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

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Volume 2

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Nomenclature

Chapter 2

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

\( A_s \) Storage tank surface area \(m^2\)

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

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

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

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

\( f \) Differential fuel inflation

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

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

\( F' \) Collector efficiency factor

\( i \) Discount rate

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

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

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

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

\( M_C \) 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 \((°C)\)

\( T_s \) 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 ($W , m^{-2} \cdot °C^{-1}$)</td>
</tr>
<tr>
<td>$U_S$</td>
<td>Storage tank heat loss coefficient ($W , m^{-2} \cdot °C^{-1}$)</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume (m$^3$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kgm$^{-3}$)</td>
</tr>
<tr>
<td>$(\bar{\tau}a)$</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 (J/kg°C)

Dh Characteristic length (m)

F' Absorber plate (or collector) efficiency factor

FR Collector heat removal factor

g Acceleration of gravity (ms⁻²)

h₁ Convective heat transfer coefficient, duct top to heat transfer fluid (W/m²°C)

h₂ Convective heat transfer coefficient, duct base to heat transfer fluid (W/m²°C)

hr Radiative heat transfer coefficient (W/m²°C)

hw Wind heat transfer coefficient (W/m²°C)

H Duct height (m)

I Equivalent normal solar irradiance (W/m²)

k Thermal conductivity (W/m°C)

L Collector length (m)

m Mass flow rate of transfer fluid (kg/s)

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)

TC Cover temperature (°C)

Te Exit fluid temperature (°C)

Ti Inlet fluid temperature (°C)

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

Tp Average absorber temperature (°C)

Ub Bottom loss heat transfer coefficient (W/m²°C)

Ue Edge loss heat transfer coefficient (W/m²°C)

UL Collector overall heat transfer (loss) coefficient (W/m²°C)
$U_t$ Top loss heat transfer coefficient ($\text{Wm}^{-2} \cdot \text{C}^{-1}$)
$V$ Wind velocity ($\text{ms}^{-1}$)
$W$ Collector width (m)
$x$ Insulation thickness (m)
$\alpha$ Absorptance of the collector absorber surface for solar radiation
$\beta$ Volume thermal expansion coefficient ($\text{K}^{-1}$)
$\epsilon_c$ Cover emissivity
$\epsilon_p$ Absorber plate emissivity
$\eta$ Efficiency
$\mu$ Absolute (dynamic) coefficient of viscosity ($\text{Kg m}^{-1} \text{s}^{-1}$)
$\rho$ Density ($\text{Kgm}^{-3}$)
$\tau$ Transmittance of the solar collector
$(\tau \alpha)$ The product of the absorptance of the collector plate and the transmittance of the cover for normal irradiance
$\sigma$ Stefan-Boltzmann constant
Nomenclature

**Chapter 5**

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

A<sub>c</sub>  Collector area (m²)

C<sub>p</sub>  Volume heat capacity at constant pressure (J/Kg°C⁻¹)

F'  Absorber plate (or collector) efficiency factor

F"  Collector flow factor

F<sub>1</sub>  Correction factor for partial shading of the collector

F<sub>2</sub>  Correction factor for variation of τ<sub>a</sub> with the angle of incidence

F<sub>3</sub>  Correction factor for variation in optical properties from normal for diffuse irradiance

F<sub>R</sub>  Collector heat removal factor

h<sub>w</sub>  Wind heat transfer coefficient (W/m²°C⁻¹)

I  Equivalent normal solar irradiance (W/m²)

I<sub>b</sub>  Direct solar irradiance in plane of collector (W/m²)

I<sub>d</sub>  Diffuse solar irradiance in plane of collector (W/m²)

I<sub>m</sub>  Measured total solar irradiation incident upon the aperture plane of the collector (W/m²)

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

m<sub>l</sub>  Mass flow rate of leak (Kg/s⁻¹)

M  Fluid capacity of collector (Kg)

(me)_e  Effective heat capacity of collector (J°C⁻¹)

q  Output power per unit aperture area conveyed by the heat transfer fluid (W/m²)

Q<sub>u</sub>  Energy per unit time, useful (W)

(Q<sub>u</sub>)<sub>t</sub>  Energy per unit time under transient conditions (W)

r  Correlation coefficient

T  Time (s)

T<sub>a</sub>  Ambient air temperature (°C)

T<sub>b</sub>  Average back plate temperature (°C)

T<sub>e</sub>  Exit fluid temperature (°C)

T<sub>f</sub>  Average temperature of the fluid in the collector (°C)

T<sub>i</sub>  Inlet fluid temperature (°C)
$T_{im}$  Measured fluid inlet temperature (°C)
$T_m$  Mean fluid temperature ($T_e + T_i)/2$ (°C)
$T_p$  Absorber plate temperature (°C)
$T_{p}$  Mean absorber temperature (°C)
$T_{sky}$  Equivalent black body sky temperature (°C)
$T^*$  Reduced temperature ($T_i - T_a)/I$ (m² °C w⁻¹)
$U_L$  Collector overall heat transfer (loss) coefficient (Wm⁻² °C⁻¹)
$V$  Wind velocity (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 (s)
$\tau_d$  Cut off time (s)
$(\tau_\alpha)_e$  Effective transmittance absorptance product
$(\tau_\alpha)_n$  Product of the absorptance and transmittance for normal irradiance
$\Delta T^*$  Time increment
$\theta$  Angle of incidence; degrees from normal
### Nomenclature

**Chapter 6**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_R$</td>
<td>Collector heat removal factor</td>
</tr>
<tr>
<td>$h_{p-c}$</td>
<td>Convective coefficient between absorber plate and cover ($\text{Wm}^{-2}\text{°C}^{-1}$)</td>
</tr>
<tr>
<td>$h_{r-c-a}$</td>
<td>Radiation coefficient between absorber plate and cover ($\text{Wm}^{-2}\text{°C}^{-1}$)</td>
</tr>
<tr>
<td>$h_{rc-a}$</td>
<td>Radiation coefficient from the cover to sky ($\text{Wm}^{-2}\text{°C}^{-1}$)</td>
</tr>
<tr>
<td>$h_w$</td>
<td>Wind heat transfer coefficient ($\text{Wm}^{-2}\text{°C}^{-1}$)</td>
</tr>
<tr>
<td>$I$</td>
<td>Equivalent normal solar irradiance ($\text{Wm}^{-2}$)</td>
</tr>
<tr>
<td>$I_{th}$</td>
<td>Threshold solar irradiance ($\text{Wm}^{-2}$)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Ambient air temperature (°C)</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Inlet fluid temperature (°C)</td>
</tr>
<tr>
<td>$U$</td>
<td>Collector heat loss coefficient $F'U_L$ ($\text{Wm}^{-2}\text{°C}^{-1}$)</td>
</tr>
<tr>
<td>$U_L$</td>
<td>Collector overall heat transfer (loss) coefficient ($\text{Wm}^{-2}\text{°C}^{-1}$)</td>
</tr>
<tr>
<td>$\varepsilon_t$</td>
<td>Thermal emissivity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency steady state</td>
</tr>
<tr>
<td>$\bar{\eta}$</td>
<td>Daily averaged efficiency</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>Zero loss collector efficiency, $F'(\alpha)$</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Solar transmissivity</td>
</tr>
<tr>
<td>$(\tau\alpha)$</td>
<td>Product of the absorptance and transmittance for normal irradiance</td>
</tr>
</tbody>
</table>
Nomenclature

Chapter 7

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

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

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

\( R \)  
Gas constant

\( Ra \)  
Rayleigh number

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

\( Re \)  
Reynolds number

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

\( t \)  
Panel wall thickness (m)

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

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

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

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

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

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

\( \alpha \)  
Thermal diffusivity (m\(^2\) 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)

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

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

\( \mu \)  
Viscosity (Pa s)

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

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

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

\( \lambda \)  
Mean free path (m)
REFERENCES

CHAPTER 1

[1] Elkington, J.

[2] Flood, M.


'No Deposit - No Return'. Addison-Wesley, Reading, Mass., USA, 1970.

[5] Brandt, W.
'North-South: a programme for survival'. The report of the independent commission on international development issues under the chairmanship of Willy Brandt, Pan 1980.
[6] Chapman, P.
'Fuels Paradise: Energy Options for Britain'.


[8] Leach, G.
'A low energy strategy for the United Kingdom'.

CHAPTER 2

[1] Leach, G.  
'A low energy strategy for the United Kingdom'.  

'Energy Technologies for the United Kingdom'.  
Published by Her Majesty's Stationary Office, U.K., 1979.

[3] Raisman, J.M.  
'The future for fossil fuels. A global perspective'.  


'Energy inputs and outputs for nuclear power stations'. Research Report ERG 005, Open University, Milton Keynes, 1974.


[9] Lewis, C.W.  

[10] Friedrich, F.J.  

[12] Barrett, M. and Everett, R.
'Cost effectiveness of grouped solar heating schemes'. A joint project between the Built Environment Research Group, Polytechnic of Central London and Energy Consultative Unit, Milton Keynes Development Corporation, September 1977.

'Design and cost effectiveness of active solar space and water heating systems'. A report to ETSV, the Department of Energy contract No. ETSV - 5 - 1087, May 1982.

[14] Torrenti, R.


[17] Ashahina, T. and Kosaka, M.
'A thermal storage analysis on packed bed of alumina spheres'. Govt. Industrial Res., Nagoya 46, Japan.

[18] O'Callaghan, P.W.


[21] Flood, M.

[22] Taylor, G.
[23] Sweet, C.J.

[24] Todd, R.

[25] Ulla Save-Ofverholm

[26] Perers, B. and Roseen, R.

[27] Roseen, R. and Perers, B.
[28] Taylor, G.

[29] Gleason, J.


[31] Radons, U.

[32] Lazzari, F. and Raffellini, G.
[33] Keller, L. and Bremer, P.

[34] Makien, R and Lund, P.D.

[35] den Ouden, C.

[36] Vachaud, G. and Ausseur, J.
[37] Platell, O.B.

[38] Turrent, D. et.al.

[39] Krass, A.S. and La Viale, R.

[40] Simonson, J.R. and Coleman, J.D.

[41] Ward, I.C.
'A preliminary feasibility study into the use of solar energy to provide year-round heating for a factory unit'. 2nd International Solar Forum, pp483-508, Germany, 1978.

[43] Jones, B.W.
'A solar power system (Prometheus) to provide 100 per cent of low-grade heat needs'. Applied Energy, 6, pp329-346, 1980.

[44] Derrick, A. and Gillet, W.B.
'Recommendations for European solar collector test methods' for the Commission of the European Communities, 1980.


[46] van Galen, E.
[47] Duffie, J.A. and Beckman, W.A.


[49] Golshekan, M.

[50] Lunde, P.J.


[54] Sorenson, B.  

[55] Jones, B.W. and Oreszczyn, T.  

[56] Office of Technology Assessment (OTA), US Congress.  

[57] Mortimer, N.D., Jenkins, G., and Harrison, R.  
[58] Symons, J.G. and Giani, R.

[59] Casper, D.A., Chapman, P.P. and Mortimer, N.D.

[60] Harrison, R., Jenkins, G. and Mortimer, N.D.

[61] Gartner, E.M. and Smith, M.A.

[62] Rogers, D.W.O.

[63] Littler, J. and Martin, C.
Quigley, B., Murtagh, P. and Cash, J.

Rassafi, M. et.al.

Charlish, G.

Margen, P.

Chapman, P.

Maw, R.
Polytechnic of Central London, Personal communication.
Andrews, D.C.F. and Lowe, R.J.

CHAPTER 3


[2] Everett, R.

[3] Chatfield, J.D.


[6] Leach, G.
CHAPTER 4

[1] Daniels, F. and Duffie, J.A.


'Solar Energy Today'. Published by UK-ISES, 19

[7] Ford, B.
'Passive Solar Heating for Existing Houses'. A
report to the London Energy Centre, London, January
1984.

'Delahaye house: First passive-active (air system)
solar house in Belgium'. Solar World Forum, Proc
ISES congress, Brighton, England, 23-28 august, 1981,

'Air collectors or heat recovery or both'. Solar
World Congress, Proc ISES congress, Perth, 14-19
1984.

[10] Szokolay, S.V.
'Solar Energy in Building'. Architectural Press,

[12] Newham, M.
'Dramatic breakthrough claimed in US solar research'. Technology Week, No. 4, 27 February 1982.


[16] Potter, I.N.
[17] Oppenheim, D.


[18] Duffie, J.A. and Beckmann, W.A.


[20] Nussett, W. and Jurges, W.


'Effect of finite width on heat transfer and fluid flow about an inclined rectangular plate'. Transaction of the American Society of Mechanical

[23] Lloyd, J.R. and Moran, W.P.


[26] Sparrow, E.M. and Tien, K.K.
[27] Oliphant, M.V.

[28] Kind, R.J., Gladstone, D.H. and Moizer, A.D.

[29] Parker, B.F.

[31] Tan, H.M. and Charters, W.W.S.


[33] De Ron, A.J.

[34] Mather Jr., G.R.

'New air heating collector design and performance'.

[37] Jenkins, J.P. and Hill, J.E.

[38] Garg, H.P., Rom Chandri and Usha Rani

'Transient studies of solar air heaters'.
Interregional symposium on solar energy for development, Tokyo, Japan, 5-10 February 1979.

[40] Jones, B.W. and Oreszcyzn, T.
'The effect of thermal capacitance on the performance of solar collectors'. International Conference 'Solar Energy at High Latitudes', Napier College, Edinburgh, Scotland, 4-6 September 1984
REFERENCES CHAPTER 5


[10] Mason, J.J. and Jones, P.C.


