>
<td>2.461</td>
<td>59.80</td>
<td>13.59</td>
<td>33.91</td>
<td>0.182</td>
<td>3.082</td>
<td>18.32</td>
</tr>
<tr>
<td></td>
<td>10.6</td>
<td>36.7</td>
<td>2.245</td>
<td>58.59</td>
<td>13.53</td>
<td>33.77</td>
<td>0.183</td>
<td>2.712</td>
<td>20.24</td>
</tr>
<tr>
<td>Air, $p = 0.3$ torr</td>
<td>10.2</td>
<td>16.6</td>
<td>0.547</td>
<td>3.504</td>
<td>10.38</td>
<td>16.42</td>
<td>0.165</td>
<td>0.414</td>
<td>6.04</td>
</tr>
<tr>
<td>Air, $p = 0.35$ torr</td>
<td>10.9</td>
<td>45.7</td>
<td>1.135</td>
<td>39.51</td>
<td>12.87</td>
<td>43.72</td>
<td>0.193</td>
<td>1.088</td>
<td>30.85</td>
</tr>
<tr>
<td>Air $p = 16$ torr and changing</td>
<td>11.2</td>
<td>51.2</td>
<td>1.186</td>
<td>47.46</td>
<td>13.57</td>
<td>48.83</td>
<td>0.198</td>
<td>1.148</td>
<td>35.26</td>
</tr>
</tbody>
</table>
FIGURE 1.1(a) 
PHYSICAL QUALITY OF LIFE INDEX VERSUS ENERGY CONSUMPTION PER CAPITA FOR THE COUNTRIES OF THE WORLD. SOURCES OF DATA: 
PQLI, BOOK OF WORLD RANKINGS 1 BY G. TURAN 1979, ENERGY CONSUMPTION, 'EUROPEAN YEARBOOK 1985'.
FIGURE 11(b) HISTOGRAM OF ENERGY CONSUMPTION PER CAPITA FOR DIFFERENT PHYSICAL QUALITY OF LIFE INDEX (PQLI) FOR THE PEOPLES OF THE WORLD. THE PERCENTAGES SHOWN IN EACH BAR ARE THE PERCENTAGES WITHIN THAT RANGE OF PQLI.
**Figure 2.1** UK Low Grade Heat, Fuel Consumption and End Use.

**Figure 2.2** Domestic Space and Hot Water Demand.
**Figure 2.3**

DISTRIBUTION OF ANNUAL GAS CONSUMPTION FOR 90 SIMILAR HOUSES IN MILTON KEYNES, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A.C.

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**Figure 2.4**

WEEKLY CONSUMPTION OF HOT WATER FOR ONE HOUSEHOLD, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A.C.
Total No of dwellings: 87
Overall mean weekly consumption: 0.841 m$^3$/week
Standard deviation: 0.351 m$^3$/week

Contribution due to OAPs flats
(1or 2 occupants)

Dwelling mean weekly hot water consumption m$^3$

FIGURE 2.5 MEAN WEEKLY HOT WATER CONSUMPTION FOR 87: VARIOUS SITES. FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS' BY G.A. RICKUP [9]

SOLAR m=0
SOLAR m=2
BLACKBODY AT 40°C

FIGURE 2.6 SOLAR AND THERMAL RADIATION SPECTRAL DISTRIBUTIONS. AIR MASS m=0 IS FOR EXTRA-TERRESTRIAL RADIATION, m=2 IS A TYPICAL CITY DISTRIBUTION.
**Figure 2.7**

Annual variation of mean daily totals of direct and diffuse insolation on a horizontal surface.

**Figure 2.8**

Average global solar radiation on a horizontal surface.

**Figure 2.10**

FIGURE 2.11 Seasonal heat storage and a central short term storage reservoir (C.S.T.) constructed for TNO DELFT [35]

One-family houses (small scale)

Apartment building (intense populated areas) (large scale)

FIGURE 2.12 Different applications for 'Sunstore' [37], seasonal storage in the ground
**Figure 2.13** Plan of Prometheus retrofitted to supply 83 houses with all their space heating and hot water.

**Figure 2.14** Collector mounted on top of store, part of Prometheus design.
PROTOTYPE OF A PROMETHEUS TYPE SOLAR AIR-COLLECTOR/HEAT STORE, INSTALLED AT THE OPEN UNIVERSITY, MILTON KEYNES, UK.

FIGURE 2.15 PROTO-PROMETHEUS
FIGURE 2.16  INSOLATION INCIDENT ON PROTO-PROMETHEUS, 28th SEPTEMBER 1981

FIGURE 2.17  COLLECTOR, STORE AND AMBIENT TEMPERATURES FOR PROTO-PROMETHEUS ON 28th SEPTEMBER 1981.
**Figure 2.19** Proto-Prometheus temperature distribution (with fan on), on 22nd September 1981 at 14:25 hrs.
SAMPLE SIZE 204
AVERAGE 1.6 cm.
STANDARD DEVIATION 0.7 cm.

FIGURE 2.19 FREQUENCY DISTRIBUTION OF PEBBLE SMALLEST DIMENSION.
FIGURE 2.20  FREQUENCY DISTRIBUTION OF PEBBLE LARGEST DIMENSION
**Figure 2.21** Proto-Prometheus Store Temperature, from 22nd September 1981 to 2nd October 1981 under stagnation (Fan off).

**Figure 2.22** Energy demand for a 3-bedroom house built to R75 building regulations (Type A) with solar heating supplied by a basic Type Prometheus.
Figure 2.23  Effect of changing the collector overall heat loss coefficient on the % of annual energy supplied by Prometheus to a type A1 house.

Figure 2.24  Effect of changing the collector area on the % of annual energy supplied by Prometheus to a type A1 house.
**Figure 2.25** The effect of changing the storage tank insulation thickness on the % of solar energy supplied by Prometheus to a Type A1 house.

**Figure 2.26** The effect of changing the storage volume on the % of solar energy supplied by Prometheus to a Type A1 house.
Figure 2.27  The effect of increasing the number of houses served by a single cubic Prometheus (size 1.12 m² per house and 28 m² of collector per house) for a type A1 house.

Figure 2.28  The effect of changing the collector overall heat loss on the % of energy supplied by a cubic Prometheus heating a type A3 house.
**FIGURE 2.29** DESIGN OF COSTED PROMETHEUS TO PROVIDE 100 HOMES WITH 100% OF THEIR ANNUAL HEATING DEMAND (27.5 GJ) WITH SOLAR ENERGY.

**FIGURE 2.30** IMPROVED COLLECTOR ORIENTATION
**Figure 3.1** Design of basic Type A0 house

**Figure 3.2** Net space heating demand for Type A0, A5 and A11 3 bedroom end of terrace house.
Figure 3.3
Useful energy saved and extra cost for various insulation options and solar systems installed while constructing a basic type AO house.

Figure 3.4
Energy demand for a 3 bedroom terrace built to 1975 building regulations and energy supplied by 4, 12 and 24 m² of solar collector.
**Figure 3.5** Energy demand for a well insulated 3 bedroom house, and energy supplied by 4.12 and 24m² of solar collector.

**Figure 3.6** Comparison of predicted solar energy supply for a house using the F-chart method with the measured solar supply for the Milton Keynes solar house.
Insulation measures

Active solar system with short term storage

Figure 37. Useful energy saved and extra costs for various insulation options and solar systems retrofitted to an existing Type B0 house.
FIGURE 4.1  NONPOROUS ABSORBER-TYPE AIR HEATERS.

