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

Volume 2
CONTENTS

Volume 2

Nomenclature
References
Tables
Figures
Plates
Appendices

Appendix A: 'Sunstore' computer model.
Appendix B: Steady state computer models
Appendix C: The effect of thermal capacitance on the performance of solar collectors
Appendix D: 'TRANS', transient testing computer model.
Nomenclature

Chapter 2

\( A_c \)
Collector area (m²)

\( A_s \)
Storage tank surface area m²)

\( c \)
Appropriate specific heat (J Kg\(^{-1}\) °C\(^{-1}\))

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

\( C_h \)
Initial capital expenditure per house (£)

\( E_T \)
Total (accumulated sum) of the radiation falling over a time period of one month on an inclined surface which is above the threshold radiation (J m\(^{-2}\))

\( f \)
Differential fuel inflation

\( F_h \)
Fuel cost per year per house (£)

\( F_R \)
Collector/heat-exchanger efficiency factor

\( F' \)
Collector efficiency factor

\( i \)
Discount rate

\( I_{th} \)
Threshold solar irradiance (W m\(^{-2}\))

\( K_h \)
Repeated capital expenditure per house (£)

\( L \)
Monthly total heating demand for space heating and hot water (J)

\( L_s \)
Energy lost from storage tank during the month (J)

\( M_C \)
Storage heat capacity (J °C\(^{-1}\))

\( N \)
Lifetime of hardware (years)

\( n \)
Number of years

\( P_{VCh} \)
Present value cost per house

\( Q \)
Heat energy (J)

\( Q_N \)
Net heat transferred to storage during the month (J)

\( Q_T \)
Solar energy collected during the month (J)

\( R_h \)
Running costs per year per house (£)

\( s \)
Pebble shape factor

\( T_a \)
Ambient temperature (°C)

\( T_{at} \)
Ambient temperature averaged over periods when the radiation level is above the threshold (°C)

\( T_g \)
Monthly average ground temperature (°C)

\( T_s \)
Store temperature (°C)

\( T_{so} \)
Monthly average store temperature (°C)

\( T_{so} \)
Store temperature at the beginning of the month (°C)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>Temperature change ($^\circ$C)</td>
</tr>
<tr>
<td>$t_m$</td>
<td>Total number of seconds in a month</td>
</tr>
<tr>
<td>$t_t$</td>
<td>Total number of seconds collector is in operation in month, i.e. when radiation level is above threshold</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Collector overall loss coefficient (W m$^{-2}$ °C$^{-1}$)</td>
</tr>
<tr>
<td>$U_S$</td>
<td>Storage tank heat loss coefficient (W m$^{-2}$ °C$^{-1}$)</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume (m$^3$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg m$^{-3}$)</td>
</tr>
<tr>
<td>$\bar{\tau\alpha}$</td>
<td>Monthly average transmittance-absorptance product</td>
</tr>
</tbody>
</table>
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 ($^\circ C$)
$T_{\text{ref}}$ An empirically derived reference temperature ($100^\circ C$)
$t_m$ Total number of seconds in a month
$U_L$ Collector overall loss coefficient ($Wm^{-2} \cdot ^\circ C^{-1}$)
$(\tau \alpha)$ Monthly average transmittance-absorptance product
Nomenclature

Chapter 4

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

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

Dₜ Characteristic length (m)

F' Absorber plate (or collector) efficiency factor

Fₚ Collector heat removal factor

g Acceleration of gravity (ms⁻²)

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

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

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

hₔ 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)

Tₑ Cover temperature (°C)

Tₑ Exit fluid temperature (°C)

Tᵢ Inlet fluid temperature (°C)

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

Tₑ Average absorber temperature (°C)

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

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

Uₑ Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)
$U_t$: Top loss heat transfer coefficient (Wm$^{-2}$ °C$^{-1}$)

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

$W$: Collector width (m)

$x$: Insulation thickness (m)

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

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

$\epsilon_c$: Cover emissivity

$\epsilon_p$: Absorber plate emissivity

$\eta$: Efficiency

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

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

$\tau$: Transmittance of the solar collector

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

$\sigma$: Stefan-Boltzmann constant
**Nomenclature**

**Chapter 5**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aperture area, or transparent frontal area for collector (m²)</td>
</tr>
<tr>
<td>Ac</td>
<td>Collector area (m²)</td>
</tr>
<tr>
<td>cp</td>
<td>Volume heat capacity at constant pressure (J/kg·°C⁻¹)</td>
</tr>
<tr>
<td>P'</td>
<td>Absorber plate (or collector) efficiency factor</td>
</tr>
<tr>
<td>P&quot;</td>
<td>Collector flow factor</td>
</tr>
<tr>
<td>Pl</td>
<td>Correction factor for partial shading of the collector</td>
</tr>
<tr>
<td>P2</td>
<td>Correction factor for variation of T_a with the angle of incidence</td>
</tr>
<tr>
<td>P3</td>
<td>Correction factor for variation in optical properties from normal for diffuse irradiance</td>
</tr>
<tr>
<td>P_R</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>h_w</td>
<td>Wind heat transfer coefficient (W/m²·°C⁻¹)</td>
</tr>
<tr>
<td>I</td>
<td>Equivalent normal solar irradiance (W/m²)</td>
</tr>
<tr>
<td>I_b</td>
<td>Direct solar irradiance in plane of collector (W/m²)</td>
</tr>
<tr>
<td>I_d</td>
<td>Diffuse solar irradiance in plane of collector (W/m²)</td>
</tr>
<tr>
<td>I_m</td>
<td>Measured total solar irradiation incident upon the aperture plane of the collector (W/m²)</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate of transfer fluid (Kg/s⁻¹)</td>
</tr>
<tr>
<td>m_t</td>
<td>Mass flow rate of leak (Kg/s⁻¹)</td>
</tr>
<tr>
<td>M</td>
<td>Fluid capacity of collector (Kg)</td>
</tr>
<tr>
<td>(mc)_e</td>
<td>Effective heat capacity of collector (J·°C⁻¹)</td>
</tr>
<tr>
<td>q</td>
<td>Output power per unit aperture area conveyed by the heat transfer fluid (W/m²)</td>
</tr>
<tr>
<td>Qu</td>
<td>Energy per unit time, useful (W)</td>
</tr>
<tr>
<td>(Qu)_t</td>
<td>Energy per unit time under transient conditions (W)</td>
</tr>
<tr>
<td>r</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>t</td>
<td>Time (s)</td>
</tr>
<tr>
<td>T_a</td>
<td>Ambient air temperature (°C)</td>
</tr>
<tr>
<td>T_b</td>
<td>Average back plate temperature (°C)</td>
</tr>
<tr>
<td>T_e</td>
<td>Exit fluid temperature (°C)</td>
</tr>
<tr>
<td>T_f</td>
<td>Average temperature of the fluid in the collector (°C)</td>
</tr>
<tr>
<td>T_i</td>
<td>Inlet fluid temperature (°C)</td>
</tr>
</tbody>
</table>
\( T_{\text{m}} \)  Measured fluid inlet temperature (°C)  
\( T_{\text{m}} \)  Mean fluid temperature \((T_e + T_i)/2\) (°C)  
\( T_p \)  Absorber plate temperature (°C)  
\( T_p \)  Mean absorber temperature (°C)  
\( T_{\text{sky}} \)  Equivalent black body sky temperature (°C)  
\( T^* \)  Reduced temperature \((T_i - T_a)/I\) \((\text{m}^2 \ °\text{C} \ \text{w}^{-1})\)  
\( U_L \)  Collector overall heat transfer (loss) coefficient  \((\text{Wm}^{-2} \ °\text{C}^{-1})\)  
\( V \)  Wind velocity \((\text{ms}^{-1})\)  
\( \eta \)  Efficiency  
\( \tau \alpha \)  Product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance.  
\( \tau_C \)  Collector time constant under flow conditions \((\text{s})\)  
\( \tau_d \)  Cut off time \((\text{s})\)  
\( (\tau \alpha)_e \)  Effective transmittance absorptance product  
\( (\tau \alpha)_o \)  Product of the absorptance and transmittance for normal irradiance  
\( \Delta T^* \)  Time increment  
\( \theta \)  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 \( F'U_L \) \((\text{Wm}^{-2}\cdot\text{C}^{-1})\)

\( U_L \) 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

\( \eta_o \) 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  Gass pressure (Nm\(^{-2}\))
P\(_{c}\)  Critical pressure when R\(_{a}\) = R\(_{ac}\)
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)

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

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

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

\( \gamma \) \( c_p/c_v \)

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

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

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

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

\( \mu \) Viscosity (Pa s)

\( \nu \) Kinematic viscosity (\( \mu/\rho \)) (Pa s m⁻³)

\( \rho \) Density (Kg m⁻³)

