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ACTIVE CHARGE/PASSIVE DISCHARGE SOLAR HEATING SYSTEMS: THERMAL ANALYSIS AND PERFORMANCE COMPARISONS

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PREFACE

This study presents the development of a simplified thermal analysis method for active charge/passive discharge solar space-heating systems. Thermal performance results are used for cost/performance comparisons with other solar designs. Although systems of this type are now being installed, this is the first detailed analysis of their performance.

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SUMMARY

OBJECTIVE

The objective of this study is to develop a simplified thermal analysis method for active charge/passive discharge solar space-heating systems and to make cost/performance comparisons with other solar designs.

DISCUSSION

This study analyzes the performance of active charge/passive discharge solar space-heating systems. This type of hybrid system combines liquid-cooled solar collector panels with a massive integral storage component that passively heats the building interior by radiation and free convection.

Although systems of this type are now being installed, there has been little detailed analysis, simulation, or testing of their performance. Simplified tools for active or passive system analysis are not adequate because neither can include both the active collector component and the passive storage-to-room coupling.

The TRNSYS simulation program is used to evaluate system performance and to provide input for the development of a simplified analysis method. This method, which provides monthly calculations of delivered solar energy, is based on Klein's Phi-bar procedure and data from hourly TRNSYS simulations. Correlations are developed to estimate monthly average collector temperature as a function of absorbed solar radiation, building load, storage capacity, and storage-to-room conductance. In the Phi-bar technique, this temperature is used, along with other system parameters and radiation data, to determine the usable fraction of the absorbed radiation. The method also accounts for energy dumped to prevent overheating and energy lost to the ground in cases where the floor slab is used as the storage component.

The method can be applied to systems using a floor slab, a structural wall, or a water tank as the storage component. Important design parameters include collector area and orientation, building heat loss, collector and heat-exchanger efficiencies, storage capacity, and storage-to-room coupling. The coupling and storage capacity are critical factors in an active charge/passive discharge system. If either is too small, the storage component will get too warm and result in poor system performance and an uncomfortable interior environment.

CONCLUSIONS AND RECOMMENDATIONS

The simplified analysis method predicts annual solar fraction with a standard error of 3% with respect to TRNSYS simulations. Experimental results for a system in Davis, Calif., monitored during February 1980, produced a solar fraction within 0.5% of the analytical prediction.

The performance of active charge/passive discharge designs is comparable to active and passive designs in a range of climatic conditions. System costs show an economic advantage over active systems. Active charge/passive discharge systems are less certain to be

competitive with passive systems. Benefits include integration of heating components with structural members, contribution to cooling and hot water loads, architectural flexibility, and comfort advantages.

Future work should seek more rigorous field validation and extension of the analysis approach to systems that use air as the heat-transfer fluid.

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NOMENCLATURE

A_c	collector area
C_{st}	total heat capacity of the storage component
$DD(T_b)$	monthly degree-days based on the balance-point temperature
e_{hx}	collector heat-exchanger effectiveness
f_s	slab heat loss factor
F_{solar}	annual solar fraction
F_R'	collector removal factor with heat-exchanger correction (see Ref. 20)
H_T	total monthly radiation on collector surface
H_n	average radiation on collector surface at noon
I_c	critical radiation level (see Ref. 3)
$\bar{K}_t$	average ratio of total to extraterrestrial radiation on a horizontal surface
p	exposed slab perimeter
P_L	monthly ratio of absorbed solar energy to heating load
P_R	monthly ratio of absorbed solar energy to storage-to-room heat-transfer capacity
P_S	monthly ratio of absorbed solar energy to storage capacity
Q_A	monthly absorbed solar energy
Q_D	monthly usable solar energy lost due to increased interior temperature
q_g	slab heat loss
q_i	internal heat production
Q_L	monthly building heating load (includes slab heat losses)
Q_S	monthly net solar energy contributed to the building load
Q_U	monthly usable solar energy
$\bar{R}$	ratio of average daily radiation on collector surface to average daily radiation on a horizontal surface
R_n	ratio of radiation on collector surface to average daily radiation on a horizontal surface at noon
t	hours in the month
T_a	average ambient temperature
T_b	balance-point temperature
T_{eu}	equivalent uniform temperature
T_h	thermostat-set temperature for heating
T_i	average collector inlet temperature
T_{mr}	mean radiant temperature
T_r	room air temperature

NOMENCLATURE (concluded)

T_s	slab temperature
T_w	mean unheated room surface temperature
UA_b	overall building heat loss factor
UA_{st}	overall thermal conductance between the storage component and building interior
U_L	collector loss coefficient
V_{st}	storage component volume
ΔT	allowable room-temperature swing
$\overline{\phi}$	monthly ratio of usable to absorbed solar energy
$(\overline{\tau\alpha})$	average transmittance-absorptance product

SECTION 1.0

INTRODUCTION

This study analyzes the performance of active charge/passive discharge solar space-heating systems. This type of hybrid system combines liquid-cooled solar collector panels with a massive integral storage component. The storage unit heats the building interior passively by radiation and free convection.

Although systems of this type are now being installed, there has been little detailed thermal analysis, simulation, or testing of their performance. Simplified tools for active or passive system analysis are not adequate because neither can include both the active collector component and the passive storage-to-room coupling. The TRNSYS simulation program [1] was chosen for this analysis because its modular structure can accommodate the unusual component arrangement of the active charge/passive discharge design.

Two types of hybrid configurations are shown in Fig. 1-1 and are contrasted with active systems and indirect-gain passive systems. In the solar-heated slab system, the solar collectors charge the floor slab via pipes embedded in the concrete, and the warm slab passively heats the interior. The perimeter of the slab must be insulated to prevent excessive losses through the ground. In the internal water-wall system, the collectors charge a radiant vertical wall, which may consist of a large water tank or a masonry structural wall. Neither system requires a fan coil unit to distribute the collected solar energy.

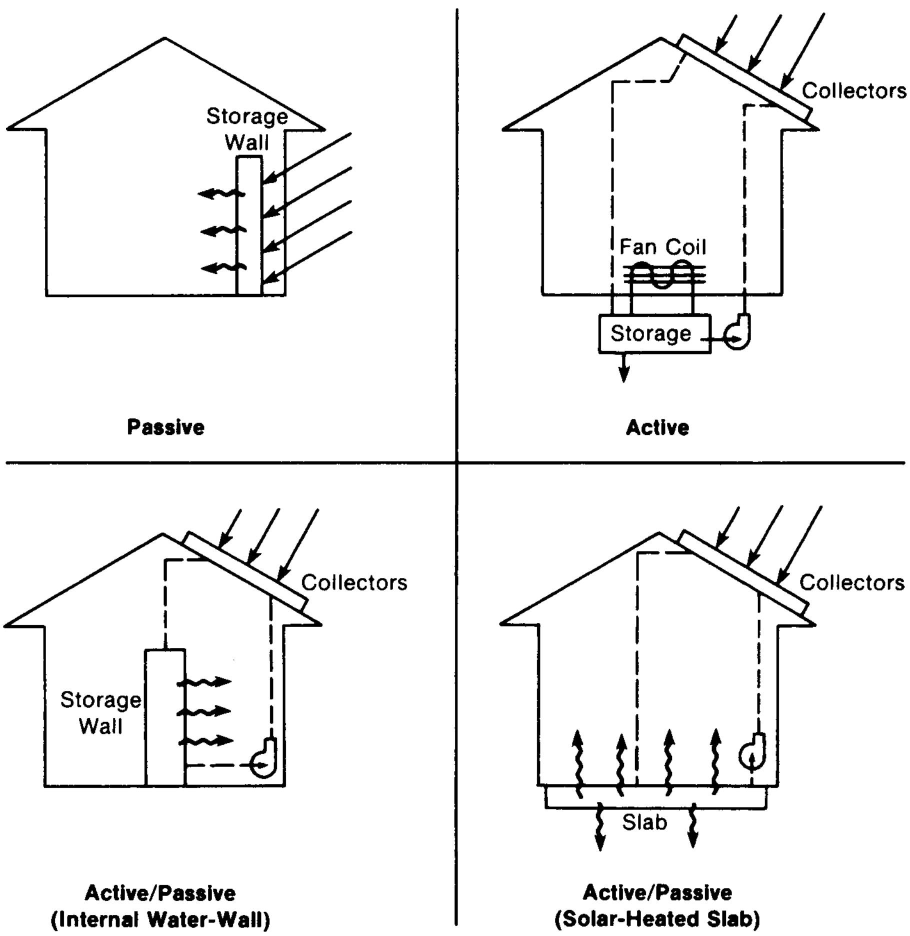

Figure 1-1. Comparison of Hybrid Solar Heating Configurations

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SECTION 2.0

THERMAL ANALYSIS

2.1 METHOD

TRNSYS is used to perform detailed simulations (0.5-h time steps) of the systems' thermal performance. The simulation results provide data for the development of a simplified thermal analysis method. This method, similar to the F-Chart and Phi-bar procedures used for active systems, can serve as a design aid or as a system comparison tool. It is included in an interactive FORTRAN program that is listed in Appendix A, together with a sample weather data file. F-Chart [2] is not a valid analysis technique for hybrid configurations because it cannot accommodate their large storage sizes, passive room coupling, or low solar delivery temperature. However, the Phi-bar procedure developed by Klein [3,4] can be adapted to this application.