FIGURE 4.2  POROUS ABSORBER-TYPE AIR HEATERS.
FIGURE 4.3  HYBRID PHOTOVOLTAIC AND AIR HEATING SOLAR COLLECTOR

FIGURE 4.4  COLLECTOR HEAT LOSSES
**Figure 4.5** Rear Duct Collector Configuration

**Figure 4.6** Top Duct Collector Configuration
The curves correspond to the following relations:

**McAdams**
\[ h_w = 5.7 + 3.5V \]

**Watmuff**
\[ h_w = 2.8 + 3.0V \]

**Lloyd**
\[ h_w = 0.15 \times R_a^{0.8} \times k \left( \frac{2.6W}{L + W} \right) \] for \( T_a = 10^\circ C, T_x = 15^\circ C, L = 1m, W = 1m \).

**Sparrow**
\[ h_w = k \times 0.86 \times R_a^{0.8} \left( \frac{2.6W}{L + W} \right) \] for \( T_a = 10^\circ C, T_x = 15^\circ C, L = 1m, W = 1m \).

**Green**
\[ h_w = \left( h_{18} + h_{35} \right)^{0.8} \] for \( A = 1.4m^2, 45^\circ \) inclination.

**KIND**
For collector length 2.4m, width 1.2m, height 4.5m, \( T_a = 25^\circ C \).

**Figure 4.7** Correlations for wind heat loss coefficient.
Figure 4.8 Flow diagram of 'EFFICZ' (see Appendix B), a program to calculate the efficiency of a forced draft air heating collector.
INPUT
ENVIRONMENTAL PARAMETERS I, V, T_a

COLLECTOR CONFIGURATION (cyl) B_i, C_e, K, H, A_l, W_D
V_e, x

COLLECTOR VARIABLES T_c, m

INITIAL ESTIMATE OF T_f, T_m

CONSTANTS
\( e, \alpha \), \( k_{\text{air}} \), \( \eta_{\text{air}} \),

\begin{align*}
R_c & = 4.25 \\
N_u & = 4.23 \\
h_{i1}, h_{i2} & = 4.22 \\
h_r & = 4.27 \\
U_b & = 4.4 \\
U_L & = 4.15 \\
F' & = 4.16 \\
F_r & = 4.20 \\
Q_u & = 4.19
\end{align*}

\( \eta = Q_u / A_I \)

CALCULATE NEW ABSORBER TEMPERATURE

\[ T_p = T_c + \frac{Q_u}{A_I} (1 - F_r) \]

\( T_f = T_f_{\text{new}} \)

\( T_p = T_p \)

\[ \frac{[T_p - T_f] \log(15) \times 10^3}{1.5} \]

YES

OUTPUT
\( \eta, T_f, U_L, U_e, U_b, V_e, F_r, F', Q_u \)

FIGURE 4.9 FLOW DIAGRAM OF 'EFFIC' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A TOP DUCT MELTING COLLECTOR
FIGURE 4.10 RESPONSE OF ZERO AND LONG TIME CONSTANT COLLECTOR TO CHANGING INSULATION
**FIGURE 4.11** NODAL CONFIGURATION OF A FLAT PLATE, REAR DUCT AIR HEATING, SOLAR COLLECTOR AS USED IN 'RROCT'.

**FIGURE 4.12** COMPARISON OF AIR OUTLET TEMPERATURE TO PREDICTED BY THE COMPUTER MODEL (SOLID CURVE) AND LABORATORY MEASUREMENTS, ON A SIMILAR, THOUGH NOT IDENTICAL, COLLECTOR (CROSSES).
Figure 4.13  Efficiency curve generated by transient model operating under steady state conditions and steady state model. For collector parameters see Table 5.3.
FIGURE 5.1 PERCENTAGE OF ENERGY FALLING ABOVE A THRESHOLD INTENSITY AVERAGED OVER A PERIOD OF ONE HOUR EACH MONTH ON A HORIZONTAL SURFACE (AT WAT 1966-1975)
SECTION X-X

**Figure 5.2** D.C. Hall Collector
**Figure 5.3** Angular variation of transmittance of 2mm thick polycarbonate (refractive index = 1.586, extinction coefficient = 20 m⁻¹)

**Figure 5.4** Tee-pieces used for absorber fins in D.C. Hall collector
Figure 5.5-5.6  Air heating collector made of structured polycarbonate

Figure 5.7  Solar transmittance of structured polycarbonate versus incident angle. Source: H.L. Redfoot et al., 'Glazing solar collectors with acrylic and double walled polycarbonate plastics.'
Figure 5.8 Orifice plate and its location for measuring mass flow rate
**Figure 5.9**  ASHRAE Standard 93-77 Testing Configuration for a Solar Collector when the Transfer Fluid is Air.

**Figure 5.10**  Open University Air Collector Testing Configuration.
Figure 5.11: RESPONSE OF STRUCTURED POLYCARBONATE COLLECTOR TO A STEP CHANGE IN INSOLATION FROM 750 W/m² TO ZERO WITH A FLUID FLOW RATE OF 7.2 kg hr⁻¹.

Figure 5.12: UNINTERRUPTED INSOLATION AS DEFINED BY ASHRAE STANDARD 93-77 [2].
FIGURE 5.13  RECORD OF INCIDENT SOLAR RADIATION ON A HORIZONTAL SURFACE
AT THE OPEN UNIVERSITY ON 19/6/83.

FIGURE 5.14  RECORD OF INCIDENT SOLAR RADIATION ON A HORIZONTAL SURFACE
AND WIND SPEED ON 21/6/83 (CONTINUED ON NEXT PAGE).
FIGURE 5.14 CONTINUED
Figure 5.15  Angle of incidence of solar radiation onto D.C. Hall collector during steady state efficiency test. Position of collector at Milton Keynes, latitude 52°, longitude 0.75° (horizontal).

Figure 5.16  Angle correction for D.C. Hall collector.
FIGURE 5.17(a) AIR HEATING COLLECTOR UNDER TEST WITH A LEAK AT THE INLET

FIGURE 5.17(b) AIR HEATING COLLECTOR UNDER TEST WITH A LEAK AT THE OUTLET
**Figure 5.18** The effect of air leaks on the measured value of \( q_{\text{in}} \), for \( m = 0.5 \) kg/hr.

**Figure 5.19** Calibration curve for perforated orifice plate for air at 20°C.
Figure 5.20  Pressure Distribution Within Collector Test Configuration With and Without Fluid Flow

Figure 5.21  Sample Output of D.C. Wall Collector to Testing Outdoors Not Under Steady-State Conditions.
Figure 5.22  Steady State Efficiency Curve for D. C. Hall Collector Tested outdoors

Figure 5.23  Steady State Efficiency Curve for Structured Polycarbonate Collector Tested outdoors.
**Figure 5.24**
Uncorrected efficiency curve with variation of wind speed between 0 - 4 m/s. Source: [25].

**Figure 5.25**
Efficiency curve corrected for variation in wind speed using a normalizing function. Source: [25].
FIGURE 5.26  VARIATION OF MASS FLOW RATE CAUSED BY CHANGE IN WIND SPEED
FIGURE 5.27 ROUNdb ROBIN TESTING OF LIQUID FLAT PLATE COLLECTORS. THE COMBINED EFFECT OF METEOROLOGICAL EXTREMES AND MEASUREMENT UNCERTAINTY. SOURCE: TAYLOR [28]

FIGURE 5.28 MEASURED DEPENDENCY OF $F(CO_2)$ ON THE DIFFUSE FRACTION FOR A SINGLE-GLAZED FLAT-PLATE COLLECTOR. SOURCE: POZORSKI [34]
Figure 5.29  COMPUTER GENERATED STEADY STATE AND TRANIENT EFFICIENCY CURVE FOR 0.5 mm ABSORBER PLATE
FIGURE 5.30  TRANSIENT DIFFUSE RADIATION

FIGURE 5.31  FLUID OUTLET TEMPERATURE UNDER TRANSIENT CONDITIONS.