[12] Rohsenow, W.M. and Hartnett, J.P.


[16] Erb, R.A.

[17] Erb, R.A.


[22] Aranovitch, E. and Roumengous, C.

[23] Cheema, L.S. and Mannan, K.D.


[26] McAdams, W.C.
[27] Parker, B.F., Colliver, D.G. and Walton, L.R.

[28] Talarek, H.D.


[31] Klein, S., Duffie, J.A. and Beckman, W.A.
[32] Taylor, B.E.,
'The determination of the steady state performance of solar collectors under transient irradiation,
*Communication to the British Standards Institution* 1977

[33] Rogers, B.A.
'Transient testing of collectors'

[34] Posorski, R., Mabreyer, K., Schroer, R. and Stein, H.J.

[35] Rogers, B.A. Solar Energy Unit, *Cardiff University*,
Personal communication, 17th October 1983.

[36] Emery, M, and Rogers, B.A.,
[37] Camm, D.M., Richards, S.L.F. and Albach, G.G.,
'A large area solar simulator construction and
performance' *Solar World Forum*, Proceedings of the

[38] Krusi, P. and Schmid, R.,
'The CSI 1000W lamp as a source for solar radiation
simulation', *Solar Energy*, Vol. 30, No.5, pp 455-462,

[39] Gillett, W.B., Rawcliffe, R.W. and Green, A.A.,
'Solar collector testing using solar simulators'.
Proceedings of conference on *solar energy codes of
practice and test procedures*, U.K. ISES, pp 57-71,
April 1980.

[40] Green, A.A., Kenna, J.P. and Rawcliffe, R.W.
'The influence of wind speed on flat plate solar
collector performance'. IEE Conference Proceedings

[41] Oliphant, M.V.
'Measurement of wind speed distributions across a
solar collector' *Solar Energy*, Vol. 24, pp403-405,
1979.
Green, A.A.

Kraus, K., Hahne, E., and Sohns, J.,

Symons, J.G.

Christie, E.A.,

Smith, C.C., and Weiss, T.A.,

[48] Jenkins, J.P. and Hill, J.E.
'A comparison of test results for flat-plate water-heating solar, collectors using BSE and ASHRAE procedures',

[49] Shewen, E.C., and Hollands, K.G.T.,

[50] Cooper, P.I., Christie, E.A., and Dunkle, R.V.,

[51] Centeno, V.M.
[52] Taylor, P.J.,
REFERENCES CHAPTER 6

High Performance Collectors

[1] Marshall, R.H.,
'A comparison of thermal storage devices for combined space heating and domestic water system', p269, Solar World Congress, 1983, Perth.


[6] Jorgensen, C.,

[7] 3M Decorative Products,
Nextel Information Sheet,
3M House, P.O. Box 1, Bracknell, Berkshire.

[8] Jordan R.C.,


'Maxorb' Section 9:11, Solar Age Magazine, June 1980.

[11] Butler B.L. and Classen, R.S.
[12] Lofving, S.

[13] Taylor, P.J.,


'High Selective absorbers utilizing electro-deposited black chrome'. AES Symposium.

'Deposition of transparent heat reflecting coatings of metal oxides using reactive planar magnetron sputtering of a Metal/Alloy', presented at Coatings on Glass, Geneva, 1980.

[17] Owens, P.
'Deposition of transparent heat reflecting coatings of metal oxides using reactive planar magnetron sputtering of a Metal/Alloy', Dept. of Physics, University of Technology, Loughborough, Leicester.

'Development of plastic honeycomb flat-plate solar collectors'. Lockheed Report, SAN/1081-76/1, 1976.


[21] Stahl, W., Wittwer,V. and Goetzberger, A.

[22] Wu Jia-qing et al

[23] Dr.Helmut Freyholdt, Personal communication, AMI-SA, 120, Avenue D'Echallens, CH-1004, Lausonne, Switzerland. 1982.
507, West Elm St., Tyler, Tx. 75702, U.S.A.
Solar Age Product Catalogue, Section 13.34, June 1980.


[26] Dancette, M.,

[27] Turrent, D. and Backer, N.

[28] Bhargava, A.K. et al
[29] Johnson, P.D.,


[31] McVeigh, J.C.


[33] Pereira, C.
[34] Szego, G. and Frazer, M.

[35] Karlsson, B., Larsson, M, and Brunstrom, C.,


[37] Rassafi, M. et al

[38] Klein, S.A., Duffie, J.A. and Beckman, W.A.


Information leaflet, AGAAB Thermia-Verken, P.O. Box 150, 5-67101, ARVIKA, Sweden.


REFERENCES CHAPTER 7

[1] Harding, G.L. and Window, B.


[7] Thompson, H.A. and Sagin, H.H.,

[8] Van de Vate, J.F. and Plomp, A.,


[10] Hollands, K.G.T.

[12] Smart, D.R. et al,

[13] British Standards Institution
'Methods for determining thermal insulating properties with definitions of thermal insulating terms', BS874 : November 1973.

[14] National Physical Laboratory,

[15] Gilbo, C.E.,

[16] Woodside, W. and Wilson, A.G.
[17] Redfoot, H.L. et al
'Glazing solar collectors with acrylic and double walled polycarbonate plastics'

[18] Duffie, J.A. and Beckman, W.A.

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

<table>
<thead>
<tr>
<th>Sector</th>
<th>Fuel</th>
<th>Total 1976</th>
<th>Total 2025</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Solid</td>
<td>Liquid</td>
<td>Gas</td>
</tr>
<tr>
<td>Iron &amp; Steel</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>Engineering and other</td>
<td>1976</td>
<td>17.2</td>
<td>71.4</td>
</tr>
<tr>
<td>metal trades</td>
<td>2025</td>
<td>32.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Chemical &amp; Allied Trades</td>
<td>1976</td>
<td>0.8</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Food, Drink &amp; Tobacco</td>
<td>1976</td>
<td>3.2</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>7.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Textiles, Leather &amp;</td>
<td>1976</td>
<td>5.1</td>
<td>21.3</td>
</tr>
<tr>
<td>Clothing</td>
<td>2025</td>
<td>7.6</td>
<td>4.2</td>
</tr>
<tr>
<td>Paper, Printing &amp;</td>
<td>1976</td>
<td>1.9</td>
<td>5.4</td>
</tr>
<tr>
<td>Stationary</td>
<td>2025</td>
<td>1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Building Materials</td>
<td>1976</td>
<td>0.9</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Other trades</td>
<td>1976</td>
<td>7.8</td>
<td>61.2</td>
</tr>
<tr>
<td></td>
<td>2025</td>
<td>19.5</td>
<td>14.2</td>
</tr>
</tbody>
</table>

| Process                 |            |            |            |        |      |
|-------------------------|------------|------------|------------|--------|
| Agricultural            | 1976       | 0.9        | 22.1       | 23.6   |
| Heating & Drying        | 2025       | -          | 16.1       | 16.1   |

| Domestic                |
| Space                   |
| Water                   | 995        | 475        |
|                         | 320        | 270        |

| Commercial              |
| Space                   |
| Water                   | 375        | 387.4      |
|                         | 120        |            |

<p>| TOTAL                   | 2323       | 1430       |</p>
<table>
<thead>
<tr>
<th>Substance</th>
<th>Comments</th>
<th>Density $\rho$/Kg m$^{-3} \times 10^3$</th>
<th>Specific heat capacity $C_p$/JK$^{-1}$ K$^{-1} \times 10^3$</th>
<th>Volume heat capacity $\rho C_p$/MJ K$^{-1}$ m$^{-3}$</th>
<th>Freezing point $Fp$/°C</th>
<th>Boiling point $Bp$/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chabazitic tuff</td>
<td>Common beolite in Italy</td>
<td>1.4</td>
<td>1.09</td>
<td>4.47</td>
<td>0</td>
<td>100</td>
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<tr>
<td>Water</td>
<td></td>
<td>1.0</td>
<td>4.19</td>
<td>4.19</td>
<td>0</td>
<td>100</td>
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<tr>
<td>Iron shot</td>
<td></td>
<td>7.86</td>
<td>0.54</td>
<td>4.27</td>
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<td>-</td>
</tr>
<tr>
<td>Scrap Iron</td>
<td>Zero voids</td>
<td>7.90</td>
<td>0.53</td>
<td>3.99</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Steel</td>
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<td>7.9</td>
<td>0.5</td>
<td>4.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnetite, Fe$_2$O$_3$</td>
<td>Zero voids</td>
<td>5.16</td>
<td>0.75</td>
<td>3.86</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Fe$_2$O$_3$</td>
<td></td>
<td>5.20</td>
<td>0.75</td>
<td>3.94</td>
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<td>-</td>
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<tr>
<td>Wet earth</td>
<td></td>
<td>1.7</td>
<td>2.1</td>
<td>3.60</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Water and salt</td>
<td>(brine)</td>
<td>1.2</td>
<td>3.0</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Alumina (Al$_2$O$_3$)</td>
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<td>4.0</td>
<td>0.9</td>
<td>3.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Scrap Alumium</td>
<td>Zero voids</td>
<td>2.74</td>
<td>0.963</td>
<td>2.64</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Therminol 55 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Caloria HT43 (oil)</td>
<td>Cracking occurs at high temperature</td>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>315</td>
</tr>
<tr>
<td>Oils</td>
<td>Cracking occurs at high temperature</td>
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<td>2.51</td>
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<td>-</td>
</tr>
<tr>
<td>MgCO$_3$·6H$_2$O</td>
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<td>1.60</td>
<td>2.72</td>
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<td>-</td>
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<tr>
<td>MgCO$_3$</td>
<td></td>
<td>3.0</td>
<td>0.84</td>
<td>2.51</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Concrete</td>
<td>Zero voids</td>
<td>2.25</td>
<td>1.13</td>
<td>2.57</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stone</td>
<td>Zero voids</td>
<td>2.74</td>
<td>0.88</td>
<td>2.43</td>
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<td>-</td>
</tr>
<tr>
<td>Material</td>
<td>Density</td>
<td>Porosity</td>
<td>Cost (1980)</td>
<td>Remarks</td>
<td></td>
<td></td>
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<tr>
<td>-------------------------</td>
<td>---------</td>
<td>----------</td>
<td>-------------</td>
<td>---------------</td>
<td></td>
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</tr>
<tr>
<td>Concrete</td>
<td>2.74</td>
<td>0.92</td>
<td>2.26</td>
<td>-</td>
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</tr>
<tr>
<td>Marble</td>
<td>2.70</td>
<td>0.75</td>
<td>2.39</td>
<td>-</td>
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<td></td>
</tr>
<tr>
<td>Granite</td>
<td>2.70</td>
<td>0.796</td>
<td>2.12</td>
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</tr>
<tr>
<td>Sulphur Liquid</td>
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<td>1.0</td>
<td>2.1</td>
<td>445</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock</td>
<td>2.5</td>
<td>0.84</td>
<td>2.09</td>
<td>-</td>
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<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>2.4</td>
<td>0.8</td>
<td>1.9</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>2.23</td>
<td>0.84</td>
<td>1.9</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paraffin Oil</td>
<td>0.8</td>
<td>2.2</td>
<td>1.8</td>
<td>38-56</td>
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<td></td>
</tr>
<tr>
<td>Olive Oil</td>
<td>0.9</td>
<td>2.0</td>
<td>1.8</td>
<td>=10</td>
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<td></td>
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<tr>
<td>Silica (Si O₂)</td>
<td>2.7</td>
<td>0.84</td>
<td>2.3</td>
<td>=300</td>
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<td></td>
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<tr>
<td>Pebbles</td>
<td>3.0</td>
<td>1.0</td>
<td>3.0</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>3.2</td>
<td>0.9</td>
<td>2.9</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>2.1</td>
<td>0.7</td>
<td>1.5</td>
<td>119</td>
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<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>0.95</td>
<td>0.963</td>
<td>0.95</td>
<td>371</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitec</td>
<td>-</td>
<td></td>
<td>1.55</td>
<td>150-590</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Draw salt</td>
<td>-</td>
<td></td>
<td>1.55</td>
<td>250-590</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry earth</td>
<td>1.26</td>
<td>0.8</td>
<td>1.0</td>
<td>-</td>
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</table>
TABLE 2.3 Basic Prometheus configuration to heat 100 houses

