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

Thesis

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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

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Appendix D: 'TRANS', transient testing computer model.
# Nomenclature

**Chapter 2**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>Collector area ($m^2$)</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Storage tank surface area ($m^2$)</td>
</tr>
<tr>
<td>$c$</td>
<td>Appropriate specific heat ($J/Kg \cdot ^\circ C$)</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Volume heat capacity at constant pressure ($J/Kg \cdot ^\circ C$)</td>
</tr>
<tr>
<td>$C_h$</td>
<td>Initial capital expenditure per house (£)</td>
</tr>
<tr>
<td>$E_T$</td>
<td>Total (accumulated sum) of the radiation falling over a time period of one month on an inclined surface which is above the threshold radiation ($J/m^2$)</td>
</tr>
<tr>
<td>$f$</td>
<td>Differential fuel inflation</td>
</tr>
<tr>
<td>$F_h$</td>
<td>Fuel cost per year per house (£)</td>
</tr>
<tr>
<td>$F_R$</td>
<td>Collector/heat-exchanger efficiency factor</td>
</tr>
<tr>
<td>$F'$</td>
<td>Collector efficiency factor</td>
</tr>
<tr>
<td>$i$</td>
<td>Discount rate</td>
</tr>
<tr>
<td>$I_{th}$</td>
<td>Threshold solar irradiance ($W/m^2$)</td>
</tr>
<tr>
<td>$K_h$</td>
<td>Repeated capital expenditure per house (£)</td>
</tr>
<tr>
<td>$L$</td>
<td>Monthly total heating demand for space heating and hot water ($J$)</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Energy lost from storage tank during the month ($J$)</td>
</tr>
<tr>
<td>$M_C$</td>
<td>Storage heat capacity ($J/\circ C$)</td>
</tr>
<tr>
<td>$N$</td>
<td>Lifetime of hardware (years)</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of years</td>
</tr>
<tr>
<td>$P_{VCh}$</td>
<td>Present value cost per house</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat energy ($J$)</td>
</tr>
<tr>
<td>$Q_N$</td>
<td>Net heat transferred to storage during the month ($J$)</td>
</tr>
<tr>
<td>$Q_T$</td>
<td>Solar energy collected during the month ($J$)</td>
</tr>
<tr>
<td>$R_h$</td>
<td>Running costs per year per house (£)</td>
</tr>
<tr>
<td>$s$</td>
<td>Pebble shape factor</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient temperature ($\circ C$)</td>
</tr>
<tr>
<td>$T_{at}$</td>
<td>Ambient temperature averaged over periods when the radiation level is above the threshold ($\circ C$)</td>
</tr>
<tr>
<td>$T_g$</td>
<td>Monthly average ground temperature ($\circ C$)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Store temperature ($\circ C$)</td>
</tr>
<tr>
<td>$\bar{T}_s$</td>
<td>Monthly average store temperature ($\circ C$)</td>
</tr>
<tr>
<td>$T_{so}$</td>
<td>Store temperature at the beginning of the month ($\circ C$)</td>
</tr>
</tbody>
</table>
\begin{align*}
\Delta T & \quad \text{Temperature change (°C)} \\
t_m & \quad \text{Total number of seconds in a month} \\
t_t & \quad \text{Total number of seconds collector is in operation in month, i.e. when radiation level is above threshold} \\
U_L & \quad \text{Collector overall loss coefficient (W m}^{-2} \text{ °C}^{-1}) \\
U_S & \quad \text{Storage tank heat loss coefficient (W m}^{-2} \text{ °C}^{-1}) \\
V & \quad \text{Volume (m}^3\text{)} \\
\rho & \quad \text{Density (kgm}^{-3}\text{)} \\
(\tau\alpha) & \quad \text{Monthly average transmittance-absorptance product}
\end{align*}
Nomenclature

Chapter 3

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

$F_R$ 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)
Dₘ  Characteristic length (m)
F'  Absorber plate (or collector) efficiency factor
Fₐ  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)
hₐ  Radiative heat transfer coefficient (Wm⁻² °C⁻¹)
hₜ  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)
Uₜ  Bottom loss heat transfer coefficient (Wm⁻² °C⁻¹)
Uₑ  Edge loss heat transfer coefficient (Wm⁻² °C⁻¹)
Uₘ  Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)
\( U_t \) Top loss heat transfer coefficient \((\text{Wm}^{-2} \cdot \text{C}^{-1})\)

\( V \) Wind velocity \((\text{ms}^{-1})\)

\( W \) Collector width \((\text{m})\)

\( x \) Insulation thickness \((\text{m})\)

\( \alpha \) Absorptance of the collector absorber surface for solar radiation

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

\( \epsilon_c \) Cover emissivity

\( \epsilon_p \) Absorber plate emissivity

\( \eta \) Efficiency

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

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

\( \tau \) 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°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$^{-1}$)

$m_l$ 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)
\[ T_{im} \quad \text{Measured fluid inlet temperature (°C)} \\
T_m \quad \text{Mean fluid temperature } \left( \frac{T_e + T_i}{2} \right) \text{ (°C)} \\
T_p \quad \text{Absorber plate temperature (°C)} \\
T_s \quad \text{Mean absorber temperature (°C)} \\
T_{sky} \quad \text{Equivalent black body sky temperature (°C)} \\
T^* \quad \text{Reduced temperature } \left( \frac{T_i - T_a}{I} \right) \text{ (m}^2 \ \text{°C w}^{-1}) \\
U_L \quad \text{Collector overall heat transfer (loss) coefficient} \\
\text{(Wm}^{-2} \ \text{°C}^{-1}) \\
V \quad \text{Wind velocity (ms}^{-1}) \\
\eta \quad \text{Efficiency} \\
\tau\alpha \quad \text{Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.} \\
\tau_C \quad \text{Collector time constant under flow conditions (s)} \\
\tau_d \quad \text{Cut off time (s)} \\
(\tau\alpha)_e \quad \text{Effective transmittance absorptance product} \\
(\tau\alpha)_n \quad \text{Product of the absorptance and transmittance for normal irradiance} \\
\Delta T^* \quad \text{Time increment} \\
\theta \quad \text{Angle of incidence; degrees from normal} \]
Nomenclature

Chapter 6

\( F_R \) Collector heat removal factor

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

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

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

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

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

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

\( T_a \) Ambient air temperature \((^\circ\text{C})\)

\( T_i \) Inlet fluid temperature \((^\circ\text{C})\)

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

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

\( \epsilon_t \) Thermal emissivity

\( \eta \) Efficiency steady state

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

\( \eta_0 \) Zero loss collector efficiency, \( F'(\alpha\tau) \)

\( \tau_s \) 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 (ms\(^{-1}\))
\( c_p \)  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 (ms\(^{-2}\))
Gr  Grashof number
h  Combined heat transfer coefficient from absorber to cover (Wm\(^{-2}\) °C\(^{-1}\))
\( h' \)  Heat transfer coefficient of material of known conductivity (Wm\(^{-2}\) °C\(^{-1}\))
\( h_b \)  Heat transfer coefficient for flow across panel wall (Wm\(^{-2}\) °C\(^{-1}\))
\( h_c \)  Heat transfer coefficient for flow across the inside of the panel due to convection and conduction (Wm\(^{-2}\) °C\(^{-1}\))
\( h_p \)  Heat transfer coefficient for flow across panel (Wm\(^{-2}\) °C\(^{-1}\))
\( h_r \)  Heat transfer coefficient for flow across the inside of the panel due to radiation (Wm\(^{-2}\) °C\(^{-1}\))
\( h_s \)  Heat transfer coefficient for flow across standard insulation (Wm\(^{-2}\) °C\(^{-1}\))
k  Thermal conductivity (Wm\(^{-1}\) °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\(^{-2}\))
Pc  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 \((m^2 \text{s}^{-1})\)

\( \beta \)  
Thermal volume expansion coefficient \(\left(= \frac{1}{T} \text{ for a perfect gas}\right)\) \((K^{-1})\)

\( \gamma \)  
\(\frac{c_p}{c_v}\)

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

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

\( \epsilon_1 \)  
Emissivity of surface at temperature \(T_1\) (°C)

\( \epsilon_2 \)  
Emissivity of surface at temperature \(T_2\) (°C)

\( \mu \)  
Viscosity (Pa s)

\( \nu \)  
Kinematic viscosity \((\mu/\rho)\) (Pa s m\(^3\)Kg\(^{-1}\))

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

\( \sigma \)  
Stefan-Boltzmann constant \((\text{Wm}^{-2} \text{K}^{-4})\)