FIGURE 5.32  INTEGRATED RESPONSE OF COLLECTOR OVER 1 AND 2 MINUTES TO TRANSIENT RADIATION.
Figure 5.33: The variation in $g_{ul}$, $F_{UL}$, and $\Delta F_{UL}$ with the number of increments used in the transient analysis.
**FIGURE 5.34** COLLECTOR RESPONSE FUNCTIONS FOR OPTIMUM VALUES OF N.

**FIGURE 5.35** CALCULATED COLLECTOR TIME CONSTANTS. FOR DIFFERENT COLLECTOR CONFIGURATIONS SEE TABLE 5.3.
FIGURE 5.36  EFFICIENCY CURVE GENERATED FROM TRANSIENT TESTING RESULTS OF THE SP COLLECTOR AND PROCESSED BY 'TRANS' FOR N = 1.
UNCORRECTED FOR ANGLE OF INCIDENCE OF RADIATION.

FIGURE 5.37  TRANSIENT INSOLATION DURING TESTING OF SP COLLECTOR ON 17/6/83, CONTINUED ON NEXT PAGE.
FIGURE 5.37 CONTINUED. TRANSIENT INSOLATION DURING TESTING OF 3P COLLECTOR ON 14/6/83 - 15/6/83.
**Figure 5.30** Standard error in \( \frac{E_{F,UL}}{F_{UL}} \) versus \( N \) the number of previous time steps influencing the collector's present performance under transient conditions for the structured polycarbonate collector.

**Figure 5.39** Efficiency curve for outdoor transient testing of structured polycarbonate collector. Data generated from 'TRANS' for No. 7, uncorrected for angle of incidence of radiation.
**Figure 5.40** Collector response function for S.P. collector N=7.

**Figure 5.41** Efficiency curve for outdoor transient testing of D.C. hall collector (Manors Arizona). Data generated from 'TRANS' for N=7, uncorrected for incident angle of radiation.
**Figure 5.42** Indoor Solar Collector Test Facility.

**Figure 5.43** Relative Spectral Intensity of 'Cool Ray' Lamps, Transmittance of Polycarbonate and Reflectance of Maxorb.
FIGURE 5.44 INTENSITY DISTRIBUTION ACROSS COLLECTOR DURING INDOOR TESTING IN Wm⁻², AVERAGE INTENSITY 2.11 Wm⁻², STANDARD DEVIATION ± 9 Wm⁻².

FIGURE 5.45 WING GENERATOR.
Figure 5.46 Variation of wind speed (m/s), 5 mm above collector surface

Measured heat loss with collector operating under stagnation and assuming \( (\frac{P}{K}) = 0.32 \) plotted against average air velocity parallel to collector plane and measured 5 mm above collector plane.

Figure 5.47 Measured and predicted heat loss \( U \) for D.C. wall collector (non-selective) with varying wind speed indoors.
Figure 5.48 Efficiency curve of structured polycarbonate collector measured indoors and outdoors.

Figure 5.49 Efficiency curve of D.C. hall collector with non-selective absorber (Nextel). Indoor measurements and computer predictions.
Figure 5.50 Redesigned Indoor Collector Test Facility

Figure 5.51 Steady State and Zero Testing Efficiency Curves
Figure 5.52: Steady state and efficiency curve plotted against mean absorber plate temperature ($T_p$) for simulated collector.
FIGURE 5.53  STEADY STATE AND ZERO TESTING EFFICIENCY CURVE PLOTTED
AGAINST MEAN FLUID TEMPERATURE (T_m) FOR SIMULATED COLLECTOR.
Figure 5.54: Collector temperature profile for model collector under steady state and zero testing conditions for the same fluid inlet temperature (303 K).

Figure 5.55: Collector temperature profile for model collector under steady state and zero testing conditions for the same mean absorber plate temperature (366 K).
**Figure 5.56** Temperature of absorber and rear duct for the same average fluid temperature with the collector under zero and steady state testing.

**Figure 5.57** $F_{u,c}$ versus mean fluid temperature for collector by 1 under zero testing and average steady state testing.
Figure 5.58 Efficiency curves for D.C. Hall collector using different test methods.
**Figure 5.59** Efficiency curve for structured polycarbonate collector under different test conditions.

**Figure 5.60** Top loss coefficient versus absorber temperature for P&O Chall type collector (maxim absorber).
Figure 5.61  Steady state efficiency of solar collector (black chrome) measured during operation and indoor testing, Source: Taylor, P.J. 'Performance of Selective and Non-Selective Solar Thermal Absorbers in a Working Installation,' Solar World Congress edited by S.V. Sionovoi, vol. 3, pp. 1149-1153.
**Figure 6.1** Efficiency curve for 'Conventional' and 'High Performance' collector.

**Figure 6.2** Typical construction of a flat plate collector.
Figure 6.4  
Percentage of energy falling above a threshold intensity averaged over a period of one hour each month on a horizontal surface (April 1970 - July 1973).

Figure 6.5  
Maximum improvement to flat plate collector performance by increasing \( \tau \) and \( \phi \).
Figure 6.6 Reflectance of Solar Collector Coatings

Figure 6.8  Efficiency curves for different methods of heat loss reduction.

FIGURE 6.10  EFFICIENCY CURVE OF ADVANCED FLAT PLATE COLLECTOR WITH XENON BETWEEN THE ABSORBER AND COVER AT A PRESSURE OF 1 TORR.

FIGURE 6.11  EFFICIENCY VERSUS MASS FLOW RATE FOR STRUCTURED POLYCARBONATE COLLECTOR. $I_{in} = 211 \text{W/m}^2\text{s}, T_a = 28^\circ\text{C}, T_{inj} > T_c, T_e = T_a$ and AIR VELOCITY = 1.5 $\text{m/s}$. 
FIGURE 6.12  PRESSURE DROP ACROSS S.P. COLLECTOR VERSUS MASS FLOW RATE

FIGURE 6.13  THEORETICAL SYSTEM EFFICIENCY VERSUS MASS FLOW RATE FOR A FLUID INLET TEMPERATURE OF 60°C, FOR THREE DUCT SPACINGS Z, AND TWO LEVELS OF INCIDENT INSOLATION.

FIGURE 6.15 Global and Diffuse Insolation Month by Month at 45° South Facing Slope.
**Figure 6.16**
Annual energy collected versus collector temperature, comparison of five types of collector. Source [33].

**Figure 6.17**
WIND = 1.0 m s⁻¹

TK = TA - 20, clear skies

TK = TA - 10, overcast skies

Figure 6.18 Simulated ambient conditions. For further details see text in Appendix C.
Figure 6.1a Steady-state efficiency ($\eta$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\bar{\eta}$ are for a variety of simulated conditions (see Table 4 and Figure 2).