The simulated building is modeled as a one-node system with constant internal heat production and rigid thermostat-set points for heating and cooling. The important building parameters are the overall building heat loss factor (UA_b), the thermostat settings, and the internal load. Important system parameters include collector area and orientation, storage capacity, storage-to-room conductance, and collector and heat-exchanger efficiencies.

The standard liquid solar collector component is used with a fluid capacitance rate of 200 $kJ/(h \cdot m^2 \cdot {}^\circ C)$. The radiant storage wall or floor slab is assumed to be uniform in temperature. Storage-to-room thermal coupling and slab-to-earth heat losses are assumed to follow the linear ASHRAE equations [5]. These assumptions are discussed in Sec. 2.2.

The monthly heating load (Eq. 1) depends on the degree-day balance-point (Eq. 2), which is the ambient temperature at which the thermostat-set temperature is maintained by internal gains only:

$$Q_L = UA_b \, DD(T_b) \quad . \tag{1}$$

$$T_b = T_h - q_i/UA_b \quad . \tag{2}$$

The balance-point often is assumed to be 18.3°C (65°F), but it is significantly lower in heavily insulated buildings. Degree-days for the calculated balance-point are obtained using the method developed by Thom [6].

The Phi-bar procedure gives the monthly fraction of usable absorbed solar energy in a system (Eq. 3) as a function of insolation level, ambient temperature, collector loss parameters, and average collector inlet temperature:

$$Q_U = Q_A \bar{\phi} \quad . \tag{3}$$

The absorbed solar energy is given by Eq. 4, and $\bar{\phi}$ (Eqs. 5, 6) is calculated according to Klein [3,4]:

$$Q_A = A_c F_R'(\overline{\tau\alpha}) H_T \ . \tag{4}$$

$$\bar{\phi} = f(\bar{K}_t, \bar{R}/R_n, H_n, I_c) \ , \tag{5}$$

where

$$I_c = U_L (T_i - T_a)/(\overline{\tau\alpha}) \ . \tag{6}$$

The collector temperature (T_i) is the only parameter in Eqs. 5 and 6 that cannot be explicitly determined from collector properties or radiation data. It is a function of absorbed solar energy, heating demand, storage capacity, and storage-to-room coupling, which can be expressed in dimensionless form (Eqs. 7-10):

$$T_i = f(P_L, P_S, P_R) \ , \tag{7}$$

where

$$P_L = Q_A/Q_L \ , \tag{8}$$

$$P_S = Q_A/(C_{st}\,\Delta T) \ , \text{ and} \tag{9}$$

$$P_R = Q_A/(UA_{st}\,\Delta T \ t) \ . \tag{10}$$

Monthly TRNSYS simulations were run for 480 combinations of values for P_L, P_S, and P_R. The results are used to develop correlations for Eq. 7 that apply to internal water-wall (Eq. 11) and solar-heated slab (Eq. 12) configurations.

Internal water-wall:

$$T_i = T_h - 1.43 + 0.707P_L + 0.0605P_S + 3.37P_R - 0.0018P_L^2 - 0.0002P_S^2 - 0.139P_R^2 \ (^\circ C) \ . \tag{11}$$

Solar-heated slab:

$$T_i = T_h - 2.46 + 3.37P_L + 0.0629P_S + 0.885P_R - 0.245P_L^2 - 0.0004P_S^2 + 0.611P_R^2 \ (^\circ C) \ . \tag{12}$$

In the case of the solar-heated slab, the thermal losses via the earth depend on the slab temperature (Eq. 13):

$$q_g = f_s p \ (T_s - T_a) \ . \tag{13}$$

The building loss factor includes slab heat losses, assuming the slab is at the thermostat-set temperature. Additional losses from the heated slab are accounted for in Eq. 14, where the slab temperature is approximated by the collector inlet temperature:

$$Q_L = UA_b \ DD(T_b) + f_s p \ t \ (T_i - T_h) \ . \tag{14}$$

The correlation for T_i (Eq. 12) includes Q_L, so Eqs. 12 and 14 must be solved simultaneously to obtain values that satisfy both equations.

In months when the solar fraction is greater than 40%, the interior temperature is usually raised above the thermostat-set temperature by the solar energy system. This increases the building heat loss, and some of the usable solar energy is lost without contributing to the actual heating load. The fraction of the absorbed solar energy lost in this way is obtained from another set of correlations (Eq. 15) from TRNSYS results:

$$Q_D/Q_A = 0.127 - 0.0653P_L + 0.000347P_S - 0.00137P_R + 0.00714P_L^2 - 0.000001P_S^2 + 0.000121P_R^2 \quad . \tag{15}$$

The additional losses caused by solar heating the building interior and the floor slab (if applicable) must be deducted from the usable solar energy to determine Q_S, the net solar energy contributed to meet the building heating load (Eqs. 16 and 17).

Internal water-wall: $$Q_S = Q_U - Q_D \quad . \tag{16}$$

Solar-heated slab: $$Q_S = Q_U - Q_D - f_s p\, t\, (T_i - T_h) \quad . \tag{17}$$

The solar fraction (Eq. 18) is based on Q_S and the building load with an unheated slab. This allows consistent comparisons of solar fractions with other designs.

$$F_{solar} = Q_S/[UA_b\, DD(T_b)] \quad . \tag{18}$$

The solar space-heating system must be deactivated in the summer to prevent overheating of the building interior. Timing the fall and spring changeovers can be difficult because the storage component can take several days to charge or discharge if sized to provide a large solar fraction. Simulations show that the changeovers should be made when the mean ambient temperature is about 18° or 19°C (64° to 67°F).

With the ambient temperature at or above this level, the space-heating load is so small that, for most residential buildings, the solar collectors can be more effectively used to heat domestic hot water. Thus, by diverting the collector fluid to a heat-exchanger in the domestic hot water tank, the hybrid solar system can provide the summer water-heating load. This is advantageous from June through September in most U.S. climates. The system can be designed to provide water and space heating simultaneously. It is more efficient, however, to use the solar energy system exclusively for space heating when this load is high, because the maximum delivery temperature [around 30°C (86°F)] is much lower than for water heating [60°C (140°F)].

The F-Chart correlations [7] can be used to calculate the water-heating performance. With the space-heating system deactivated, the hybrid system performs as an active system supplying the water-heating load. All the system parameters necessary for an F-Chart calculation are determined in the active charge/passive discharge analysis method.

2.2 VALIDITY OF THE ANALYSIS

The two major restrictions on the use of this analysis method are that the storage capacity (C_{st}) and the storage-to-room conductance (UA_{st}) must be sufficiently large. The minimum capacity is about 800 kJ/°C per square metre of collector area. Capacities below this value result in high storage temperatures, causing low collector efficiencies and frequent overheating of the room air, and should not be considered for a passive discharge application. System performance continues to improve as storage capacity increases (see Fig. 2-1).

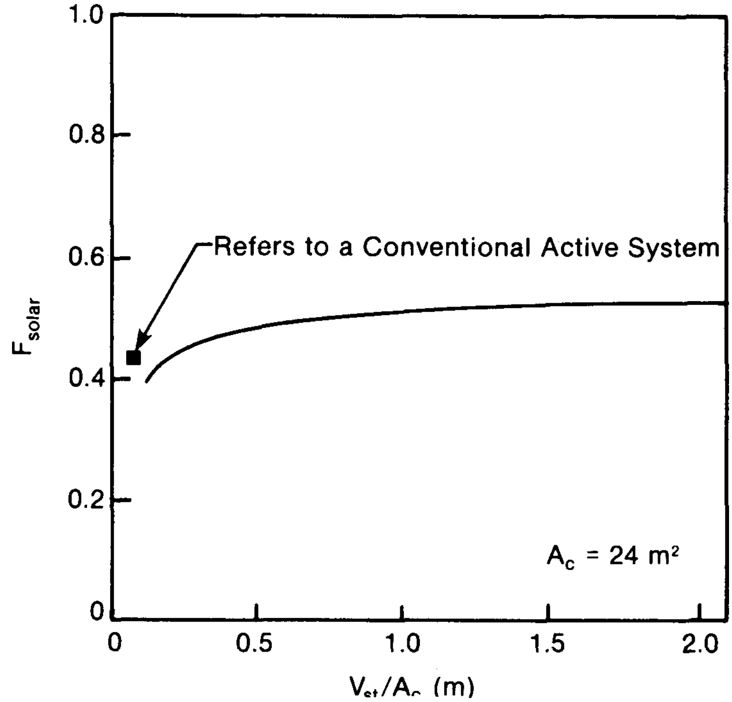

Figure 2-1. System Performance vs. Storage Capacity for Internal Water-Wall (Washington, D.C.)