\( \lambda \)  
Mean free path (m)
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**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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<tbody>
<tr>
<td></td>
<td>Solid</td>
<td>Liquid</td>
<td>Gas</td>
</tr>
<tr>
<td><strong>Industry</strong></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>
<tr>
<td>Paper, Printing &amp; Stationary</td>
<td>1976</td>
<td>1.9</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>1.7</td>
<td>0.3</td>
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<tr>
<td>Building Materials</td>
<td>1976</td>
<td>0.9</td>
<td>4.6</td>
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<tr>
<td></td>
<td>2025</td>
<td>1.9</td>
<td>1.2</td>
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<tr>
<td>Other trades</td>
<td>1976</td>
<td>7.8</td>
<td>61.2</td>
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<tr>
<td></td>
<td>2025</td>
<td>19.5</td>
<td>14.2</td>
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<tr>
<td><strong>Process</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural</td>
<td>1976</td>
<td>0.9</td>
<td>22.1</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>-</td>
<td>16.1</td>
</tr>
<tr>
<td>Heating &amp; Drying</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Domestic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Space</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL** 2323 1430
<table>
<thead>
<tr>
<th>Substance</th>
<th>Comments</th>
<th>Density $\rho$/Kg m$^{-3} \times 10^3$</th>
<th>Specific heat capacity $C_p$/JK$^{-1}$ K$^{-1} \times 10^3$</th>
<th>Volume heat capacity $\rho C_p$/MJ K$^{-1}$ m$^{-3}$</th>
<th>Freezing point $^{\circ}$C</th>
<th>Boiling point $^{\circ}$C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chabazite tuff</td>
<td>Common beolite in Italy</td>
<td>1.4</td>
<td>1.09</td>
<td>4.47</td>
<td>0</td>
<td>100</td>
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<tr>
<td>Water</td>
<td></td>
<td>1.0</td>
<td>4.19</td>
<td>4.19</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Iron shot</td>
<td></td>
<td>7.86</td>
<td>0.54</td>
<td>4.27</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scrap Iron</td>
<td>Zero voids (at 30% void $\rho C_p = 2.8$)</td>
<td>7.90</td>
<td>0.53</td>
<td>3.99</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>7.9</td>
<td>0.5</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids (at 30% void $\rho C_p = 2.7$)</td>
<td>5.16</td>
<td>0.75</td>
<td>3.86</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Fe$_2$O$_3$</td>
<td></td>
<td>5.20</td>
<td>0.75</td>
<td>3.94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wet earth</td>
<td></td>
<td>1.7</td>
<td>2.1</td>
<td>3.60</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Water and salt (brine)</td>
<td></td>
<td>1.2</td>
<td>3.0</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td></td>
<td>4.0</td>
<td>0.9</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scrap Aluminium</td>
<td>Zero voids (30% void $\rho C_p = 1.8$)</td>
<td>2.74</td>
<td>0.963</td>
<td>2.64</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td>2.4</td>
<td>-18</td>
<td>315</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td>2.3</td>
<td>-10</td>
<td>315</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Oils</td>
<td>Cracking occurs at high temp.</td>
<td>1.0</td>
<td>2.51</td>
<td>2.51</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>MgCO$_3$,6H$_2$O</td>
<td></td>
<td>1.7</td>
<td>1.60</td>
<td>2.72</td>
<td>-</td>
<td>-</td>
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<tr>
<td>MgCO$_3$</td>
<td></td>
<td>3.0</td>
<td>0.84</td>
<td>2.51</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Concrete</td>
<td>Zero voids (30% void $\rho C_p = 1.7$)</td>
<td>2.25</td>
<td>1.13</td>
<td>2.57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stone</td>
<td>Zero voids (30% void $\rho C_p = 1.7$)</td>
<td>2.74</td>
<td>0.88</td>
<td>2.43</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Material</td>
<td>Density</td>
<td>Porosity</td>
<td>Cost (1980) £25/m³</td>
<td>Notes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>---------</td>
<td>----------</td>
<td>---------------------</td>
<td>-------</td>
<td></td>
<td></td>
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<tr>
<td>Concrete</td>
<td>2.74</td>
<td>0.92</td>
<td>2.26</td>
<td>-</td>
<td></td>
<td></td>
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<tr>
<td>Marble</td>
<td>2.70</td>
<td>0.75</td>
<td>2.39</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>2.70</td>
<td>0.796</td>
<td>2.12</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur Liquid</td>
<td>2.1</td>
<td>1.0</td>
<td>2.1</td>
<td>445</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
<td>2.09</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>2.4</td>
<td>0.8</td>
<td>1.9</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>2.23</td>
<td>0.84</td>
<td>1.9</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paraffin Oil</td>
<td>0.8</td>
<td>2.2</td>
<td>1.8</td>
<td>38-56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Olive Oil</td>
<td>0.9</td>
<td>2.0</td>
<td>1.8</td>
<td>=10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>2.7</td>
<td>0.84</td>
<td>2.3</td>
<td>=300</td>
<td></td>
<td></td>
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<tr>
<td>Pebbles</td>
<td>3.0</td>
<td>1.0</td>
<td>3.0</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>3.2</td>
<td>0.9</td>
<td>2.9</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>2.1</td>
<td>0.7</td>
<td>1.5</td>
<td>119</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>0.95</td>
<td>0.963</td>
<td>0.95</td>
<td>371</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitec</td>
<td>Molten salt</td>
<td></td>
<td>1.55</td>
<td>150</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cost £0.28/Kg (1980)</td>
<td></td>
<td></td>
<td>590</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Draw salt</td>
<td>Molten salt</td>
<td></td>
<td>1.55</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cost £0.32/Kg (1980)</td>
<td></td>
<td></td>
<td>590</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
<td>1.0</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 2.3 Basic Prometheus configuration to heat 100 houses

<table>
<thead>
<tr>
<th>Store</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>280 m</td>
</tr>
<tr>
<td>width</td>
<td>10 m</td>
</tr>
<tr>
<td>height</td>
<td>4 m</td>
</tr>
<tr>
<td>volume</td>
<td>1120 m$^3$</td>
</tr>
<tr>
<td>storage material pebbles, density</td>
<td>1600 kg m$^{-3}$</td>
</tr>
<tr>
<td>storage material pebbles; specific heat capacity</td>
<td>837 J kg$^{-1}$°C$^{-1}$</td>
</tr>
<tr>
<td>store insulation; thickness</td>
<td>0.6 m</td>
</tr>
<tr>
<td>store insulation; thermal conductivity</td>
<td>0.036 Wm$^{-2}$°C$^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collector</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>2,800 m$^2$</td>
</tr>
<tr>
<td>heat transfer factor ($F_R$)</td>
<td>0.9</td>
</tr>
<tr>
<td>overall heat loss coefficient</td>
<td>1.0 Wm$^{-2}$°C$^{-1}$</td>
</tr>
<tr>
<td>optical efficiency averaged</td>
<td>0.8</td>
</tr>
<tr>
<td>over useful incident angles ($\tau_\alpha$)</td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>1800</td>
<td>Energy Input</td>
</tr>
<tr>
<td>600</td>
<td>Energy Input</td>
</tr>
<tr>
<td>540</td>
<td>Energy Input</td>
</tr>
<tr>
<td>1200</td>
<td>Energy Input</td>
</tr>
<tr>
<td>2200</td>
<td>Energy Input</td>
</tr>
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<td>4350</td>
<td>Energy Input</td>
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<td>5700</td>
<td>Energy Input</td>
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<td>90</td>
<td>Energy Input</td>
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<td>103</td>
<td>Energy Input</td>
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<td>2340</td>
<td>Energy Input</td>
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<td>69</td>
<td>Energy Input</td>
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<tr>
<td>880</td>
<td>Energy Input</td>
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<tr>
<td>118</td>
<td>Energy Input</td>
</tr>
</tbody>
</table>

* TABLE 2.4 Inventory, energy and economic 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>
</thead>
<tbody>
<tr>
<td>$C_h/\pounds$</td>
<td>5700</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>$K_h/\pounds$</td>
<td>0</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>$F_h/\pounds \text{ yr}^{-1}$</td>
<td>18</td>
<td>117</td>
<td>146</td>
</tr>
<tr>
<td>$R_h/\pounds \text{ yr}^{-1}$</td>
<td>11</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>$P V C_h$</td>
<td>i=0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f=0.04$</td>
<td>6600</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>$f=0.02$</td>
<td>7500</td>
<td>11700</td>
</tr>
<tr>
<td>$P V C_h$</td>
<td>i=0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$f=0.04$</td>
<td>8500</td>
<td>17800</td>
</tr>
<tr>
<td></td>
<td>$f=0.02$</td>
<td>7500</td>
<td>11700</td>
</tr>
</tbody>
</table>