(i) SÖJ/TÖJ, flow 2  (ii) SÖM/TÖM, flow 2  (iii) SÖD/TÖD1, flow 2
(iv) SÖM/TÖM, flow 3  (v) SÖM/TÖM, flow 2  (vi) SÖD/TÖD1, flow 3
(vii) SÖD1/TÖD1, flow 2  (viii) SÖD/TÖD2, flow 3  (ix) SÖD2/TÖD1, flow 2  (x) SÖD3/TÖD1, flow 2  (xi) SÖD/TÖD1, flow 2.
Figure 6.20 'EMTC' Air Heating Solar Collector Developed by GE [42]

Figure 6.21 Incident Angle Modifier for the EMTC Prototype. This depends on the orientation of the cover. A - the maximum occurs when the plane of the angle of incidence is perpendicular to the cylindrical axes of the tube cover. B - the maximum value occurs when the plane of the angle of incidence is normal to the cylindrical axes of the tubes in the cover [42].
Figure 6.22  Instantaneous efficiencies of the FMTC collector and a single glazed flat plate collector and their variation with insolation. [42]
FIGURE 7.1 THERMAL CONDUCTIVITY OF VARIOUS GASES AT 20°C VERSUS MOLECULAR WEIGHT.

FIGURE 7.2 CELLULAR CONVECTION FOR A LIQUID. FOR GASES, DUE TO THEIR DIFFERENT TEMPERATURE VISCOSITY RELATIONSHIP, THE GAS FALLS IN THE CENTRE OF THE CELL.
**FIGURE 7.3** Observation of cellular convection

**FIGURE 7.4** Base flow between inclined plates

FIGURE 7.6 SCHEMATIC DEPICTING EFFECT OF GAP SPACING ON CONDUCTANCE.
Figure 7.2: Plot of $h_c$ versus plate separation $S$. $T_{in} = 400^\circ F$, $T_{out} = 325^\circ F$, $14$th November.

Figure 7.8: $h_c$ versus tilt angle to the horizontal for air radiative for various absorber temperatures ($T_a$) with cover temp = 10°C.
Figure 7.9

Heat transfer coefficient variation with absorber temperature for convection and radiation.

$h_r$, heat transfer due to radiation between a non-selective absorber ($\epsilon = 0.9$) and a glass cover ($\epsilon = 0.9$).

$h_c$, heat transfer due to convection and conduction in air at atmospheric pressure.

$h_s$, heat transfer due to radiation between a selective absorber ($\epsilon = 0.09$) and low iron glass cover ($\epsilon = 0.88$).
FIGURE 7.10  TRUE AND PREDICTED HEAT LOSS BETWEEN TWO PARALLEL PLATES S = 5 cm
COVER TEMPERATURE 10 °C
**FIGURE 7.11** EFFECTIVE RAYLEIGH NUMBER VERSUS MOLECULAR WEIGHT FOR DIFFERENT GASES, AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL PLATES, SEPARATION 3 = 0.05 m, COLD PLATE TEMPERATURE 10°C, HOT PLATE 30°C.
FIGURE 7.12 Heat transfer coefficient for gases of different molecular weight. For S = 5 cm, cold plate temperature 10°C, hot plate temperature 30°C.
FIGURE 7.13  COST VERSUS HEAT TRANSFER COEFFICIENT FOR DIFFERENT GASES. 
$\beta = 5 \text{ cm}$, VOLUME OF GAS REQUIRED FOR EACH SQUARE METRE OF 
COLLECTOR IS 50 LITRES.
FIGURE 7.14 VARIATION OF HEAT TRANSFER COEFFICIENT $h_c$ WITH PRESSURE FOR A FLAT PLATE COLLECTOR, $s = 5 \text{ cm}$, $T = 293 \text{ K}$, $T_2 = 823 \text{ K}$ FOR CURVE 1, 723 K FOR CURVE 2 AND 473 K FOR CURVE 3.

FIGURE 7.15 DESCRIPTION OF TWO COVER SYSTEM.
FIGURE 7.16 VARIATION OF HEAT TRANSFER WITH GAP ACROSS A TWO COVER AND A SINGLE COVER SYSTEM. SOURCE: NAMOTRA, A AND GARG, H.P.
MINIMIZING CONVECTIVE HEAT LOSSES: SOLAR ENERGY, VOL. 25, NO. 6, P. 523.

FIGURE 7.17 REFLECTED SOLAR RAYS FOR A MULTI COVER SOLAR COLLECTOR.
**Figure 7.18** A solar ray and cut-away diagram of a hexagonal honeycomb collector. Source: Hollands K.G.T. 'Advanced Non-Concentrating Solar Collectors' Solar Energy Conversion ed by A.E. Dixon and J.D. Leslie, Pergamon Press 1979.
FIGURE 7.19 HEAT TRANSFER COEFFICIENT $h_c$ DUE TO NATURAL CONVECTION FOR AIR AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL FLAT PLATES SPACING $5 \text{cm}$, $T_e = 293 \text{K}$, WITH A HONEYCOMB AND WITH SLATS ASPECT RATIO 5
Figure 7.20  Thermal Conductivity versus Rayleigh Number for various gases. $T_1 = 10^\circ C$, $T_2 = 80^\circ C$, $\delta = 5\text{ cm}$. 
Figure 7.21
Rayleigh Number versus temperature for argon and air at atmospheric pressure between two parallel flat plates spacing $s = 5$ cm, cold plate temperature $T_c = 10^\circ C$.
Figure 7.22  Heat transfer coefficients for several collector configurations

$S = 5\, \text{cm}, \, T_i = 10\, ^\circ\text{C}$
Figure 7.23: Guard Ring Heater

Figure 7.24: Guard Ring Unbalance versus Measured Heat Transfer Across a 5 cm Thick 'Styrofoam Sp' Sample
FIGURE 7.27 COPPER COLD PLATES.
**Figure 7.28** Measured and theoretical heat transfer coefficients for different gases between two parallel plates, $s = 5$ in, various temperature difference.
Figure 7.29 Theoretical and measured heat transfer $h_c$ for air and argon.
FIGURE 7.30  THEORETICAL HEAT TRANSFER ACROSS STRUCTURED POLYCARBONATE OF VARIOUS THICKNESSES, BOTH RADIATION AND CONVECTION, ASSUMING FLAT CONVECTION AND A MEASURED EMISIVITY OF 0.72.
PLATE 2.1  PROTO PROMETHEUS, 1. COLLECTOR, 2. STORE TOP INSULATION AND COLLECTOR REAR INSULATION, 3. FAN MOTOR 4. MONITORING EQUIPMENT, 5. SPACE FOR INSULATION.
PLATE 2.2  PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
PLATE 5.1

SOLAR SIMULATOR TESTING A STRUCTURED POLYCARBONATE COLLECTOR.
17. STRUCTURED POLYCARBONATE COLLECTOR, 16. WIND GENERATOR,
19. COOL RAY LAMPS.
PLATE 5.2  INDOOR COLLECTOR TEST FACILITY
7. DATA LOGGER, 8. STRUCTURED POLYCARBONATE COLLECTOR,
9. PRESSURE TAPS, 10. SITE OF ORIFICE PLATE
PLATE 7.1

VIEW OF HEATED OIL FILM FROM AN INFRARED CAMERA.
THE BRIGHTER THE SPOT THE HOTTER THE SPOT.
PLATE 7.2  GUARDED HOT PLATE THERMAL CONDUCTIVITY RIG
11. INSULATED GUARD RING AND TEST CELL, 12. GAS CYLINDER
13. WATER COOLER, 14. HEATER POWER SUPPLY
APPENDIX A

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM **************************** SUNSTORE ******************************

100 DATA 
110 DATA 
120 DATA 
130 DATA 
140 DATA 
150 DATA 
160 DATA 
170 DATA 
180 DATA 
190 DATA 
200 DATA 
210 DATA 
220 DATA 
230 DATA 
240 DATA 
250 DATA 
260 DATA 
270 DATA 
280 DATA 
290 DATA 
300 DATA 
310 DATA 
320 DATA 
330 DATA 
340 DATA 
350 DATA 
360 DATA 
370 DATA 
380 DATA 
390 DATA 
400 DATA 
410 DATA 
420 DATA 
430 DATA 
440 DATA 
450 DATA 
460 DATA 
470 DATA 
480 DATA 
490 DATA 
500 DATA 
510 DATA 
520 DATA 
530 DATA 
540 DATA 
550 DATA 
560 DATA 
570 DATA 
580 DATA 
590 DATA 
600 DATA 
610 DATA 
620 DATA 
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195
### SOLAR RADIATION AT NEW DISTRIBUTION OF HOURLY-GLOBAL IRRADIATION