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

\( \lambda \) Mean free path (m)
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<th>Sector</th>
<th>Fuel</th>
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<th>Total 2025</th>
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<td></td>
<td>Solid</td>
<td>Liquid</td>
<td>Gas</td>
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<tr>
<td>Industry</td>
<td></td>
<td></td>
<td></td>
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<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>
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<tr>
<td></td>
<td>2025</td>
<td>32.8</td>
<td>14.1</td>
</tr>
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<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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<td>Building Materials</td>
<td>1976</td>
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<td>4.6</td>
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<td></td>
<td>2025</td>
<td>1.9</td>
<td>1.2</td>
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<td>7.8</td>
<td>61.2</td>
</tr>
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<td>2025</td>
<td>19.5</td>
<td>14.2</td>
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<td>Process</td>
<td></td>
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<td></td>
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<tr>
<td>Agricultural</td>
<td>1976</td>
<td>0.9</td>
<td>22.1</td>
</tr>
<tr>
<td>Heating &amp; Drying</td>
<td>2025</td>
<td>-</td>
<td>16.1</td>
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<tr>
<td>Domestic</td>
<td>Space</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td>Space</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substance</td>
<td>Comments</td>
<td>Density $\rho$/Kg m$^{-3} \times 10^3$</td>
<td>Specific heat capacity $C_p$/JK$^{-1}$ K$^{-1} \times 10^3$</td>
</tr>
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<td>-----------------------</td>
<td>---------------------------------</td>
<td>--------------------------------------</td>
<td>-------------------------------------------------</td>
</tr>
<tr>
<td>Chabazitic tuff</td>
<td>Common beolite in Italy</td>
<td>1.4</td>
<td>1.09</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>1.0</td>
<td>4.19</td>
</tr>
<tr>
<td>Iron shot</td>
<td></td>
<td>7.86</td>
<td>0.54</td>
</tr>
<tr>
<td>Scrap Iron</td>
<td>Zero voids</td>
<td>7.90</td>
<td>0.53</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td>7.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids (at 30% void $\rho C_p = 2.8$)</td>
<td>5.16</td>
<td>0.75</td>
</tr>
<tr>
<td>Fe$_2$O$_3$, Wet earth</td>
<td></td>
<td>5.20</td>
<td>0.75</td>
</tr>
<tr>
<td>Water and salt</td>
<td>(brine)</td>
<td>1.2</td>
<td>2.1</td>
</tr>
<tr>
<td>Alumina (Al$_2$O$_3$)</td>
<td></td>
<td>1.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Scrap Aluminium</td>
<td>Zero voids (30% void $\rho C_p = 1.8$)</td>
<td>4.0</td>
<td>0.9</td>
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<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temper.</td>
<td>2.74</td>
<td>0.963</td>
</tr>
<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temper.</td>
<td>2.4</td>
<td>-18</td>
</tr>
<tr>
<td>Oils</td>
<td>Cracking occurs at high temp.</td>
<td>2.3</td>
<td>-10</td>
</tr>
<tr>
<td>MgCO$_3$·6H$_2$O</td>
<td></td>
<td>2.51</td>
<td>1.60</td>
</tr>
<tr>
<td>MgCO$_3$</td>
<td></td>
<td>2.51</td>
<td>0.84</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>
</tr>
<tr>
<td>Stone</td>
<td>Zero voids (30% void $\rho C_p = 1.7$)</td>
<td>2.74</td>
<td>0.88</td>
</tr>
<tr>
<td>Material</td>
<td>Density</td>
<td>Sound Speed</td>
<td>Cost (1980)</td>
</tr>
<tr>
<td>-------------------</td>
<td>---------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.74</td>
<td>0.92</td>
<td>2.26</td>
</tr>
<tr>
<td>Marble</td>
<td>2.70</td>
<td>0.75</td>
<td>2.39</td>
</tr>
<tr>
<td>Granite</td>
<td>2.70</td>
<td>0.796</td>
<td>2.12</td>
</tr>
<tr>
<td>Sulphur Liquid</td>
<td>2.1</td>
<td>1.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
<td>2.09</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.4</td>
<td>0.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Brick</td>
<td>2.23</td>
<td>0.84</td>
<td>1.9</td>
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<tr>
<td>Paraffin Oil</td>
<td>0.8</td>
<td>2.2</td>
<td>1.8</td>
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<tr>
<td>Olive Oil</td>
<td>0.9</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Silica (SiO₂)</td>
<td>2.7</td>
<td>0.84</td>
<td>2.3</td>
</tr>
<tr>
<td>Pebbles</td>
<td>3.0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
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<td>Basalt</td>
<td>3.2</td>
<td>0.9</td>
<td>2.9</td>
</tr>
<tr>
<td>Sulphur</td>
<td>2.1</td>
<td>0.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.95</td>
<td>0.963</td>
<td>0.95</td>
</tr>
<tr>
<td>Mitec</td>
<td>Molten salt</td>
<td>Cost £0.28/Kg (1980)</td>
<td>-</td>
</tr>
<tr>
<td>Draw salt</td>
<td>Molten salt</td>
<td>Cost £0.32/Kg (1980)</td>
<td>-</td>
</tr>
<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>
TABLE 2.3  Basic Prometheus configuration to heat 100 houses

<table>
<thead>
<tr>
<th>Store</th>
<th>Value</th>
</tr>
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<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>11200 m³</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>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>2,900 m²</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 over useful incident angles (τα)</td>
<td>0.8</td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>1800</td>
<td>40000</td>
</tr>
<tr>
<td>1200</td>
<td>103000</td>
</tr>
<tr>
<td>1155</td>
<td>22700</td>
</tr>
<tr>
<td>2420</td>
<td>53750</td>
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<tr>
<td>1800</td>
<td>55700</td>
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<td>90</td>
<td>3210</td>
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<tr>
<td>103</td>
<td>2340</td>
</tr>
<tr>
<td>39</td>
<td>880</td>
</tr>
<tr>
<td>118</td>
<td>9357</td>
</tr>
</tbody>
</table>

Refer to Chapter 2 for references.

Energy Intensity

on-site construction

cans and ducting

plumbing

insulation without back

collector

transportation

sand, including gravel, including

cement, including

Insulation

concrete sections

sheet piling

concrete

asphalt

base - hardcore

Preparation and Site

Excavation and Site

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

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

\[ i=0.05 \, f=0.04 \, 6600 \quad 6000 \quad 6300 \]

\[ PVC_h \quad i=0 \quad f=0.04 \quad 8500 \quad 17800 \quad 20200 \]

\[ i=0 \quad f=0.02 \quad 7500 \quad 11700 \quad 12500 \]
<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector type</td>
<td>Flat plate</td>
<td>Evacuated</td>
<td>Concentrating</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>selective</td>
<td>tube collector</td>
<td>collector</td>
<td>performance</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/(^\circ C)</th>
<th>Cost/£1982 per KWh recovered energy seasonal storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tank</td>
<td>80</td>
</tr>
<tr>
<td>Pit storage</td>
<td>50</td>
</tr>
<tr>
<td>Rock cavern</td>
<td>70</td>
</tr>
<tr>
<td>Storage in clay</td>
<td>12</td>
</tr>
<tr>
<td>Multiple well systems in rock</td>
<td>50</td>
</tr>
<tr>
<td>Aquifers</td>
<td>15</td>
</tr>
<tr>
<td>Prometheus (pebble bed, using data from Table 2.6)</td>
<td>100</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Location of Store/or Centre of Study</th>
<th>Design Study or Constructed</th>
<th>Storage Material</th>
<th>Number of Houses Per Store</th>
<th>% of Annual House Heating Supplied by System</th>
<th>Cost Per House £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamboho, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td></td>
<td>27 000</td>
</tr>
<tr>
<td>Inglestad, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td></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></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></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></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></td>
<td>6 000</td>
</tr>
<tr>
<td>Sussex, UK</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>100</td>
<td>100</td>
<td></td>
<td>10 000</td>
</tr>
<tr>
<td>City University, London, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>100</td>
<td>78</td>
<td></td>
<td>4 000</td>
</tr>
<tr>
<td>ERR, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td></td>
<td>2 416</td>
</tr>
<tr>
<td>PCL, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>50</td>
<td>100</td>
<td></td>
<td>5 480</td>
</tr>
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</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⁻²°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>Total fabric specifics loss</td>
<td></td>
<td></td>
<td>224W°C⁻¹</td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td></td>
<td>80W°C⁻¹</td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td></td>
<td>304W°C⁻¹</td>
</tr>
</tbody>
</table>
TABLE 3.2  Average weather data (1969-1977) for Kew, London, Latitude 51°N

<table>
<thead>
<tr>
<th>Month</th>
<th>Days in month</th>
<th>Solar radiation on a South-facing vertical surface (KWh/m²/month)</th>
<th>Solar radiation on a South-facing surface 30° to horizontal (KWh/m²/month)</th>
<th>Ambient Temperature °C</th>
<th>Degree days baseline 15.5°C</th>
</tr>
</thead>
<tbody>
<tr>
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<td>31</td>
<td>28</td>
<td>25.2</td>
<td>5.2</td>
<td>346</td>
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<tr>
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<td>28</td>
<td>42</td>
<td>45</td>
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<td>304</td>
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<tr>
<td>March</td>
<td>31</td>
<td>74</td>
<td>91</td>
<td>5.7</td>
<td>282</td>
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<tr>
<td>April</td>
<td>30</td>
<td>75</td>
<td>115</td>
<td>8.2</td>
<td>197</td>
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<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>
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<td>Dec</td>
<td>31</td>
<td>25</td>
<td>22</td>
<td>5.3</td>
<td>333</td>
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</table>
### TABLE 3.3  Thermal characteristics of new houses with different levels of 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 and water heating demand (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
</tr>
<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
<td>304</td>
<td>41.7</td>
</tr>
<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
<td>291</td>
<td>39.5</td>
</tr>
<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>255</td>
<td>33.7</td>
</tr>
<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
<td>251</td>
<td>33.0</td>
</tr>
<tr>
<td>A5</td>
<td>A4 + extra layer of glazing (i.e. double)</td>
<td>213</td>
<td>27.5</td>
</tr>
<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>186</td>
<td>23.5</td>
</tr>
<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>182</td>
<td>22.7</td>
</tr>
<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>182</td>
<td>20.2</td>
</tr>
<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>177</td>
<td>19.7</td>
</tr>
<tr>
<td>A10</td>
<td>A9 + extra layer of glazing (i.e. triple)</td>
<td>164</td>
<td>18.4</td>
</tr>
<tr>
<td>A11</td>
<td>A10 + cavity increased to 200 mm</td>
<td>150</td>
<td>16.7</td>
</tr>
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</table>
TABLE 3.4 Thermal characteristics of Basic Type BO house