### 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>
<thead>
<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>
</tr>
<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
<td>130-30</td>
</tr>
<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>
</tr>
<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>
</tr>
<tr>
<td>Storage volume required for type A5 house /m³</td>
<td>127</td>
<td>65</td>
<td>49</td>
<td>112</td>
</tr>
<tr>
<td>Cost per A5 house/£1980</td>
<td>5480</td>
<td>2416</td>
<td>2215</td>
<td>5700</td>
</tr>
</tbody>
</table>

[ ] Chapter 2 reference numbers
### TABLE 2.7 Specific investment costs for water storage systems as reported by Per-Olov Karlsson*

<table>
<thead>
<tr>
<th>Store temperature rise/(°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>
</tr>
<tr>
<td>Storage in clay 12</td>
<td>0.07 - 0.13</td>
</tr>
<tr>
<td>Multiple well systems in rock 50</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, using data from Table 2.6) 100</td>
<td>0.43</td>
</tr>
</tbody>
</table>

### TABLE 2.8 Summary of domestic communal interseasonal storage systems

<table>
<thead>
<tr>
<th>Name 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>
</thead>
<tbody>
<tr>
<td>Lamboho, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td>27 000</td>
</tr>
<tr>
<td>Inglestad, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td>19 320</td>
</tr>
<tr>
<td>Studsvik, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>400</td>
<td>93</td>
<td>5 150</td>
</tr>
<tr>
<td>Lyckebo, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>500</td>
<td>100</td>
<td>10 500</td>
</tr>
<tr>
<td>Arizona, USA</td>
<td>Design Study</td>
<td>Water</td>
<td>250</td>
<td>100</td>
<td>3 012</td>
</tr>
<tr>
<td>Northampton, USA</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>10 000</td>
<td>100</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>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>4 000</td>
</tr>
<tr>
<td>ERR, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td>2 416</td>
</tr>
<tr>
<td>PCL, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>50</td>
<td>100</td>
<td>5 480</td>
</tr>
</tbody>
</table>
TABLE 3.1  Thermal Characteristics of Basic Type AO House

<table>
<thead>
<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (Wm⁻¹°C⁻¹)</th>
<th>UA (W°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>88.5</td>
<td>1.0</td>
<td>88.5</td>
</tr>
<tr>
<td>Roof</td>
<td>48.6</td>
<td>0.6</td>
<td>29.2</td>
</tr>
<tr>
<td>Floor</td>
<td>48.6</td>
<td>0.5</td>
<td>24.3</td>
</tr>
<tr>
<td>Window</td>
<td>15.0</td>
<td>5.5</td>
<td>82.5</td>
</tr>
<tr>
<td><strong>Total fabric specific loss</strong></td>
<td><strong>224W°C⁻¹</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ventilation specific loss</strong></td>
<td><strong>80W°C⁻¹</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total house specific loss</strong></td>
<td><strong>304W°C⁻¹</strong></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>
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<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>A0</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>291</td>
<td>39.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>255</td>
<td>33.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
<td>251</td>
<td>33.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>A4 + extra layer of glazing (i.e. double)</td>
<td>213</td>
<td>27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>186</td>
<td>23.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>182</td>
<td>22.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>182</td>
<td>20.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>177</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>164</td>
<td>18.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A11</td>
<td>A10 + cavity increased to 200 mm</td>
<td>150</td>
<td>16.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE 3.4 Thermal characteristics of Basic Type BO house

<table>
<thead>
<tr>
<th>Component</th>
<th>Area A (m²)</th>
<th>U-value (W m⁻²°C⁻¹)</th>
<th>UA (W°C⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>73.9</td>
<td>1.0</td>
<td>73.9</td>
</tr>
<tr>
<td>Roof</td>
<td>41.2</td>
<td>0.6</td>
<td>24.7</td>
</tr>
<tr>
<td>Floor</td>
<td>41.2</td>
<td>0.5</td>
<td>20.6</td>
</tr>
<tr>
<td>Window</td>
<td>13.3</td>
<td>5.5</td>
<td>73.2</td>
</tr>
</tbody>
</table>

Total fabric specific loss: 192 W°C⁻¹
Ventilation specific loss: 68 W°C⁻¹
Total house specific loss: 260 W°C⁻¹
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°C⁻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>Date</td>
<td>Location</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>1979-07-25</td>
<td>20th Street</td>
<td>Collection of garbage.</td>
<td></td>
</tr>
<tr>
<td>1979-11-18</td>
<td>3rd Avenue</td>
<td>Collection of trash.</td>
<td></td>
</tr>
<tr>
<td>1980-05-22</td>
<td>1st Avenue</td>
<td>Collection of garbage.</td>
<td></td>
</tr>
<tr>
<td>1980-09-13</td>
<td>5th Street</td>
<td>Collection of trash.</td>
<td></td>
</tr>
<tr>
<td>1980-12-26</td>
<td>7th Avenue</td>
<td>Collection of garbage.</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 4.1: ART COLLECTOR, TEST FACILITIES AND IMPROVED SYSTEMS IN THE UNITED KINGDOM**
### Table 5.2(a) Results of steady state testing on D.C. Hall collector

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Date</th>
<th>Time of test</th>
<th>Air mass flow rate</th>
<th>Air temp. at inlet</th>
<th>Air temp. at outlet</th>
<th>Air temp. increase ((T_e - T_i))</th>
<th>Ambient Temp.</th>
<th>Total irradiance ((I_m))</th>
<th>(\frac{(T_e - T_i)}{I_m})</th>
<th>Collector efficiency</th>
<th>Wind speed</th>
<th>Absorber Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21/6/83</td>
<td>1344-1354</td>
<td>65.5</td>
<td>51.1</td>
<td>66.0</td>
<td>14.9</td>
<td>21.1</td>
<td>788</td>
<td>0.0409</td>
<td>43.4</td>
<td>1.6</td>
<td>77.2</td>
</tr>
<tr>
<td>2</td>
<td>25/6/83</td>
<td>1434-1443</td>
<td>59.6</td>
<td>73.2</td>
<td>83.5</td>
<td>10.3</td>
<td>22.1</td>
<td>737</td>
<td>0.0745</td>
<td>29.2</td>
<td>&lt;0.4</td>
<td>95.3</td>
</tr>
<tr>
<td>3</td>
<td>26/6/83</td>
<td>1123-1132</td>
<td>79.1</td>
<td>22.9</td>
<td>39.6</td>
<td>16.7</td>
<td>22.9</td>
<td>730</td>
<td>0.0000</td>
<td>63.4</td>
<td>&lt;0.4</td>
<td>50.1</td>
</tr>
<tr>
<td>4</td>
<td>5/7/83</td>
<td>1151-1200</td>
<td>61.9</td>
<td>75.1</td>
<td>84.3</td>
<td>9.2</td>
<td>27.7</td>
<td>745</td>
<td>0.0684</td>
<td>26.8</td>
<td>&lt;0.4</td>
<td>93.9</td>
</tr>
<tr>
<td>5</td>
<td>19/8/83</td>
<td>1235-1244</td>
<td>64.7</td>
<td>60.1</td>
<td>69.9</td>
<td>9.8</td>
<td>28.6</td>
<td>624</td>
<td>0.0543</td>
<td>33.1</td>
<td>1.5</td>
<td>78.1</td>
</tr>
<tr>
<td>6</td>
<td>19/8/83</td>
<td>1209-1218</td>
<td>63.9</td>
<td>59.9</td>
<td>68.6</td>
<td>8.7</td>
<td>27.5</td>
<td>614</td>
<td>0.0567</td>
<td>31.7</td>
<td>2.3</td>
<td>76.8</td>
</tr>
<tr>
<td>7</td>
<td>19/8/83</td>
<td>1343-1352</td>
<td>63.8</td>
<td>76.1</td>
<td>80.7</td>
<td>4.6</td>
<td>28.8</td>
<td>583</td>
<td>0.0872</td>
<td>17.6</td>
<td>2.2</td>
<td>88.6</td>
</tr>
<tr>
<td>8</td>
<td>19/8/83</td>
<td>1430-1439</td>
<td>63.8</td>
<td>79.7</td>
<td>83.1</td>
<td>3.4</td>
<td>29.8</td>
<td>572</td>
<td>0.0938</td>
<td>13.3</td>
<td>1.6</td>
<td>91.1</td>
</tr>
<tr>
<td>9</td>
<td>18/8/83</td>
<td>1142-1151</td>
<td>69.1</td>
<td>24.9</td>
<td>42.0</td>
<td>17.1</td>
<td>25.2</td>
<td>667</td>
<td>-0.0005</td>
<td>62.1</td>
<td>&lt;0.4</td>
<td>51.4</td>
</tr>
<tr>
<td>Day/Time, y/p, hrs.</td>
<td>C_0</td>
<td>f</td>
<td>n</td>
<td>( \frac{C_0}{C_0} \times \frac{m^3}{s} )</td>
<td>( \frac{C_0}{C_0} \times \frac{m^3}{s} )</td>
<td>( \frac{C_0}{C_0} \times \frac{m^3}{s} )</td>
<td>( \frac{C_0}{C_0} \times \frac{m^3}{s} )</td>
<td>( \frac{C_0}{C_0} \times \frac{m^3}{s} )</td>
<td>( \frac{C_0}{C_0} \times \frac{m^3}{s} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-----</td>
<td>---</td>
<td>---</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
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<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>0.091085  16.2</td>
<td>17.2</td>
<td>2.0</td>
<td>3.5</td>
<td>22.5</td>
<td>30.5</td>
<td>34.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>0.091085  30.5</td>
<td>50.9</td>
<td>2.7</td>
<td>3.3</td>
<td>22.0</td>
<td>26.0</td>
<td>34.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
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<tr>
<td>7.4</td>
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<td>7.409696  0.0</td>
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<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
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</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td></td>
<td></td>
<td></td>
<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
<td></td>
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<tr>
<td>7.4</td>
<td></td>
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<td>7.409696  0.0</td>
<td>49.2</td>
<td>16.9</td>
<td>2.9</td>
<td>27.5</td>
<td>23.9</td>
<td>42.2</td>
<td></td>
<td></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>Description</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 absorbance</td>
<td>0.95 at θ = 0 falling slightly as θ 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>
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<tr>
<td>Cover polycarbonate thinkness</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</td>
<td></td>
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<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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TABLE 5.4 Results of transient and steady state testing with multi node model