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<tr>
<th>Store</th>
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</tr>
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<tbody>
<tr>
<td>length</td>
<td>280 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>width</td>
<td>10 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>height</td>
<td>4 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume</td>
<td>11200 m$^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>storage material pebbles, density</td>
<td>1600 kg m$^{-3}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>storage material pebbles; specific heat capacity</td>
<td>837 J kg$^{-1}$°C$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>store insulation; thickness</td>
<td>0.6 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>store insulation; thermal conductivity</td>
<td>0.036 Wm$^{-2}$°C$^{-1}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Collector</th>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>area</td>
<td>2,900 m$^2$</td>
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</tr>
<tr>
<td>heat transfer factor ($F_R$)</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>overall heat loss coefficient</td>
<td>1.0 Wm$^{-2}$°C$^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>optical efficiency averaged over useful incident angles ($\tau_a$)$_0$</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
<td>Quantity</td>
<td>Energy Input</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>----------</td>
<td>--------------</td>
</tr>
<tr>
<td>1.5%</td>
<td>Preparing site</td>
<td>425</td>
<td>0.045</td>
</tr>
<tr>
<td>10%</td>
<td>Excavation and site preparation</td>
<td>4935</td>
<td>0.351</td>
</tr>
<tr>
<td>3%</td>
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<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>9%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.28</td>
</tr>
<tr>
<td>39%</td>
<td>Base - hardcore</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>32%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>557</td>
<td>0.25</td>
</tr>
<tr>
<td>0%</td>
<td>aggregate</td>
<td>6238</td>
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</tr>
<tr>
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<td>packing, incl. tight 200 mm thick</td>
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<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>27%</td>
<td>concrete sections</td>
<td>557</td>
<td>0.28</td>
</tr>
<tr>
<td>10%</td>
<td>concrete -</td>
<td>250</td>
<td>0.1</td>
</tr>
<tr>
<td>2%</td>
<td>concrete sections</td>
<td>118</td>
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</tr>
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<td>31%</td>
<td>concrete sections</td>
<td>6238</td>
<td>0.112</td>
</tr>
<tr>
<td>32%</td>
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<td>0.29</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>557</td>
<td>0.133</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>557</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
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<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
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<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
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<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
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<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
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<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.124</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
<tr>
<td>39%</td>
<td>packing, incl. tight 200 mm thick</td>
<td>577</td>
<td>0.133</td>
</tr>
<tr>
<td>3%</td>
<td>paperwork, o.4'm. shovels plus</td>
<td>24</td>
<td>0.003</td>
</tr>
</tbody>
</table>
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>
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<tr>
<th></th>
<th>Prometheus</th>
<th>Gas</th>
<th>Electricity (Economy 7)</th>
</tr>
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<tbody>
<tr>
<td>( C_h /£ )</td>
<td>5700</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>( K_h /£ )</td>
<td>0</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>( F_h /£ \ yr^{-1} )</td>
<td>18</td>
<td>117</td>
<td>146</td>
</tr>
<tr>
<td>( R_h /£ \ yr^{-1} )</td>
<td>11</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>

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

\[ PVC_h \]
\[ i=0 \ f=0.04 \ 8500 \ 17800 \ 20200 \]
\[ i=0 \ f=0.02 \ 7500 \ 11700 \ 12500 \]
### TABLE 2.6 Costs and inventory of various interseasonal solar heating systems modelled along with the cost, collector area and storage volume required to provide 27.5 GJ per annum.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector type</td>
<td>Flat plate selective</td>
<td>Evacuated tube collector</td>
<td>Concentrating collector</td>
<td>High performance evacuated</td>
</tr>
<tr>
<td>Collector area /m²</td>
<td>2100</td>
<td>4600</td>
<td>14000</td>
<td>2800</td>
</tr>
<tr>
<td>Storage volume /m³</td>
<td>7500</td>
<td>17700</td>
<td>38500</td>
<td>11200</td>
</tr>
<tr>
<td>Insulation thickness/m</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Operating temperature of store/°C</td>
<td>72-42</td>
<td>95-60</td>
<td>70-30</td>
<td>130-30</td>
</tr>
<tr>
<td>Number of houses heated by system</td>
<td>50</td>
<td>300</td>
<td>400</td>
<td>100</td>
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<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>
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<tr>
<td>Cost per A5 house/£1980</td>
<td>5480</td>
<td>2416</td>
<td>2215</td>
<td>5700</td>
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</table>

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

<table>
<thead>
<tr>
<th>Store temperature rise/(°C)</th>
<th>Cost/£1982 per KWh recovered energy seasonal storage</th>
</tr>
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<tbody>
<tr>
<td>Steel tank</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.28 - 0.39</td>
</tr>
<tr>
<td>Pit storage</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.19 - 0.30</td>
</tr>
<tr>
<td>Rock cavern</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.11 - 0.21</td>
</tr>
<tr>
<td>Storage in clay</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.07 - 0.13</td>
</tr>
<tr>
<td>Multiple well systems in rock</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.07 - 0.12</td>
</tr>
<tr>
<td>Aquifers</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.025 - 0.08</td>
</tr>
<tr>
<td>Prometheus (pebble bed, using data from Table 2.6)</td>
<td>100</td>
</tr>
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</table>

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

<table>
<thead>
<tr>
<th>Name Location of Store/or Centre of Study</th>
<th>Design Study or Constructed</th>
<th>Storage Material</th>
<th>Number of Houses Per Store</th>
<th>% of Annual House Heating Supplied by System</th>
<th>Cost Per House £</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamboho, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>56</td>
<td>100</td>
<td>27 000</td>
</tr>
<tr>
<td>Inglestad, Sweden</td>
<td>Constructed</td>
<td>Water</td>
<td>52</td>
<td>50</td>
<td>19 320</td>
</tr>
<tr>
<td>Studsvik, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>400</td>
<td>93</td>
<td>5 150</td>
</tr>
<tr>
<td>Lyckebo, Sweden</td>
<td>Design Study</td>
<td>Water</td>
<td>500</td>
<td>100</td>
<td>10 500</td>
</tr>
<tr>
<td>Arizona, USA</td>
<td>Design Study</td>
<td>Water</td>
<td>250</td>
<td>100</td>
<td>3 012</td>
</tr>
<tr>
<td>Northampton, USA</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>10 000</td>
<td>100</td>
<td>6 000</td>
</tr>
<tr>
<td>Sussex, UK</td>
<td>Design Study</td>
<td>Solar Pond</td>
<td>100</td>
<td>100</td>
<td>10 000</td>
</tr>
<tr>
<td>City University, London, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>100</td>
<td>78</td>
<td>4 000</td>
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<tr>
<td>ERR, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>300</td>
<td>100</td>
<td>2 416</td>
</tr>
<tr>
<td>PCL, UK</td>
<td>Design Study</td>
<td>Water</td>
<td>50</td>
<td>100</td>
<td>5 480</td>
</tr>
<tr>
<td>Component</td>
<td>Area A (m²)</td>
<td>U-value $\text{Wm}^{-2}\text{°C}^{-1}$</td>
<td>UA $\text{W}^\text{°C}^{-1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td>-------------</td>
<td>---------------------------------------</td>
<td>-----------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>88.5</td>
<td>1.0</td>
<td>88.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>48.6</td>
<td>0.6</td>
<td>29.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>48.6</td>
<td>0.5</td>
<td>24.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window</td>
<td>15.0</td>
<td>5.5</td>
<td>82.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total fabric specific loss</td>
<td></td>
<td></td>
<td>224$\text{W}^\text{°C}^{-1}$</td>
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<td></td>
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<tr>
<td>Ventilation specific loss</td>
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<td></td>
<td>80$\text{W}^\text{°C}^{-1}$</td>
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<tr>
<td>Total house specific loss</td>
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<td></td>
<td>304$\text{W}^\text{°C}^{-1}$</td>
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<td></td>
</tr>
<tr>
<td>Month</td>
<td>Days in month</td>
<td>Solar radiation on a South-facing vertical surface (KWh/m²/month)</td>
<td>Solar radiation on a South-facing surface 30° to horizontal (KWh/m²/month)</td>
<td>Ambient Temperature (°C)</td>
<td>Degree days baseline 15.5°C</td>
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<td>-------</td>
<td>--------------</td>
<td>-------------------------------------------------</td>
<td>-----------------------------------------------------------------</td>
<td>-----------------</td>
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<tr>
<td>Jan</td>
<td>31</td>
<td>28</td>
<td>25.2</td>
<td>5.2</td>
<td>346</td>
</tr>
<tr>
<td>Feb</td>
<td>28</td>
<td>42</td>
<td>45</td>
<td>4.6</td>
<td>304</td>
</tr>
<tr>
<td>March</td>
<td>31</td>
<td>74</td>
<td>91</td>
<td>5.7</td>
<td>282</td>
</tr>
<tr>
<td>April</td>
<td>30</td>
<td>115</td>
<td>8.2</td>
<td>2.8</td>
<td>197</td>
</tr>
<tr>
<td>May</td>
<td>31</td>
<td>115</td>
<td>146</td>
<td>11.8</td>
<td>113</td>
</tr>
<tr>
<td>June</td>
<td>30</td>
<td>166</td>
<td>14.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>July</td>
<td>31</td>
<td>150</td>
<td>17.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug</td>
<td>31</td>
<td>123</td>
<td>16.8</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Sept</td>
<td>30</td>
<td>95</td>
<td>13.9</td>
<td>56</td>
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</tr>
<tr>
<td>Oct</td>
<td>31</td>
<td>66</td>
<td>10.8</td>
<td>132</td>
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</tr>
<tr>
<td>Nov</td>
<td>30</td>
<td>37</td>
<td>6.7</td>
<td>256</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>31</td>
<td>22</td>
<td>5.3</td>
<td>333</td>
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<tr>
<td>House type</td>
<td>Insulation level</td>
<td>Total house specific loss (W°C⁻¹)</td>
<td>Net annual space and water heating demand (GJ)</td>
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<td></td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
<td>----------------------------------</td>
<td>---------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A0</td>
<td>Basic (1975 Building Regs.)</td>
<td>304</td>
<td>46.4</td>
<td></td>
<td></td>
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<tr>
<td>A1</td>
<td>A0 + orientate house north-south</td>
<td>304</td>
<td>41.7</td>
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<tr>
<td>A2</td>
<td>A1 + 50 mm loft insulation (100 mm total)</td>
<td>291</td>
<td>39.5</td>
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<td></td>
</tr>
<tr>
<td>A3</td>
<td>A2 + fill cavity with fibre</td>
<td>255</td>
<td>33.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>A3 + 50 mm loft insulation (150 mm total)</td>
<td>251</td>
<td>33.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>A4 + extra layer of glazing (i.e. double)</td>
<td>213</td>
<td>27.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>A5 + cavity increased to 100 mm</td>
<td>186</td>
<td>23.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>A6 + 25 mm floor edge insulation</td>
<td>182</td>
<td>22.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>A7 + all windows on south side</td>
<td>182</td>
<td>20.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>A8 + 100 mm of loft insulation (250 mm total)</td>
<td>177</td>
<td>19.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A10</td>
<td>A9 + extra layer of glazing (i.e. triple)</td>
<td>164</td>
<td>18.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A11</td>
<td>A10 + cavity increased to 200 mm</td>
<td>150</td>
<td>16.7</td>
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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></td>
<td>192 $W^0°C^{-1}$</td>
</tr>
<tr>
<td>Ventilation specific loss</td>
<td></td>
<td></td>
<td>68 $W^0°C^{-1}$</td>
</tr>
<tr>
<td>Total house specific loss</td>
<td></td>
<td></td>
<td>260 $W^0°C^{-1}$</td>
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</table>
### TABLE 3.5 Thermal Characteristics of existing houses with different levels of retrofitted insulation.

<table>
<thead>
<tr>
<th>House type</th>
<th>Insulation level</th>
<th>Total house specific loss ($W^0C^{-1}$)</th>
<th>Net annual space water heating demand (GJ)</th>
</tr>
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<tbody>
<tr>
<td>B0</td>
<td>Basic (average UK housing stock)</td>
<td>260</td>
<td>34.9</td>
</tr>
<tr>
<td>B1</td>
<td>B0 + 50 mm of loft insulation (100 mm total)</td>
<td>249</td>
<td>33.1</td>
</tr>
<tr>
<td>B2</td>
<td>B1 + fibre-fill cavity (50 mm)</td>
<td>219</td>
<td>28.3</td>
</tr>
<tr>
<td>B3</td>
<td>B2 + 50 mm of loft insulation (150 mm total)</td>
<td>215</td>
<td>27.7</td>
</tr>
<tr>
<td>B4</td>
<td>B3 + extra layer of glazing (i.e. double)</td>
<td>182</td>
<td>23.1</td>
</tr>
<tr>
<td>B5</td>
<td>B4 + extra layer of glazing (i.e. triple)</td>
<td>170</td>
<td>21.7</td>
</tr>
<tr>
<td>B6</td>
<td>B5 + 100 mm external wall insulation</td>
<td>156</td>
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<td>Location</td>
<td>Event Description</td>
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<td>----------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td>1966-07-16</td>
<td>Arthurian</td>
<td>Baseball game</td>
<td></td>
</tr>
<tr>
<td>1966-07-20</td>
<td>Boston</td>
<td>Football match</td>
<td></td>
</tr>
<tr>
<td>1966-07-26</td>
<td>Washington</td>
<td>Basketball game</td>
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**Table 4.4: Art Collector, Lost Factories and Inscribed Stones in the United Kingdom**
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<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
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</thead>
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<tr>
<td>21 June 1983</td>
<td>142</td>
<td>6.5</td>
<td>761</td>
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<td>51.1</td>
<td>65.9</td>
<td>7.1</td>
<td>0.2</td>
<td>0.080</td>
<td>0.071</td>
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</tr>
<tr>
<td>143</td>
<td>61.0</td>
<td>87</td>
<td>14.7</td>
<td>21.1</td>
<td>50.8</td>
<td>66.2</td>
<td>7.2</td>
<td>1.4</td>
<td>0.080</td>
<td>0.071</td>
<td></td>
<td></td>
</tr>
<tr>
<td>144</td>
<td>61.5</td>
<td>87</td>
<td>14.7</td>
<td>21.2</td>
<td>51.1</td>
<td>66.2</td>
<td>7.2</td>
<td>1.4</td>
<td>0.080</td>
<td>0.071</td>
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<tr>
<td>145</td>
<td>61.9</td>
<td>87</td>
<td>14.7</td>
<td>21.1</td>
<td>50.8</td>
<td>66.2</td>
<td>7.2</td>
<td>1.4</td>
<td>0.080</td>
<td>0.071</td>
<td></td>
<td></td>
</tr>
<tr>
<td>146</td>
<td>64.4</td>
<td>87</td>
<td>14.5</td>
<td>20.9</td>
<td>50.5</td>
<td>66.1</td>
<td>7.2</td>
<td>1.5</td>
<td>0.080</td>
<td>0.071</td>
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<td>147</td>
<td>64.8</td>
<td>87</td>
<td>14.7</td>
<td>21.2</td>
<td>51.1</td>
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<td>7.2</td>
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<td>0.071</td>
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<tr>
<td>148</td>
<td>65.7</td>
<td>77.8</td>
<td>14.7</td>
<td>21.1</td>
<td>51.1</td>
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<td>7.1</td>
<td>0.2</td>
<td>0.080</td>
<td>0.072</td>
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</tr>
<tr>
<td>149</td>
<td>65.9</td>
<td>77.8</td>
<td>14.7</td>
<td>21.2</td>
<td>51.1</td>
<td>66.2</td>
<td>7.2</td>
<td>0.1</td>
<td>0.079</td>
<td>0.072</td>
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<tr>
<td>150</td>
<td>66.9</td>
<td>77.8</td>
<td>14.7</td>
<td>21.2</td>
<td>51.1</td>
<td>66.3</td>
<td>7.3</td>
<td>0.1</td>
<td>0.079</td>
<td>0.072</td>
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<td></td>
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<tr>
<td>151</td>
<td>65.9</td>
<td>77.8</td>
<td>14.7</td>
<td>21.1</td>
<td>51.1</td>
<td>66.3</td>
<td>7.3</td>
<td>0.1</td>
<td>0.079</td>
<td>0.072</td>
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**Table 5.1** Data collected during steady state testing of the D.C.Hall collector

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<th>Air mass flow rate (Kg/hr)</th>
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<th>Air temp. at outlet (°C)</th>
<th>Air temp. increase (T_o - T_i) (°C)</th>
<th>Ambient Temp. (°C)</th>
<th>Total irradiance in plate of collector (W/m²)</th>
<th>(T_o - T_i) / I_m</th>
<th>Collector efficiency (%)</th>
<th>Wind speed (m/s)</th>
<th>Absorber Temp. (°C)</th>
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TABLE 5.2(b) Results of steady state testing of structured polycarbonate collector
TABLE 5.3 Collector configuration modelled for transient analysis by RRDCT.