If the storage conductance/capacity ratio is too small, insufficient energy will be transferred into the building interior, increasing the storage temperature and collector losses. The minimum value for this ratio is about 0.006 h^{-1}, which corresponds to about 170 h in Fig. 2-2.

The simulations were performed by varying the storage component surface area and keeping the conductances at the values from ASHRAE [5]. The ASHRAE values are only rough approximations because the convective and radiative coupling mechanisms are not well defined. The heat-transfer mechanism can be influenced by surface emissivity, induced room air movement, floor and wall coverings, and other factors. Any of these effects can be included in evaluating UA_{st}, as long as the effect can be expressed in a linear function. A linear approximation is acceptable for radiative transfer because the temperature differences between the storage and room surfaces are small.

Other major assumptions in this analysis are the uniform storage temperature and the ASHRAE slab heat loss equation. The error introduced by the uniform temperature assumption is generally insignificant compared to the uncertainty of the heat-transfer mechanisms. In masonry storage components more than 0.2 m thick, the temperature profile may be sufficiently nonuniform to cause some inaccuracy, but walls or slabs of such thickness are not common or desirable. The slab heat loss is a more difficult problem, however, as it significantly influences system performance. Unfortunately, the literature is very sketchy in this area. If an improved relationship between the slab temperature and the heat loss is available, it can be substituted for Eq. 14 and solved simultaneously with Eq. 12 to determine T_i.

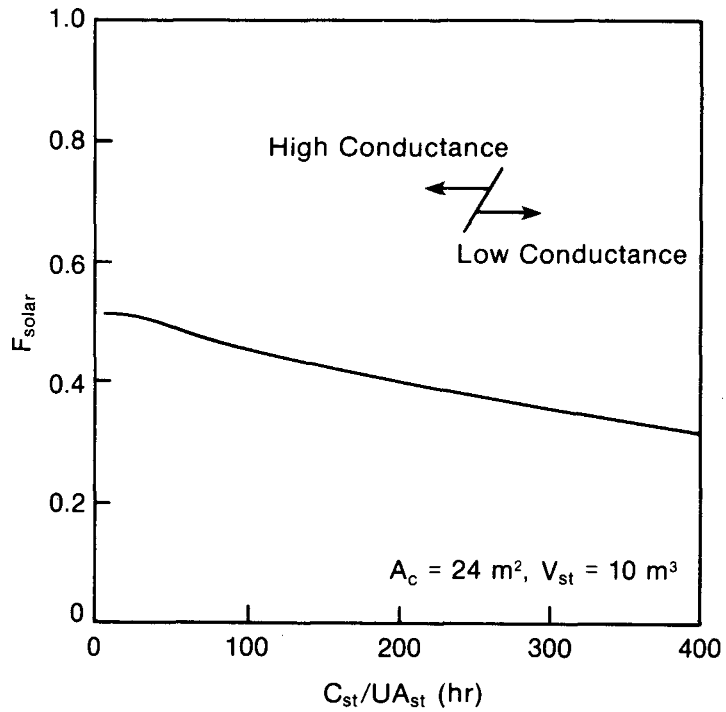

Figure 2-2. System Performance vs. Storage-Room Conductance for Solar Heated Slab (Washington, D.C)

The results of this simplified thermal analysis method were compared with TRNSYS simulations of the same systems in ten U.S. locations. The ranges of the system parameters considered are shown in Table 2-1. All comparison runs used a building loss factor of 250 W/°C and a balance-point temperature of 18.3°C (65°F). The standard error between TRNSYS and the simpler method's predicted annual solar fraction was less than 3%.

Table 2-1. Range of Parameters

A_c	8-56 m^2
$(\overline{\tau\alpha})$	0.8-0.9
U_L	2-10 W/($m^2 \cdot °C$)
C_{st}	5000-200,000 kJ/°C
e_{hx}	0.4-1.0
UA_{st}	20-500 W/°C
$f_s p$	0-40 W/°C
ΔT	4-8 °C

Locations: Fort Worth, Tex.; Albuquerque, N. Mex.; Fresno, Calif.; Cape Hatteras, N.C.; Nashville, Tenn.; Omaha, Nebr.; Washington, D.C.; Bismarck, N. Dak.; Medford, Oreg.; Madison, Wis.

An example of the use of the thermal analysis method is performed below. The building studied is in Davis, Calif. It uses a solar-heated slab system manufactured by Trident Energy Systems [8], who had the building monitored during February 1980 [9]. The system has 22.3 m^2 of single-glazed collectors, and the storage component includes an 0.85-m^3 water tank and 8.5 m^3 of concrete in the 0.1-m thick floor slab, which is insulated around the perimeter. The important analysis parameters are listed in Table 2-2 [9,10,11].

Table 2-2. Example Parameters

T_h	18.3°C (unoccupied building)
DD	227 at 18.3°C balance point
UA_b	235 W/°C = 20,300 kJ/(°C · day)
H_T	12,165 kJ/(m^2 · day) at 45 degrees south tilt
A_c	22.3 m^2
$F_R'(\overline{\tau\alpha})$	0.70 (with e_{hx} = 0.46)
$F_R'U_L$	6.18 W/($m^2 \cdot °C$)
T_a	8.6°C
C_{st}	22,680 kJ/°C
UA_{st}	875 W/°C
ΔT	5°C
f_s	0.5 W/(m · °C)
p	40 m

Using these values, Eq. 3 gives Q_A as 5.32 GJ. P_S is 46.9 (Eq. 9) and P_R is 0.50 (Eq. 10). Equations 12 and 14 are solved simultaneously to give T_i as 22.0°C (71.6°F) and Q_L as 4.79 GJ. I_c is 118.3 W/m^2 (Eq. 6), ϕ is 0.665 (Eq. 5, see Refs. 3,4), and Q_U is 3.54 GJ (Eq. 3). From Eq. 15, Q_D is 0.43 GJ, so Q_S is 2.93 GJ (Eq. 17), and F_{solar} is 63.9% (Eq. 18). This is very close to the 63.4% solar fraction reported for the February test period [9].

The utility of this method is clear if one attempts to use the F-Chart method to perform the same analysis. Using the same weather data and design parameters and replacing the load heat-exchanger capacitance rate with the passive storage-to-room conductance, UA_{st}, F-Chart gives a solar fraction of only 54.4%. The passive storage-to-room coupling and low collector temperature in the hybrid configuration result in significantly more delivered solar energy than F-Chart would predict.

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SECTION 3.0

SYSTEM PERFORMANCE

3.1 FEATURES

Several features of the active charge/passive discharge configurations can provide cost/performance advantages over other types of systems. Because the solar storage component is integral with the building interior, as in a purely passive system, the storage capacity must be large to allow uniform and relatively low storage temperatures and provide a comfortable interior environment. The collectors, therefore, operate at temperatures lower than those necessary in conventional active systems. This decreases the impact of collector losses and suggests the application of less efficient and less costly collectors, resulting in significant system-cost savings.

Figure 3-1 shows the influence of the collector loss coefficient on system performance for an active system and an internal water-wall system. The hybrid system performance is less sensitive to high-loss collectors. This effect is more drastic at high solar fractions, where the storage temperature and collector losses increase.

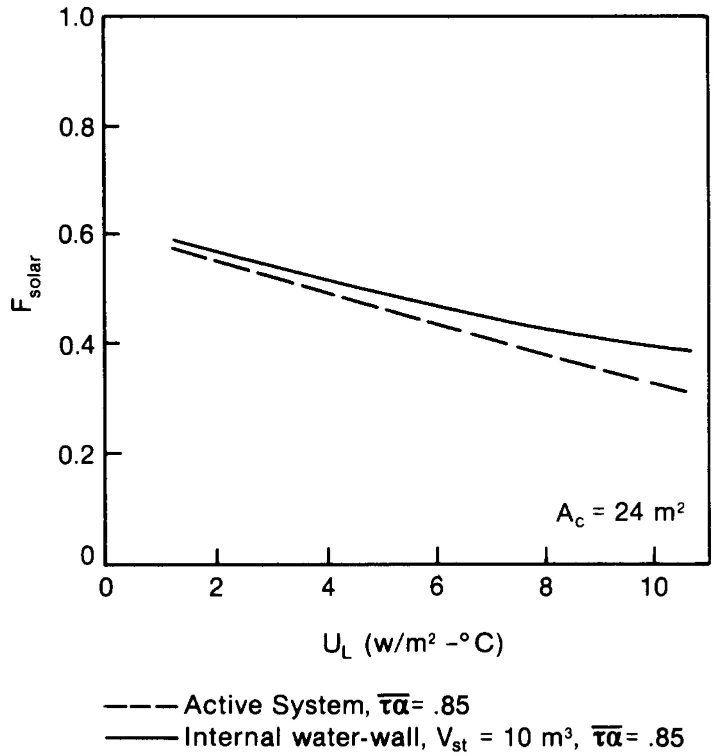


Figure 3-1. System Performance vs. Collector Loss Coefficient for Active and Hybrid Systems (Washington, D.C.)