<table>
<thead>
<tr>
<th></th>
<th>Steady state</th>
<th>Transient 0.5mm (DY2)</th>
<th>Transient 2mm (DY4)</th>
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<tbody>
<tr>
<td>Δt/(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>τc/(min)</td>
<td>-</td>
<td>2.8</td>
<td>9.7</td>
</tr>
<tr>
<td>FRUL/(Wm⁻²K⁻¹)</td>
<td>2.83*</td>
<td>2.768</td>
<td>2.604</td>
</tr>
<tr>
<td>FRTα</td>
<td>0.683</td>
<td>0.585</td>
<td>0.569</td>
</tr>
<tr>
<td>KFRTα</td>
<td>0.683</td>
<td>0.706</td>
<td>0.686</td>
</tr>
<tr>
<td>δFRUL</td>
<td>-</td>
<td>0.012</td>
<td>0.036</td>
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<tr>
<td>δFRTα</td>
<td>-</td>
<td>0.0008</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

K = correction factor for equivalent normal direct radiation = \( \frac{(\tau α)_{direct}}{(\tau α)_{diffuse}} \)

\( \frac{0.830}{0.688} = 1.206 \)

* = at low fluid inlet temperatures
### TABLE 5.8
Temperature distribution within DY1 collector (0.2mm thick plate and duct back) during ASHRAE steady state testing, $T_a = 293k$, $I = 700\text{wm}^{-2}$, $\text{Wind} = 1\text{m s}^{-1}$, $T\text{ sky} = 273k$

<table>
<thead>
<tr>
<th>$T_1/k$</th>
<th>$T_e/k$</th>
<th>$\bar{T}_p/k$</th>
<th>$\bar{T}_b/k$</th>
<th>$T_m/k$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{aveUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>332.73</td>
<td>342.01</td>
<td>322.1</td>
<td>317.86</td>
<td>2.762</td>
<td>.645</td>
<td>3.111</td>
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<tr>
<td>343</td>
<td>364.98</td>
<td>356.28</td>
<td>357.16</td>
<td>354.00</td>
<td>2.902</td>
<td>.476</td>
<td>3.230</td>
</tr>
<tr>
<td>383</td>
<td>396.47</td>
<td>391.47</td>
<td>389.73</td>
<td>3.044</td>
<td>.293</td>
<td>3.362</td>
<td></td>
</tr>
<tr>
<td>423</td>
<td>427.23</td>
<td>425.00</td>
<td>425.11</td>
<td>3.185</td>
<td>.095</td>
<td>3.503</td>
<td></td>
</tr>
<tr>
<td>433</td>
<td>435.13</td>
<td>433.57</td>
<td>434.06</td>
<td>3.226</td>
<td>.037</td>
<td>3.564</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 5.9
Temperature distribution and energy lost from DY1 collector (0.2mm thick plate and duct back) during zero radiation testing, $T_a = 293k$, $\text{Wind} = 1\text{m s}^{-1}$, $T\text{ sky} = 273k$

<table>
<thead>
<tr>
<th>$T_1/k$</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$^{-2}$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
<th>$F_{aveUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
</tr>
</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>
</tr>
<tr>
<td>343</td>
<td>333.32</td>
<td>333.79</td>
<td>336.20</td>
<td>338.16</td>
<td>146.66</td>
<td>2.932</td>
<td>3.247</td>
</tr>
<tr>
<td>383</td>
<td>365.41</td>
<td>366.41</td>
<td>370.42</td>
<td>374.20</td>
<td>266.50</td>
<td>2.961</td>
<td>3.282</td>
</tr>
<tr>
<td>423</td>
<td>396.74</td>
<td>398.43</td>
<td>403.88</td>
<td>409.87</td>
<td>397.80</td>
<td>3.060</td>
<td>3.404</td>
</tr>
<tr>
<td>433</td>
<td>404.46</td>
<td>406.34</td>
<td>412.12</td>
<td>418.73</td>
<td>432.40</td>
<td>3.088</td>
<td>3.439</td>
</tr>
<tr>
<td>*303</td>
<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>
</tr>
<tr>
<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>
<td>3.245</td>
</tr>
</tbody>
</table>

* $T\text{ sky} = 293k$
<table>
<thead>
<tr>
<th>Structured Poly-carbonate Collector</th>
<th>Indoor</th>
<th>Transient</th>
<th>Steady State</th>
<th>ASHRAE D.C. Hall Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>600 ~ 2 ~ 20 ~ 0639 ~ 6 ~ 46 ~ 4.53</td>
<td>7.77 ~ 8.48</td>
<td>7.37 ~ 9.29</td>
<td>Theory</td>
<td>Zero Radiation</td>
</tr>
<tr>
<td>300 ~ 5.19</td>
<td>5.13</td>
<td>Transient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700 ~ 2.5</td>
<td>2.67</td>
<td>ASHRAE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \frac{(\text{cm}^3)}{\text{Lm}^2} )</td>
<td>( \frac{(\text{cm}^3)}{\text{Lm}^2} )</td>
<td>( \frac{(\text{cm}^3)}{\text{Lm}^2} )</td>
<td>( \frac{(\text{cm}^3)}{\text{Lm}^2} )</td>
<td>Test method Summary of collector testing results</td>
</tr>
<tr>
<td>( P_{\text{U}} )</td>
<td>( P_{\text{T}} )</td>
<td>( P_{\text{C}} )</td>
<td>( P_{\text{F}} )</td>
<td>( P_{\text{R}} )</td>
</tr>
</tbody>
</table>

TABLE 5.10
<table>
<thead>
<tr>
<th>Material</th>
<th>Reflective index (n)</th>
<th>Solar (0.2-4.0 µm)</th>
<th>Infrared (3.0-500 µm)</th>
<th>Expansion coefficient (°C⁻¹)</th>
<th>Temperature Limits (°C)</th>
<th>Weather-ability (comments)</th>
<th>Chemical Resistance (comments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
<td>125 mil</td>
<td>125 mil</td>
<td>7.98 x 10⁻⁵</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 10⁻⁵</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 10⁻⁵</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 10⁻⁵</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>
</tr>
<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 lime sheet 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>Sunlite 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>
</tbody>
</table>