**ON A HORIZONTAL SURFACE IN MJ/m²**

<table>
<thead>
<tr>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
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<tr>
<th>JAN</th>
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**TOTAL ANNUAL SOLAR RADIATION = 3410.94 MJ/m²**

### STORE

**STORE LENGTH** 280 Meters  
**WIDTH** 10 Meters  
**HEIGHT** 4 Meters  
**Vc, Ic, Tc** = 11200 m³  
**STORAGE MATERIAL PEBBLES** DENSITY = 1600 kg/m³  
**SPECIFIC HEAT** = 0.837 KJ/kg°C  
**STORE INSULATION THICKNESS** = .6 m  
**THERMAL CONDUCTIVITY** = .026 W/m°C

### COLLECTOR

**TOTAL COLLECTOR AREA** = 2800 m²  
**Ft=HEAT TRANSFER FACTOR(equivalent to Fr heat removal factor if store has a good heat exchanger) = .9**  
**UL=OVERALL HEAT LOSS COEFFICIENT** = 1  
**T=OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES** = .8

### HOUSE

**NUMBER OF HOUSES** = 100  
**THE MONTHLY HEATING LOAD FOR EACH HOUSE IS** (heating and hot water): MJ  
**JAN** = 7750  
**FEB** = 6490  
**MAR** = 5560  
**APR** = 4320  
**MAY** = 980  
**JUN** = 770  
**JUL** = 770  
**AUG** = 770  
**SEP** = 770  
**OCT** = 1790  
**NOV** = 5270  
**DEC** = 7450  
**TOTAL ENERGY DEMAND OF HOUSE PER ANNUM** = 4169.6 GJ (11580.555556 kWh)

### SYSTEM OPERATION

**Tso = Original Store Temperature at the beginning of month**  
**Ta = Ambient Temperature Averaged over periods of collector operation**  
**tT = Time Period of Collector Operation (h)**  
**It = Total Irradiation which is above Threshold (MJ/m²)**  
**qN = Normalized Net Heat to Storage = qT - tT - I (MJ/m²)**  
**tsf = Store Temperature at the end of the month**  
**qT = Useful Heat Collected = qN + I (MJ/m²)**  
**ls = Normalized Total Monthly Load (MJ/m²)**  
**qAUX = Auxiliary Heat - is + (MJ/m²)**

| APR  | 29.00 | 30     | 1.296 | 350.7 | 88.54 | 269.76 | 118.57 | 12.4  | 0.0  |
| MAY  | 25.13 | 46     | 1.562 | 477.1 | 209.7 | 243.97 | 35.0  | 25.48 | 0.0  |
| JUN  | 21.13 | 65     | 1.728 | 549.9 | 192.0 | 219.16 | 27.50 | 41.18 | 0.0  |
| JUL  | 18.25 | 121    | 1.674 | 513.1 | 116.2 | 143.08 | 25.70 | 55.50 | 0.0  |
| AUG  | 18.38 | 143    | 1.562 | 424.4 | 36.3  | 63.98  | 27.50 | 61.08 | 0.0  |
| SEP  | 21.50 | 150    | 1.296 | 306.3 | -21.0 | 145.6  | 27.27 | 60.50 | 0.0  |
| OCT  | 25.25 | 146    | 1.116 | 186.0 | -110.0 | 125.0 | -46.56 | 63.93 | 27.0  |
| NOV  | 29.50 | 128    | .864  | 93.3  | -236.0 | 81.0  | -47.47 | 188.21 | 40.9  |
| DEC  | 30.50 | 81     | .670  | 53.0  | -251.0 | 30.0  | 15.02 | 266.07 | 9.1  22 |
| JAN  | 32.38 | 30     | .670  | 60.8  | -257.0 | 30.0  | 19.80 | 276.79 | 9.1  257 |
| FEB  | 32.25 | 30     | .806  | 120.4 | -171.0 | 30.0  | 60.93 | 231.79 | 8.2  171 |
| MAR  | 31.25 | 30     | 1.116 | 241.5 | -57.0 | 30.0  | 141.99 | 198.57 | 9.1  57 |

**TOTAL** = 1026.80 1488.93 390.2 -462.0

**% OF ENERGY SUPPLIED BY SOLAR SYSTEM = 69.0**

**% OF SOLAR ENERGY COLLECTED ABOVE THRESHOLD = 42.0**

**% OF SOLAR ENERGY COLLECTED 41.5**

**TOTAL AUXILIARY ENERGY FOR SYSTEM = 129360.78649 MJ (359433.551803 kWh)**

**TOTAL AUXILIARY ENERGY PER HOUSE = 129360.78649 MJ (359433.551803 kWh)**
APPENDIX B

Computer models used to predict steady state performance of air heating collectors.

TOPAIR: calculates the top heat loss $U_t$ for different absorber temperatures.

EFFIC: Calculates the efficiency of a top duct air heating collector.