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<th>Parameter</th>
<th>Value</th>
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<td>Collector length (along flow)</td>
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<td>Collector width</td>
<td>1.00 m</td>
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<tr>
<td>Cover to plate spacing</td>
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</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 θ = 0 falling slightly as θ increases</td>
</tr>
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<td>Emissivity of upper surface of the plate (diffuse)</td>
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<tr>
<td>Emissivity of duct surface (diffuse)</td>
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<tr>
<td>Emissivity of cover (diffuse)</td>
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<tr>
<td>Cover polycarbonate thickness</td>
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</tr>
<tr>
<td>Mass flow rate</td>
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</tr>
<tr>
<td>Thickness of plate and of duct-back</td>
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TABLE 5.4 Results of transient and steady state testing with multi node model

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<td>τc/(min)</td>
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K = correction factor for equivalent normal direct radiation = \((\tau α)_{\text{direct}} / (\tau α)_{\text{diffuse}}\) = \(0.830 / 0.688\) = 1.206

* = at low fluid inlet temperatures
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<th>( cF_R(\tau_0, k_n) )</th>
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<th>( T^* )</th>
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<td>( 0.011 )</td>
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<td></td>
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<tr>
<td>23</td>
<td>( 0.546242420031 )</td>
<td>( 0.021 )</td>
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<td></td>
</tr>
<tr>
<td>24</td>
<td>( 0.439368903096 )</td>
<td>( 0.02 )</td>
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<td>25</td>
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<td>( 0.026 )</td>
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<td>26</td>
<td>( 0.433936890307 )</td>
<td>( 0.026 )</td>
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<td>27</td>
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</tr>
<tr>
<td>28</td>
<td>( 0.27312120016 )</td>
<td>( 0.013 )</td>
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<td></td>
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<tr>
<td>29</td>
<td>( 0.415619232632 )</td>
<td>( 0.021 )</td>
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<td></td>
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<tr>
<td>30</td>
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<td>31</td>
<td>( 0.415619232632 )</td>
<td>( 0.029 )</td>
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<td>32</td>
<td>( 0.403744397415 )</td>
<td>( 0.026 )</td>
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<td></td>
</tr>
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</table>

**Points on Thermal Performance Characteristic BO**

From least squares fits each way

Minimum ETAO: \( 0.732545318781 \)

Maximum ETAO: \( 0.714184616622 \)

\( U = 7.33893217894 \)

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

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\overline{T}_p/k$</th>
<th>$\overline{T}_b/k$</th>
<th>$T_m/k$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
<th>$\eta$</th>
<th>$F_{aveUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>303</td>
<td>332.73</td>
<td>333.01</td>
<td>322.1</td>
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<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>
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<td>.293</td>
<td>3.362</td>
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<td>428.06</td>
<td>425.11</td>
<td>425.11</td>
<td>3.185</td>
<td>.095</td>
<td>3.503</td>
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<tr>
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<td>435.94</td>
<td>433.57</td>
<td>434.06</td>
<td>3.226</td>
<td>.037</td>
<td>3.564</td>
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### TABLE 5.9
Temperature distribution and energy lost from DY1 collector (0.2mm thick plate and duct base) during zero radiation testing, $T_a = 293K$, $T_{wind} = 1\text{m s}^{-1}$, $T_{sky} = 273K$

<table>
<thead>
<tr>
<th>$T_i/k$</th>
<th>$T_e/k$</th>
<th>$\overline{T}_p/k$</th>
<th>$\overline{T}_b/k$</th>
<th>$T_m/k$</th>
<th>Energy lost per unit time per unit area W m$^{-2}$</th>
<th>$F_{RUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
<th>$F_{aveUL}$ (Wm$^{-2}$ °C$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>303</td>
<td>300.34</td>
<td>300.41</td>
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<td>301.67</td>
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<td>343</td>
<td>333.32</td>
<td>333.79</td>
<td>336.20</td>
<td>338.16</td>
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<td>3.247</td>
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<td>365.41</td>
<td>366.41</td>
<td>370.42</td>
<td>374.20</td>
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<td>2.961</td>
<td>3.282</td>
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<tr>
<td>423</td>
<td>396.74</td>
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<td>397.80</td>
<td>3.060</td>
<td>3.404</td>
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<tr>
<td>433</td>
<td>404.46</td>
<td>406.34</td>
<td>412.12</td>
<td>418.73</td>
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<td>3.088</td>
<td>3.439</td>
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<td>301.71</td>
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<td>2.098</td>
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<tr>
<td>433</td>
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</table>

* $T_{sky} = 293K$
<table>
<thead>
<tr>
<th>Temp (°C)</th>
<th>Wind Speed (m/s)</th>
<th>Test Method</th>
<th>Tm (°C)</th>
<th>Tm-1°C</th>
<th>R United States</th>
<th>R Decline</th>
<th>R Increase</th>
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</thead>
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<td>211</td>
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<td>28</td>
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<td>7.77</td>
<td>8.48</td>
<td>9.29</td>
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<tr>
<td>0.4 - 3.0</td>
<td>17</td>
<td>Transient</td>
<td>20</td>
<td>0.639</td>
<td>2.46</td>
<td>4.53</td>
<td>5.19</td>
</tr>
<tr>
<td>0.4</td>
<td>16</td>
<td>Steady State</td>
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<td>5.13</td>
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<td></td>
</tr>
<tr>
<td>1.5</td>
<td>26</td>
<td>ASHRAE</td>
<td>26</td>
<td>0.627</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>9.5</td>
<td>Structured Polycarbonate Collector</td>
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<td>0.545</td>
<td>5.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>9.5</td>
<td>Structured Polycarbonate Collector</td>
<td>23</td>
<td>0.545</td>
<td>5.13</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5.10: Summary of Collector Testing Results
<table>
<thead>
<tr>
<th>Material</th>
<th>Transmittance Solar (0.2-4.0um) (%)</th>
<th>Reflective Index (n)</th>
<th>Expansion Coefficient (3.0-5.0um) (%)</th>
<th>Temperature Limits (°C)</th>
<th>Chemical Resistance to acids (Comments)</th>
<th>Weatherability (Comments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lexan (Polycarbonate)</td>
<td>1.586</td>
<td>1.49</td>
<td>85.1</td>
<td>125 mil</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Flexiglass (Acrylic)</td>
<td>1.49</td>
<td>85.6</td>
<td>125 mil</td>
<td>120-130</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Teflon F F (Fluorocarbon)</td>
<td>1.46</td>
<td>92.3</td>
<td>4 mil</td>
<td>200-220</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Teflon P P (Fluorocarbon)</td>
<td>1.46</td>
<td>92.2</td>
<td>4 mil</td>
<td>100-170</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Mylar (Polyester)</td>
<td>1.58</td>
<td>86.9</td>
<td>25 mil</td>
<td>95-100</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Sunlite (Polyester)</td>
<td>1.51</td>
<td>84.3</td>
<td>25 mil</td>
<td>230</td>
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<td>Good to excellent</td>
</tr>
<tr>
<td>Float glass (Glass)</td>
<td>1.50</td>
<td>89</td>
<td>25 mil</td>
<td>200</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Tempered glass (Glass)</td>
<td>1.50</td>
<td>89.6</td>
<td>25 mil</td>
<td>200</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear tempered glass (Glass)</td>
<td>1.50</td>
<td>89</td>
<td>25 mil</td>
<td>200</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Clear white glass</td>
<td>1.50</td>
<td>89</td>
<td>25 mil</td>
<td>200</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
<tr>
<td>Sunde white crystal glass (Glass)</td>
<td>1.50</td>
<td>89</td>
<td>25 mil</td>
<td>200</td>
<td>Good</td>
<td>Good to excellent</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thickness (μm)</th>
<th>Material</th>
<th>Supporter</th>
<th>Substrate</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010 - 0.016</td>
<td>Black Nickel</td>
<td>In-house</td>
<td>Aluminum</td>
<td>6</td>
</tr>
<tr>
<td>0.016 - 0.020</td>
<td>Black Nickel</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
</tr>
<tr>
<td>0.020 - 0.023</td>
<td>Aluminum</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
</tr>
<tr>
<td>0.023 - 0.026</td>
<td>Aluminum</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
</tr>
<tr>
<td>0.026 - 0.030</td>
<td>Aluminum</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
</tr>
<tr>
<td>0.030 - 0.033</td>
<td>Aluminum</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
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<tr>
<td>0.033 - 0.036</td>
<td>Aluminum</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
</tr>
<tr>
<td>0.036 - 0.040</td>
<td>Aluminum</td>
<td>In-house</td>
<td>Stainless Steel</td>
<td>6</td>
</tr>
</tbody>
</table>

**Notes:**
- Table contains optical properties of selective absorber surface coatings.
- The materials listed include Black Nickel, Aluminum, Stainless Steel, and Copper.
- The supporters are In-house and DBN.
- The substrates are Aluminum and Stainless Steel.
**TABLE 6.3** Key to collector variable features, used to obtain Figure 6.19

<table>
<thead>
<tr>
<th>cover material: cover 1</th>
<th>plate glass, thickness 6.0 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>cover 2</td>
<td>polycarbonate, thickness 2.0 mm</td>
</tr>
</tbody>
</table>

**thickness of the plate and of the duct-back:**

| DY1  | 0.2 mm |
| DY2  | 0.5 mm |
| DY3  | 1.0 mm |
| DY4  | 2.0 mm |
| DY5  | 5.0 mm |

**air flow in the rear-duct:**

<p>| 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 = 128W |
| flow 3 | TI = 323 K (M = 0.0562) kg s(^{-1}) PON = 124W |</p>
<table>
<thead>
<tr>
<th>Gas</th>
<th>Surface</th>
<th>Surface condition</th>
<th>Temp. (°C)</th>
<th>a</th>
</tr>
</thead>
<tbody>
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<td>Bronze</td>
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<td>-</td>
<td>0.88</td>
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<td>Cast Iron</td>
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</tr>
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<td>Aluminium</td>
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<td>0.87</td>
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<tr>
<td></td>
<td>W</td>
<td>Clean</td>
<td>-30</td>
<td>0.804</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>Clean</td>
<td>-183</td>
<td>0.942</td>
</tr>
</tbody>
</table>