Source: Gary, H.P. 'Treatise on solar energy' Vol.1, A Wiley Interscience Publication, Chichester, 1982
<table>
<thead>
<tr>
<th>Engine Water Temperature</th>
<th>Zonarinsp</th>
<th>Supplementary</th>
<th>Paint Surface ( T )</th>
<th>Substrate</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30</td>
<td>0.92</td>
<td>Supporting</td>
<td>Peckle</td>
<td>Copper/Aluminum</td>
<td>Black Chrome (BC)</td>
</tr>
<tr>
<td>0.09 - 0.10</td>
<td>0.94</td>
<td>Supporting</td>
<td>Blue Stainless Steel</td>
<td>Copper oxide</td>
<td>Black Nickel</td>
</tr>
<tr>
<td>0.15</td>
<td>0.95</td>
<td>Supporting</td>
<td>Stainless Steel</td>
<td>Copper oxide</td>
<td>Black Nickel</td>
</tr>
<tr>
<td>0.10</td>
<td>0.96</td>
<td>Supporting</td>
<td>Aluminum</td>
<td>Black Nickel</td>
<td>Black Nickel</td>
</tr>
<tr>
<td>0.09 - 0.10</td>
<td>0.97</td>
<td>Supporting</td>
<td>Stainless Steel</td>
<td>Copper oxide</td>
<td>Black Nickel</td>
</tr>
<tr>
<td>0.10</td>
<td>0.98</td>
<td>Supporting</td>
<td>Copper/Aluminum</td>
<td>Copper oxide</td>
<td>Black Nickel</td>
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</table>

Source: HELLO 14, CARDIFF UNIVERSITY
TABLE 6.3  Key to collector variable features, used to obtain Figure 6.19

<table>
<thead>
<tr>
<th>Cover Material</th>
<th>Plate Glass, Thickness</th>
<th>Polycarbonate, Thickness</th>
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</thead>
<tbody>
<tr>
<td>Cover 1</td>
<td>6.0 mm</td>
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<tr>
<td>Cover 2</td>
<td>2.0 mm</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness of the Plate and of the Duct-Back:</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY1</td>
</tr>
<tr>
<td>DY2</td>
</tr>
<tr>
<td>DY3</td>
</tr>
<tr>
<td>DY4</td>
</tr>
<tr>
<td>DY5</td>
</tr>
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<table>
<thead>
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<th>Air Flow in the Rear-Duct:</th>
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</tr>
<tr>
<td>Flow 1</td>
</tr>
<tr>
<td>Flow 2</td>
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<td>Flow 3</td>
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<td>Gas</td>
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</tbody>
</table>

<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>$\frac{Q}{A}$/(Wm$^{-2}$)</th>
<th>$T_f/°C$</th>
<th>$\frac{h_r}{(\text{Wm}^{-2}\text{°C}^{-1})}$</th>
<th>$h_c$/(Wm$^{-2}\text{°C}^{-1}$)</th>
<th>$\Delta T/°C$</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>20.7</td>
<td>1.910</td>
<td>20.05</td>
<td>11.10</td>
<td>19.70</td>
<td>0.168</td>
<td>2.193</td>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>21.3</td>
<td>1.725</td>
<td>19.32</td>
<td>11.07</td>
<td>20.33</td>
<td>0.169</td>
<td>1.915</td>
</tr>
<tr>
<td></td>
<td>10.5</td>
<td>33.3</td>
<td>2.195</td>
<td>50.05</td>
<td>13.00</td>
<td>30.80</td>
<td>0.180</td>
<td>2.632</td>
</tr>
<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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<tr>
<td></td>
<td>10.35</td>
<td>38.8</td>
<td>1.621</td>
<td>46.12</td>
<td>12.66</td>
<td>36.49</td>
<td>0.185</td>
<td>1.750</td>
</tr>
<tr>
<td>Air, p = 81 torr</td>
<td>10.3</td>
<td>43</td>
<td>1.567</td>
<td>51.24</td>
<td>12.86</td>
<td>40.44</td>
<td>0.189</td>
<td>1.669</td>
</tr>
<tr>
<td>Air, p = 71 torr</td>
<td>10.2</td>
<td>24.9</td>
<td>0.925</td>
<td>13.60</td>
<td>10.88</td>
<td>24.22</td>
<td>0.172</td>
<td>0.847</td>
</tr>
<tr>
<td>Freon/Air</td>
<td>10.3</td>
<td>22.1</td>
<td>1.685</td>
<td>19.88</td>
<td>11.29</td>
<td>21.11</td>
<td>0.170</td>
<td>1.856</td>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>17.8</td>
<td>1.635</td>
<td>12.59</td>
<td>10.73</td>
<td>17.17</td>
<td>0.166</td>
<td>1.789</td>
</tr>
<tr>
<td>Carbon Tet/Air</td>
<td>10.1</td>
<td>17.9</td>
<td>1.645</td>
<td>12.83</td>
<td>10.74</td>
<td>17.26</td>
<td>0.166</td>
<td>1.803</td>
</tr>
<tr>
<td></td>
<td>10.4</td>
<td>27.9</td>
<td>1.986</td>
<td>34.75</td>
<td>12.14</td>
<td>26.16</td>
<td>0.175</td>
<td>2.303</td>
</tr>
<tr>
<td></td>
<td>10.5</td>
<td>31.3</td>
<td>2.081</td>
<td>43.28</td>
<td>12.66</td>
<td>29.14</td>
<td>0.178</td>
<td>2.450</td>
</tr>
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<td></td>
<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>
</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>
</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>
</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>
</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>
</tr>
</tbody>
</table>
PHYSICAL QUALITY OF LIFE INDEX VERSUS ENERGY CONSUMPTION PER CAPITA FOR THE COUNTRIES OF THE WORLD. SOURCES OF DATA:
PQI, "BOOK OF WORLD RANKINGS" BY G.T. HURIAN 1979, ENERGY CONSUMPTION, "EUROPEAN YEARBOOK 1983."
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.7]

Figure 2.4: Weekly consumption of hot water for one household, from 'The Performance of Domestic Wet Heating Systems', Pickup, G.A.C.7]
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
(for 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.

**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 (w/m²/µm²)

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)

with heat storage in
preferably soft ground or clay
solid rock

APARTMENT BUILDING (INTENSE POPULATED AREAS)
(LARGE SCALE)

with heat storage in
• preferably solid rock
• most types of ground

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 2.18 PROTO-PROMETHEUS TEMPERATURE DISTRIBUTION (WITH FAN ON), ON 22nd SEPTEMBER 1981 AT 14:25 hrs.
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 A75 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 on 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 112 m² PER HOUSE AND 2.8 m² OF COLLECTOR PER HOUSE) FOR A TYPE A1 HOUSE.

FIGURE 2.28  THE EFFECT OF CHANGING THE COLLECTOR OVERALL HEAT LOSS COEFFICIENT \( U_c \) ON THE % OF ENERGY SUPPLIED BY A CUBIC PROMETHEUS HEATING A TYPE A5 HOUSE.
**Figure 2.29** Design of costed Prometheus to provide 100 houses 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 24 m² 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.
FIGURE 37 USEFUL ENERGY SAVED AND EXTRA COSTS FOR VARIOUS INSULATION OPTIONS AND SOLAR SYSTEMS RETROFITTED TO AN EXISTING TYPE B6 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:

**M. Normans**
\[ h_w = 5.7 + 3.5v \]

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

**Lloyd**
\[ h_w = 0.15 \times \frac{R_x}{L + W} \times k \] for \( T_e = 10^\circ C, T_s = 15^\circ C, L = 1m, W = 1m \).

**Sparrow**
\[ h_w = \frac{k \times 0.86 \times R_x^{1/4} \times T_e^{1/4}}{L + W} \] for \( T_e = 10^\circ C, T_s = 15^\circ C, L = 4m, W = 1m \).

**Green**
\[ h_w = (h_0 + h_1 T_e^{1/2})^{1/2} \] for \( p = 1.4m, 45^\circ \) inclination

**Kind**

For condenser length 2.9m, width 1.2m, height 4.5m, \( T_e = 25^\circ C \).

**Figure 4.7** Correlations for wind heat loss coefficient.
**Figure 4.8** Flow diagram of 'EFFIC2' (see Appendix B) a program to calculate the efficiency of a radiant duct air heating collector.
INPUT
ENVIRONMENTAL PARAMETERS
I, V, T_a

COLLECTOR CONFIGURATION
\( E, \theta, \varepsilon, k, h, A, L, W, D \)
\( U_e, x \)

COLLECTOR VARIABLES
\( T_c, m \)

INITIAL ESTIMATE of \( T_f, T_m \)

CALCULATE
- \( R_c \) - see equation 4.25
- \( N_u \) - 4.23
- \( h_{1,2} \) - 4.22
- \( h_r \) - 4.27
- \( U_b \) - 4.4
- \( U_g \) - 4.15
- \( U_L \) - 4.16
- \( F' \) - 4.20
- \( F_r \) - 4.19
- \( Q_u \) - 4.18

\( \eta = Q_u / A_I \)

CALCULATE NEW ABSORBER TEMPERATURE
\( T_p = T_c + (Q_u / A_I) (1 - F_r) / U_L F_r \)

1.5

[\( T_{P_{new}} - T_p \)] < L0.1

\( T_f = T_{P_{new}} \)

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

FIGURE 4.9 FLOW DIAGRAM OF 'EFFIC' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A TYPICAL ABSORBING COLLECTOR
**Figure 4.10** Response of Zero and Long Time Constant Collector to Changing Insolation
FIGURE 4.11 NODAL CONFIGURATION OF A FLAT PLATE, REAR-DUCT AIR HEATING, SOLAR COLLECTOR AS USED IN 'RRDCT'.