EFFIC2: Calculates the efficiency of a rear duct air heating collector.
20 REM ~~~~~~ PROGRAM TOPAIR ~~~~~~~~~
25 LETtemp~ THE TOP LOSS COEFFICIENT FOR A SINGLE GLASS UNIT
20 REM
30 REM
40 ' 
50 FOR i=0 TO 20
60 TP=10+i*5 ' ABSORBER TEMP
70 TA=10 ' Ambient temp (C)
80 WIND=1 ' Wind speed (m/s)
90 EPS=.95 ' Absorber emissivity
100 EC=.8 ' Cover plate emissivity
110 S=5 ' Plate separation (cm)
120 G=9.812 ' Acceleration due to gravity (m/s^2) at LONDON
130 K=.0257 ' Thermal conductivity of gas at Tave (Wm-20C)
140 B=0 ' 1/tilt angle(=Horizontal)
150 CP=1007 ' Heat capacity of air (J/kgK)
155 CP=1007 ' Heat capacity of GAS BETWEEN COVER AND ABSORBERkgK
160 S/S=100 ' CONVERT TO METERS
170 L=1
180 W=1
190 SW=2*LW/(L+W)
200 REM ~~~~~~~~~~ PROGRAM TOPAIR ~~~~~~~~~
210 Tc=Ta+(TP-Ta)/2 ' guess the cover temp
220 Tt=273.15+TC ' CONVERT TO KELVIN
230 Ta=273.15+TA ' CONVERT TO KELVIN
240 Tc=273.15+TC ' CONVERT TO KELVIN
250 TP=TP+273.15 ' CONVERT TO KELVIN
260 T=TP ' CONVERT TO KELVIN
270 DT=2T-Tt ' TEMP DIFFERENCE DELTA T
280 Tave=(Tt+DT/2) ' AVERAGE GAS TEMPERATURE
290 DEN=352.91/Tave
300 k=Tave.0000764+.0034606
310 VIS=Tave.0000646+.000064351
320 VOL/Tave ' THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERF.
330 V=VIS/DEN ' KINEMATIC VISCOSITY
340 Gr=G*VOL*SW*31DT/VT/2 ' GRASHOF NUMBER
350 Pr=CP*VIS/K
360 Ra=GrPr ' RAYLEIGH No
370 REM --------------- CALCULATE NUSSELT NUMBER
380 N=1708/(Ra*COS(B))/5830/(1/3-1)
390 IF N<0 THEN N=0 ' TAKE ONLY POSITIVE TERMS
400 N2=(Ra*COS(B))/5830/(1/3-1)
410 IF N2<0 THEN N2=0 ' TAKE ONLY POSITIVE TERMS
420 N2=(1.44411+(1.841171/1.61708/(Ra*COS(B)))+N2 ' NUSSELT No
430 h=K/SN ' HEAT TRANSFER COEFFICIENT
440 h=r.0000000567*(TP+2*TC)^2/(TP+TC)/(1/EP=1/EC-1) ' RAD FROM PLATE TO COVER
450 hsvy=0.000000567*EC/(TC+2*TA)^2*(TC+TA) ' RAD COVER TO SKY
470 DTW=TC-TA
480 Tave=Ta+DTW/2
490 DENW=352.91/TaveW
500 K=VW=0.000764+.0034406
510 VIS=VW=.0000646+.000064351
...
10 REM ★★★★★★★★★★★★★★ EFFIC ★★★★★★★★★★★★★★
40 REM ★★★★★★★★★★★★★★ AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN ★★★★★★★★★★★★★★★
50 REM ★★★★★★★★★★★★★★ INPUT VARIABLE DATA ★★★★★★★★★★★★★★★
65 FOR J=0 TO 10  " MASS FLOW RATE (kg/hr)
80 Ta=16.2  " AMBIENT TEMP (°C)
120 Ti=T2-TA)/2+TA  " FLOW TEMPERATURE (°C)
120 Ti=T2=0.4  " ABSORBER TEMPERATURE (°C) IF THIS CHANGES ALSO CHANGE Ti
130 Ti=Ta=2  " PLATE SEPARATION IN CM
140 L=2  " COLLECTOR LENGTH IN METERS
150 W=1  " WIDTH OF COLLECTOR IN METERS
160 D=1  " FIN SEPARATION IN CM
340 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ????"
245 IF J>0 THEN GOTO 470
250 PRINT AS
260 IF AS="N" THEN GOTO 470
270 PRINT AS=701
280 PRINT """ COLLECTOR INITIAL PARAMETERS ARE """'
290 PRINT USING 930  " " MASS FLOW RATE, M, "kg/hr"
300 PRINT USING 930  " AMBIENT TEMP, TA, °C"
310 PRINT USING 930  " INLET FLUID TEMPERATURE, Ti, °C"
320 PRINT USING 930  " WIND SPEED, m/s"
330 PRINT USING 930  " INTENSITY OF SOLAR RADIATION, W/m2"
340 PRINT USING 930  " SOLAR RADIATION, W/m2"
350 PRINT USING 930  " EMISSIVITY OF COVER, E1"
360 PRINT USING 930  " EMISSIVITY OF ABSORBER, E2"
370 PRINT USING 930  " COLLECTOR AREA, A, m2"
380 PRINT USING 930  " COLLECTOR LENGTH, L, m"
390 PRINT USING 930  " PLATE SEPARATION, S, cm"
400 PRINT USING 930  " FOCUS SEPARATION, D, cm"
410 PRINT """ EFFICIENCY OF COLLECTOR EFFIC ★★★★★★★★★★★★★★★
420 PRINT """ EFFICIENCY OF COLLECTOR EFFIC ★★★★★★★★★★★★★★★
430 PRINT """ EFFICIENCY OF COLLECTOR EFFIC ★★★★★★★★★★★★★★★
440 PRINT """ EFFICIENCY OF COLLECTOR EFFIC ★★★★★★★★★★★★★★★
450 PRINT """ EFFICIENCY OF COLLECTOR EFFIC ★★★★★★★★★★★★★★★
460 REM ★★★★★★★★★★★★★★ INPUT CONSTANT DATA ★★★★★★★★★★★★★★★
480 STE=0.0000000057  " STEFAN-BOLTZMAN CONSTANT (W/m2K4)
490 VISA=0.000188  " VISCOSITY OF AIR IN DUCT (N.s/m2)
500 W=0.0241  " THERMAL CONDUCTIVITY OF AIR IN DUCT (W/m.K)
510 C=1009  " HEAT CAPACITY OF AIR AT CONSTANT PRESSURE (J/L°C)
520 REM ★★★★★★★★★★★★★★ END OF PROGRAM ★★★★★★★★★★★★★★★
530 Ti=11.273.15  "
540 I2=I2+T2/2,
560 SM=S/100  "
570 D=D/100  "
APPENDIX C

A multi-node dynamic computer model of a flat-plate, rear-duct, air-heating solar collector is described, and its verification is outlined. Results from the model are then presented of the daily averaged thermal efficiencies for a variety of simulated ambient conditions pertinent to mid to high maritime latitudes. The collectors differ significantly only in their thermal capacitances. The diurnal variation of insolation produces a modest spread of thermal efficiencies, the lower the thermal capacitance of the collector the higher the efficiency. More rapid fluctuations in insolation produce only a slightly further spread in the thermal efficiencies, though such fluctuations have a more significant effect on peak temperatures.

Keywords: air-heating solar collectors; thermal capacitance effects in solar collectors.

NOMENCLATURE

DY1-5 plate and duct-back thicknesses (5)
f(θ) transmittance - absorptance function of the collector
FR collector heat-removal factor
HPA(I) heat-transfer coefficient plate (or duct-back) to air in the I'th segment of the duct
M duct air flow rate
NI number of duct segments
PON threshold power for switch on of air flow
S irradiance in cover plane
S0 solar beam irradiance
S1 diffuse irradiance on a horizontal surface
SP irradiance absorbed by plate
TA ambient temperature
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>TI</td>
<td>air inlet temperature</td>
</tr>
<tr>
<td>TK</td>
<td>sky temperature</td>
</tr>
<tr>
<td>TO</td>
<td>air outlet temperature</td>
</tr>
<tr>
<td>Uc</td>
<td>overall U-value of the collector</td>
</tr>
<tr>
<td>W</td>
<td>width of collector</td>
</tr>
<tr>
<td>Wind</td>
<td>wind speed</td>
</tr>
</tbody>
</table>

M, J, D, D1, D2, D3 various subscripts (see text)

η         steady-state thermal efficiency of the collector

\[ \eta \] daily averaged thermal efficiency of the collector

\[ \theta \] angle between collector normal and solar beam

1 INTRODUCTION

Low mass in solar collectors offers the advantage of low construction and installation costs. But the mass also influences the thermal capacitance and hence the thermal efficiency, because even a smooth diurnal variation of insolation prevents a collector from achieving a true steady-state, and the lower the mass the closer the varying conditions are followed. Earlier studies (for example {1}, {2}, {4}) have shown that lowering the mass will improve the thermal efficiency, though perhaps by not very much. However, there seem to be few data on the diurnal performance in various ambient conditions of collectors which differ only in their thermal capacitances. This is particularly the case for air-collectors.

Therefore we have developed and verified a dynamic computer model of a flat-plate, rear-duct, air-heating solar collector. We have used it to obtain daily averaged thermal efficiencies for a wide variety of simulated ambient conditions pertinent to maritime mid to high latitudes. The basic configuration of the collector was varied to yield a wide spread of thermal capacitances. The model is of the multi-node kind, because various studies (for example {1}, {3}, {4}) have shown that simple one-node models are unlikely to give accurate results in non steady-state conditions.