TABLE 7.2 Convection and conduction heat transfer coefficients for various gases at different temperatures as measured with guarded hot plate.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T_s/°C$</th>
<th>$T_i/°C$</th>
<th>$h_P/(\text{Wm}^{-2}\text{°C}^{-1})$</th>
<th>$Q_{\text{rA}}/(\text{Wm}^{-2})$</th>
<th>$T_1/°C$</th>
<th>$T_2/°C$</th>
<th>$h_{rP}/(\text{Wm}^{-2}\text{°C}^{-1})$</th>
<th>$h_{rc}/(\text{Wm}^{-2}\text{°C}^{-1})$</th>
<th>$\Delta T/°C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air at atmospheric pressure</td>
<td>10</td>
<td>14</td>
<td>0.798</td>
<td>3.19</td>
<td>10.16</td>
<td>13.84</td>
<td>0.163</td>
<td>0.704</td>
<td>3.68</td>
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<tr>
<td></td>
<td>10.1</td>
<td>20.7</td>
<td>1.910</td>
<td>20.05</td>
<td>11.10</td>
<td>19.70</td>
<td>0.168</td>
<td>2.193</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>10.1</td>
<td>21.3</td>
<td>1.725</td>
<td>19.32</td>
<td>11.07</td>
<td>20.33</td>
<td>0.169</td>
<td>1.915</td>
<td>9.26</td>
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<td></td>
<td>10.5</td>
<td>33.3</td>
<td>2.195</td>
<td>50.05</td>
<td>13.00</td>
<td>30.80</td>
<td>0.180</td>
<td>2.632</td>
<td>17.8</td>
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<tr>
<td>Air, $p = 82$ torr</td>
<td>10.35</td>
<td>37.9</td>
<td>1.60</td>
<td>44.08</td>
<td>12.55</td>
<td>35.70</td>
<td>0.185</td>
<td>1.720</td>
<td>23.15</td>
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<td>10.35</td>
<td>38.8</td>
<td>1.621</td>
<td>46.12</td>
<td>12.66</td>
<td>36.49</td>
<td>0.185</td>
<td>1.750</td>
<td>23.83</td>
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<tr>
<td>Air, $p = 81$ torr</td>
<td>10.3</td>
<td>43</td>
<td>1.567</td>
<td>51.24</td>
<td>12.86</td>
<td>40.44</td>
<td>0.189</td>
<td>1.669</td>
<td>27.58</td>
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<tr>
<td>Air, $p = 71$ torr</td>
<td>10.2</td>
<td>24.9</td>
<td>0.925</td>
<td>13.60</td>
<td>10.88</td>
<td>24.22</td>
<td>0.172</td>
<td>0.847</td>
<td>13.34</td>
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<tr>
<td>Freon/Air</td>
<td>10.3</td>
<td>22.1</td>
<td>1.685</td>
<td>19.88</td>
<td>11.29</td>
<td>21.11</td>
<td>0.170</td>
<td>1.856</td>
<td>9.82</td>
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<td></td>
<td>10.1</td>
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<td>1.635</td>
<td>12.59</td>
<td>10.73</td>
<td>17.17</td>
<td>0.166</td>
<td>1.789</td>
<td>6.44</td>
</tr>
<tr>
<td>Carbon Tet/Air</td>
<td>10.1</td>
<td>17.9</td>
<td>1.645</td>
<td>12.83</td>
<td>10.74</td>
<td>17.26</td>
<td>0.166</td>
<td>1.803</td>
<td>6.52</td>
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<td>10.4</td>
<td>27.9</td>
<td>1.986</td>
<td>34.75</td>
<td>12.14</td>
<td>26.16</td>
<td>0.175</td>
<td>2.303</td>
<td>14.02</td>
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<tr>
<td></td>
<td>10.5</td>
<td>31.3</td>
<td>2.081</td>
<td>43.28</td>
<td>12.66</td>
<td>29.14</td>
<td>0.178</td>
<td>2.450</td>
<td>16.48</td>
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<tr>
<td></td>
<td>10.6</td>
<td>34.9</td>
<td>2.461</td>
<td>59.80</td>
<td>13.59</td>
<td>33.91</td>
<td>0.182</td>
<td>3.082</td>
<td>18.32</td>
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<tr>
<td></td>
<td>10.6</td>
<td>36.7</td>
<td>2.245</td>
<td>58.59</td>
<td>13.53</td>
<td>33.77</td>
<td>0.183</td>
<td>2.712</td>
<td>20.24</td>
</tr>
<tr>
<td>Air $p = 0.3$ torr</td>
<td>10.2</td>
<td>16.6</td>
<td>0.547</td>
<td>3.504</td>
<td>10.38</td>
<td>16.42</td>
<td>0.165</td>
<td>0.414</td>
<td>6.04</td>
</tr>
<tr>
<td>Air $p = 0.35$ torr</td>
<td>10.9</td>
<td>45.7</td>
<td>1.135</td>
<td>39.51</td>
<td>12.87</td>
<td>43.72</td>
<td>0.193</td>
<td>1.088</td>
<td>30.85</td>
</tr>
<tr>
<td>Air $p = 16$ torr and changing</td>
<td>11.2</td>
<td>51.2</td>
<td>1.186</td>
<td>47.46</td>
<td>13.57</td>
<td>48.83</td>
<td>0.198</td>
<td>1.148</td>
<td>35.26</td>
</tr>
</tbody>
</table>
FIGURE 1.1(a)  PHYSICAL QUALITY OF LIFE INDEX VERSUS ENERGY CONSUMPTION PER CAPITA FOR THE COUNTRIES OF THE WORLD. SOURCES OF DATA: PQI, BOOK OF WORLD RANKINGS¹ BY G. ST. KURIAN 1979, ENERGY CONSUMPTION: 'EUROPEAN YEARBOOK 1983.'
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. [7]

Figure 2.4 Weekly consumption of hot water for one household, from 'The Performance of Domestic Wet Heating Systems', Pickup, G.A. [7]
Total No of dwellings: 87
Overall mean weekly consumption: 0.841 m$^3$/week
Standard deviation: 0.351 m$^3$/week

Contribution due to
OAPs flats
(10+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 (W/m²/year).
FIGURE 2.9 DEMONSTRATION PROJECT IN STUDSVIK. [26]


FIGURE 2.10
FIGURE 2.11  SEASONAL HEAT STORAGE AND A CENTRAL SHORT TERM STORAGE RESERVOIR (C.S.T.) CONSTRUCTED FOR TNO DELFT [35]

ONE-FAMILY HOUSES (SMALL SCALE)

with heat storage in
preferably soft ground or clay
solid rock

APARTMENT BUILDING (INTENSE POPULATED AREAS) (LARGE SCALE)

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

FIGURE 2.12  DIFFERENT APPLICATIONS FOR 'SUNSTORE' [37], SEASONAL STORAGE IN THE GROUND
**Figure 2.13** Plan of Prometheus retrofitted to supply 83 houses with all their space heating and hot water.

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

FIGURE 2.15 PROTO-PROMETHEUS
Figure 2.16  Insolation incident on Proto-Prometheus, 28th September 1981.

Figure 2.17  Collector, store and ambient temperatures for Proto-Prometheus on 28th September 1981.
FIGURE 2.19 PROTO-PROMETHEUS TEMPERATURE DISTRIBUTION (WITH FAN ON), ON 22nd SEPTEMBER 1981 AT 14:25 HRS.
SAMPLE SIZE 264
AVERAGE 1.6 cm.
STANDARD DEVIATION 0.7 cm.

**Figure 2.19** Frequency distribution of pebble smallest dimension.
FIGURE 2.20 FREQUENCY DISTRIBUTION OF PEBBLE LARGEST DIMENSION
**Figure 2.21**  Proto-Prometheus store temperature, from 22nd September 1981 to 2nd October 1981 under stratification (fan off).

**Figure 2.22** Energy demand for a 3-bedroom house built to R75 building regulations (type M) 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 A house.

**Figure 2.26**

The effect of changing the storage volume on the % of solar energy supplied by Prometheus to a Type A house.
FIGURE 2.27 The effect of increasing the number of houses served by a single cubic Prometheus (size, 112 m² per house and 2.8 m² of collector per house) for a type A1 house.

FIGURE 2.28 The effect of changing the collector overall heat loss 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, A5, and A11 3-bedroom end of terrace house.
**Insulation measures**
- Standard solar system with short term storage
- Interseasonal solar system

---

**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 1975 building regulations and energy supplied by 4, 12 and 24 m² of solar collector.*
Figure 3.5  ENERGY DEMAND FOR A WELL INSULATED 3 BEDROOM HOUSE, AND ENERGY SUPPLIED BY, 4.12 AND 24m² OF SOLAR COLLECTOR.

Figure 3.6  COMPARISON OF PREDICTED SOLAR ENERGY SUPPLY FOR A HOUSE USING THE F-CHART METHOD WITH THE MEASURED SOLAR SUPPLY FOR THE MILTON KEYNES SOLAR HOUSE.
Useful energy saving per annum (GJ)

--- Insulation measures
--- Active solar system with short term storage

**Figure 37**

Useful energy saved and extra costs for various insulation options and solar systems retrofitted to an existing type 80 house.
FIGURE 4.1. NONPOROUS ABSORBER-TYPE AIR HEATERS.

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

FIGURE 4.4 COLLECTOR HEAT LOSSES
Figure 4.5 Rear Duct Collector Configuration

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

**M- Howard**
\[ h_w = 5.7 + 3.5v \]

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

**Lloyd**
\[ h_w = 0.15 x \frac{R_{2.4}^{0.8} + k}{L + w} \] for \( T_a = 10^\circ C, T_w = 15^\circ C, L = 1m, W = 1m \)

**Sparrow**
\[ h_w = k x 0.86 x \frac{R_{k}^{0.8} - T_r}{L + w} \] for \( T_w = 10^\circ C, T_r = 15^\circ C, L = 0.1m \)

**Green**
\[ h_w = (h_{10} + h_{15})^{0.8} \] for \( A = 1.4m^2, 45^\circ \) inclination

**Kind**
For condenser length 2.4 m, width 1.2 m, height 4.5 m, \( T_a = 25^\circ C \)

**Figure 4.7** Correlations for wind heat loss coefficient
**Figure 4.8** Flow diagram of 'EFFICZ' (see Appendix B) A program to calculate the efficiency of a parapneustic air heating collector.
**INPUT**

Environmental parameters $I, v, T_a$

Collector configuration $(	heta_0, R, f, k, H, L, W, D, \ U_v, \ x)$

Collector variables $T_c, \ m$

Initial estimate of $T_f, T_m$

---

**CALCULATE**

- $R_c$  (see Equation 4.25)
- $N_x$  4.23
- $h_1, h_2$  4.22
- $h_r$  4.27
- $U_b$  4.4
- $U_L$  4.15
- $F'$  4.16
- $F_r$  4.20
- $Q_u$  4.19

**$\eta = Q_u/A_l$**

**CALCULATE NEW ABSORBER TEMPERATURE**

$T_{nf} = T_c + \frac{(Q_u/A_l)(1-F_r)}{U_L F_r}$

---

IF $T_f = T_{f_{new}}$

No

$[T_{f_{new}} - T_f] > \text{tol}$

No

OUTPUT

$z, T_f, U_L, U_v, U_b, V_e, F_r, F', Q_u$

Yes

---

**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 'Rradct'.

**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 KIVI 1966-1975)
SECTION X-X

DIRECTION OF FLUID FLOW

'MAXORB'

ABSORBER

'NEETEL'

BAMM DUCT BOTTOM

INSULATION

FIGURE 5.2  D.C. HALL COLLECTOR
**FIGURE 5.3**  ANGULAR VARIATION OF TRANSMITTANCE OF 2mm THICK POLYCARBONATE (REFRACTIVE INDEX = 1.586, EXTINCTION COEFFICIENT = 20 m⁻¹)

**FIGURE 5.4**  TEE-PIECES USED FOR ABSORBER FINS IN D.C. HALL COLLECTOR
Figure 5.5-5.6 Air heating collector made of structured polycarbonate.

Figure 5.7 Solar transmittance of structured polycarbonate versus incident angle. Source: H. L Redfret 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 72 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. WALL COLLECTOR DURING STEADY STATE EFFICIENCY TEST. POSITION OF COLLECTOR MILTON KEYNES, LATITUDE 52°, LONGITUDE 0.75° (HORIZONTAL).

FIGURE 5.16  ANGLE CORRECTION FOR D.C. WALL COLLECTOR
FIGURE 5.17(a) AIR HEATING COLLECTOR UNDER TEST WITH A LEAK AT THE INLET

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

FIGURE 5.19 Calibration curve for orifice plate for air at 20°C.
FIGURE 5.20  PRESSURE DISTRIBUTION WITHIN COLLECTOR TEST CONFIGURATION WITH AND WITHOUT FLUID FLOW

FIGURE 5.21  SAMPLE OUTPUT OF D.C. WALL COLLECTOR TO TESTING OUTDOORS NOT UNDER STEADY STATE CONDITIONS.
Figure 5.22  Steady state efficiency curve for D.C. Hall collector tested outdoors.

Figure 5.23  Steady state efficiency curve for structured polycarbonate collector tested outdoors.
FIGURE 5.24  UNCORRECTED EFFICIENCY CURVE WITH VARIATION OF WIND SPEED BETWEEN 0 - 4 m/s. SOURCE: [25].

FIGURE 5.25  EFFICIENCY CURVE CORRECTED FOR VARIATION IN WIND SPEED USING A NORMALIZING FUNCTION. SOURCE: [25].
FIGURE 5.26  VARIATION OF MASS FLOW RATE CAUSED BY CHANGE IN WIND SPEED
FIGURE 5.27 ROUND ROBIN TESTING OF LIQUID FLAT PLATE COLLECTORS. THE COMBINED EFFECT OF METEOROLOGICAL EXTREMES AND MEASUREMENT UNCERTAINTY. SOURCE: TAYLOR [28]

FIGURE 5.28 MEASURED DEPENDENCY OF $F(\eta_{CO_2})$ ON THE DIFFUSE FRACTION FOR A SINGLE-GLAZED FLAT-PLATE COLLECTOR. SOURCE: FORDISKI [34]
Figure 5.29  Computer generated steady state and transient efficiency curve for 0.5 mm absorber plates.
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 $F_e U_l$, $F_e (U_l)$, AND $\delta F_e U_l$ 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 SP COLLECTOR ON 14/6/93, 15/6/93.
Figure 5.30  Standard error in \( F_{UL} \) versus 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 (MANUAL ASST.). 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.
**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 $(T_e)_{out} = 0.72$ plotted against average air velocity parallel to collector plane and measured 5mm above collector plane.

**Figure 5.47** Measured and predicted heat loss $U_1$ for D.C. wall collector (non-selective) with varying wind speed indoors.
Figure 5.48  
Efficiency curve of structured polycarbonate collector measured indoors and outdoors.