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
FOR EACH MONTH ON A HORIZONTAL SURFACE (AT WIND 1966-1975)
SECTION X-X

**Figure 5.2** D.C. Hall Collector
FIGURE 5.3  ANGULAR VARIATION OF TRANSMITTANCE OF 2mm THICK POLYCARBOCATE (REFRACTIVE INDEX = 1.526, 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 WAILED 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.
**EXPERIMENTAL**

+ THEORETICAL $(T_e = 0.8, F = 0.6, C = 0.9, U_t = 8 \text{ W/m}^2)$

$(T_e) = 3300 \text{ J/kg}^\circ C$

**Figure 5.11**
Response of structured polycarbonate collector to a step change in insolation from 750 W/m$^2$ to zero with a fluid flow rate of 72 kg/hr.$^-1$

**Figure 5.12**
Uninterrupted insolation as defined by ASHRAE Standard 93-97 [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. WALL COLLECTOR DURING STEADY STATE EFFICIENCY TEST. POSITION OF COLLECTOR MILTON KEYNES, LATITUDE 52°, LONGITUDE 0.75° (HORIZONTAL).

FIGURE 5.16 ANGLE CORRECTION FOR D.C. WALL 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 $F_{nL}$, for $m = 0.5$ kg/hr.

**Figure 5.19**

Calibration curve for Periflow 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 ROUND 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: FORDSKÉ [34]
Figure 5.29 COMPUTER GENERATED STEADY STATE AND TRANSIENT EFFICIENCY CURVE FOR 0.5 mm ABSORBER PLATE.
**FIGURE 5.30** TRANSMISSION 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 $F_{uL}$, $F_u(C_d)$, 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 14/6/93-15/6/93.
Figure 5.30 Standard error in $\frac{F_{Ux}}{F_{Ux}}$ versus $N$, the number of previous time steps influencing the collector's present performance under transient conditions for the structured polycarbonate collector.

Figure 5.31 Efficiency curve for outdoor transient testing of structured polycarbonate collector. Data generated from 'TRANS' for N=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 (Manor paper). 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 Maxor.
**Figure 5.44**  INTENSITY DISTRIBUTION ACROSS COLLECTOR DURING INDOOR TESTING IN W m⁻², AVERAGE INTENSITY 2.11 W m⁻², STANDARD DEVIATION ± 0.9 W m⁻².

**Figure 5.45**  WING GENERATOR.
Figure 5.46 Variation of Wind Speed (ms⁻¹), 5mm above Collector Surface

Figure 5.47 Measured and Predicted Heat Loss Uₗ 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. wall 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°C).

Figure 5.55: Collector temperature profile for model collector under steady state and zero testing conditions for the same mean absorber plate temperature (364°C).
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  $F_{\text{in}}$ versus mean fluid temperature for collector D1 under zero testing and above 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&D chamical type collector (Maxima 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 ED BY S.V. DZIONDRY, VOL 2, 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-November).

**Figure 6.5** Maximum improvement to flat plate collector performance by increasing ε and α.
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.

[27]

FIGURE 6.11  EFFICIENCY VERSUS MASS FLOW RATE FOR STRUCTURED POLYCARBONATE COLLECTOR. \( I_m = 2.11 \text{Wm}^2 \), \( T_a = 28^\circ \text{C} \), \( T_{350} > T_a \), \( T_e = T_a \) and AIR VELOCITY = 1.5 m s\(^{-1}\).
**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 separations Z and two levels of incident insolation.
Figure 6.14: Efficiency curve for a combined parabolic concentrator compared with a flat plate collector. Source: Argonne National Laboratory Tech Report.

Figure 6.15: Global and diffuse insolation month by month at noon on a 45° south facing slope.
**Figure 6.16**
Annual energy collected versus collector temperature. Comparison of five types of collector. Source [33].

**Figure 6.17**
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 1 and Figure 3).

(i) SÜJ/TAJ, flow 2  (ii) SOM/TAM, flow 2  (iii) SÜD/TAD1, flow 2
(iv) SOM/TAM, flow 3  (v) SÜM/TAM, flow 2  (vi) SÜD/TAD1, flow 3
(vii) SÜD1/TAD1, flow 2  (viii) SÜD/TAD2, flow 3  (ix) SÜD2/TAD1, flow 2
(x) SÜD3/TAD1, flow 2  (x) SÜD/TAD1, 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 FMT C 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 7.5  LOCAL HEAT TRANSFER COEFFICIENT BETWEEN TWO INCLINED PLATES
(SEE FIGURE 7.6); SOURCE: NORMAND, C. AND POMERANCY, 'CONVECTIVE
INSTABILITY: A PHYSICISTS APPROACH', JOURNAL OF MODERN PHYSICS VOL. 49,
NO 3, JULY 1974.

FIGURE 7.6  SCHEMATIC DEPENDING EFFECT OF GAP SPACING ON CONDUCTANCE
Figure 7.2
Plot of $h_v$ versus plate separation $s$. $T_{wall} = 160^\circ\text{C}$, $T_{air} = 325^\circ\text{K}$. The legend indicates different angles.

Figure 7.8
$h_v$ versus tilt angle to the horizontal for air immersion for various absorber temperatures ($T_a$) with cover temp $= 10^\circ\text{C}$. 
Figure 7.9

Heat transfer coefficient variation with absorber temperature for convection and radiation.
FIGURE 7.10  TRUE AND PREDICTED HEAT LOSS BETWEEN TWO PARALLEL PLATES 5 x 5cm
COVER TEMPERATURE 10 °C
**FIGURE 7.11** EFFECTIVE RAYLEIGH NUMBER VersUS MOLECULAR WEIGHT FOR DIFFERENT GASES, AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL PLATES, SEPARATING $S = 0$ cm, COLD PLATE TEMPERATURE $10^\circ C$, HOT PLATE $30^\circ C$.
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.

$= 5 \text{ cm}$, 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, $s=5$ cm, $T=293$ K, $T_2=323$ K for curve 1, 373 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: Nowotny, 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 cm, $T_i = 293 K$, WITH A HONEYCOMB PAD WITH SLATS ASPECT RATIO 5
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

$S = 5$ cm, $T = 10^°C$
**FIGURE 7.22**
Guard Ring Heater

**FIGURE 7.23**
Guard RingUnbalance Versus Measured Heat Transfer Across a 5cm Thick Styrofoam Sp Sample
Figure 7.25 Acrylic Test Panel