2 THE COLLECTOR MODEL

The collector is of the flat-plate rear-duct air-heating single-cover kind, with dimensions selected to give good performance. It is divided into nodes as shown in Figure 1. (This collector could be complete, or it could be a strip width W of a larger assembly.) Heat balance equations are defined at each node, and the equations are numerically integrated in sequence using the Adams-Bashforth-Moulton predictor-corrector method {5}.

The model was tested in a variety of ways, including a comparison of its predictions with the actual behaviour in the laboratory of a flat-plate rear-duct air-heating single-cover collector. In all cases the agreement between prediction and actuality was satisfactory.
RESULTS

5.1 The collectors

Table 1 specifies the collector configurations, and the rear-duct air flow conditions. The basic configuration was selected to give good steady-state performance, the configurations differing only in the thickness of the plate and duct-back (DY1 to DY5 in Table 1). The main effect of these changes in configuration is on the thermal capacitance of the components and hence of the whole collector.

Table 1 Collector configurations, and rear-duct air flow

| collector length (along flow) | 4.00 m |
| collector width (W)           | 1.00 m |
| cover to plate spacing        | 0.05 m |
| rear duct gap                 | 0.01 m |
| back insulation               | dry glass fibre, thickness 0.10 m |
| edge insulation               | dry glass fibre, thickness 0.05 m |
| material of plate and duct-back | duralumin HS15TB |
| cover                         | polycarbonate, thickness 2.00 mm |
| plate absorbtance             | 0.95 at θ=0, falling slightly as θ increases |
| emissivity of upper surface of the plate (diffuse) | 0.10 |
| emissivity of duct surfaces (diffuse) | 0.91 |
| emissivity of the cover (diffuse) | 0.85 |
| thermal properties of air at 283 K for ambient air, at 303 K elsewhere |
| latitude                      | 52°N |
| collector tilt (to horizontal) | 35° |
| collector orientation         | south-facing |
| thickness of plate and of duct-back | collector time-constant (flow 1) |
| DY1                           | 0.2 mm | 85 s |
| DY2                           | 0.5 mm | 170 s |
| DY3                           | 1.0 mm | 300 s |
| DY4                           | 2.0 mm | 580 s |
| DY5                           | 5.0 mm | 1400 s |

Air flow in the rear-duct

<table>
<thead>
<tr>
<th>flow</th>
<th>stagnation (M=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>all TI M = 0.0600 kg s⁻¹ (PON irrelevant)</td>
</tr>
<tr>
<td>2</td>
<td>TI = 303 K M = 0.0600 kg s⁻¹ PON = 128 W</td>
</tr>
<tr>
<td>3</td>
<td>TI = 323 K M = 0.0562 kg s⁻¹ PON = 124 W</td>
</tr>
</tbody>
</table>

The air flow rate is a compromise between attaining large values of HPA(I) and keeping low the power required to maintain the air flow in the rear-duct. At $M = 0.0600$ kg s⁻¹ and $TI = 303$ K (flow 2 in Table 1) this power is 6.4 W. The corresponding pressure drop across the duct is 12 mm water gauge. If it is
assumed that the circulation fan gives a constant volumetric flow rate then at
other values of $T_i$ the value of $M$ will be different from $0.0600$ kg s$^{-1}$; at
$T_i = 323$ K, $M = 0.0562$ kg s$^{-1}$ (flow 3 in Table 1).

It is also necessary to specify the minimum power that must be delivered by a
complete array of collectors in order for the air flow to either be switched
on or be sustained. This power must be some multiple of the electrical power
required by the fan to circulate air around the whole system incorporating the
array. We adopted a multiple of two. In order to estimate the electrical
power it is necessary to allow for the efficiency of the fan and for the pressure
drop in the whole system. For a modest domestic system we ended up with a
minimum power per collector of the sort specified in Table 1 of $128$ W for flow 2.
For flow 3 PON is slightly less. The values of PON are shown in Table 1. Note that
the values of PON are for a $4 \times 1$ m collector, and not for the whole array.
These values of PON correspond to an air temperature rise of between $2$ K and $3$ K
for the flow conditions specified.

The collector time-constants in Table 1 vary with ambient conditions and with
operating conditions, particularly with the air flow rate. The values in the
Table are representative for all ambient conditions considered here, and for
the various (similar) air flow rates, except for flow 0 (stagnation), in which
case the time-constants in Table 1 should be multiplied by about a factor of 5.
Note that the time-constants in Table 1 are the 1/e time-intervals following a
step change in insolation. However, only in stagnation is the response very close
to exponential. Note also that the thermal capacitance of the cover has a
relatively small effect, because the cover is coupled to the plate via a rather
large thermal resistance.

3.2 Steady-state efficiency curve

We obtained a standard steady-state thermal efficiency curve, of the form (6)

\[ \eta = \frac{F_R (f(\theta) - U_L (T_i - T_A)/S)}{S} \]  

(1)

where $f(\theta)$ is such that

\[ SF = f(\theta) \cdot S \]  

(2)

For the steady state efficiency curve $S$ is beam irradiance normal to the cover,
such that $S = 700$ W m$^{-2}$. Furthermore, $T_A = 293$ K, $T_K = 273$ K, $WIND = 1.0$ m s$^{-1}$,
$M = 0.0600$ kg s$^{-1}$. These values lie within the ASHRAE specifications for steady-
state collector testing (6).

In order to obtain the efficiency curve the value of $T_i$ was varied, everything
else remaining constant. The outcome is shown in Figure 2 for collector
configuration DY1 (Table 1), though the results for DY2 to DY5 are
indistinguishable from those for DY1 on the scale of Figure 2. The intercept
on the $\eta$-axis, 0.683 gives $F_R \cdot f(\theta)$ (equation (1)). The program yields a value of
0.830 for $f(\theta)$, and therefore $F_R$ is 0.823. The slope gives $-F_R \cdot U_L$, and at low
values of $(T_i-T_A)/S$ this is $-2.83$ W m$^{-2}$ K$^{-1}$, giving a value of $U_L$ of $3.44$ W m$^{-2}$ K$^{-1}$.
The value of $F_R \cdot U_L$ increases as $T_i$ increases ($T_A$, $S$ constant), largely because
the radiative heat transfer coefficients increase with increasing temperature
differences, and though $F_R$ decreases it does not offset the increase in $U_L$.
These values of $f(\theta)$, $F_R$ and $U_L$ indicate good performance for a flat-plate rear-
duct air-heating single-cover collector with a selective plate-surface.

We had a "quick look" at the effect of varying the wind speed on the steady-state
temperatures. The effect was fairly modest, because of the large thermal resistance between cover and plate. Wind speed variations will be deferred to a later study.

3.3 Daily-averaged efficiency

The collector configurations DY1 to DY5 were run under conditions flow 2 and flow 3 for a variety of simulated days 21 June (J), 21 March (M), 21 December (D). The simulated conditions of insolation and weather on these days are shown in Figure 3. The ambient temperature TA varies sinusoidally through the day (Figure 3(a)) with an amplitude of 5 K. Note that there are two temperature curves for 21 December, TAD1 and TAD2. The irradiance S consists of a diffuse component from the ground, and of a sky component which can either correspond to clear sky conditions or to overcast diffuse conditions. Figure 3(b) shows some of the various insulations, the prefix S0 denoting the clear sky irradiance normal to the beam, and the prefix S1 the overcast diffuse irradiance on a horizontal surface. In the cases in Figure 3(b) the only variation in insolation is the diurnal envelope shown. By contrast in Figures 3(c) and (d) the insolation flips between the two envelopes shown, the square wave periods being indicated, the conditions remaining diffuse throughout. In clear sky conditions the sky temperature is 20 K below TA, and in overcast conditions it is 10 K below TA. In all cases the wind speed is constant at 1.0 m s⁻¹.