Figure 5.49  
Efficiency curve of D.C. wall collector with non-selective absorber (Nextel). Indoor measurements and computer predictions.
FIGURE 5.50 REDESIGNED INDOOR COLLECTOR TEST FACILITY

FIGURE 5.51 STEADY STATE AND ZERO TESTING EFFICIENCY CURVES.
ASHRAE STEADY STATE

ZERO TESTING $T_{\text{sky}} = T_m - 20$

$T_{\text{sky}} = T_m$

**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 dyi under zero testing and a warm 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. Chahil type collector (maxima absorber).
Figure 5.6 
**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 (June to December)

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

**Figure 6.8**
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.

**Figure 6.11** Efficiency versus mass flow rate for structured polycarbonate collector. $I_{in} = 211 \text{ W/m}^2$, $T_a = 28^\circ\text{C}$, $T_{cover} > T_a$, $T_c = T_a$ 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 6.15  GLOBAL AND DIFFUSE INSOLATION MONTH BY MONTH AT 45° SOUTH FACING SLOPE.
FIGURE 6.16
ANNUAL ENERGY COLLECTED VERSUS COLLECTOR TEMPERATURE. COMPARISON
OF FIVE TYPES OF COLLECTOR. SOURCE [33].

FIGURE 6.17
INTEGRATED GLOBAL AND DIFFUSE SOLAR RADIATION FROM MARCH
TO OCTOBER AS A FUNCTION OF THE GLOBAL INTENSITY. SOURCE [35]
FOR SWEDEN.
Simulated ambient conditions. For further details see text in Appendix C.
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 4 and Figure 3).

(i) S0U/TAJ, flow 2  (ii) S0M/TAM, flow 2  (iii) S0D/TAD1, flow 2
(iv) S0M/TAM, flow 3  (v) S1M/TAM, flow 2  (vi) S0D/TAD1, flow 3
(vii) S1D1/TAD1, flow 2  (viii) S0D/TAD2, flow 3  (ix) S1D2/TAD1, flow 2
(x) S1D3/TAD1, flow 2  (xi) S1D/TAD1, flow 2.
Figure 6.20 'FMTC' air heating solar collector developed by GE [42].

Figure 6.21 Incident angle modifier for the FMTC prototype: this depends on the orientation of the cover. A - the maximum occurs when the plane of the angle of incidence is perpendicular to the cylindrical axes of the tubes in the cover. B - the maximum value occurs when the plane of the angle of incidence is normal to the cylindrical axes of the tubes in the cover [42].
Figure 6.22 Instantaneous efficiencies of the FMTC collector and a single glazed flat plate collector and their variation with insolation. [42]
**Figure 7.1** Thermal conductivity of various gases at 20°C versus molecular weight.

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

FIGURE 7.4  BASE FLOW BETWEEN INCLINED PLATES

FIGURE 7.6 SCHEMATIC DEPICTING EFFECT OF GAP SPACING ON CONDUCTANCE
**Figure 7.2**

Plot of $h_c$ versus plate separation $s$. $T_{air} = 150^\circ C$, $T_{wall} = 325^\circ C$, $D = 186$ mm.

**Figure 7.8**

$h_c$ versus tilt angle to the horizontal for air inundation for various absorber temperatures ($T_a$) with cover temp = $10^\circ C$. 

**Table 7.1**

<table>
<thead>
<tr>
<th>$T_a$ (°C)</th>
<th>$h_c (W/m^2K)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2.5</td>
</tr>
<tr>
<td>40</td>
<td>3.0</td>
</tr>
<tr>
<td>50</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Graph 7.3**

Graph showing the relationship between $h_c$ and the tilt angle of the absorber for different air temperatures ($T_a$).
Figure 7.9
Heat transfer coefficient variation with absorber temperature for convection and radiation.
**Figure 7.10** True and predicted heat loss between two parallel plates 5x 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, spacing $s = 6.0$ cm, cold plate temperature $10^\circ$C, hot plate $30^\circ$C.
FIGURE 7.12  Heat transfer coefficient for gases of different molecular weight, for S = 5 cm, cold plate temperature 10°C, hot plate temperature 30°C.
**FIGURE 7.14** VARIATION OF HEAT TRANSFER COEFFICIENT $h_c$ WITH PRESSURE FOR A FLAT PLATE COLLECTOR, $s = 5$ cm, $T = 293K$, $T_2 = 323K$ FOR CURVE 1, 273K FOR CURVE 2 AND 473K 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: HONOUDA, A. AND GARG, H. P. MINIMIZING CONVECTIVE HEAT LOSS. SOLAR ENERGY, VOL. 25, NO. 6, PS53.

**FIGURE 7.17** REFLECTED SOLAR RAYS FOR A MULTI COVER SOLAR COLLECTOR.
FIGURE 7.18 A SOlAR RAY AND CUT-AWAY DIAGRAM OF A HEXAGONAL HONEYCOMB COLLECTOR. SOURCE: HOLLANDS K.G.T. 'ADVANCED NON-CONCENTRATING SOLAR COLLECTORS' SOLAR ENERGY CONVERSION ED BY A.E. DIXON AND J.D. LESLIE. PERGAMON PRESS 1979
FIGURE 7.19 HEAT TRANSFER COEFFICIENT $h_c$ DUE TO NATURAL CONVECTION FOR AIR AT ATMOSPHERIC PRESSURE BETWEEN TWO PARALLEL FLAT PLATES SPACING $5 \text{ cm}$, $T_1 = 283 \text{ K}$, WITH A HONEYCOMB PAD WITH SLATS ASPECT RATIO 5
**Figure 7.20** Thermal Conductivity versus Rayleigh Number for various gases $T_1 = 10^\circ$C, $T_2 = 50^\circ$C, $g = 5$ cm/second.
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 Tc = 10°C
Figure 7.22 Heat transfer coefficients for several collector configurations

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

Figure 7.24
Guard Ring Unbalance Versus Measured Heat Transfer Across a 5 cm Thick 'Styrofoam' EP Sample
FIGURE 7.25 ACRYLIC TEST PANEL

FIGURE 7.26 SCHEMATIC DIAGRAM OF GUARDED HOT PLATE APPARATUS
**FIGURE 7.27 COPPER COLD PLATES.**

15mm DIAMETER Cu PIPE

TO TEMPERATURE CONTROLLED WATER BATH

SOFT SOLDER

3mm Cu SHEET
FIGURE 7.28  MEASURED AND THEORETICAL HEAT TRANSFER COEFFICIENTS FOR DIFFERENT GASES BETWEEN TWO PARALLEL PLATES, S = 5 cm, VARIOUS TEMPERATURE DIFFERENCE.
Figure 7.29 Theoretical and Measured Heat Transfer $h_c$ for Air and Argon
**FIGURE 7.30** THEORETICAL HEAT TRANSFER ACROSS STRUCTURED POLYCARBONATE OF VARIOUS THICKNESSES. BOTH RADIATION AND CONVECTION, ASSUMING FLAT CONVECTION AND A MEASURED EMISIVITY OF 0.72.
PLATE 21
PRO TO PROMETHEUS, 1. COLLECTOR, 2. STORE TOP INSULATION
AND COLLECTOR RR RR INSULATION, 3. FAN MOTOR 4. Menerynck
EQUIPMENT, 5. SPACE FOR INSULATION.
PLATE 2.2  PROTO PROMETHEUS STORAGE TANK FILLED WITH PEBBLES.
PLATE 5.1

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

VIEW OF HEATED OIL FILM FROM AN INFRARED CAMERA.

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

SUNSTORE: Computer model of interseasonal store and sample output.
10 REM **************************** SUNSTORE ****************************
20 LET W=10
30 SHORT DEMAND(12)
40 SHORT SOL(12,24)
50 ASSIGN 1 TO "SUN DATA"
60 READ# 1 ; SOL();
70 SHORT TEM(12,24)
80 ASSIGN 2 TO "TEM DATA"
90 READ# 2 ; TEM();
100 DIM MONTHs(12)(13)
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
180 PRINT "******************************* ON A HORIZONTAL SURFACE IN MJ/m2 ****************************
190 PRINT "*******************************";
200 IMAGE \\
210 PRINT USING 220
220 IMAGE "*********** SOLAR RADIATION AT KEW DISTRIBUTION OF HOURLY GLOBAL IRRIGATION ***********
230 "*********** ON A HORIZONTAL SURFACE IN MJ/m2 ***********"
240 PRINT TAB (64M):MONTHs(M):;
250 NEXT M
260 FOR H=1 TO 24
270 FOR M=1 TO 12
280 PRINT TAB (64M):SOL(M,H); TOTSUN=TOTSUN+SOL(M,H);DAYS(M)! calculate total annual solar radiation.
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 FIX,9 ! HEAT TRANSFER FACTOR
360 c=5,837 ! SPECIFIC HEAT OF STORE MATERIAL (kJ/KGC)
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 SERVED BY STORE
420 DENSITY=1600 ! DENSITY OF STORAGE MATERIAL (Kg/m3)
430 "m"=1 ! OVERALL COLLECTOR HEAT LOSS COEFFICIENT (W/m2)
440 COLAREA=2800 ! TOTAL AREA OF COLLECTORS SERVING STORE (m2)
450 COND=.036 ! THERMAL CONDUCTIVITY OF STORAGE INSULATING MATERIAL (W/m2C)
460 THICK=.6 ! THICKNESS OF INSULATING MATERIAL (m2C)
470 Tm,B ! OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES
480 YEARS=1 ! NUMBER OF YEARS PROGRAM TO RUN DO NOT USE MORE THAN 1 IF gaUX=0
490 Tg=10 ! TEMPERATURE OF GROUND SURROUNDING STORE (C)
500 TGX=30 ! MINIMUM STORAGE TEMPERATURE (C)
510 REM **************************** STORE **************
520 REM **************************** calculate storage volume
530 REM **************************** storage volume per house
540 REM **************************** mass of store per house in 1000 Kg normalized mass mass per m2 collect;
550 REM **************************** store surface area per m2 of collect;
560 REM **************************** store heat loss(U-value)
570 REM ****************************
580 REM ****************************
590 REM ****************************
600 REM ****************************
610 REM ****************************
620 REM ****************************
630 REM ****************************
640 REM ****************************
650 REM ****************************
660 REM ****************************
670 REM ****************************
680 REM ****************************
690 REM ****************************
700 REM ****************************
710 REM ****************************
720 REM ****************************
730 VOL=WIDTH*HEIGHT*LENGTH !
740 VOLH=VOL/HOUSE !
750 MASM=VOLH*DENSITY/1000 !
760 m=MASS/(COLAREA/HOUSE) !
770 AREAVERAGE=WIDTH*HEIGHT/(LENGTH+2)*HEIGHT+LENGTH*LENGTH ! store surface are.
780 s=AREASTO/COLAREA! store surface area per m2 of collect.
790 US=COND/THICK !
800 US=COND/THICK
810 PRINT USING B20
820 IMAGE \\
830 PRINT "STORE LENGTH="LENGTH;"Meters"; WIDTH="WIDTH;"Meters"; HEII="HEIGHT;"Meters"; W40 "VOLUME="VOL;"m3";
850 PRINT "STORAGE MATERIAL "METE"; DENSITY="DENSITY;"Kg/m3"; SPECIFI
860 PRINT "STORE INSULATION THICKNESS="THICK;"m"," THERMAL CONDUCTIVITY="CONI
870 PRINT USING B80
880 IMAGE \\
890 PRINT "TOTAL COLLECTOR AREA="COLAREA;"m2"
900 PRINT "Fi=HEAT TRANSFER FACTOR=equivalent to Fr heat removal factor if st; has a good heat heater";Fi
910 PRINT "UL=OVERALL HEAT LOSS COEFFICIENT;=UL"
920 PRINT "Ta-OPTICAL EFFICIENCY AVERAGED OVER USEFUL INCIDENT ANGLES;=Ta
930 PRINT USING 940
940 IMAGE \\
950 PRINT "NUMBER OF HOUSES=";HOUSE
960 PRINT "THE MONTHLY HEATING LOAD FOR EACH HOUSE IS (heating and hot water);"
970 FOR Kr=1 TO 12
980 REM **************************** DATA **************
990 READ DEMAND(K) ! READS MONTHLY DATA OF HEATING LOAD FOR EACH HOUSE(MJ)
0100 REM
0110 PRINT TAB (10); "TMTH = (TSO+TSD)/2; " 'temperature

0120 IF TSD<TMTH THEN TSD=TMT
0130 IF TSD>TMTH THEN TSD=TMT+1
0140 PRINT TSD

0150 PRINT "ADJUSTMENT"
0160 PRINT "THROUGH寒冷年月"
0170 PRINT "temperature adjustment needs to be made"
0180 PRINT "for the following months:"
0190 PRINT "JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC"
0200 PRINT "and then add "
0210 PRINT "ADJUSTMENT"
0220 PRINT "to the current temperature"
### SOLAR-RADIATION-AT-NEW-DISTRIBUTION OF HOUFLY-GLOBAL IRADIATION-********

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<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
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<td>0.94</td>
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<td>0.15</td>
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</table>

TOTAL ANNUAL SOLAR RADIATION = 410.94 MJ/m²

### STORE ********

<table>
<thead>
<tr>
<th>STORE LENGTH</th>
<th>280 Meters</th>
<th>WIDTH</th>
<th>10 Meters</th>
<th>HEIGHT</th>
<th>4 Meter</th>
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</thead>
<tbody>
<tr>
<td>VOLUME (V)</td>
<td>11200 m³</td>
<td></td>
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<tr>
<td>STORAGE MATERIL PEBBLES</td>
<td>DENSITY = 1600 kg/m³</td>
<td>SPECIFIC HEAT = 0.837 KJ/Kg°C</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>STORE INSULATION THICKNESS = .6 m</td>
<td>THERMAL CONDUCTIVITY = 0.056 W/m²°C</td>
<td></td>
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</table>