<table>
<thead>
<tr>
<th>Component</th>
<th>Area A ($m^2$)</th>
<th>U-value ($Wm^{-2}°C^{-1}$)</th>
<th>UA ($W^0°C^{-1}$)</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>
<tr>
<td>Total fabric specific loss</td>
<td></td>
<td>192 $W^0°C^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td>68 $W^0°C^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td>260 $W^0°C^{-1}$</td>
<td></td>
</tr>
<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss (W°C⁻¹)</td>
<td>Net annual space water heating demand (GJ)</td>
</tr>
<tr>
<td>------------</td>
<td>------------------------------------------------------</td>
<td>-----------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>BO</td>
<td>Basic (average UK housing stock)</td>
<td>260</td>
<td>34.9</td>
</tr>
<tr>
<td>B1</td>
<td>BO + 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>
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</table>
### TABLE 5.21

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 at inlet</th>
<th>Air temp. at inlet</th>
<th>Absorber temp.</th>
<th>Wind speed</th>
<th>collector efficiency</th>
<th>Air temp. at outlet</th>
<th>Ambient temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21/6/83</td>
<td>13h14-15h34</td>
<td>65.5</td>
<td>51.1</td>
<td>14.9</td>
<td>21.1</td>
<td>7.8</td>
<td>1.6</td>
<td>77.2</td>
</tr>
<tr>
<td>2</td>
<td>25/6/83</td>
<td>14h34-15h43</td>
<td>59.6</td>
<td>73.2</td>
<td>11.7</td>
<td>22.1</td>
<td>7.7</td>
<td>0.0409</td>
<td>43.4</td>
</tr>
<tr>
<td>3</td>
<td>26/6/83</td>
<td>11h23-11h32</td>
<td>79.1</td>
<td>22.2</td>
<td>22.9</td>
<td>7.3</td>
<td>0.0745</td>
<td>29.2</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>5/7/83</td>
<td>11h31-12h00</td>
<td>75.1</td>
<td>22.5</td>
<td>84.3</td>
<td>9.2</td>
<td>0.0000</td>
<td>73.0</td>
<td>0.0040</td>
</tr>
<tr>
<td>5</td>
<td>19/8/83</td>
<td>12h25-13h44</td>
<td>61.9</td>
<td>28.6</td>
<td>84.3</td>
<td>9.2</td>
<td>0.0084</td>
<td>74.6</td>
<td>0.0543</td>
</tr>
<tr>
<td>6</td>
<td>19/8/83</td>
<td>12h09-12h18</td>
<td>64.7</td>
<td>28.6</td>
<td>84.3</td>
<td>9.2</td>
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<tr>
<td>7</td>
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<td>13h43-13h52</td>
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<td>28.6</td>
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<td>76.8</td>
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<tr>
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<td>14h30-14h39</td>
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<td>28.6</td>
<td>84.3</td>
<td>9.2</td>
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<td>9</td>
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<td>11h42-12h15</td>
<td>69.1</td>
<td>24.9</td>
<td>84.3</td>
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<td>-0.0000</td>
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<tr>
<td>Date</td>
<td>Day/Freq. yr' Hor.</td>
<td>Days to Freq / yr'</td>
<td>Days to Freq / yr'</td>
<td>Days to Freq / yr'</td>
<td>Days to Freq / yr'</td>
<td>Days to Freq / yr'</td>
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<td>-------------------</td>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>12</td>
<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<tr>
<td>11</td>
<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<td>10</td>
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<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
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<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<tr>
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<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<tr>
<td>7</td>
<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
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<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
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<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
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<td>16/6/84 1977-1971</td>
<td>30.3 74.8 29.5 22.9 15.9 27.9 17.0 17.2</td>
<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>27.5 17.0 7.5 7.5 6.2 5.0 2.0 1.7</td>
<td>2.0 1.7 1.0 0.9 0.8 0.7 0.6 0.5</td>
<td>0.4 0.3 0.2 0.1 0.0 0.0 0.0 0.0</td>
<td>0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0</td>
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</tr>
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</table>

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

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

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

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

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

* = at low fluid inlet temperatures
<table>
<thead>
<tr>
<th>Column 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 2</td>
</tr>
<tr>
<td>Column 3</td>
</tr>
<tr>
<td>Column 4</td>
</tr>
<tr>
<td>Column 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Index</th>
<th>Incident Insolation</th>
<th>Output Power per Unit Spectral Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>I</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$n$</td>
<td>$F_R(t_0,k_n)$</td>
<td>$F_R(t_0)$ $k_n$</td>
</tr>
<tr>
<td>-----</td>
<td>----------------</td>
<td>------------------</td>
</tr>
<tr>
<td>1</td>
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<td>.0017945235996</td>
</tr>
</tbody>
</table>

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

*Data Sets Accepted for Analysis 80*

<table>
<thead>
<tr>
<th>$n/F$</th>
<th>$n/F^*$</th>
<th>$T^*$</th>
</tr>
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<tbody>
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</tr>
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<td>.007</td>
</tr>
<tr>
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<td>.021</td>
<td>.006</td>
</tr>
<tr>
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<td>.022</td>
<td>.005</td>
</tr>
<tr>
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<td>.021</td>
<td>.005</td>
</tr>
<tr>
<td>.476993408723</td>
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<td>.005</td>
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<td>.005</td>
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<td>.006</td>
<td>.005</td>
</tr>
<tr>
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<td>.005</td>
<td>.006</td>
</tr>
<tr>
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<td>.003</td>
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<td>.005</td>
<td>.009</td>
</tr>
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<td>.006</td>
<td>.009</td>
</tr>
<tr>
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<td>.004</td>
<td>.009</td>
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<td>.009</td>
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<td>.009</td>
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<tr>
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<td>.052</td>
<td>.009</td>
</tr>
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<td>.009</td>
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<td>.025</td>
<td>.009</td>
</tr>
</tbody>
</table>

**POINTS ON THERMAL PERFORMANCE CHARACTERISTIC 80**

**FROM LEAST SQUARES FITS EACH WAY**

**MINIMUM ETAO= .73452318781**

**MAXIMUM ETAO= .714184616622**

**U= 7.33893217894**

**U= 7.4561890148**
### TABLE 5.8
Temperature distribution within DY1 collector (0.2mm thick plate and duct back) during ASHRAE steady state testing, \( T_a = 293k \), \( I = 700\text{um}^{-2} \), Wind = 1m s\(^{-1} \), T sky = 273k

<table>
<thead>
<tr>
<th>( T_1/k )</th>
<th>( T_e/k )</th>
<th>( \bar{\bar{T}}_p/k )</th>
<th>( \bar{\bar{T}}_b/k )</th>
<th>( T_m/k )</th>
<th>( F_{RUL} ) (( \text{Wm}^{-2} \text{OC}^{-1} ))</th>
<th>( \eta )</th>
<th>( F_{ave\text{UL}} ) (( \text{Wm}^{-2} \text{OC}^{-1} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>332.73</td>
<td>333.01</td>
<td>322.1</td>
<td>317.86</td>
<td>2.762</td>
<td>.645</td>
<td>3.111</td>
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<tr>
<td>343</td>
<td>364.98</td>
<td>365.28</td>
<td>357.16</td>
<td>354.00</td>
<td>2.902</td>
<td>.476</td>
<td>3.230</td>
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<tr>
<td>383</td>
<td>396.47</td>
<td>396.94</td>
<td>391.47</td>
<td>389.73</td>
<td>3.044</td>
<td>.293</td>
<td>3.362</td>
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<tr>
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<td>427.23</td>
<td>428.06</td>
<td>425.00</td>
<td>425.11</td>
<td>3.185</td>
<td>.095</td>
<td>3.503</td>
</tr>
<tr>
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<td>435.94</td>
<td>433.57</td>
<td>434.06</td>
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<td>.037</td>
<td>3.564</td>
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</table>

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

<table>
<thead>
<tr>
<th>( T_1/k )</th>
<th>( T_e/k )</th>
<th>( \bar{\bar{T}}_p/k )</th>
<th>( \bar{\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} ) (( \text{Wm}^{-2} \text{OC}^{-1} ))</th>
<th>( F_{ave\text{UL}} ) (( \text{Wm}^{-2} \text{OC}^{-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>3.080</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>3.439</td>
<td>4.039</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 sky = 293k
| 211 | 1.6 | 28 | 0.541 | 7.77 |
| 400 | 0.4 - 3.0 | 17 | 0.520 | 8.48 |
| 362 | 0.4 | 16 | 0.557 | 7.37 |
| 741 | 1.5 | 23 | 0.545 | 9.29 |
| Indoor | | | | |
| | | | | |
| | | | | |
| | | | | |

Structured Polycarbonate Collector

| 600 | 2 | 20 | 0.639 | 9.46 |
| - | 0 | 12 | - | 4.53 |
| 300 | 2.5 | 13 | 0.583 | 5.19 |
| 700 | 1 | 26 | 0.627 | 5.13 |
| Theory | | | | |