In addition to making a fan coil unit unnecessary to distribute solar energy, the active charge/passive discharge configuration can obviate the expense of a separate forced-air or baseboard heating system. This can be accomplished by using an auxiliary heater to boost the temperature of the solar storage component when necessary.

If the storage component also serves as a necessary structural component, such as the floor slab, the only incremental solar storage cost is for embedding a heat-exchanger coil. Otherwise, the entire storage cost must be charged to the solar system. A non-structural storage component, however, can significantly increase the thermal mass of the building and provide energy savings in the cooling mode.

During much of the cooling season in many climates, the internal heat gains and average ambient temperatures are low enough that the average interior temperature can be kept within the comfort zone without air conditioning. However, the daily ambient temperature peaks, which are approximately coincident with maximum solar gains, drive the room temperature above the comfort level. A substantial increase in internal thermal capacity (with sufficient conductance to the room air) can damp out these temperature peaks, reducing the air-conditioning demand. This additional energy stored during the day can be expelled if night-time ventilation is available. TRNSYS simulations show 20% to 60% reductions in sensible cooling loads for internal water-wall systems compared to conventional systems with similar building construction and ventilation capability.

The collector system can provide an additional benefit if operated at night to provide radiative cooling in arid climates. Glass is nearly opaque to thermal infrared radiation and therefore not a suitable glazing for this type of application. Collectors with plastic glazings, removable glazing, or no glazing are necessary. These collectors have higher loss coefficients than those with glass, but, given the low collector temperatures in hybrid systems, they may be acceptable if substantial summer cooling is provided. Some experimentation has been performed with this application [12,13], but it is unclear whether sufficient cooling can be provided to justify operating the collector pump. Use of the collectors in the cooling mode is not considered in the simulations or the performance comparisons.

The active charge/passive discharge configuration also has performance advantages over passive systems. These features can compensate for the expense of extra hardware, including collectors, plumbing, and controls. Separation of the collector and storage components provides several benefits. The collectors are external to the building envelope and thus do not have to be shaded to prevent summer overheating (they can heat domestic hot water instead). This provides greater architectural flexibility, especially because the collectors can be located on the roof or the ground, as well as on the south wall.

Concentration of heating on the southern exposure is a problem in many passive designs, but the hybrid design facilitates more balanced heat distribution and better use of the radiant transmission from the storage component (the solar-heated slab suffers in this regard when applied to multistory frame buildings). Night insulation is unnecessary because the storage component is thermally coupled only to the interior, not the ambient air.

3.2 COMFORT

As in passive systems, comfort in an active charge/passive discharge design depends on large storage capacity and adequate ventilation to avoid overheating. With adequate storage, the room air temperature is less sensitive to outdoor temperature fluctuations and therefore more stable than in a conventional building. Also, the radiant heating provided by passive coupling yields a comfortable environment at a lower air temperature than in conventional buildings.

A simple index of thermal comfort has been defined by Wray [14], using the general comfort equations developed by Fanger [15]. This index, the equivalent uniform temperature (T_{eu}), is given by Eq. 19 for a typical indoor situation of medium clothing and light activity.

$$T_{eu} = 0.45\ T_{mr} + 0.55\ T_r \ . \qquad (19)$$

The mean radiant temperature (T_{mr}) during the winter is slightly below the room temperature (T_r) for conventional buildings, because the walls, floor, and ceiling are cooled by the outdoor temperature. Introducing a warm radiant surface in a passive or hybrid design raises T_{mr}, usually above T_r. This allows the comfort level to be achieved at a lower room-air temperature.

The mean radiant temperature depends on the emissivities and the angle factors, with respect to the occupant, of the room surfaces. For typical geometries, building materials, and temperature ranges, T_{mr} can be linearized and approximated as the mean temperature of all room surface areas [15]. This is expressed in Eq. 20 for a conventional building and in Eq. 21 for a passive or hybrid building where the heated surface (such as the floor slab) occupies 25% of the interior area.

Conventional: $$T_{mr} = T_w \ . \qquad (20)$$

Passive/hybrid: $$T_{mr} = 0.75\ T_w + 0.25\ T_s \ . \qquad (21)$$

The mean unheated surface temperature (T_w) depends on the thermal resistance between the interior surface and the outdoor environment. In a well-insulated building, convection from the interior surfaces accounts for about 5% of the total thermal resistance. An energy balance on the surface reduces to Eq. 22, giving T_w:

$$T_w = 0.05\ T_a + 0.95\ T_r \ . \qquad (22)$$

Eqs. 19 through 22 can be used to determine the room temperature needed in a passive or hybrid building to maintain the same T_{eu} as in a conventional building typically kept at 20.5°C (68.9°F). In a winter situation, with the outdoor temperature at 0°C (32°F), T_{mr} and T_w are 19.5°C (67.1°F) and T_{eu} is 20.0°C (68.0°F). Using this value of T_{eu} and a typical winter value of 30°C (86°F) for T_s, Eqs. 19, 21, and 22 can be solved simultaneously, giving T_{mr} as 21.1°C (70.0°F) and T_r as 19.1°C (66.4°F).

Thus the passive or hybrid room air can be 1.4°C (2.5°F) cooler than in the conventional building and still be equally comfortable. Reducing the thermostat-set temperature by this amount decreases the heating load by about 10% in most climates, providing further fuel savings. If the radiant surface is actively cooled in the summer, similar cooling-load reductions result.

3.3 COST/PERFORMANCE COMPARISONS

Figures 3-2, 3-3, and 3-4 compare the solar fractions delivered, as a function of collector area, for active, passive, and two hybrid configurations (the SLR method was used to estimate passive performance) [16]. The collectors for the active and hybrid systems are single-glazed, with a relatively high loss coefficient of 7 W/(m^2 • °C). The allowed interior temperature swing for the passive and hybrid systems is 5°C (9°F). Both active charge/ passive discharge designs show heating performances comparable to the active and passive designs in a range of climatic conditions.

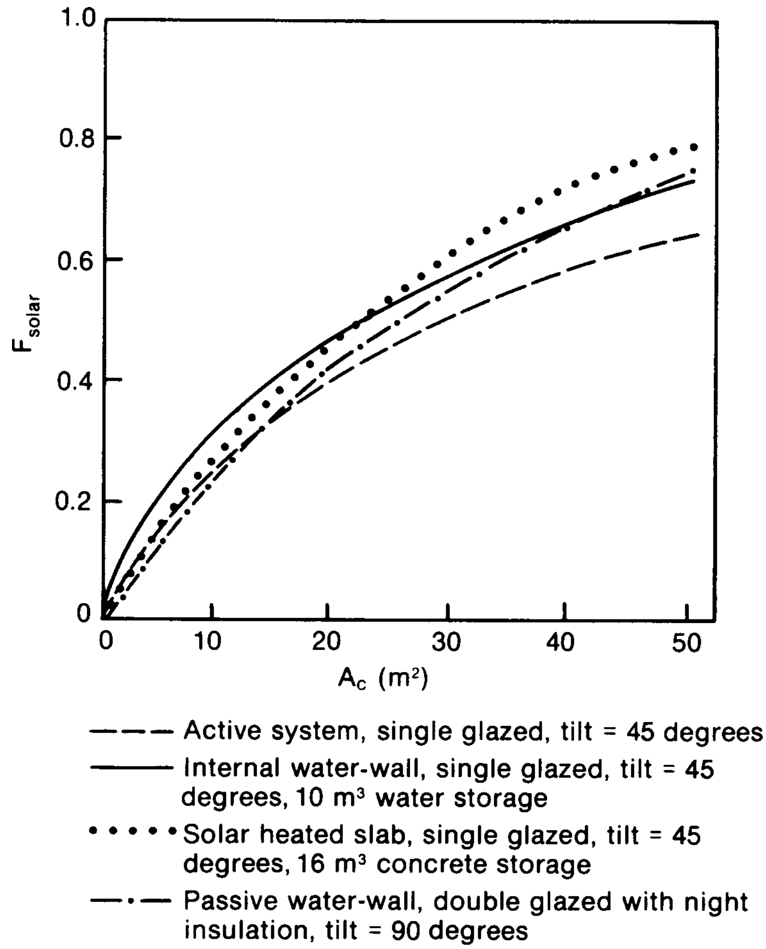


Figure 3-2. Performance Comparison of Four Solar Heating Systems (Washington, D.C.)