### COLLECTOR ********

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

### HOUSE ********

| NUMBER OF HOUSES | 100 |
| THE MONTHLY HEATING LOAD FOR EACH HOUSE IS (heating and hot water) MJ |
| JAN | 7750 |
| FEB | 6490 |
| MAR | 5560 |
| APR | 3320 |
| MAY | 980 |
| JUN | 770 |
| JUL | 770 |
| AUG | 770 |
| SEP | 770 |
| OCT | 1790 |
| NOV | 5270 |
| DEC | 7450 |
| TOTAL ENERGY DEMAND OF HOUSE PER ANNUM | 41.69 GJ (11580.555556 kWh) |

### SYSTEM OPERATION ********

| ITH | Original Store Temperature at the beginning of month |
| Tso | Ambient Temperature Averaged over periods of collector operation |
| tT | Time Period of Collector Operation (MJ) |
| It | Total Radiation which is above Threshold (MJ/m²) |
| qN | Normalized Net Heat to Storage = qT - Ie - Is (MJ/m²) |
| tsf | Store Temperature at the end of the month (MJ) |
| qU | Useful Heat Collected = qN + Is (MJ/m²) |
| Is | Normalized Total Monthly Load (MJ/m²) |
| qaux | Auxiliary Heat = Is + (MJ/m²) |

| APR | 29.00 |
| 30 | 10 |
| 1.296 | 350.7 |
| 88. | 46.4 |
| 206.67 | 118.57 |
| 12.4 | 0. |
| MAY | 25.13 |
| 46 | 13 |
| 1.562 | 477.1 |
| 209. | 85.5 |
| 243.97 | 35.0 |
| 35.4 | 0. |
| JUN | 21.13 |
| 65 | 16 |
| 1.728 | 549.9 |
| 192. | 121.2 |
| 219.16 | 27.50 |
| 41.1 | 0. |
| JUL | 18.25 |
| 121 | 19 |
| 1.674 | 513.1 |
| 116. | 142.8 |
| 143.08 | 27.50 |
| 55.5 | 0. |
| AUG | 18.38 |
| 143 | 18 |
| 1.562 | 424.4 |
| 36. | 149.6 |
| 63.88 | 27.50 |
| 61.9 | 0. |
| SEP | 21.50 |
| 150 | 16 |
| 1.296 | 306.3 |
| -21. | 145.6 |
| 6.27 | 27.50 |
| 60.5 | 0. |
| OCT | 25.25 |
| 146 | 12 |
| 1.116 | 186.0 |
| -110. | 125.0 |
| -46.56 | 63.93 |
| 27.0 | 0. |
| NOV | 25.50 |
| 8 | 12 |
| 0.864 | 93.3 |
| -236. | 81.0 |
| -47.47 | 188.21 |
| 40.9 | 0. |
| DEC | 30.50 |
| 81 | 7 |
| 0.670 | 53.0 |
| -251. | 30.0 |
| 15.06 | 266.07 |
| 9.1 | 22. |
| JAN | 32.38 |
| 30 | 5 |
| 0.670 | 60.8 |
| -257. | 30.0 |
| 19.80 | 276.79 |
| 9.1 | 257. |
| FEB | 32.25 |
| 30 | 6 |
| 0.806 | 120.4 |
| -171. | 30.0 |
| 60.93 | 231.79 |
| 8.2 | 171. |
| MAR | 31.25 |
| 30 | 7 |
| 1.116 | 241.5 |
| -57. | 30.0 |
| 141.99 | 198.57 |
| 9.1 | -57. |

TOTAL | -462 |
| 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 (35943.3551803 kWh)
AUXILIARY ENERGY PER HOUSE: 129599.6078649 MJ (3594.33521803 kWh)

---

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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.
10 REM **************************************** PROGRAM TOPAIR ****************************************
20 REM **************************** CALCULATE THE TOP LOSS COEFFICIENT FOR A SINGLE GLASS TYP ****************************
30 REM
40 FOR I=0 TO 20
50 FOR J=0 TO 20
60 TP=10+185 ! ABSORBER TEMP
70 TA=10 ! Ambient temp (C)
80 WIND=1 ! Wind speed (ms-1)
90 EP=0.95 ! Absorber emissivity
100 E=0.8 ! Cover plate emissivity
110 S=0.1 ! Plate separation (cm)
120 G=9.812 ! Acceleration due to gravity (ms-2) at LONDON
130 K=0.0257 ! Thermal conductivity of gas at Tave (Wm-20C)
140 B=0 ! 11t angle=0(Horizontal)
150 CP=1007 ! Heat capacity of air (J/kgK)
155 CP=1007 ! Heat capacity of GAS BETWEEN COVER AND ABSORBER/kgK
160 S=0.1/100 ! CONVERT TO METERS
170 L=1
180 W=1
190 SW=2TLW/(L+W)
200 REM
210 Tc=TA+(TP-TA)/2 ! guess the cover temp
220 T1=273.15*C ! CONVERT TO KELVIN
230 T2=273.15*C ! CONVERT TO KELVIN
240 Tc=273.15*C ! CONVERT TO KELVIN
250 TP=TP-273.15 ! CONVERT TO KELVIN
260 Tc=TP ! CONVERT TO KELVIN
270 DT=T2-T1 ! TEMP DIFFERENCE DELTA T
280 Tave=(T1+DT)/2 ! AVERAGE GAS TEMPERATURE
290 D=0.035 ! Kelvin
300 n=0.00074+0.00344/6
310 VIS=Tc^4*0.00000046+0.000004351
320 VOL/V=1/Tave ! THERMAL VOLUME EXPANSION COEFFICIENT ONLY HOLDS FOR PERFECT GAS
330 V=VIS/DEN ! KINEMATIC VISCOSITY
340 Gr=G*VOL*3*DT/V^2 ! GRAHAM NUMBER
350 Pr=CP/Vis/K
360 Ra=Gr*Pr ! RAYLEIGH No
370 REM ****************************CALCULATE NUSSELT NUMBER **********************************
380 N=1-170/Ra(COS (B))/5830/(1-1)
390 IF N<0 THEN N=0 ! TAKE ONLY POSITIVE TERMS
400 N2=170/Ra(COS (B))/5830
410 IF N<0 THEN N=0 ! TAKE ONLY POSITIVE TERMS
420 Nu=1.44N1-(1-SIN (1.8B))1.6*170/Ra(COS (B)) ! NUSSELT No
430 h=K/SINU ! HEAT TRANSFER COEFFICIENT
440 hr=0.000000067*(TP+2*TC^2)*(1+EP/1/EC-1) ! RAD FROM PLATE TO COVER
450 hs=y=0.00000067*EC(TC+2*TA^2)*(TC+TA) ! RAD COVER TO SKY
470 DT=TA+DT/V
480 Ta=Ta+DTH/2
490 D=0.035 ! Kelvin
500 W=0.00076+0.00344/6
510 VS=VIS/DEN=0.00000046+0.000004351

---
910 PRINT USING "7A,DDD, DD, 2A, DD, DD, 2A" ! COVER TEMPERATURE=",Tc","Tc-273.15","C"
915 NEXT I
920 END
10 REM **************************** EFFIC ****************************
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 p237 Figure 6.12.1 (d)
50 REM
60 REM **************************** INPUT VARIABLE DATA ****************************
70 FOR J=0 TO 10
80 n1=14+J*10  ' MASS FLOW RATE (kg/hr)
90 Ta=16.2  ' AMBIENT TEMP (°C)
100 T1=20.4  ' ABSORBER TEMPERATURE (°C) IF THIS CHANGES ALSO CHANGE T3
110 T3=(T2-TA)/2+TA
120 WIND=-5  ' WIND SPEED (m/s)
130 T=236  ' INTENSITY OF SOLAR RAD (W/m2)
140 E=0.8  ' TRANSMISSIVITY & ABSORPTIVITY OF COVER AND ABSORBER
150 E2=0.45  ' EMISIVITY OF ABSORBER
160 L=3.4  ' CONDUCTIVITY OF REAR INSULATION (W/m°C)
170 T1=0.075  ' INSULATION THICKNESS (m)
190 A=1  ' COLLECTOR AREA (m2)
200 L=2  ' COLLECTOR LENGTH IN METERS
210 W=1  ' WIDTH OF COLLECTOR IN METERS
220 S=1  ' PLATE SEPARATION IN CM
230 S=1  ' FIN SEPARATION IN CM
240 DISP "DO YOU WANT ALL THE COLLECTOR PARAMETERS PRINTED Y OR N ?????"
245 IF Y=0 THEN GOTO 470
250 INPUT A$  ' IF A$="N" THEN GOTO 470
260 IF A$="N" THEN GOTO 470
270 PRINTER IS 701
280 PRINT "#----------------- COLLECTOR INITIAL PARAMETERS ARE -----------------#"
290 PRINT USING 930  ' "MASS FLOW RATE",M,"Kg/hr"
300 PRINT USING 930  ' "AMBIENT TEMP",TA,"°C"
310 PRINT USING 930  ' "INLET FLOW TEMP",TIN,"°C"
320 PRINT USING 930  ' "ABSORBER TEMP",T2,"°C"
330 PRINT USING 930  ' "WIND SPEED",WIND,"m/s"
340 PRINT USING 930  ' "SOLAR RADIATION",T,"W/m2"
350 PRINT USING 930  ' "TRANSMISSIVITY & ABSORPTIVITY",Ta
360 PRINT USING 930  ' "EMISIVITY OF COVER ",E1
370 PRINT USING 930  ' "EMISIVITY OF ABSORBER ",E2
380 PRINT USING 930  ' "INSULATION CONDUCTIVITY",K1,"W/m°C"
390 PRINT USING 930  ' "INSULATION THICKNESS",T1,"m"
400 PRINT USING 930  ' "COLLECTOR AREA",A,"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 "#----------------- INPUT CONSTANT DATA -----------------#"
480 BET=.00000000567  ' STEFAN-BOLTZMANN CONSTANT (W/m2K4)
490 VISC=.0001888  ' VISCOITY OF AIR IN DUCT (kg/m2)
500 k=0.0241  ' THERMAL CONDUCTIVITY OF AIR IN DUCT (W/mK)
510 C=1000  ' HEAT CAPACITY OF AIR AT CONSTANT PRESSURE (J/Kg°C)
520 REM
530 T1=11273.15  ' KELVIN
540 T2=T1+15  " #----
550 M=M/3600  ' CONVERT TO Kg/s
560 S=S/100  " #----
570 D=D/100  " #----
580 N=W/D  ' CALCULATE NO OF COMPARTMENTS
590 MM=M/N  ' CALCULATE MASS FLOW RATE IN EACH COMPARTMENT
600 F=245+2*D  ' DIAMETER OF DUCT
610 AF=8*D  ' CROSS SECTIONAL AREA OF COMPARTMENT
620 DH=4*AF  ' HYDRAULIC DIAMETER
630 RE=M*DH/(AF*VIS)  ' REYNOLDS NUMBER
640 D=L/DH  ' LENGTH TO DIAMETER RATIO
650 NUM=.0158*RE  ' RESULT NUMBER AT INFINITY
652 CON=14.3*log(L/DH)-7.9
653 IF L/DH<60 THEN CON=1.5
654 NU=NUM*(CON*DH/L)
660 H=H*KND/DH  ' HEAT TRANSFER FROM COVER TO WORKING FLUID
670 H2=H1+H  ' HEAT TRANSFER COEFFICIENT W/M°C
680 HR=STEM*(T1+T2)/((T1+T2)/2/(1/E1+1/E2)-1)  ' RADIATION HEAT TRANSFER
690 UB=K1/T1  ' BOTTOM LOSS DUE TO INSULATION
700 UT=5.7*3.6*WIND  ' TOP LOSS DUE TO WIND
710 UL=(UB*UT)*((H1+H2)/(H1+H2+H2*UT+H2*H1+H1*H2))
720 DISP "THE U-VALUE OF THE COLLECTOR IS ":UL/"W/m°C"
730 F1=(H1+H2*UT+H2*H1)/(H1+H2+H2*UT+H2*H1+H1*H2)
740 DISP "THE COLLECTOR EFFICIENCY FACTOR IS":FR
750 CAP=MIC/(AVL*FL)  ' DIMENSIONLESS CAPACITY RATIO
760 F2=CAP*(1-EXP(-1/CAP))  ' COLLECTOR FLOW RATE
770 FR=2*F1  ' COLLECTOR HEAT REMOVAL FACTOR
780 DISP "THE COLLECTOR HEAT REMOVAL FACTOR IS":FR
790 DUALAFR=(I1Af=L*(T1-TA))  ' USEFUL ENERGY GAIN (W/m2)
800 EFF=MC*(UAFR/AFR)
810 DISP "THE EFFICIENCY IS ":EFF
820 TOUT=TIN+OU/MIC  ' OUT LET TEMPERATURE
830 DISP "THE FLUID OUTLET TEMPERATURE IS ":TOUT/"°C"
840 END
850 DISP "DO YOU WANT HARD COPY OF RESULTS ???????????????"
860 INPUT B$  ' UF
870 DISP "BYE BYE"  THEN PRINTER IS 701
875 IF Y>0 THEN GOTO 890
880 PRINT " "
890 PRINT USING 940  ' M,RE,NU,HR,UB,UL,UT,FR,OU,EFF,(T1-TAMB)/Tout
900 IF B$="Y" THEN PRINTER IS 1
910 NEXT J
920 END
930 IMAGE 25A,DDDD.DDDD,XX,10A
940 IMAGE 3D.D,7D.D,DDD.D,DDD,DDD,DDD,DDD.D,DDD.D,DDD.D,DDD.D,DDD.D,DDD.D,DDD.D,DDD.D,DDD.D,DDD.D
APPENDIX C