D.C. Hall Collector

<table>
<thead>
<tr>
<th>Test method</th>
<th>Summary of collector testing results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Reflective index (n)</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
</tr>
<tr>
<td>Plexiglass (Acrylic)</td>
<td>1.49</td>
</tr>
<tr>
<td>Teflon F.F.P. (Fluorocarbon)</td>
<td>1.343</td>
</tr>
<tr>
<td>Tedlar P.V.F. (fluorocarbon)</td>
<td>1.46</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.64-1.67</td>
</tr>
<tr>
<td>Sunlite (Fibre glass)</td>
<td>1.54</td>
</tr>
<tr>
<td>Float glass (Glass)</td>
<td>1.518</td>
</tr>
<tr>
<td>Tempar glass (Glass)</td>
<td>1.518</td>
</tr>
<tr>
<td>Clear lime sheet glass (Low iron glass)</td>
<td>1.51</td>
</tr>
<tr>
<td>Clear lime temper glass (Low iron glass)</td>
<td>1.51</td>
</tr>
<tr>
<td>Sunode white crystal glass (0.01% iron glass)</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Source: Gary, H.P. 'Treatise on solar energy' Vol.1, A Wiley Interscience Publication, Chichester, 1982
<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Coating Material</th>
<th>Support Material</th>
<th>Backing Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03 - 0.05</td>
<td>Copper/Glass</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
<tr>
<td>0.15 - 0.18</td>
<td>Stainless steel</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
<tr>
<td>0.23 - 0.25</td>
<td>Aluminum</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
<tr>
<td>0.30 - 0.33</td>
<td>Aluminum</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
<tr>
<td>0.30 - 0.36</td>
<td>Aluminum</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
<tr>
<td>0.40 - 0.45</td>
<td>Aluminum</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
<tr>
<td>0.50 - 0.55</td>
<td>Aluminum</td>
<td>Copper</td>
<td>Copper oxide</td>
</tr>
</tbody>
</table>

**Notes:**
- **Copper oxide coated black enamel**
- **Adhesive**
- **Black paint**
- **Black night**
- **Black chrome (BC)**

**Table 6.2**

**Optical Properties of Selective Absorber Surface Coatings**
### 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>
</tr>
</thead>
<tbody>
<tr>
<td>Cover 1</td>
<td>6.0 mm</td>
<td></td>
</tr>
<tr>
<td>Cover 2</td>
<td>2.0 mm</td>
<td></td>
</tr>
</tbody>
</table>

**Thickness of the Plate and of the Duct-Back:**

<table>
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<tr>
<th>Code</th>
<th>Thickness</th>
</tr>
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<tbody>
<tr>
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</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>
</tr>
<tr>
<td>DY5</td>
<td>5.0 mm</td>
</tr>
</tbody>
</table>

**Air Flow in the Rear-Duct:**

- **Flow 0**: Stagnation \((M = 0)\)
  - All \(T_I = 303\) K \(M = 0.0600\) kg s\(^{-1}\) \(PON\) irrelevant

- **Flow 1**: All \(T_I = 303\) K \(M = 0.0600\) kg s\(^{-1}\) \(PON = 128W\)
- **Flow 2**: \(T_I = 323\) K \(M = 0.0562\) kg s\(^{-1}\) \(PON = 124W\)
### TABLE 7.1 Some typical thermal accommodation coefficients

<table>
<thead>
<tr>
<th>Gas</th>
<th>Surface</th>
<th>Surface condition</th>
<th>Temp. (°C)</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
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<td>Indeterminate</td>
<td>-</td>
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<tr>
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<td>Cast Iron</td>
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<td>-</td>
<td>0.87 - 0.96</td>
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<tr>
<td></td>
<td>Aluminium</td>
<td>Indeterminate</td>
<td>-</td>
<td>0.87 - 0.97</td>
</tr>
<tr>
<td>N₂</td>
<td>W</td>
<td>Indeterminate</td>
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<td>-</td>
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<td>CO₂</td>
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<td>K on H₂</td>
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<td>W</td>
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TABLE 7.2 Convection and conduction heat transfer coefficients for various gases at different temperatures as measured with guarded hot plate.

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<th>Condition</th>
<th>$T_s/\degree C$</th>
<th>$T_i/\degree C$</th>
<th>$h_p/(\text{Wm}^{-2}\text{O}^{-1})$</th>
<th>$Q_A/(\text{Wm}^{-2})$</th>
<th>$T_f/\degree C$</th>
<th>$h_r/(\text{Wm}^{-2}\text{O}^{-1})$</th>
<th>$h_c/(\text{Wm}^{-2}\text{O}^{-1})$</th>
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<td>Air at atmospheric pressure</td>
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<td>13.84</td>
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<td>Air, $p = 82$ torr</td>
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<td>37.9</td>
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<td>12.55</td>
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<td>10.35</td>
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<td>12.86</td>
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<td>Air, $p = 71$ torr</td>
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<td>Air $p = 16$ torr and changing</td>
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<td>48.83</td>
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**FIGURE 1.1(a)**

**PHYSICAL QUALITY OF LIFE INDEX VERSUS ENERGY CONSUMPTION PER CAPITA FOR THE COUNTRIES OF THE WORLD. SOURCES OF DATA:**

FIGURE 1.1(b) HISTOGRAM OF ENERGY CONSUMPTION PER CAPITA FOR DIFFERENT PHYSICAL QUALITY OF LIFE INDEX (PQLI) FOR THE PEOPLE OF THE WORLD. THE PERCENTAGES SHOWN IN EACH BAR ARE THE PERCENTAGES WITHIN THAT RANGE OF PQLI.
**FIGURE 2.1** UK LOW GRADE HEAT, FUEL CONSUMPTION AND END USE.

**FIGURE 2.2** DOMESTIC SPACE AND HOT WATER DEMAND.
FIGURE 2.3  DISTRIBUTION OF ANNUAL GAS CONSUMPTION FOR 90 SIMILAR HOUSES IN MILTON KEYNES, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A.

FIGURE 2.4  WEEKLY CONSUMPTION OF HOT WATER FOR ONE HOUSEHOLD, FROM 'THE PERFORMANCE OF DOMESTIC WET HEATING SYSTEMS', PICKUP, G.A.
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 [7]

**Figure 2.6** SOLAR AND THERMAL RADIATION SPECTRAL DISTRIBUTIONS. AIR MASS m=0 IS FOR EXTRA-TERRESTRIAL RADIATION, m=2 IS A TYPICAL CITY DISTRIBUTION.
Figure 2.7
Annual variation of mean daily totals of direct and diffuse insolation on a horizontal surface.

Figure 2.8
Average global solar radiation on a horizontal surface.

**Figure 2.10**

Fig. 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

Fig. 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.
Sample size 204
Average 1.6 cm.
Standard deviation 0.7 cm.

**Figure 2.19** Frequency distribution of pebble smallest dimension.
FIGURE 2.20 FREQUENCY DISTRIBUTION OF PEBBLE LARGEST DIMENSION

SAMPLE SIZE 204
AVERAGE 3.8 cm
STANDARD DEVIATION 0.95 cm
FIGURE 2.21  
PROTO-PROMETHEUS STORE TEMPERATURE, FROM 2ND SEPTEMBER 1981 TO 2ND OCTOBER 1981 UNDER STANDBY (FAN OFF).

FIGURE 2.22  
ENERGY DEMAND FOR A 3-BEDROOM HOUSE BUILT TO R75 BUILDING REGULATIONS (TYPE A) WITH SOLAR HEATING SUPPLIED BY A BASIC TYPE PROMETHEUS.
Figure 2.23 Effect of changing the collector overall heat loss coefficient on the % of annual energy supplied by Prometheus 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 28 m² OF COLLECTOR PER HOUSE) FOR A TYPE A1 HOUSE.

FIGURE 2.28 THE EFFECT OF CHANGING THE COLLECTOR OVERALL HEAT LOSS ON THE % OF ENERGY SUPPLIED BY A CUBIC PROMETHEUS HEATING A TYPE A5 HOUSE.
**Figure 2.29** Design of costed Prometheus to provide 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 AO HOUSE

FIGURE 3.2  NET SPACE HEATING DEMAND FOR TYPE AO, AS AND AI
            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 A0 house.

**Figure 3.4**

Energy demand for a 3-bedroom terrace built to TSB 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, 12m² AND 24m² OF SOLAR COLLECTOR.

Figure 3.6  COMPARISON OF PREDICTED SOLAR ENERGY SUPPLY FOR A HOUSE USING THE F-CHART METHOD WITH THE MEASURED SOLAR SUPPLY FOR THE MILTON KEYNES SOLAR HOUSE.
**Figure 37** Use of energy saved and extra costs for various insulation options and solar systems retrofitted to an existing Type B0 house.
Figure 4.1. Nonporous Absorber-Type Air Heaters.