The active and hybrid systems also can provide water-heating with few additional components. With collector area sized to provide a 50% solar fraction for space-heating, the active system can provide about 50% of a typical hot water load, while the hybrid systems can provide about 40% in Albuquerque, N. Mex.; 30% in Washington, D.C.; and 20% in Madison, Wis.

A sample economic comparison of four solar configurations is outlined below to illustrate the impact of the various hybrid system features. Each system has 28 m^2 of solar collection area and is located in Omaha, Nebr. Other system-design parameters are shown in Table 3-1.

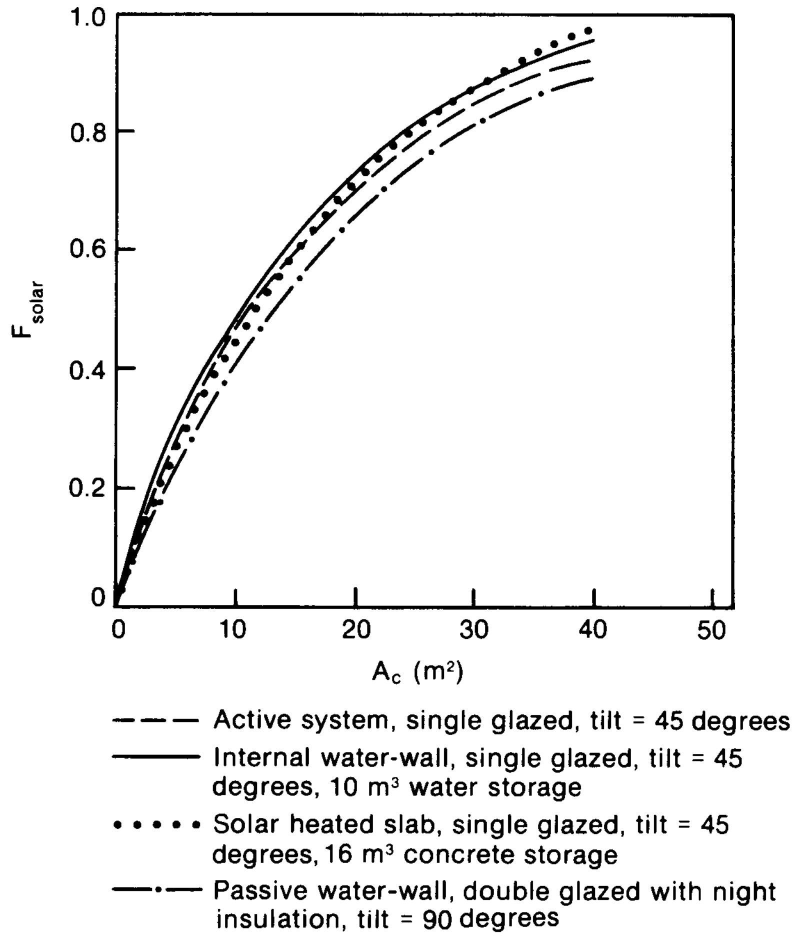
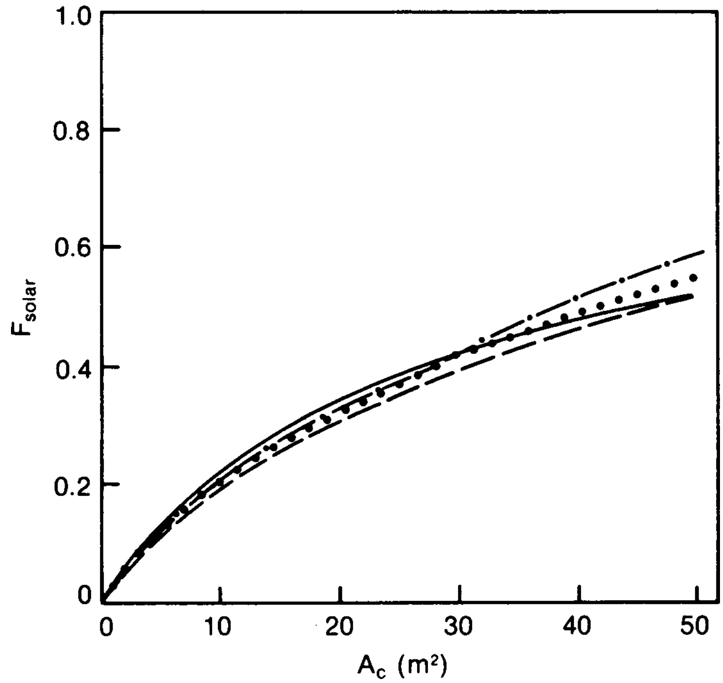


Figure 3-3. Performance Comparison of Four Solar Heating Systems (Albuquerque, N. Mex.)



——— Active system, single glazed, tilt = 45 degrees

——— Internal water-wall, single glazed, tilt = 45 degrees, 10 m^3 water storage

• • • • • Solar heated slab, single glazed, tilt = 45 degrees, 16 m^3 concrete storage

—•— Passive water-wall, double glazed with night insulation, tilt = 90 degrees

Figure 3-4. Performance Comparison of Four Solar Heating Systems (Madison, Wis.)

Table 3-1. Design Parameters for Four Solar Systems

	Active	Passive	Internal Water-Wall	Solar-Heated Slab
Collector area (m^2)	28	28	28	28
Collector glazing	double	double	single	single
Collector tilt (degrees)	45	90	45	45
Storage volume (m^3)	2.2	6.0	5.6	16.0
Storage material	water	water	water	concrete
Structure replaced	—	wall	wall	floor
Night insulation	no	yes	no	no
Hot water provided	yes	no	yes	yes
Separate furnace	yes	yes	no	no

Installed-cost estimates for each system are broken down in Table 3-2 [10,17,18,19]. The relative component costs reflect the design parameters from Table 3-1 and the overall design features of each configuration.

Table 3-2. Cost Comparison of Four 28-m^2 Solar Systems (Late 1980 $)

Component	Active	Passive	Internal Water-Wall	Solar-Heated Slab	Comments
Collectors	5400	1340	4600	4600	Cheaper single-glazed collector for hybrid system
Storage	1510	1610	1400	—	Extra cost relative to conventional wall or floor
Pump(s)	660	—	220	440	Active system has the most complex plumbing, requiring the most pumps, controls, valves, and heat exchangers
Controls, valves	720	—	180	540	
Heat-exchanger(s)	440	—	—	220	
Pipes, insulation	2140	—	2140	2140	
DHW tank, valves	280	—	280	280	Additional plumbing for active, hybrid system to heat DHW
Framing, overhang	—	1600	—	—	
Night insulation	—	1650	—	—	For passive systems only, where storage is adjacent to glazing
Furnace credits	—	—	-480	-480	Cheaper auxiliary heater integrated into hybrid system
NET COST (installed)	11,150	6,200	8,340	7,740	

Table 3-3 presents, for the four Omaha systems, the ratio of the installed cost to the net energy delivered annually. This ratio is an index of the cost-effectiveness of each design; it indicates the cost of each unit of energy supplied annually by the system.

Table 3-3. System Performance and Cost-Effectiveness Comparison

	Systems in Omaha (28 m^2)			
	Active	Passive	Internal Water Wall	Solar Heated Slab
Space heating (GJ/yr)	35.0	34.7	31.1	34.7
(solar fraction)	49%	48%	43%	48%
Water heating (GJ/yr)	10.7	—	6.9	6.9
(solar fraction)	52%	—	34%	34%
Pump work (GJ/yr)	-1.4	—	-0.4	-0.8
Net energy delivered (GJ/yr)	44.3	34.7	37.6	40.8
Net installed cost (see Table 3-2)	11,150	6,200	8,340	7,740
Cost/performance ratio [$/(GJ/yr)]	252	179	222	190

Active charge/passive discharge system costs appear to lie between those of active and passive systems. This gives the hybrid designs an economic advantage over active systems. It is less certain, however, whether they are competitive with passive systems. The most favorable economic condition occurs when a structural component can serve as solar storage, as in the solar-heated slab design. If this type of design can contribute to the cooling or hot water loads as well as to space-heating, the total system energy delivered per unit cost can compete with passive designs, as Table 3-3 shows. When architectural flexibility and comfort advantages of the hybrid designs are considered, these designs present a promising approach to economical solar energy in the building market.