For each "day" an average thermal efficiency was obtained, defined by

\[ \eta = \frac{\text{total energy extracted by the air flow in the day}}{\text{integration of } S \text{ over the day}}. \]  

(3)

Note that a day spans the time from sunrise to sunset. In no case did a collector deliver energy before or after sunset, and therefore \( \eta \) is never being wrongly evaluated.

In order to plot \( \eta \) on Figure 2 it is necessary to re-define the abscissa \((TI-\text{TA})/S\). TI is constant (303 K or 323 K), and for TA and S the arithmetic mean values for the period sunrise to sunset are taken. The outcome is shown in Figure 2, the results being coded in accord with Table 1 and Figure 3, except that the thermal capacitance configuration DY1 to DY5 is not shown. However, you can see that at each value of \((TI-\text{TA})/S\) there is a column of results, and in every case DY1 is at the top, then comes DY2, and so on, to DY5, though in some cases DY1-DY3 merge on the scale of Figure 2. Clearly, the lower the thermal capacitance the better the performance.

Consider first those cases in which the insolation only varies over the diurnal envelope: this covers the cases (i)-(vi), (viii), (xi). The increase in \( \eta \) is marked in going from the rather massive DY5 to the rather less massive DY4. However, the improvement in going from DY4 to the low mass DY1 is also significant, particularly in marginal conditions (large \((TI-\text{TA})/S\)). This general improvement with reducing thermal capacitance arises because with a diurnal envelope the slower warm-up of a high mass collector in the morning is not compensated by the slower cool-down in the afternoon. Note that the sinusoidal variations in TA and TK do not make an appreciable contribution to the spread of \( \eta \) with thermal capacitance on the scale of Figure 2.

The advantage of low mass could, in principle, be more marked under intermittent insolation. SID1-SID3 provide such conditions (Figure 3), the periodicities lying within the range of time-constants in Table 1. However, Figure 2 shows that, even in marginal conditions, very little further advantage in low mass is obtained, though DY1-DY3 are more spread out than with the diurnal envelope alone.
The reason for such a slight improvement is that whereas a low mass collector will "follow" the insolation, possibly switching the air flow on and off, a high mass collector, once it has warmed to the point where the air flow switches on, will tend to stay at a fairly constant temperature. The overall effect, for a wide variety of conditions, is that the time-averaged temperatures of the air flow are not very sensitive to the mass. Therefore there is very little difference in the amount of heat extracted. A similar conclusion was reached by Klein et al. [1].

Figure 2 also shows that the values of $\bar{\eta}$ differ from those of $\eta$. This is particularly the case at low thermal capacitances, as can be seen from the performance of DY1, which is not very different from that which would have been obtained for a collector of zero thermal capacitance. Two prominent and opposing effects operating here are that for $\eta$ in Figure 2 the value of $\theta$ is always zero, thus raising $f(\theta)$, and more importantly, that in insolation conditions which vary, intermittently or otherwise, a collector can "grab" peak insolation, yet entirely miss the corresponding steady state insolation which never reaches such peak values. Low thermal capacitance is again an advantage.

In addition to $\bar{\eta}$, the daily average of $T_{O}$ was also obtained, such that only those periods were included in which air flowed in the rear duct. In general the lower the thermal capacitance of the collector the higher the daily average, though the improvement from DY5 to DY1 never exceeded 2 K. However, the peak temperatures for DY1 can be up to about 10 K higher than for DY5, the greatest difference occurring in intermittent conditions. In some circumstances this will be an important advantage of low thermal capacitance.

A set of results analogous to those in Figure 2 was obtained for lower flow rates, around 0.02 kg s$^{-1}$. This is a potentially useful domain, because in spite of the lower thermal efficiencies the values of $T_{O}$ are raised and can reach values such that useful energy can be extracted from ambient conditions which would yield no useful energy at higher flow rates, because of the lower values of $T_{O}$. However the variation of $\bar{\eta}$ with thermal capacitance (DY1-DY5) was not remarkably different from that shown in Figure 2.

It can be concluded that collectors with low thermal capacitance can have significantly larger thermal efficiencies at non-small daily averaged values of $(T-I_{A})/S$ in non-steady insolation, and that this is largely because of the diurnal variation, rather than because of more rapid fluctuations in insolation. Peak temperatures can also be significantly larger at low thermal capacitance, particularly when there are rapid fluctuations in insolation.

REFERENCES


2 M. Yusoff and D. J. Close, Transient studies of solar air heaters, presented at the Inter-regional symposium on solar energy for development, Tokyo 5-10 February (1979).


Figure 1  Flat-plate, rear duct, air heating solar collector.
Figure 2  Steady-state efficiency ($\eta_\ast$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\bar{\eta}$ are for a variety of simulated conditions (see Table 1 and Figure 3).

(i) S0J/TAJ, flow 2  (ii) S0M/TAM, flow 2  (iii) S0D/TAD1, flow 2  
(iv) S0M/TAM, flow 3  (v) S1M/TAM, flow 2  (vi) S0D/TAD1, flow 3  
(vii) S1D1/TAD1, flow 2  (viii) S0D/TAD2, flow 3  (ix) S1D2/TAD1, flow 2  
(x) S1D3/TAD1, flow 2  (xi) S1D/TAD1, flow 2.
Figure 3 Simulated ambient conditions. For further details see text.

\[ WIND = 1.0 \text{ m s}^{-1} \]

\[ TK = TA - 20, \text{ clear skies} \]

\[ TK = TA - 10, \text{ overcast skies} \]
APPENDIX D

TRANS: Computer programme for analysing collector data under transient conditions.
214
940 NEXT K
950 NEXT K
960 Z=SOR (Z=EYY/(NP-NC))
970 PRINT "ETIAO":"E","E":Z/E
980 U=U-NC
990 PRINT "FU=U","F":Z/(NC)
1000 PRINT "TABLE F.4"
1010 FOR K=1 TO NK
1020 C(K)*X(K)/E
1030 PRINT K,C(K)
1035 NEXT K
1040 F=U/(1+LOG (1-U/H)))
1050 PRINT "F="IF
1060 E=E/F
1070 U=U/F
1080 PRINT "ETIAO":"E","U":U
1090 PRINT "DATA SETS ACCEPTED FOR ANALYSIS":NP
1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN 1 TO "TRANSDAT00"
1120 NP=0
1130 READ# 1 : I,X(NK),Y,T(NK)
1140 IF I=0 AND X(NK)="O THEN GOTO 1570
1150 I=I+1
1160 FOR K=2 TO NK
1170 X=MK"K+1
1170 READ# 1 : I,X(L),Y,T(L)
1180 IF I=0 AND X(L)="O THEN GOTO 1570
1190 I=I+1
1200 NEXT K
1210 GOTO 1400
1220 FOR K=2 TO NK
1230 L=MK"K+2
1240 X(L)=X(L'-1)
1250 T(L)=T(L'-1)
1260 NEXT K
1270 READ# 1 : I,X(I),Y,T(I)
1280 IF I=0 AND X(I)="O THEN GOTO 1570
1290 I=I+1
1300 NEXT K
1310 GOTO 1400
1320 FOR K=1 TO NK
1330 E=E+X(K)C(K)
1340 X=NC"X(NC)+T(K)
1350 NEXT K
1360 Y=Y/(FRE)
1370 X=NC"X(NC)"NC/E
1380 PRINT Y,X(NC)
1390 REM CALC LEAST SOR TO THERMAL PERFORMANCE
1400 SX=SXX/NC
1410 SY=SY+Y
1420 SY=SYY+Y
1430 SY=SY+Y
1440 SY=SY+Y