Figure 4.2. Porous Absorber-Type Air Heaters.
Figure 4.3 Hybrid Photovoltaic and Air Heating Solar Collector

Figure 4.4 Collector Heat Losses
FIGURE 4.5  REAR DUCT COLLECTOR CONFIGURATION

FIGURE 4.6  TOP DUCT COLLECTOR CONFIGURATION
The curves correspond to the following relations:

- **MCDONALD**
  \[ h_w = 5.7 + 3.5 \sqrt{\nu} \]

- **WATMUFF**
  \[ h_w = 2.8 \nu + 3.0 \nu \]

- **LLOYD**
  \[ h_w = 0.15 \frac{R_0}{h_w} \times \frac{L}{W} \quad \text{for} \quad T_w = 10^\circ C, \ T_v = 15^\circ C, \ L = 1m, \ W = 1m. \]

- **SPARROW**
  \[ h_w = \frac{k}{L} \frac{R_0}{h_w} \times \frac{L}{W} \quad \text{for} \quad T_w = 10^\circ C, \ T_v = 15^\circ C, \ L = W = 1m. \]

- **GREEN**
  \[ h_w = \left( h_w^{10} + h_w^{15} \right)^{1/2} \quad \text{for} \quad A = 1.4m^2, \ 45^\circ \text{inclination} \]

- **KIND**
  \[ \text{for} \quad \text{collective length} 2.4\text{m}, \ \text{width} 1.2\text{m}, \ \text{height} 4.5\text{m}, \ T_w = 25^\circ C. \]

**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 FRESH DIRECT AIR HEATING COLLECTOR.
INPUT

ENVIRONMENTAL PARAMETERS  \( I, V, T_a \)

COLLECTOR CONFIGURATION  \((Dx)  \theta_1, C_L, k, H, A_L, W_D\)
\( V_e, x \)

COLLECTOR VARIABLES  \( T_c, m \)

INITIAL ESTIMATE OF  \( T_f, T_m \)

CALCULATE

\[ R_c = \text{see equation} \quad 4.25 \]
\[ N_h = 4.23 \]
\[ h_1, h_2 = 4.22 \]
\[ h_t = 4.27 \]
\[ U_b = 4.4 \]
\[ U_b = 4.15 \]
\[ U_L = 4.16 \]
\[ F' = 4.20 \]
\[ F_r = 4.19 \]
\[ Q_u = 4.18 \]

\( \eta = \frac{Q_u}{A_i} \)

CALCULATE NEW ABSORBER TEMPERATURE

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

IS

\[ \frac{[T_m - T_p]}{L_01} \]

\[ \text{NO} \]

\[ \text{YES} \]

OUTPUT

\( z, T_p, U_L, U_b, V_e, F_r, F', Q_u \)

FIGURE 4.9  FLOW DIAGRAM OF 'EFFIC' (SEE APPENDIX B) A PROGRAM TO CALCULATE THE EFFICIENCY OF A TOP DUCT AIR HEATING 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 EACH MONTH ON A HORIZONTAL SURFACE (AT WIN 1966-1975)
SECTION X-X

FIGURE 5.2  D.C. HALL COLLECTOR
**Figure 5.3** Angular variation of transmittance of 2 mm thick polycarbonate (refractive index = 1.586, extinction coefficient = 20 ft⁻¹)

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

Figure 5.7  Solar transmittance of structured polycarbonate versus incident angle. Source: H.L. Redfoot et al., 'Glazing solar collectors with acrylic and double-walled polycarbonate plastics.'
Figure 5.8 Orifice Plate and Its Location for Measuring Mass Flow Rate
**FIGURE 5.9** ASHRAE STANDARD 93-77 TESTING CONFIGURATION FOR A SOLAR COLLECTOR WHEN THE TRANSFER FLUID IS AIR.

**FIGURE 5.10** OPEN UNIVERSITY AIR COLLECTOR TESTING CONFIGURATION.
FIGURE 5.11  RESPONSE OF STRUCTURED POLYCARBONATE COLLECTOR TO A
STEP CHANGE IN INSOLATION FROM 750 W/m² TO ZERO
WITH A FLUID FLOW RATE OF 7.2 kg/hr⁻¹.

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

FIGURE 5.14  RECORD OF INCIDENT SOLAR RADIATION ON A HORIZONTAL SURFACE
AND WIND SPEED ON 21/6/83 (CONTINUED ON NEXT PAGE).
Figure 5.14 continued
**FIGURE 5.15**

Angle of incidence of solar radiation onto D.C. Hall Collector during steady state efficiency test. Position of collector, Milton Keynes, latitude 52°, longitude 0.75° (horizontal).

**FIGURE 5.16**

Angle correction for D.C. Hall Collector.
**Figure 5.17(a)** Air heating collector under test with a leak at the inlet

**Figure 5.17(b)** Air heating collector under test with a leak at the outlet
**Figure 5.18**
The effect of air leaks on the measured value of $P_{\text{in}}$, for $m = 0.5 \text{ kg/hr}$.

**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. Hall 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 ANormalizing Function. SOURCE: [25].
FIGURE 5.26  VARIATION OF MASS FLOW RATE CAUSED BY CHANGE IN WIND SPEED
FIGURE 5.27 RONK 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 $F(\beta, \phi)$ ON THE DIFFUSE FRACTION FOR A SINGLE-GLAZED FLAT-PLATE COLLECTOR. SOURCE: FORDSKI [34]
Figure 5.29  Computer generated steady state and transient efficiency curve for 0.5 mm absorber plate.
FIGURE 5.30 TRANSIENT DIFFUSE RADIATION

FIGURE 5.31 FLUID OUTLET TEMPERATURE UNDER TRANSIENT CONDITIONS.

FIGURE 5.32 INTEGRATED RESPONSE OF COLLECTOR OVER 1 AND 2 MINUTES TO TRANSIENT RADIATION.
Figure 5.33

The variation in $F_{eUL}$, $F_{e} \theta_{UL}$, and $\delta F_{eUL}$ 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 5.38** Standard error in $F_{UL}$ versus $N$ the number of previous time steps influencing the collector's present performance under transient conditions for the structured polycarbonate collector.

**Figure 5.39** Efficiency curve for outdoor transient testing of structured polycarbonate collector. Data generated from 'TRANS' for $N=7$, 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 (MANAS ABBAOD), 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 Maxoro.
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**Figure 5.44** Intensity distribution across collector during indoor testing in W/m². Average intensity 2.11 W/m². Standard deviation ± 0.4 W/m².

**Figure 5.45** Wing generator.
Figure 5.46 Variation of windspeed (ms⁻¹), 5mm above collector surface.

Measured heat loss with collector operating under stagnation and assuming (Re) = 0.72 plotted against average air velocity parallel to collector plane and measured 5mm above collector plane.

Figure 5.47 Measured and predicted heat loss U₂ 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 flat plate collector with non-selective absorber (Nextel). Indoor measurements and computer predictions.
FIGURE 5.50 REDESIGNED INDOOR COLLECTOR TEST FACILITY

FIGURE 5.51 STEADY STATE AND ZERO TESTING EFFICIENCY CURVES.
Figure 5.52 Steady State and Efficiency Curve Plotted Against Mean Absorber Plate Temperature ($T_p$) for Simulated Collector.
FIGURE 5.53  STEADY STATE AND ZERO TESTING EFFICIENCY CURVE PLOTTED AGAINST MEAN FLUID TEMPERATURE ($T_m$) FOR SIMULATED COLLECTOR.
**Figure 5.54** Collector temperature profile for model collector under steady-state and zero testing conditions for the same fluid inlet temperature (303 K).

**Figure 5.55** Collector temperature profile for model collector under steady-state and zero testing conditions for the same mean absorber plate temperature (366 K).
Figure 5.56  Temperature of Absorber and Rear Duct for the Same Average Fluid Temperature with the Collector Under Zero and Steady State Testing

Figure 5.57  $F_{w, U}$ versus Mean Fluid Temperature for Collector D1 Under Zero Testing and Ashape 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 Chall 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. BIZONGARY, 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.

Figure 6.5  Maximum improvement to flat plate collector performance by increasing $\alpha$ and $\delta$. 
**Figure 6.6** Reflectance of Solar Collector Coatings

**Figure 6.7** Steady State Efficiency of Solar Collector Measured During Operation and Indoor Testing. Source: Taylor, P. J., Performance of Selective and Non-Selecting Solar Thermal Absorbers in a Working Installation, Solar World Congress ed by S. N. Sardone, Vol. 2, pp 1149-1153.
Figure 6.8  
Efficiency Curves for Different Methods of Heat Loss Reduction

Figure 6.9  
**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. $I_{in} = 211 \text{ Wm}^{-2}$, $T_a = 28^\circ C$, $T_{amb} > T_a$, $T_e = T_a$ and air velocity $= 1.5 \text{ m s}^{-1}$.
**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 insulation month by month at 1000 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** Integrated global and diffuse solar radiation from March to October as a function of the global intensity. Source [35] for Sweden.
Figure 6.18 Simulated ambient conditions. For further details see text in Appendix C.

- **WIND = 1.0 m s⁻¹**
- **TK = TA - 20, clear skies**
- **TK = TA - 10, overcast skies**
Figure 6.19 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 3 and Figure 3).

(i) S0J/TAJ, flow 2  (ii) SOM/TAM, flow 2  (iii) S0D/TAD1, flow 2
(iv) SOM/TAM, flow 3  (v) S1M/TAM, flow 2  (vi) S0D/TAD1, flow 3
(vii) S1D1/TAD1, flow 2  (viii) S0D/TAD2, flow 3  (ix) S1D2/TAD1, flow 2
(x) S1D3/TAD1, flow 2  (xi) S1D/TAD1, flow 2.
FIGURE 6.20 'E M T C.' AIR HEATING SOLAR COLLECTOR DEVELOPED BY G.E. [42]

FIGURE 6.22 INSTANTANEOUS EFFICIENCIES OF THE FMTC COLLECTOR AND A SINGLE GLAZED FLAT PLATE COLLECTOR AND THEIR VARIATION WITH INSOLATION. [42]
**Figure 7.1** Thermal Conductivity of Various Gases at 20°C Versus Molecular Weight.