SECTION 4.0

CONCLUSION

The solar designer can use the method described to analyze the thermal performance of two classes of active charge/passive discharge solar space-heating systems. It employs familiar, well-used relationships that can be assimilated into larger analysis tools that consider active and passive configurations. Future work should seek more rigorous field validation and comparisons, using extensively instrumented systems as well as rough energy balances from a cross section of hybrid buildings. This work should also be extended to hybrid systems that use air as the heat-transfer fluid.

SERI

SECTION 5.0

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APPENDIX A

SIMPLIFIED ACTIVE CHARGE/PASSIVE DISCHARGE ANALYSIS METHOD: FORTRAN LISTING AND EXAMPLE DATA FILE

```
      PROGRAM PHIHYB(INPUT,OUTPUT,ANSWER,METCOM,TAPE5=INPUT,
     1        TAPE6=OUTPUT,TAPE7=ANSWER,TAPE8=METCOM)
C  THIS PROGRAM USES THE PHI-BAR PROCEDURE TO ANALYZE MONTHLY
C  THERMAL PERFORMANCE OF ACTIVE CHARGE/PASSIVE DISCHARGE SOLAR
C  HEATING SYSTEMS WITH LIQUID COLLECTORS AND STORAGE IN A
C  TANK, WALL, OR FLOOR SLAB.
C  UNITS ARE IN SI, BUT TIMES ARE IN HOURS AND ENERGY IS IN KJ.
      REAL DEC(12),SD(12),CD(12),TD(12),C(12),HT(12),PAR(20),QDHW(12)
      REAL RR(12),SUN(10,12),QSUN(12),QLOAD(12),QAUX(12),QDMP(12)
      REAL ABRR(12),DDA(12),DD(10,12),TAMB(10,12),FSUN(12),TX(12)
      REAL DLAT(10),SOL(12)
      INTEGER LOC(10,2),MON(13,2),N(12),NI(12)
      PI=3.14159
      DATA(N(J),J=1,12)/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA(NI(J),J=1,12)/17,47,75,105,135,162,198,228,
     1  258,288,318,344/
C  CALCULATE SOLAR DECLINATION ON A REPESENTATIVE DAY OF EACH MONTH.
      DO 100 I=1,12
      DEC(I)=.40928*SIN(2*PI*(NI(I)+284)/365)
      SD(I)=SIN(DEC(I))
      CD(I)=COS(DEC(I))
      TD(I)=SD(I)/CD(I)
 100  CONTINUE
      DATA(MON(J,1),J=1,12)/"JANUA","FEBRU","MARCH","APRIL","MAY  ",
     1  "JUNE ","JULY ","AUGUS","SEPTE","OCTOB","NOVEM","DECEM"/
      DATA(MON(J,2),J=1,12)/"RY   ","ARY  ","     ","     ",
     1  "     ","     ","T    ","MBER ","ER   ","BER  ","BER  "/
      MON(13,1)="TOTAL"
      MON(13,2)="     "
C  INITIALIZE VARIABLES AND CONSTANTS.
      I0=0
      I1=2
      I2=2
      TB=18.+1./3.
      K=7.658
      UA=1000.
      FP=2.0
      VOLW=0.
      VOLS=0.
      RHOCP=2000.
      UATR=1000.
      DHW=0.
      UASR=1000.
      DT=5.
      PER=40.
      AREA=20.
      DTLT=30.
      REF=.2
      FRUL=22
      EHX=1.0
      FRTA=.8
      TSET=20.
```

```
      QINT=36000.
      MONON=10
      MOFF=6
C  READ IN WEATHER DATA(LOCATION,LATITUDE,DEGREE DAYS
C  BASED ON 65 DEGREES-F,MEAN AMBIENT
C  TEMPERATURE,AVERAGE DAILY HORIZONTAL INSOLATION) FROM
C  FILE METCOM(LOGICAL UNIT 8), AND ASSIGN TO
C  THE APPROPRIATE WEATHER PARAMETER ARRAYS.
      WRITE(6,650)
      WRITE(6,101)
 101  FORMAT(" NUMBER OF CITIES IN WEATHER DATA FILE--10 MAXIMUM")
      READ(5,*) NCIT
      DO 105 I=1,NCIT
      READ(8,103)(LOC(I,J),J=1,2)
 103  FORMAT(2A10)
      READ(8,*) DLAT(I)
      READ(8,*)(DD(I,J),J=1,12)
      READ(8,*)(TAMB(I,J),J=1,12)
      READ(8,*)(SUN(I,J),J=1,12)
 105  CONTINUE
      GOTO 135
C  EACH TIME THROUGH THE CALCULATIONS, ANY COMBINATION OF
C  WEATHER DATA AND SYSTEM DESIGN DATA CAN BE ALTERED.
C  IF THE LOCATION IS NOT TO BE CHANGED, THEN THE WEATHER
C  DATA NEED NOT BE READ. IF THE SYSTEM IS UNCHANGED, THEN
C  THE USER CAN SKIP BEING ASKED FOR VALUES FOR THE DESIGN
C  PARAMETERS.
 110  WRITE(6,495)
      WRITE(6,137) ICIT,(LOC(ICIT,J),J=1,2)
      WRITE(6,520)
      WRITE(6,120)
      WRITE(6,125)
      WRITE(6,130)
 120  FORMAT(" 0-STOP")
 125  FORMAT(" 1-CONTINUE WITH SAME WEATHER DATA")
 130  FORMAT(" 2-INPUT NEW WEATHER DATA")
      READ(5,*) I1
      IF(I1.EQ.0) GOTO 700
      IF(I1.LT.1.5) GOTO 220
 135  WRITE(6,520)
      WRITE(6,136)
 136  FORMAT(" CITY NUMBER"/"    TYPE 0 TO LIST AVAILABLE CITIES")
      READ(5,*) ICIT
      IF(ICIT.GT.0) GOTO 200
      DO 138 I=1,NCIT
      WRITE(6,137) I,(LOC(I,J),J=1,2)
 137  FORMAT(1H ,1I2,2X,2A10)
 138  CONTINUE
      GOTO 135
 200  XLAT=.0174533*DLAT(ICIT)
      IF(I0.EQ.0) GOTO 234
```

```
 220  WRITE(6,495)
      WRITE(6,137) ICIT,(LOC(ICIT,J),J=1,2)
      WRITE(6,520)
      WRITE(6,225)
      WRITE(6,226)
 225  FORMAT(" 1-CONTINUE WITH SAME SYSTEM DESIGN DATA")
 226  FORMAT(" 2-INPUT NEW DESIGN DATA")
      READ(5,*) I2
      IF(I2.LT.1.5) GOTO 300
      GOTO 230
C  IF SYSTEM DESIGN PARAMETERS ARE TO BE CHANGED, THE USER
C  SPECIFIES THE PARAMETER TO BE CHANGED AND ITS NEW VALUE.
C  ONE MAY ALSO LIST THE PARAMETERS AND THEIR CURRENT VALUES.
 227  WRITE(6,495)
      WRITE(6,137) ICIT,(LOC(ICIT,J),J=1,2)
      WRITE(6,235) PAR(1)
      WRITE(6,236) PAR(2)
      WRITE(6,420) PAR(3)
      WRITE(6,425) PAR(4)
      WRITE(6,426) PAR(5)
      WRITE(6,427) PAR(6)
      WRITE(6,428) PAR(7)
      WRITE(6,429) PAR(8)
      WRITE(6,430) PAR(9)
      WRITE(6,431) PAR(10)
      WRITE(6,432) PAR(11)
      WRITE(6,433) PAR(12)
      WRITE(6,434) PAR(13)
      WRITE(6,435) PAR(14)
      WRITE(6,440) PAR(15)
      WRITE(6,444) PAR(16)
      WRITE(6,446) PAR(17)
      WRITE(6,447) PAR(18)
      WRITE(6,449) PAR(19)
      WRITE(6,451) PAR(20)
      WRITE(6,520)
 230  WRITE(6,231)