Figure 7.26 Schematic Diagram of Guarded Hot Plate Apparatus
FIGURE 7.27 COPPER COLD PLATES.
**Figure 7.28** Measured and theoretical heat transfer coefficients for different gases between two parallel plates, $s = 5\text{ cm}$, various temperature differences.
Figure 7.29 Theoretical and Measured Heat Transfer \( h_L \) 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 21. PROTO PROMETHEUS, 1. COLLECTOR, 2. STORE TOP INSULATION AND COLLECTOR RGR INSULATION, 3. FAN MOTOR 4, 5. MONITORING EQUIPMENT, 6. 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 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 ***************************
20 LOAD 7:
30 REM **************************** SUNSTORE ***************************
40 REM **************************** SUNSTORE ***************************
50 REM **************************** SUNSTORE ***************************
60 REM **************************** SUNSTORE ***************************
70 REM **************************** SUNSTORE ***************************
80 REM **************************** SUNSTORE ***************************
90 REM **************************** SUNSTORE ***************************
100 REM **************************** SUNSTORE ***************************
110 REM **************************** SUNSTORE ***************************
120 REM **************************** SUNSTORE ***************************
130 REM **************************** SUNSTORE ***************************
140 REM **************************** SUNSTORE ***************************
150 REM **************************** SUNSTORE ***************************
160 REM **************************** SUNSTORE ***************************
170 REM **************************** SUNSTORE ***************************
180 REM **************************** SUNSTORE ***************************
190 REM **************************** SUNSTORE ***************************
200 REM **************************** SUNSTORE ***************************
210 REM **************************** SUNSTORE ***************************
220 REM **************************** SUNSTORE ***************************
230 REM **************************** SUNSTORE ***************************
240 REM **************************** SUNSTORE ***************************
250 REM **************************** SUNSTORE ***************************
260 REM **************************** SUNSTORE ***************************
270 REM **************************** SUNSTORE ***************************
280 REM **************************** SUNSTORE ***************************
290 REM **************************** SUNSTORE ***************************
300 REM **************************** SUNSTORE ***************************
310 REM **************************** SUNSTORE ***************************
320 REM **************************** SUNSTORE ***************************
330 REM **************************** SUNSTORE ***************************
340 REM **************************** SUNSTORE ***************************
350 REM **************************** SUNSTORE ***************************
360 REM **************************** SUNSTORE ***************************
370 REM **************************** SUNSTORE ***************************
380 REM **************************** SUNSTORE ***************************
390 REM **************************** SUNSTORE ***************************
400 REM **************************** SUNSTORE ***************************
410 REM **************************** SUNSTORE ***************************
420 REM **************************** SUNSTORE ***************************
430 REM **************************** SUNSTORE ***************************
440 REM **************************** SUNSTORE ***************************
450 REM **************************** SUNSTORE ***************************
460 REM **************************** SUNSTORE ***************************
470 REM **************************** SUNSTORE ***************************
480 REM **************************** SUNSTORE ***************************
490 REM **************************** SUNSTORE ***************************
500 REM **************************** SUNSTORE ***************************
510 REM **************************** SUNSTORE ***************************
1010 PRINT TAB (10)+"MONTHS()";"=": DEMAND();" print heating demand each mon.
1020 TOTE=TOTAL DEMAND(); calculate total annual heating dem.
1030 DEMAND();DEMAND();(COLAREA/HOUSE) = heating demand per m^2 of collector
1040 print 1050
1050 PRINT "TOTAL EMERGENCY HP FOR PER ANNUM "; TOTE/1000;"GJ(1);"; TOTDI
1060 print 1070
1070 PRINT USING 1080
1080 IMAGE // System Operation System Operation
1090 "ITH = Threshold Level (collector will only operate above this int.
ity (w/m^2)
1100 PRINT "Tso = Original Store Temperature at the beginning of month (C)
1110 PRINT "Ta = Ambient Temperature Averaged over periods of collector operat
n (C)
1120 PRINT "Tt = Time Period of Collector Operation (H)
1130 PRINT "It = Total Radiation which is above Threshold (MJ/m^2)
1140 PRINT "qn = Normalized Net Heat to Storage =q1-1-m (MJ/m^2)
1150 PRINT "qT = Useful Heat Collected= qn*l (MJ/m^2)
1160 PRINT "qT = Normalized Total Monthly Load (MJ/m^2)
1170 PRINT "qN = Normalized Total Monthly Tank Losses (MJ/m^2)
1180 PRINT "qAux = Aux Heat (-MJ/m^2)
1190 PRINT "
1200 PRINT 
1210 M ITH Tso Ta Tt It qN ts4 qT im qaux
1220 PRINT 
1230 FOR I=1 TO 12
1240 T3=0
1250 TSOL=0
1260 TEMP=0
1270 FOR J=1 TO 24
1280 IT=0;Ta=tT=IT=EM(1,J)
1290 IF IT=600,1,J)/0.0056 THEN GOTO 1330 print test if radiation level is above
1300 T=IT=600,1,J)/0.0056 THEN GOTO 1330 clamp to prevent dividing by zero
1310 TSOL=TSOL+J=TSOL
1320 TEMP=TEMP+IT=EM(1,J)
1330 NEXT J
1340 IF IT=0 THEN GOTO 1360
1350 TEMP=TEMP/TIM
1360 TIM=3600*DAY(1)
1370 T=IT=3600*DAY(1)
1380 IF IT=0 AND COUNT=0 THEN GOTO 1770 check which month to turn system
1390 t=3600*24*DAY(1)/1000000
1400 IT=IT=3600*DAY(1)
1410 IT=IT=3600*DAY(1)
1420 IT=IT=3600*DAY(1)
1430 IT=IT=3600*DAY(1)
1440 IT=IT=3600*DAY(1)
1450 IT=IT=3600*DAY(1)
1460 IT=IT=3600*DAY(1)
1470 IT=IT=3600*DAY(1)
1480 IF COUNT=0 THEN GOTO 1770
1490 IF NUT=1 THEN GOTO 1520
1500 EXA=TSOL-TSF;Aq=m
1510 NUT=1
1520 GOTO 1540
1530 Tsm=2(TSF-TSF)/2
1540 It=USelT(USelT-TT);Tsm
1550 Qn=(qT-Demand)(1-1)=(FtFtT);USelT
1560 Tsf=Tsf=Tsf=Tsf
1570 Qn=USelT=USelT
1580 COUNT=1
1590 Qaux=Qn*EXTRA
1600 EXTRA=0
1610 IF Tsf THEN Qaux=0
1620 PRINT USING 1960:MONTHS(); ITH; TEMP; tt; TSOL; qn; Tsf. TUSE; DEMAND();
1630 qaux
1630 X=110
1640 Y=TSO/2
1650 PLOT X; Y
1660 TOTAL=TOTAL+TSOL!
1670 qT=qT+qT!
1680 qn=qn+qNT!
1690 qT=qT+qT!
1700 l=T=DEMAND()+l=MT!
1710 l=T=DEMAND()+l=MT!
1720 qAux=qAux+qAux!
1730 MT=MT+1
1740 IF DT=YEARS12 THEN GOTO 1780 annual rad when collector is on
1750 TSO=TSF!
1760 IF 12 THEN 160
1770 NEXT I
1780 THSOL=THSOL+TOTAL+100!
1790 TOTSUN=qT/TOTSUN+100!
1800 PRINT "
1810 PRINT USING 1970:TOTAL, qn;entoT; qAux; l=mt; qAux; l=mt
1820 PRINT "
1830 SUN=(1-I-(qAux; TTSOL))/100! % energy supplied by solar system
1840 PRINT USING 1980: % OF ENERGY SUPPLIED BY SOLAR SYSTEM="SUN;
1850 PRINT USING 1990: % OF SOLAR ENERGY COLLECTED IN EACH ROAD; %
1860 PRINT PRINT USING 2000: % OF SOLAR ENERGY COLLECTED; TTSOL; X
1870 PRINT "TOTAL AUXILIARY ENERGY FOR SYSTEM=": qAux= qAux+qAux
1880 PRINT "PRINT AUXILIARY ENERGY PER HOUSE=": qAux; qAux
1890 PRINT "
1900 PRINT "
1910 PRINT "
1920 PRINT "
1930 PRINT "
1940 PRINT "
1950 PRINT "
1960 PRINT "
1970 PRINT "
1980 PRINT "
1990 PRINT "
2000 PRINT "
2010 PRINT "
2020 END
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 Calculate the top loss coefficient for a single glass tower.
30 REM
40 FOR I=0 TO 20
50 Tp=10+I*5 ! ABSORBER TEMP
60 Ta=10 ! Ambient temp (C)
70 W=1 ! Wind speed (ms-1)
80 Ep=0.95 ! Absorber emissivity
100 E=0.8 ! Cover plate emissivity
110 S=5 ! Plate separation (cm)
120 g=9.81 ! Acceleration due to gravity (ms-2) at LONDON
130 K=0.0257 ! Thermal conductivity of gas at Tave (Wm-2C-1)
140 B0=1 ! Tilt angle (0Horizontal)
150 CPw=1007 ! Heat capacity of air (J/kgK)
155 CP=1007 ! Heat capacity of GAS BETWEEN COVER AND ABSORBER kgK
160 S=9/100 ! CONVERT TO METERS
170 L=1
180 W=1
190 Sw=9/100 !/(L+W)
200 REM
210 Tc=Ta+(Tp-Ta)/2 ! guess the cover temp
220 T1=273.15+Ta ! CONVERT TO KELVIN
230 Ta=273.15+Ta ! CONVERT TO KELVIN
240 Tc=273.15+Ta ! CONVERT TO KELVIN
250 Tp=273.15+Ta ! CONVERT TO KELVIN
260 Tc=273.15+Ta ! CONVERT TO KELVIN
270 DT2=Ta1 ! TEMP DIFFERENCE DELTA T
280 Tave=Ta1+DT2/2 ! AVERAGE GAS TEMPERATURE
290 DEN=352.91/Tave
300 k=Tave/.000076+0.034406
310 V1=V1/Tave.00000465+.0000046351
320 VOL=V1/Tave ! THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERF.
330 V=V1/DEN ! KINEMATIC VISCOSITY
340 Gr=6.5V1sW=3*DT/0/2 ! GRASHOF NUMBER
350 Pr=CpTVIS/K
360 Ra=GrPr ! RAYLEIGH No
370 REM ! CALCULATE NUSLDT NUMBER
380 Nu=1.1708/(RatCos (B))
390 IF Nu<0 THEN Nu=0 ! TAKE ONLY POSITIVE TERMS
400 N2=(RatCos (B))5/1930/(1/1)=1
410 IF Nu>0 THEN Nu2=1 ! TAKE ONLY POSITIVE TERMS
420 Num=(1.4411*1-Sin (1.081)*1.6708/(RatCos (B)))+N2 ! NUSLDT No
430 hCk=RatSin W ! HEAT TRANSFER COEFFICIENT
440 hCk=0.00000000567*(Tp*2+Tc2)/(Tp/1+EP1/1*EC-1) ! RAD FROM PLATE TO COVER
450 hsky=0.0000000567*EC1(Tc2+Tc2)*Tc1 ! RAD COVER TO SKY
460 Td1=TC+Ta
470 Tave=TC+Ta
480 Tave=Ta+DTW/2
490 DEN=352.91/Tave
500 W=V1/DEN ! HEAT TRANSFER COEFFICIENT IN W/m2C
510 REM
520 V=V1/DEN ! KINEMATIC VISCOSITY
530 Gr=6.5V1sW=3*DT/0/2 ! GRASHOF NUMBER
540 Pr=CpTVIS/K
550 hCk=GrPr ! RAYLEIGH No
560 Ra=GrPr ! RAYLEIGH No
570 REM ! CALCULATE NUSLDT NUMBER
580 Nu=1.708/(RatCos (B))
590 IF Nu<0 THEN Nu=0 ! TAKE ONLY POSITIVE TERMS
600 N2=(RatCos (B))5/1930/(1/1)=1
610 IF Nu>0 THEN Nu2=1 ! TAKE ONLY POSITIVE TERMS
620 Num=(1.4411*1-Sin (1.081)*1.6708/(RatCos (B)))+N2 ! NUSLDT No
630 hCk=RatSin W ! HEAT TRANSFER COEFFICIENT
640 hCk=0.00000000567*(Tp*2+Tc2)/(Tp/1+EP1/1*EC-1) ! RAD FROM PLATE TO COVER
650 hsky=0.0000000567*EC1(Tc2+Tc2)*Tc1 ! RAD COVER TO SKY
660 Td1=TC+Ta
670 Tave=TC+Ta
680 Tave=Ta+DTW/2
690 DEN=352.91/Tave
700 W=V1/DEN ! HEAT TRANSFER COEFFICIENT IN W/m2C
710 REM
720 V=V1/DEN ! KINEMATIC VISCOSITY
730 Gr=6.5V1sW=3*DT/0/2 ! GRASHOF NUMBER
740 Pr=CpTVIS/K
750 hCk=GrPr ! RAYLEIGH No
760 Ra=GrPr ! RAYLEIGH No
770 REM ! CALCULATE NUSLDT NUMBER
780 Nu=1.708/(RatCos (B))
790 IF Nu<0 THEN Nu=0 ! TAKE ONLY POSITIVE TERMS
800 N2=(RatCos (B))5/1930/(1/1)=1
810 IF Nu>0 THEN Nu2=1 ! TAKE ONLY POSITIVE TERMS
820 Num=(1.4411*1-Sin (1.081)*1.6708/(RatCos (B)))+N2 ! NUSLDT No
830 hCk=RatSin W ! HEAT TRANSFER COEFFICIENT
840 hCk=0.00000000567*(Tp*2+Tc2)/(Tp/1+EP1/1*EC-1) ! RAD FROM PLATE TO COVER
850 hsky=0.0000000567*EC1(Tc2+Tc2)*Tc1 ! RAD COVER TO SKY
860 Td1=TC+Ta
870 Tave=TC+Ta
880 Tave=Ta+DTW/2
890 DEN=352.91/Tave
900 W=V1/DEN ! HEAT TRANSFER COEFFICIENT IN W/m2C
910 REM ! CALCULATE NUSLDT NUMBER
920 Nu=1.708/(RatCos (B))
APPENDIX C