**Figure 7.2** Cellular Convection for a Liquid. For gases, due to their different temperature viscosity relationship, the gas falls in the centre of the cell.
FIGURE 7.3  OBSERVATION OF CELLULAR CONVECTION

FIGURE 7.4  BASE FLOW BETWEEN INCLINED PLATES

**FIGURE 7.6** SCHEMATIC DEPICTING EFFECT OF GAP SPACING ON CONDUCTION
Figure 7.2
Plot of $h_r$ versus plate separation $s$, $T_{wall} < 10^6$, $T_{air} = 325^\circ F$.

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

Heat transfer coefficient variation with absorber temperature for convection and radiation and for radiation between a selective absorber ($\varepsilon = 0.09$) and a low-iron glass cover ($\varepsilon = 0.88$).

$H_r$ heat transfer due to radiation between a non-selective absorber ($\varepsilon = 0.9$) and a glass cover ($\varepsilon = 0.9$).
Figure 7.10  True and predicted heat loss between two parallel plates 5 x 5 cm
Cover temperature 10 °C
FIGURE 7.11  EFFECTIVE RAYLEIGH NUMBER VERSUS MOLECULAR WEIGHT FOR DIFFERENT GASES, AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL PLATES, SEPARATION 520 OSM, COLD PLATE TEMPERATURE 10°C, HOT PLATE 30°C.
FIGURE 7.12  $h$, HEAT TRANSFER COEFFICIENT FOR GASES OF DIFFERENT MOLECULAR WEIGHT, FOR $S = 5$ cm, COLD PLATE TEMPERATURE $10^\circ$C, HOT PLATE TEMPERATURE $30^\circ$C.
FIGURE 7.13  COST VERSUS HEAT TRANSFER COEFFICIENT FOR DIFFERENT GASES. $s =$ 5 cm, VOLUME OF GAS REQUIRED FOR EACH SQUARE METRE OR COLLECTOR IS 50 LITRES.
FIGURE 7.14 VARIATION OF HEAT TRANSFER COEFFICIENT $h_c$ WITH PRESSURE
FOR A FLAT PLATE COLLECTOR, $z = 5 \text{cm}$, $T = 293 \text{K}$, $T_s = 323 \text{K}$ FOR CURVE 1, 273 \text{K} FOR CURVE 2 AND 473 \text{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: Mohnot, A. and Garg, H. P. "Minimizing convective heat loss." 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 SPACED 5 cm, $T_c = 293 K$, WITH A HONEYCOMB PATTERN 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

- Convection and conduction, air, atmospheric pressure, tilt angle $\theta = 0^\circ$
- Convection and conduction, air, atmospheric pressure, tilt angle $\theta = 60^\circ$
- Convection and conduction, argon, atmospheric pressure, tilt angle $\theta = 0^\circ$
- Convection and conduction, air, honeycomb, tilt angle (60°)
- Radiation, maxorb absorber ($E_r = 0.09$) & iron/iron glass cover ($E_r = 0.98$)
- Conduction only, air at $4 \times 10^3$ Pa
- Conduction only, argon at $3 \times 10^3$ Pa

$s = 5$ cm, $T_e = 10^\circ$C
**FIGURE 7.23**
GUARD RING HEATER

**FIGURE 7.24**
GUARD RING UNBALANCE VERSUS MEASURED HEAT TRANSFER ACROSS A 5 cm THICK 'STYROFOAM' EPS 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 cm, versus temperature difference.

- **ΔT (°C)**
- **Heat Transfer Coefficient h (W/m²°C)**

**Experimental Data Points**
- Air at atmospheric pressure
- Freon and air at atmospheric pressure
- Carbon tetrachloride and air at atmospheric pressure
- Air at 71 < p < 102, corr. ~ 0.94 Pa
- Air at p = 0.25 corr. ~ 50 Pa
**Figure 7.29** Theoretical and measured heat transfer $h_c$ for air and argon
FIGURE 7.30 THEORETICAL HEAT TRANSFER ACROSS STRUCTURED POLYCARBONATE OF VARIOUS THICKNESSES. BOTH RADIATION AND CONVECTION, ASSUMING FLAT CONVECTION AND A MEASURED EMISIVITY OF 0.72.
PLATE 2.1

PROTO PROMETHEUS: 1. COLLECTOR, 2. STORE TOP INSULATION AND COLLECTOR BEAR 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,
14. COOL RAY LAMPS.
PLATE 5.2  INDOOR COLLECTOR TEST FACILITY
7. DATA LOGGER, 8. STRUCTURED POLYCARBONATE COLLECTOR,
9. PRESSURE TAPS, 10. SITE OF ORIFICE PLATE
PLATE 7.1  

VIEW OF HEATED OIL FILM FROM AN INFRARED CAMERA. 

THE BRIGHTER THE SPOT THE HOTTER THE SPOT.
PLATE 7.2  GUARDED HOT PLATE THERMAL CONDUCTIVITY RIG
11. INSULATED GUARD RING AND TEST CELL, 12. GAS CYLINDER
13. WATER COOLER, 14. HEATER POWER SUPPLY
APPENDIX A

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM **************************** SUNSTORE ****************************
20 REM
30 SHORT DEMAND(12)
40 SHORT SOL(12,24)
50 ASSIGN 1 TO "SUN DATA"
60 READ# 1 SOL()
70 SHORT TEMP(12,24)
80 ASSIGN 2 TO "TEM DATA"
90 READ# 1 TEM()
100 DIM MONTHS(12)(3)
110 ASSIGN 3 TO "MONTH"
120 READ# 3 MONTH()
130 SHORT DAYS(12)
140 ASSIGN 4 TO "DAYS"
150 READ# 4 DAYS()
160 PRINT USING 200
170 TOTSUN=0 TOTSUN=total annual solar radiation
180 PRINT "****************************** DATA INPUT******************************
190 PRINT "******************************
200 IMAGE //****SOLAR RADIATION AT KER DISTRIBUTION OF HOURS GLOBAL IRRADIATION ****//
210 PRINT USING 220
220 IMAGE "********** ON A HORIZONTAL SURFACE IN MJ/m2 **************
230 FOR H=1 TO 12 ! print month heading
240 PRINT TAB (6&M):MONTHS(M):
250 NEXT M
260 FOR H=1 TO 24 ! print level of solar rad for each hour ! each month.
270 FOR M=1 TO 12
280 PRINT TAB (M6):SOL(M, H):
290 TOTSUN=TOTSUN+SOL(M, H) DAYS(M) ! calculate total annual solar radiation.
300 NEXT M
310 PRINT"
320 NEXT H
330 PRINT "TOTAL ANNUAL SOLAR RADIATION = "TOTSUN"MJ/m2"
340 REM **************************** DATA INPUT****************************
350 F=1.9 ! HEAT TRANSFER FACTOR
360 c=,837 ! SPECIFIC HEAT OF STORE MATERIAL (K/J/KG)
370 METE="PEBBLES" ! STORAGE MATERIAL
380 WIDTH=10 ! STORAGE WIDTH IN METERS
390 HEIGHT=4 ! STORAGE HEIGHT IN METERS
400 LENGTH=280 ! STORAGE LENGTH IN METERS
410 HOUSE=100 ! NUMBER OF HOUSES SURVED BY STORE
420 DENSITY=1600 ! DENSITY OF STORAGE MATERIAL (Kg/m3)
430 W=4 ! OVERALL COLLECTOR HEAT LOSS COEFFICIENT (W/m2)
440 COLAREA=2800 ! TOTAL AREA OF COLLECTORS SURVING STORE (m2)
450 COND=.036 ! THERMAL CONDUCTIVITY OF STORAGE INSULATING MATERIAL (W/m2C)
460 THICK=.6 ! THICKNESS OF INSULATING MATERIAL (Meters)
470 Ta=8 ! OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES
480 YEARS=1 ! NUMBER OF YEARS PROGRAM TO RUN DO NOT USE MORE THAN 1 IF qaux>0
490 T=10 ! TEMPERATURE OF GROUND SURROUNDING STORE (C)
500 ISO=30 ! MINIMUM STORAGE TEMPERATURE (C)
510 REM **************************** DATA INPUT****************************
520 REM **************************** STORE ************************************
530 VOL=W1*HEIGHT1*LENGTH1 ! calculate storage volume
540 m=VOL*VOLUME/1000 ! normalized mass (mass per m2 collect)
550 m=mass/(COLAREA/HOUSE)
560 AREA=HEIGHT2*HEIGHT1*LENGTH1 ! store surface area
570 a=AREA/COLAREA ! store surface area per m2 of collector
580 US=COND/THICK !
590 US=COND/THICK
600 qaux=0
610 PRINT USING 820
620 B&O //**************************************************************************
630 PRINT "STORE LENGTH","METERS","Meters";" WIDTH","METERS","Meters","HEII","HEIGHT","Meters";"VOLU","VOLUME";"VOL","m3"
640 PRINT "STORAGE MATERIAL","METE","DENSITY","Kg/m3";" SPECIFICATION ","C1","K3","Kg/C"
650 PRINT "STORE INSULATION THICKNESS","THICK","m","THERMAL CONDUCTIVITY","W/m2C"
660 B&O //**************************************************************************
670 PRINT USING 880
680 B&O //**************************************************************************
690 PRINT "TOTAL COLLECTOR AREA","COLAREA","m2"
700 PRINT "Fi=HEAT TRANSFER FACTOR:equivalent to r Fr heat removal factor if s=1","Fi=1","Fi=1"
710 PRINT "UL=OVERRALL HEAT LOSS COEFFICIENT","UL"
720 Ta=OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES","Ta"
730 PRINT "MONTHLY HEATING LOAD FOR EACH HOUSE IS (heating and hot water)"
740 FOR K=1 TO 12
750 REM **************************** DATA INPUT****************************
760 READ DEMAND(K) ! READS MONTHLY DATA OF HEATING LOAD FOR EACH HOUSE(MJ)
### Solar Radiation at New Distribution of Hourly-Global Irradiation