      WRITE(6,232)
 231  FORMAT(" INPUT PARAMETER NUMBER AND NEW VALUE")
 232  FORMAT("    TYPE 0 0 TO RUN THE ANALYSIS"/"    OR 2 NEGATIVE",
     1  " VALUES TO LIST THE PARAMETERS")
      READ(5,*) JIN,XIN
      IF(JIN.EQ.0) GOTO 300
      IF(JIN.LT.0) GOTO 227
      PAR(JIN)=XIN
      GOTO 230
 234  WRITE(6,495)
      WRITE(6,137) ICIT,(LOC(ICIT,J),J=1,2)
      WRITE(6,520)
      WRITE(6,235) REF
```

```
 235   FORMAT("  1 REFLECTIVITY OF GROUND OR REFLECTOR"T60,1F7.2)
       READ(5,*) PAR(1)
       WRITE(6,236) DTLT
 236   FORMAT("  2 COLLECTOR TILT IN DEGREES"T60,1F7.2)
       READ(5,*) PAR(2)
 300   XREF=PAR(1)
       XTLT=PAR(2)
       IF(XREF.EQ.REF.AND.DTLT.EQ.XTLT.AND.I1.LT.1.5) GOTO 456
       DTLT=XTLT
       TLT=.0174533*DTLT
       REF=XREF
C   THE RADIATION PROCESSING ALGORITHM CONVERTS HORIZONTAL
C   INSOLATION VALUES TO VALUES FOR TILTED SURFACE(HT)
C   AND COMPUTES RADIATION RATIOS NEEDED FOR PHI-BAR(A,B,C,
C   RR,RN,RBAR). SEE KREITH AND KREIDER OR KLEIN.
       DO 410 M=1,12
       SL=SIN(XLAT)
       CL=COS(XLAT)
       TL=SL/CL
       CB=COS(TLT)
       SLB=SIN(XLAT-TLT)
       CLB=COS(XLAT-TLT)
       TLB=SLB/CLB
       HSS=ACOS(-1*TL*TD(M))
       HS2=ACOS(-1*TLB*TD(M))
       HSR=AMIN1(HSS,HS2)
       HO=(24*4871/PI)*(1+.034*COS(2*PI*NI(M)/365))
     1  *(CL*CD(M)*SIN(HSR)+HSR*SL*SD(M))
       XKT=SUN(ICIT,M)/HO
       DH=1.39-4.027*XKT+5.531*XKT**2-3.108*XKT**3
       RB=(CLB*CD(M)*SIN(HSR)+HSR*SLB*SD(M))
     1  /(CL*CD(M)*SIN(HSS)+HSS*SL*SD(M))
       RBAR=(1-DH)*RB+DH*(1+CB)/2+REF*(1-CB)/2
       HT(M)=RBAR*SUN(ICIT,M)
       RD=(PI/24)*(1-COS(HSS))/(SIN(HSS)-HSS*COS(HSS))
       RT=(1.09+.01*SIN(HSS-.0186))*RD
       RX=RD/RT
       RBN=(CLB*CD(M)+SLB*SD(M))/(CL*CD(M)+SL*SD(M))
       RN=(1-RX*DH)*RBN+RX*DH*(1+CB)/2+REF*(1-CB)/2
       RR(M)=RT*RN
       A=7.476-20.0*XKT+11.188*XKT**2
       B=-8.562+18.679*XKT-9.948*XKT**2
       C(M)=-.722+2.426*XKT+.439*XKT**2
 400   ABRR(M)=A+B*RN/RBAR
 410   CONTINUE
       IF(IO.GT.0) GOTO 456
 415   WRITE(6,420) UA
 420   FORMAT("  3 BUILDING HEAT LOSS EXCLUDING SLAB IN KJ/HR-DEG"T58,
     1  1F7.0)
 421   FORMAT("  3 BUILDING HEAT LOSS INCLUDING SLAB IN KJ/HR-DEG"T58,
     1  1F7.0)
       READ(5,*) PAR(3)
       WRITE(6,425) AREA
```

```
425  FORMAT("  4 COLLECTOR AREA IN SQUARE M"T58,1F7.0)
     READ(5,*) PAR(4)
     WRITE(6,426) VOLW
426  FORMAT("  5 WATER STORAGE VOLUME IN CUBIC M"T60,1F7.2)
     READ(5,*) PAR(5)
     WRITE(6,427) VOLS
427  FORMAT("  6 SOLID WALL OR SLAB STORAGE VOLUME"T60,1F7.2)
     READ(5,*) PAR(6)
     WRITE(6,428) RHOCP
428  FORMAT("  7 DENSITY*SPEC HEAT OF WALL OR SLAB IN KJ/DEG-M3"T58,
    1  1F7.0)
     READ(5,*) PAR(7)
     WRITE(6,429) UATR
429  FORMAT("  8 STOR/ROOM CONDUCTANCE IN KJ/HR-DEG FOR WATER"T58,
    1  1F7.0)
     READ(5,*) PAR(8)
     WRITE(6,430) UASR
430  FORMAT("  9 STOR/ROOM CONDUCTANCE FOR WALL OR SLAB"T58,1F7.0)
     READ(5,*) PAR(9)
     WRITE(6,431) DHW
431  FORMAT(" 10 DAILY DOMESTIC HOT WATER USE IN KG OR LIT"T58,1F7.0)
     READ(5,*) PAR(10)
     WRITE(6,432) DT
432  FORMAT(" 11 ALLOWED INTERIOR TEMPERATURE SWING IN DEG-C"T60,1F7.2)
     READ(5,*) PAR(11)
     WRITE(6,433) FP
433  FORMAT(" 12 SLAB LOSS FACTOR IN KJ/HR-DEG-M"T60,1F7.2)
     READ(5,*) PAR(12)
     WRITE(6,434) PER
434  FORMAT(" 13 EXPOSED PERIMETER OF HEATED SLAB IN M"T58,1F7.0)
     READ(5,*) PAR(13)
     WRITE(6,435) FRTA
435  FORMAT(" 14 FR*TA"T60,1F7.2)
     READ(5,*) PAR(14)
     WRITE(6,440) FRUL
440  FORMAT(" 15 FR*UL IN KJ/HR-DEG-M2"T60,1F7.2)
     READ(5,*) PAR(15)
     WRITE(6,444) EHX
444  FORMAT(" 16 HEAT EXCHANGER EFFECTIVENESS(1.0 FOR NO HX)"T60,1F7.2)
     READ(5,*) PAR(16)
     WRITE(6,446) TSET
446  FORMAT(" 17 THERMOSTAT SETTING IN DEG C"T60,1F7.2)
     READ(5,*) PAR(17)
     WRITE(6,447) QINT
447  FORMAT(" 18 INTERNAL HEAT PRODUCTION IN KJ/DAY"T58,1F7.0)
     READ(5,*) PAR(18)
     WRITE(6,448) MONON
448  FORMAT(" 19 MONTH COLLECTORS ARE ACTIVATED 1=JAN 12=DEC"T57,1I7)
449  FORMAT(" 19 MONTH COLLECTORS ARE ACTIVATED 1=JAN 12=DEC"T58,1F7.0)
     READ(5,*) PAR(19)
```

```
      WRITE(6,450) MOFF
 450  FORMAT(" 20 MONTH COLLECTORS ARE DISABLED"T57,1I7)
 451  FORMAT(" 20 MONTH COLLECTORS ARE DISABLED"T58,1F7.0)
      READ(5,*) PAR(20)
 456  IO=1
      UA=PAR(3)
      AREA=PAR(4)
      VOLW=PAR(5)
      VOLS=PAR(6)
      RHOCP=PAR(7)
      UATR=PAR(8)
      UASR=PAR(9)
      DHW=PAR(10)
      DT=PAR(11)
      FP=PAR(12)
      PER=PAR(13)
      FRTA=PAR(14)
      FRUL=PAR(15)
      EHX=PAR(16)
      TSET=PAR(17)
      QINT=PAR(18)
      MONON=PAR(19)
      MOFF=PAR(20)
C   STORAGE CAPACITIES AND CONDUCTANCES ARE SUMMED.
      STCAP=RHOCP*VOLS+4186*VOLW
      UAR=UATR+UASR
C   THE HEAT EXCHANGER LOSS FACTOR IS CALCULATED ACCORDING TO
C   DEWINTER ASSUMING A COLLECTOR FLUID CAPACITANCE RATE OF
C   200 KJ/HR-DEG.
      FHX=1/(1+(1/EHX-1)*FRUL/200)
      FTA=FRTA*FHX
      FUL=FRUL*FHX
      UU=UA+PER*FP
C   THE BASE TEMPERATURE FOR DEGREE DAY CALCULATIONS DEPENDS
C   ON THE THERMOSTAT SETTING, THE BUILDING LOAD, AND THE
C   INTERNAL GAINS.
      TBX=TSET-QINT/(24*UU)
      TOTA=0
      TOTS=0
      TOTL=0
      TOTW=0
      DO 490 M=1,12
C   SOL IS THE ABSORBED SOLAR RADIATION(CORRECTED FOR
C   TAU-ALPHA AND HEAT EXCHANGER LOSSES).