THE EFFECT OF THERMAL CAPACITANCES ON THE
PERFORMANCE OF SOLAR COLLECTORS

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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(6) 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
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 absorptance | 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

- Flow 0: stagnation (M=0)
- Flow 1: all TI M = 0.0600 kg s⁻¹ (PON irrelevant)
- Flow 2: TI = 303 K M = 0.0600 kg s⁻¹ PON = 128 W
- Flow 3: TI = 323 K M = 0.0562 kg s⁻¹ PON = 124 W

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 $T_1$ the value of $M$ will be different from $0.0600$ kg s$^{-1}$: at $T_1 = 323$ 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 airflow 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 m x 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 airflow rate. The values in the Table are representative for all ambient conditions considered here, and for the various (similar) airflow 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)

$$\eta = \frac{F_R (f(\theta) - U_L (T_1 - T_A)/S)}{S}$$

(1)

where $f(\theta)$ is such that

$$S P = f(\theta) . S$$

(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 $T_1$ 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 $(T_1 - T_A)/S$ 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 $T_1$ 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 rearduct 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

\[ \eta = \frac{\text{total energy extracted by the air flow in the day}}{\text{integration of } S \text{ over the day}} \quad (3) \]

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 \((TI-\overline{TA})/S\). 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 \((TI-\overline{TA})/S\) 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 \((TI-\overline{TA})/S\)). 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. S1D1-S1D3 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 \( \bar{\eta} \). 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 \( \bar{\eta} \) in Figure 2 the value of \( \theta \) is always zero,
thus raising \( \bar{f}(\theta) \), 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 \( T_0 \) 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 \( T_0 \) 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 \( T_0 \).
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
\((T_1-T_A)/S\) 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.

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

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

TRANS: Computer program for analysing collector data under transient conditions.
270 FOR K=1 TO NC
271 NEXT K
272 FOR L=1 TO NC
273 IF 465 (DENOM) = 1 THEN GOTO 210
274 YY=YY+XY
275 FOR K=1 TO NC
276 IF 465 (YY(K))=YY(K)+ZY(K)
277 IF 465 (XY(K))=XY(K)+XX(K)
278 NEXT L
279 FOR M=1 TO NC
280 IF 465 (PT(K,L))=PT(K,L)+PT(K,L)
281 NEXT L
282 NEXT M
283 NEXT K
284 NEXT L
285 NEXT K
286 NEXT K
287 NEXT M
288 PRINT "TAKE F.J"
214
215 NEXT K
216 ZE=SOR (ZE*YY/(NF-NC))
217 PRINT "ETA0"=I.E,"+/I":Z.E
218 U=X(NC)
219 PRINT "FU=U","+-",Z(NC)
220 PRINT "TABLE F.4"
221 FOR I=1 TO NR
222 C(K)=X(I)/E
223 PRINT K,C(K)
224 NEXT K
225 F=F-((HLOG (1-U/H)))/U
226 PRINT "F"=I.F
227 E=E/F
228 U=U+F
229 PRINT "ETAD0"=I.E,"U"=U
230 PRINT "DATA SETS ACCEPTED FOR ANALYSIS":INP
1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN# 1 TO "TRANID700"
1120 NF=0
1130 READ# 1 I,X(NK),Y,T(NK)
1135 IF I=0 AND X(NK)=0 THEN GOTO 1570
1140 II=I+1
1145 FOR K=2 TO NK
1150 L=NF-K+1
1160 L=NF-K+1
1170 READ# 1 I,X(L),Y,T(L)
1175 IF I=0 AND X(L)=O THEN GOTO 1570
1180 IF II=1 THEN GOTO 1135
1190 II=1+1
1200 NEXT K
1210 GOTO 1400
1220 FOR K=2 TO NK
1225 L=NF-K+2
1230 X(L)=X(L-1)
1235 T(L)=T(L-1)
1240 NEXT K
1270 READ# 1 I,X(I),Y,T(I)
1275 IF I=0 AND X(I)=0 THEN GOTO 1570
1280 IF II=1 THEN GOTO 1150
1290 II=1+1
1300 E=0
1310 X(NC)=0
1320 FOR K=1 TO NK
1330 E=E+X(K)*E(C(K))
1340 X(NC)=X(NC)+T(K)
1350 NEXT K
1360 Y=Y/(FRE)
1370 X(NC)=X(NC)/(X*FRE)
1380 PRINT Y,X(NC)
1390 REM CALC LEAST SOR TO THERMAL PERFORMANCE
1400 SX=SX+X(NC)
1410 SY=SY+Y
1420 SX=SY+X(NC)*Y(NC)
1430 SY=SY+Y
1440 SX=SY+X(NC)*Y
214