- **On a horizontal surface in MJ/m²**

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**Total Annual Solar Radiation**: 3410.94 MJ/m²

### System Operation

- **Tso = Original Store Temperature at the beginning of month**
- **Tt = Ambient Temperature Averaged over periods of collector operation (C)**
- **It = Time Period of Collector Operation (MJ)**
- **Itn = Total Irradiance which is above Threshold (MJ/m²)**
- **Qn = Normalized Net Heat to Storage = qT - Iₚₕ - Iₚₕ (MJ/m²)**
- **tsf = Store Temperature at the end of the month (C)**
- **q = Useful Heat Collected = qN + Iₚₕ (MJ/m²)**
- **Is = Normalized Total Monthly Load (MJ/m²)**
- **qAUX = Auxiliary Heat - Is + (MJ/m²)**

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<td>198.57</td>
<td>9.1</td>
<td>57.0</td>
</tr>
</tbody>
</table>

**Total**: 1026.80 1488.93 390.2 -462.

- **% of energy supplied by solar system**: 69.0%
- **% of solar energy collected above threshold**: 42.0%
- **% of solar energy collected**: 41.5%

**Total Auxiliary Energy for System**: 129360.7849 MJ (359433.551803 KWh)

**Auxiliary Energy per House**: 129399.6078649 MJ (359433.3551803 KWh)

### Collector

- **Total Collector Area**: 2800 m²
- **Fₐ = Heat Transfer Factor (equivalent to Fr heat removal factor if store has a good heat exchanger)**: 0.9
- **UL = Overall Heat Loss Coefficient**: 1
- **Ta = Optical Efficiency Averaged Over Useful Incident Angles**: 0.8

### House

**Number of Houses**: 100

**The Monthly Heating Load for Each House Is** (heating and hot water) MJ

<table>
<thead>
<tr>
<th>Jan</th>
<th>7750</th>
<th>Feb</th>
<th>6490</th>
<th>Mar</th>
<th>5560</th>
<th>Apr</th>
<th>3320</th>
<th>May</th>
<th>980</th>
<th>Jun</th>
<th>770</th>
<th>Jul</th>
<th>770</th>
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</thead>
<tbody>
<tr>
<td>Aug</td>
<td>770</td>
<td>Sep</td>
<td>770</td>
<td>Oct</td>
<td>1790</td>
<td>Nov</td>
<td>5270</td>
<td>Dec</td>
<td>7450</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Energy Demand of House per Annum**: 41.69 GJ (11580.5555556 KWh)
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.
... PROGRAM TOPAIR ...

20 REM .......................... CALCULATE THE TOP LOSS COEFFICIENT FOR A SINGLE GLASS }
LECTOR SEE DUFFIE & BECKMAN P204
30 REM
40 I = 0 TO 20
50 FOR I=0 TO 20
60 Td=10+185 ! ABSORBER TEMP
70 T=10 ! Ambient temp (C)
80 WIND=1 ! Wind speed (ms-1)
90 EP=1.95 ! Absorber emissivity
100 EPD=1.95 ! Cover plate emissivity
110 S=1 ! Plate separation (cm)
120 G=9.812 ! Acceleration due to gravity (ms2) at LONDON
130 K=0.0257 ! Thermal conductivity of gas at Tave (W/mC)
140 B=0 ! tilt angle (Horizontal)
150 CP=1007 ! Heat capacity of air (J/KgK)
155 CP=1007 ! Heat capacity of GAS BETWEEN COVER AND ABSORBER (K)
160 S/S=100 ! CONVERT TO METERS
170 L=1
180 k=1
190 Sw=2/LW/(L+W)
200 REM .......................... VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFECT
GAS
210 T=TA+((TP-1)/2) ! guess the cover temp
220 T=273.15+T ! CONVERT TO KELVIN
230 T=273.15+T ! CONVERT TO KELVIN
240 T=273.15+T ! CONVERT TO KELVIN
250 T=273.15+T ! CONVERT TO KELVIN
260 T=273.15+T ! CONVERT TO KELVIN
270 DT2=T2-T1 ! TEMP DIFFERENCE DELTA T
280 Tave=(T1+DT2)/2 ! AVERAGE GAS TEMPERATURE
290 DEN=352.91/Tave
300 k=Tave.000007+.0034406
310 VIS=Tave.0000046+.000004351
320 VOL=1/Tave ! THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFECT
GAS
330 VIS/DEN ! KINEMATIC VISCOSITY
340 Gr=8.064X10^3DT/W^2 ! GRASHOF NUMBER
350 Pr=CP/8.064 ! RAYLEIGH No
360 REM .......................... CALCULATE NUSSELT NUMBER
370 REM .......................... TAKE ONLY POSITIVE TERMS
380 N2=1/(RatCOS(B)+5830)1.5
390 IF N10 THEN N10=1 TAKE ONLY POSITIVE TERMS
400 N=1/(RatCOS(B)+5830)1.5
410 IF N2=0 THEN N2=0 TAKE ONLY POSITIVE TERMS
420 N=1/(RatCOS(B)+5830)1.5
430 h=0.000010567*(TP*2+TP/C)*(TP/C)1.5/(EP+1/EP-C1) ! RAD FROM PLATE TO COVER
440 h=0.000010567*(TP*2+TP/C)*(TP/C)1.5/(EP+1/EP-C1) ! RAD FROM PLATE TO COVER
450 h=0.000010567*(TP*2+TP/C)*(TP/C)1.5/(EP+1/EP-C1) ! RAD FROM PLATE TO COVER
460 T=273.15+T ! CONVERT TO KELVIN
470 T=273.15+T ! CONVERT TO KELVIN
480 T=T+50.1 ! CONVERT TO KELVIN
490 DEN=352.91/Tave
500 k=Tave.000007+.0034406
510 VIS=Tave.0000046+.000004351

...
10 REM **************************************** EFFICIENCY ****************************************
20 REM -- This program calculates the steady state efficiency of a top duct.
30 REM AIR HEATING SOLAR COLLECTOR USING EQUATIONS FROM DUFFIE AND BECKMAN
40 REM p.237 Figure 6.12.1 (d)
50 REM
60 REM
70 FOR J=0 TO 10
80 M=14.1(0
90 T=16.2
100 T1=60.4
110 T2=60.4
120 WIND=5
130 I=236
140 E=8
150 E=8
160 E=95
170 N=34
180 I=75
190 A1=1
200 L2=2
210 W1=1
220 S1=1
230 D1=1
240 D30 "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ?????
245 IF Y THEN GOTO 520
250 PRINT A1
260 IF A1="N" THEN GOTO 470
270 PRINTERS IS 701
280 PRINT "---------------------------------- COLLECTOR INITIAL PARAMETERS ARE ------------------------------
290 PRINT USING 930 "MASS FLOW RATE, M"; "Kg/hr"
300 PRINT USING 930 "AMBIENT TEMP., T"; "C"
310 PRINT USING 930 "INLET FLUID TEMP., T"; "C"
320 PRINT USING 930 "ABSORBER TEMP., Ta"; "C"
330 PRINT USING 930 "WIND SPEED, W"; "m/s"
340 PRINT USING 930 "SOLAR RADIATION, I"; "W/m2"
350 PRINT USING 930 "TRANSMISSIVITY & ABSORPTIVITY, Ta"; "W/m°C"
360 PRINT USING 930 "EMISSION OF COVER, E1"; "W/m°C"
370 PRINT USING 930 "EMISSION OF ABSORBER, E2"; "W/m°C"
380 PRINT USING 930 "INSULATION CONDUCTIVITY, K1"; "W/m°C"
390 PRINT USING 930 "INSULATION THICKNESS, T1"; "m"
400 PRINT USING 930 "COLLECTOR AREA, A1"; "m2"
410 PRINT USING 930 "COLLECTOR LENGTH, L"; "m"
420 PRINT USING 930 "COLLECTOR WIDTH, W"; "m"
430 PRINT USING 930 "PLATE SEPARATION, S"; "cm"
440 PRINT USING 930 "FIN SEPARATION", D; "cm"
450 PRINT "----------------------------------
460 PRINT "----------------------------------
470 REM ---------------------------------- INPUT CONSTANT DATA ----------------------------------
480 STE=0.00000000567 STEFAN-BOLTZMANN CONSTANT (W/m²K⁴)
490 VIS=0.0000188 VISCOSITY OF AIR IN DUCT (N·s/m²)
500 K=0.0241 THERMAL CONDUCTIVITY OF AIR IN DUCT (W/mK)
510 C=1000 HEAT CAPACITY OF AIR AT CONSTANT PRESSURE (J/g°C)
520 REM ----------------------------------
530 T1=11.273.15 "ELVII
APPENDIX C