THE EFFECT OF THERMAL CAPACITANCES ON THE PERFORMANCE OF SOLAR COLLECTORS

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

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

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY1-5</td>
<td>plate and duct-back thicknesses (5)</td>
</tr>
<tr>
<td>f(θ)</td>
<td>transmittance - absorptance function of the collector</td>
</tr>
<tr>
<td>F_R</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 cover | polycarbonate, thickness 2.00 mm |
| Plate absorptance | 0.95 at θ=0, falling slightly as θ increases |
| Emissivity of upper surface of the plate (diffuse) | 0.10 |
| Emissivity of duct surfaces (diffuse) | 0.91 |
| Emissivity of the cover (diffuse) | 0.85 |
| Thermal properties of air at 283 K for ambient air, at 303 K elsewhere |
| Latitude | 52° N |
| Collector tilt (to horizontal) | 35° |
| Collector orientation | South-facing |
| Thickness of plate and of duct-back | Collector time-constant (flow 1) |
| DY1 | 0.2 mm | 85 s |
| DY2 | 0.5 mm | 170 s |
| DY3 | 1.0 mm | 300 s |
| DY4 | 2.0 mm | 580 s |
| DY5 | 5.0 mm | 1400 s |

Air flow in the rear-duct

<table>
<thead>
<tr>
<th>Flow</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Stagnation (M=0)</td>
</tr>
<tr>
<td>1</td>
<td>All TI M = 0.0600 kg s^{-1} (PON irrelevant)</td>
</tr>
<tr>
<td>2</td>
<td>TI = 303 K M = 0.0600 kg s^{-1} PON = 128 W</td>
</tr>
<tr>
<td>3</td>
<td>TI = 323 K M = 0.0562 kg s^{-1} PON = 124 W</td>
</tr>
</tbody>
</table>

The air flow rate is a compromise between attaining large values of HPA(I) and keeping low the power required to maintain the air flow in the rear-duct. At M = 0.0600 kg s^{-1} and TI = 303 K (flow 2 in Table 1) this power is 6.4 W. The corresponding pressure drop across the duct is 12 mm water gauge. If it is
assumed that the circulation fan gives a constant volumetric flow rate then at
other values of $T_i$ the value of $M$ will be different from $0.0600 \text{ kg s}^{-1}$. 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 $128 \text{ W}$ 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 $4 \text{ m} \times 1 \text{ m}$ collector, and not for the whole array.
These values of $PON$ correspond to an air temperature rise of between $2 \text{ K}$ and $3 \text{ K}$
for the flow conditions specified.

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

3.2 Steady-state efficiency curve

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

$$\eta = \frac{F_R (f(\theta) - U_L (T_i - T_A)/S)}{SP}$$  \hspace{1cm} (1)

where $f(\theta)$ is such that

$$SP = f(\theta)S$$  \hspace{1cm} (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 (TA, 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 DYL 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 $S_0$ denoting the clear sky irradiance normal to the  
beam, and the prefix $S_1$ the overcast diffuse irradiance on a horizontal surface.  
In the cases in Figure 3(b) the only variation in insolation is the diurnal  
envelope shown. By contrast in Figures 3(c) and (d) the insolation flips between  
the two envelopes shown, the square wave periods being indicated, the conditions  
remaining diffuse throughout. In clear sky conditions the sky temperature is 20 K  
below TA, and in overcast conditions it is 10 K below TA. In all cases the wind  
speed is constant at 1.0 m s$^{-1}$.  

For each "day" an average thermal efficiency was obtained, defined by  
$$\eta = \text{total energy extracted by the air flow in the day/integration of } S \text{ over the }$$  
$$\text{day.} \tag{3}$$  

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

In order to plot $\eta$ on Figure 2 it is necessary to re-define the abscissa ($T_I-T_A)/S$.  
$T_I$ is constant (303 K or 323 K), and for $T_A$ 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 DYL 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 DYL is at  
the top, then comes DY2, and so on, to DY5, though in some cases DYL-DY3 merge on  
the scale of Figure 2. Clearly, the lower the thermal capacitance the better the  
performance.

Consider first those cases in which the insolation only varies over the diurnal  
envelope: this covers the cases (i)-(vi), (viii), (xi). The increase in $\eta$ is  
marked in going from the rather massive DY5 to the rather less massive DY4.  
However, the improvement in going from DY4 to the low mass DYL 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 $T_A$ and  
$T_K$ do not make an appreciable contribution to the spread of $\eta$ with thermal  
capacitance on the scale of Figure 2.

The advantage of low mass could, in principle, be more marked under intermittent  
insolation. S1D1-S1D3 provide such conditions (Figure 3), the periodicities  
lying within the range of time-constants in Table 1. However, Figure 2 shows that,  
even in marginal conditions, very little further advantage in low mass is obtained,  
though DYL-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 $\overline{n}$ differ from those of $\bar{n}$. This is particularly the case at low thermal capacitances, as can be seen from the performance of DY1, which is not very different from that which would have been obtained for a collector of zero thermal capacitance. Two prominent and opposing effects operating here are that for $\bar{n}$ in Figure 2 the value of $\theta$ is always zero, thus raising $\delta f(\theta)$, 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 $\overline{n}$, the daily average of $\overline{T}_0$ was also obtained, such that only those periods were included in which air flowed in the rear duct. In general the lower the thermal capacitance of the collector the higher the daily average, though the improvement from DY5 to DY1 never exceeded 2 K. However, the peak temperatures for DY1 can be up to about 10 K higher than for DY5, the greatest difference occurring in intermittent conditions. In some circumstances this will be an important advantage of low thermal capacitance.

A set of results analogous to those in Figure 2 was obtained for lower flow rates, around 0.02 kg s$^{-1}$. This is a potentially useful domain, because in spite of the lower thermal efficiencies the values of $\overline{T}_0$ are raised and can reach values such that useful energy can be extracted from ambient conditions which would yield no useful energy at higher flow rates, because of the lower values of $\overline{T}_0$. However the variation of $\overline{n}$ with thermal capacitance (DY1-DY5) was not remarkably different from that shown in Figure 2.

It can be concluded that collectors with low thermal capacitance can have significantly larger thermal efficiencies at non-small daily averaged values of $(T_{1}-T_{A})/S$ in non-steady insolation, and that this is largely because of the diurnal variation, rather than because of more rapid fluctuations in insolation. Peak temperatures can also be significantly larger at low thermal capacitance, particularly when there are rapid fluctuations in insolation.

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.

- nodes in airflow
- other nodes
Figure 2  Steady-state efficiency ($\eta_0$ - the solid curve) and daily averaged efficiency ($\bar{\eta}$). The values of $\eta$ are for a variety of simulated conditions (see Table 1 and Figure 3).

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

TRANS: Computer program for analysing collector data under transient conditions.
250 DIM E(16,16),X(16),I(16),J(16),PT(16,16),ZY(16),XY(16)
4 FOR N=1 TO 8
45 SIGNED=1 TO "Program"
51 FOR T=1 TO 16
52 FOR Z=1 TO 16
53 F(2T,2Z)=0 & PT(2T,2Z)=0 & XY(2T,2Z)=0 & ZZ(2T,2Z)=0
54 NEXT Z
55 NEXT T
60 H=22.3 / NC/A
61 YY=0
62 NF=0
63 ZE=0
64 E=0
66 SXX=0
67 SXY=0
68 SYX=0
70 NC=NC+1
75 DNK=DNK
80 FOR K=1 TO NC
90 P(K,K)=1
100 NEXT K
110 READ I,J,X(NK),Y(L)
115 IF I=0 AND X(NK)=0 THEN GOTO 650
120 I=I+1
130 FOR K=2 TO NK
140 L=LNK+K-L
150 READ I,J,X(L),Y(T)
155 IF I=0 AND X(L)=0 THEN GOTO 650
160 IF I=I THEN GOTO 110
170 I=I+1
180 Z(L)=INT (X(L)/100)/10
190 NEXT K
200 GOTO 300
210 FOR K=2 TO NK
220 L=LNK+K+2
230 X(L)=X(L-1)
240 Z(L)=Z(L-1)
250 T(L)=T(L-1)
260 NEXT K
270 READ I,J,X(1),Y(I)
275 IF I=0 AND X(I)=0 THEN GOTO 650
280 IF I=I THEN GOTO 110
290 I=I+1
295 Z(I)=INT (X(I)/100)/10
300 X(NC)=0
310 FOR K=1 TO NC
320 X(NC)=X(NC)+T(K)
330 NEXT K
340 Y(NC)=Y(NC)+SQR
350 Z(NC)=INT (X(NC)/2)/50
360 DENOM=P+1
270 FOR K=1 TO NC
280 FOR I=1 TO NC
290 I=I+1
300 IF I=655 THEN GOTO 210
310 YY=YY*YY
320 FOR K=1 TO NC
330 ZY(K)=ZY(K)+Z(K)*Y
340 NEXT K
350 NEXT I
360 IF DENOM=1 THEN GOTO 210
370 YY=YY*YY
380 FOR K=1 TO NC
390 IF K=1 THEN GOTO 210
400 P(K,L)=F(K,L)-PT(K,L)/DENOM
410 NEXT L
420 NEXT K
430 NEXT I
440 NEXT K
450 IF A(V) (DENOM)<>1 THEN GOTO 210
460 YY=YY*YY
470 FOR L=1 TO NC
480 YY=YY*YY
490 NEXT L
500 PT(K,L)=0
510 FOR M=1 TO NC
520 FOR N=1 TO NC
530 PT(K,L)=PT(K,L)+P(K,M)*X(N)*Z(M)*P(N,L)
540 NEXT N
550 NEXT M
560 NEXT L
570 NEXT K
580 FOR F=1 TO NC
590 FOR L=1 TO NC
600 P(K,L)=P(K,L)-PT(K,L)/DENOM
610 NEXT L
620 NEXT K
630 NP=NF+1
640 GOTO 210
650 IF NF<>NC THEN STOP 1 STOP IF NOT ENOUGH DATA POINTS
651 REM EVALUATES ESTIMATES OF PARAMETERS AND STANDARD ERRORS
655 FOR K=1 TO NC
660 X(K)=0
670 FOR L=1 TO NC
680 X(K)=X(K)+P(K,L)*Z(L)
690 NEXT L
700 NEXT K
710 FOR K=1 TO NC
720 YY=YY-2*X(K)*XY(K)
730 FOR L=1 TO NC
740 YY=YY+X(K)*X(K)*X(L)
750 NEXT L
760 NEXT K
770 FOR K=1 TO NC
780 FOR L=1 TO NC
790 PT(K,L)=0
800 FOR M=1 TO NC
810 FOR N=1 TO NC
820 PT(K,L)=PT(K,L)+P(K,M)*X(N)*Z(M)*P(N,L)
830 NEXT N
840 NEXT M
850 NEXT L
860 Z(K)=SQR (PT(K,K)*Z(K)/(NP-NC))
870 NEXT K
880 PRINT "TABLE F.3"
890 FOR K=1 TO NC
900 PRINT K,X(K),Z(K)
910 END
920 FOR L=1 TO NC.
1550 NEF=1
1560 GOTO 1220
1570 DNF=NF
1580 PRINT "POINTS ON THERMAL PERFORMANCE CHARACTERISTIC":NF
1590 PRINT "FROM LEAST SQUARES FITS EACH WAY"
1600 E=(SY*SY-SX*SX)/((DNF*SY-SX)*SY)
1610 U=(SX*SY-DNF*SY)/(DNF*SY-SX*SX)
1620 PRINT "MINIMUM ETAO"="E,"U"="U"
1630 E=(SY*SY-SX*SX)/((DNF*SY-SX)*SY)
1640 U=(SY*SY-DNF*SY)/(DNF*SY-SX*SX)
1650 PRINT "MAXIMUM ETAO"="E,"U"="U"
1655 NEXT NK
1660 STOP
1670 END

1100 REM READ DATA TO GENERATE THERMAL PERFORMANCE CURVE
1110 ASSIGN 1 TO "TRANS700"
1120 NP=0
1130 READ #1 : I,X(NK),Y,T(NK)
1135 IF I=0 AND X(NK)=0 THEN GOTO 1570
1140 I=I+1
1150 FOR K=2 TO NK
1160 L=NK-K+1
1170 READ #1 : I,X(L),Y,T(L)
1175 IF I=0 AND X(L)=0 THEN GOTO 1570
1180 IF I=1 THEN GOTO 1130
1190 I=I+1
1200 NEXT K
1210 GOTO 1400
1220 FOR K=2 TO NK
1230 L=NK-K+2
1240 X(L)=X(L-1)
1250 T(L)=T(L-1)
1260 NEXT K
1270 READ #1 : I,X(I),Y,T(I)
1275 IF I=0 AND X(I)=0 THEN GOTO 1570
1280 IF I=1 THEN GOTO 1150
1290 I=I+1
1300 E=0
1310 X(NC)=0
1320 FOR K=1 TO NK
1330 E=E+X(K)X(K)
1340 T(NC)=X(NC)+T(K)
1350 NEXT K
1360 Y=Y/(FRE)
1370 X(NC)=X(NC)/Y
1380 PRINT Y,X(NC)
1390 REM CALC LEAST SOR TO THERMAL PERFORMANCE
1400 SX= SX+X(NC)
1410 SY= SY+Y
1420 SK= SY+Y
1430 SY= SY+Y
1440 SY= SY+Y
1450 SY= SY+Y