Paper presented at the International Conference
on Solar Energy at High Latitudes, Napier College,
Edinburgh, Scotland, 4-6 September, 1984, describing
transient model of collector.
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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>DY1-5</td>
<td>plate and duct-back thicknesses (5)</td>
</tr>
<tr>
<td>f(θ)</td>
<td>transmittance - absorbance function of the collector</td>
</tr>
<tr>
<td>FR</td>
<td>collector heat-removal factor</td>
</tr>
<tr>
<td>HPA(I)</td>
<td>heat-transfer coefficient plate (or duct-back) to air in the I'th segment of the duct</td>
</tr>
<tr>
<td>M</td>
<td>duct air flow rate</td>
</tr>
<tr>
<td>NI</td>
<td>number of duct segments</td>
</tr>
<tr>
<td>PON</td>
<td>threshold power for switch on of air flow</td>
</tr>
<tr>
<td>S</td>
<td>irradiance in cover plane</td>
</tr>
<tr>
<td>S0</td>
<td>solar beam irradiance</td>
</tr>
<tr>
<td>S1</td>
<td>diffuse irradiance on a horizontal surface</td>
</tr>
<tr>
<td>SP</td>
<td>irradiance absorbed by plate</td>
</tr>
<tr>
<td>TA</td>
<td>ambient temperature</td>
</tr>
</tbody>
</table>
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 | polycarbonate, thickness 2.00 mm |
| plate absorbtance             | 0.95 at θ=0, falling slightly as θ increases |
| emissivity of upper surface of the plate (diffuse) | 0.10 |
| emissivity of duct surfaces (diffuse) | 0.91 |
| emissivity of the cover (diffuse) | 0.85 |
| thermal properties of air at 283 K for ambient air, at 303 K elsewhere | |
| latitude                      | 52°N |
| collector tilt (to horizontal) | 35° |
| collector orientation         | south-facing |
| thickness of plate and of duct-back | collector time-constant (flow 1) |
| DY1 0.2 mm                    | 85 s |
| DY2 0.5 mm                    | 170 s |
| DY3 1.0 mm                    | 300 s |
| DY4 2.0 mm                    | 580 s |
| DY5 5.0 mm                    | 1400 s |

Air flow in the rear-duct

| 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 $T_i$ the value of $M$ will be different from $0.0600 \text{ kg s}^{-1}$ at $T_i = 323 \text{ K}$, $M = 0.0562 \text{ kg s}^{-1}$ (flow 3 in Table 1).

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

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

3.2 Steady-state efficiency curve

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

$$\eta = \frac{F_R (f(\theta) - U_L (T_i - T_A)/S)}{f(\theta) \cdot S} \tag{1}$$

where $f(\theta)$ is such that

$$SP = f(\theta) \cdot S \tag{2}$$

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

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

These values of $f(\theta)$, $F_R$ and $U_L$ indicate good performance for a flat-plate rear-duct air-heating single-cover collector with a selective plate-surface.

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

3.3 Daily-averaged efficiency

The collector configurations DY1 to DY5 were run under conditions flow 2 and flow 3 for a variety of simulated days 21 June (J), 21 March (M), 21 December (D). The simulated conditions of insolation and weather on these days are shown in Figure 3. The ambient temperature TA varies sinusoidally through the day (Figure 3(a)) with an amplitude of 5 K. Note that there are two temperature curves for 21 December, TAD1 and TAD2. The irradiance S consists of a diffuse component from the ground, and of a sky component which can either correspond to clear sky conditions or to overcast diffuse conditions. Figure 3(b) shows some of the various insolations, 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

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

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 \( \bar{n} \) is never being wrongly evaluated.

In order to plot \( \bar{n} \) on Figure 2 it is necessary to re-define the abscissa \((T_I-T_A)/S\). \( T_I \) 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 \((T_I-T_A)/S\) 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), (vii), (xi). The increase in \( \bar{n} \) 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 \((T_I-T_A)/S\)). 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 \( \bar{n} \) 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 $\eta$. This is particularly the case at low thermal capacitances, as can be seen from the performance of DY1, which is not very different from that which would have been obtained for a collector of zero thermal capacitance. Two prominent and opposing effects operating here are that for $\eta$ in Figure 2 the value of $\theta$ is always zero, thus raising $f(\theta)$, and, more importantly, that in insolation conditions which vary, intermittently or otherwise, a collector can "grab" peak insolation, yet entirely miss the corresponding steady state insolation which never reaches such peak values. Low thermal capacitance is again an advantage.

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

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

It can be concluded that collectors with low thermal capacitance can have significantly larger thermal efficiencies at non-small daily averaged values of $(T_I-T_A)/S$ 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.

REFERENCES


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


Figure 1 Flat-plate, rear duct, air heating solar collector.
Figure 2  Steady-state efficiency ($\eta_-$ 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) SUD/TAJ, flow 2  (ii) SOD/TAM, flow 2  (iii) SOD/TAD1, flow 2
(iv) SOD/TAM, flow 3  (v) SOD/TAM, flow 2  (vi) SOD/TAD1, flow 3
(vii) SLD1/TAD1, flow 2  (viii) SUD/TAD2, flow 3  (ix) SLD2/TAD1, flow 2
(x) SLD3/TAD1, flow 2  (xi) SLD/TAD1, flow 2.
Figure 3  Simulated ambient conditions. For further details see text.

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

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

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

TRANS: Computer program for analysing collector data under transient conditions.
**REM** 
**CALCULATE THE COLLECTOR EFF FROM TRAUGHTIT DATA**

**DIM**

1. **FOR** N=1 TO 8
2. **NEXT** K
3. **FOR** I=1 TO 10
4. **NEXT** S
5. **FOR** I=1 TO 10
6. **NEXT** T
7. **FOR** M=1 TO NC
8. **NEXT** K
9. **FOR** K=1 TO NC
10. **FOR** L=1 TO NC
11. **FOR** K=1 TO NC
12. **FOR** K=1 TO NC
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940 NEXT \( K \)
950 NEXT \( K \)
960 \( Z=E+SQR \left( ZE \times Y \times \left( 1-NF-NC \right) \right) \)
970 PRINT "ETA='E,'Z'/\( E \)
980 \( U=\frac{X(1)}{NC} \)
990 PRINT "F='UU++/-'/\( Z(1) \)
1000 PRINT "TABLE F.4"
1010 FOR \( K=1 \) TO \( N \)
1020 \( C(K) \times X(K)/\( E \)
1030 PRINT \( K \)
1035 NEXT \( K \)
1040 \( F=\left( U/(1-HLOG(1-U/H)) \right) \)
1050 PRINT "F='F'E\)
1060 \( E=F \)
1070 \( U=U \)
1080 PRINT "ETA='E,'U'\)
1090 PRINT "DATA SETS ACCEPTED FOR ANALYSIS'\)
1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN 1 TO "TRANSD700"
1120 \( NP=0 \)
1130 READ \#1 \( : I, X(N), Y(T) \)
1135 IF \( I=0 \) AND \( X(N)=0 \) THEN GOTO 1570
1140 \( I=1+1 \)
1150 FOR \( K=2 \) TO \( N \)
1160 \( L=\left( N-K \right) \)
1170 READ \#1 \( : I, X(L), Y(T) \)
1175 IF \( I=0 \) AND \( X(L)=0 \) THEN GOTO 1570
1180 IF \( I=11 \) THEN GOTO 1130
1190 \( I=1+1 \)
1200 NEXT \( K \)
1210 GOTO 1460
1220 FOR \( K=2 \) TO \( N \)
1230 \( L=\left( N-K \right) \)
1240 \( X(L)=X(L-1) \)
1250 \( T(L)=T(L-1) \)
1260 NEXT \( K \)
1270 READ \#1 \( : I, X(I), Y(T(I)) \)
1275 IF \( I=0 \) AND \( X(I)=0 \) THEN GOTO 1570
1280 IF \( I=11 \) THEN GOTO 1150
1290 \( I=1+1 \)
1300 \( E=0 \)
1410 \( X(NC)=0 \)
1420 FOR \( K=1 \) TO \( N \)
1430 \( E=E+X(K) \times C(K) \)
1440 \( X(NC)=X(NC)+T(K) \)
1450 NEXT \( K \)
1460 \( Y=Y/(\text{FRE}) \)
1470 \( X(NC)=X(NC)/\left( \text{FRE} \times \text{FRE} \right) \)
1480 PRINT \( X, Y(NC) \)
1490 REM CALC LEAST SQRT TO THERMAL PERFORMANCE
1500 \( S=S X+X(NC) \)
1510 \( S Y=S Y+Y \)
1520 \( S Y=S Y+X(NC) \times X(NC) \)
1530 \( S Y=S Y+Y \times Y \)
1540 \( X=S Y+S Y+X(NC) \times X(NC) \)
1550 \( N F=E \)
1560 GOTO 1240
1570 \( D N F=E \)
1580 PRINT "POINTS ON THERMAL PERFORMANCE CHARACTERISTIC'\)
1590 PRINT "FROM LEAST SQUARES FITS EACH WAY'\)
1600 \( E=(S Y+S X-S X+S Y)/(\text{DFN} \times S X-S X+S Y) \)
1610 \( U=(S X-D N F-S Y)/(\text{DFN} \times S X-S X+S Y) \)
1620 PRINT "MINIMUM ETA='E,'U'\)
1630 \( E=(S Y+S X-S X+S Y)/(\text{DFN} \times S X-S X+S Y) \)
1640 \( U=(S X-D N F-S Y)/(\text{DFN} \times S X-S X+S Y) \)
1650 PRINT "MAXIMUM ETA='E,'U'\)
1655 NEXT \( N \)
1660 STOP
1670 END