      SOL(M)=AREA*HT(M)*N(M)*FTA
C   THE HOT WATER LOAD IS CALCULATED ASSUMING CONSTANT
C   DAILY USAGE AND A TEMPERATURE RISE OF 45 DEG-C.
      QDHW(M)=188*N(M)*DHW
C   DEGREE DAYS ARE ADJUSTED FROM A 65 DEG-F BASE TO THE
C   CALCULATED BASE TEMPERATURE ACCORDING TO THE METHOD
```

```
C   DEVELOPED BY THOM.
        DELT=TB-TAMB(ICIT,M)
        JJ=0
        IF(DELT.GE.0) GOTO 458
        JJ=1
  458   DDAO=N(M)*(DELT+(.34*(EXP(-4.7*DELT/K))-.15*(EXP(-7.8*DELT/K))
       1  -DELT*JJ/K))
        DELT=TBX-TAMB(ICIT,M)
        JJ=0
        IF(DELT.GE.0) GOTO 459
        JJ=1
  459   DDAN=N(M)*(DELT+(.34*(EXP(-4.7*DELT/K))-.15*(EXP(-7.8*DELT/K))
       1  -DELT*JJ/K))
        IF(DDAN.GT.0) GOTO 460
        DDA(M)=DD(ICIT,M)
        GOTO 461
  460   DDA(M)=DD(ICIT,M)-DDAO+DDAN
        IF(DDA(M).GT.0) GOTO 461
        DDA(M)=0.
  461   QLOAD(M)=24*DDA(M)*UA
C   QLODX IS THE BUILDING LOAD WITHOUT A HEATED SLAB.
        QLODX=24*DDA(M)*UU
        IF(QLOAD(M).GT.0.OR.QDHW(M).GT.0) GOTO 462
        QSUN(M)=0
        QAUX(M)=0
        FSUN(M)=0
        GOTO 480
C   IN MOST CLIMATES, THE SYSTEM MUST BE DEACTIVATED DURING
C   THE SUMMER. WHEN THE SPACE HEATING SYSTEM IS INACTIVE,
C   THE SOLAR COLLECTORS ARE USED TO MEET THE DOMESTIC HOT
C   WATER LOAD, IF ONE IS SPECIFIED. THE USABLE SOLAR ENERGY
C   FOR WATER HEATING IS CALCULATED USING THE F-CHART
C   CORRELATIONS. SEE BECKMAN KLEIN & DUFFIE.
  462   IF(M.LT.MOFF.OR.M.GE.MONON) GOTO 465
        IF(QDHW(M).GT.0) GOTO 463
        QSUN(M)=0
        QLOAD(M)=QLODX
        GOTO 476
  463   QLOAD(M)=QLODX
        PX=24*N(M)*(100-TAMB(ICIT,M))*AREA/QDHW(M)
        PY=SOL(M)/QDHW(M)
        FDHW=1.029*PY-.065*PX-.245*PY**2+.0018*PX**2+.0215*PY**3
        IF(FDHW.LT.1.0) GOTO 464
        FDHW=1.0
  464   QSUN(M)=FDHW*QDHW(M)
        GOTO 476
  465   IF(QLOAD(M).GT.0) GOTO 466
        QSUN(M)=0
        GOTO 476
  466   TOLD=20
        QQ=QLOAD(M)
```

```
C   THE ACTUAL LOAD DEPENDS ON THE STORAGE TEMPERATURE, WHICH IS
C   A FUNCTION OF LOAD, SOLAR INPUT, STORAGE CAPACITY, AND
C   STORAGE-TO-ROOM CONDUCTANCE.
C   IF THE STORAGE COMPONENT IS A FLOOR SLAB,
C   THE TEMPERATURE AND THE LOAD MUST BE DETERMINED
C   SIMULTANEOUSLY BY ITERATION.
 467   QLOAD(M)=QQ+FP*PER*24*N(M)*(TOLD-TAMB(ICIT,M))
       PL=SOL(M)/QLOAD(M)
       PT=SOL(M)/(STCAP*DT)
       PQ=SOL(M)/(UAR*24*N(M)*DT)
C   THE TEMPERATURE FUNCTIONS FOR SLAB AND NO-SLAB CASES ARE
C   CORRELATIONS DEVELOPED FROM 480 MONTHLY TRNSYS SIMULATIONS.
       IF(PER.EQ.0.0) GOTO 468
       TX(M)=TSET-2.46+3.368*PL+.06289*PT+.8846*PQ-.2449*PL**2
     1  -.000399*PT**2+.6111*PQ**2
       GOTO 469
 468   TX(M)=TSET-1.43+.707*PL+.06048*PT+3.372*PQ-.001761*PL**2
     1  -.0001975*PT**2-.1386*PQ**2
 469   ERR=ABS(TOLD-TX(M))
       IF(ERR.LT.0.01) GOTO 470
       TOLD=TX(M)
       GOTO 467
 470   IF(TX(M).LE.50) GOTO 471
       TX(M)=50.
 471   IF(TX(M).GE.TSET) GOTO 472
       TX(M)=TSET
 472   QLOAD(M)=QQ+FP*PER*24*N(M)*(TX(M)-TAMB(ICIT,M))
C   PHIBR(PHI-BAR) IS THE MONTHLY RATIO OF USABLE TO ABSORBED
C   SOLAR ENERGY(SEE KLEIN).
       XC=FUL*(TX(M)-TAMB(ICIT,M))/(FTA*RR(M)*SUN(ICIT,M))
       PHIBR=EXP(ABRR(M)*(XC+C(M)*XC**2))
       QABS=SOL(M)*PHIBR
C   IN MONTHS WITH HIGH SOLAR FRACTIONS, SOME OF THE USABLE SOLAR
C   ENERGY MERELY SERVES TO RAISE THE ROOM TEMPERATURE, AND DOES
C   NOT CONTRIBUTE TO REDUCING THE HEATING DEMAND. THE FRACTION
C   OF ABSORBED SOLAR ENERGY THUS WASTED COMES FROM ANOTHER
C   TRNSYS CORRELATION. IT IS ONLY APPLIED WHEN THE SOLAR FRACTION
C   IS GREATER THAN .4 AND THE STORAGE TEMPERATURE IS ABOVE THE
C   MID-POINT OF THE ROOM TEMPERATURE RANGE.
       FDUMP=.1273-.06527*PL+.0003466*PT-.001368*PQ
     1  +.007136*PL**2-.000000727*PT**2+.000121*PQ**2
       IF(FDUMP.LE.0.5) GOTO 474
       FDUMP=.5
 474   QDMP(M)=FDUMP*SOL(M)
       FA=QABS/QLOAD(M)
       TZ=TSET+.5*DT
       IF(QDMP(M).GE.0.AND.TX(M).GT.TZ.AND.FA.GT.0.4) GOTO 475
       QDMP(M)=0.
 475   QUSE=QABS-QDMP(M)
       QSUN(M)=AMIN1(QUSE,QLOAD(M))
C   AUXILIARY ENERGY NEEDED IS THE ACTUAL LOAD MINUS THE USABLE SOLAR.
 476   QAUX(M)=QLOAD(M)-QSUN(M)+QDHW(M)
```

```
C   SOLAR FRACTION IS BASED ON THE UNHEATED SLAB LOAD TO ALLOW
C   CONSISTENT COMPARISON WITH OTHER SYSTEMS.
        QLOAD(M)=QLODX
        QSUN(M)=QLOAD(M)-QAUX(M)+QDHW(M)
        FSUN(M)=QSUN(M)/(QLOAD(M)+QDHW(M))
  480   TOTL=TOTL+QLOAD(M)
        TOTS=TOTS+QSUN(M)
        TOTA=TOTA+QAUX(M)
        TOTW=TOTW+QDHW(M)
  490   CONTINUE
C   THE ANALYSIS RESULTS ARE WRITTEN TO FILE ANSWER
C   (LOGICAL UNIT 7).
        WRITE(7,520)
        WRITE(7,520)
        WRITE(7,520)
        WRITE(7,495)
  495   FORMAT(" LOCATION:")
        WRITE(7,103)(LOC(ICIT,J),J=1,2)
        WRITE(7,520)
        WRITE(7,235) PAR(1)
        WRITE(7,236) PAR(2)
        WRITE(7,421) UU
        WRITE(7,425) PAR(4)
        WRITE(7,426) PAR(5)
        WRITE(7,427) PAR(6)
        WRITE(7,428) PAR(7)
        WRITE(7,429) PAR(8)
        WRITE(7,430) PAR(9)
        WRITE(7,431) PAR(10)
        WRITE(7,432) PAR(11)
        WRITE(7,433) PAR(12)
        WRITE(7,434) PAR(13)
        WRITE(7,435) PAR(14)
        WRITE(7,440) PAR(15)
        WRITE(7,444) PAR(16)
        WRITE(7,446) PAR(17)
        WRITE(7,447) PAR(18)
        WRITE(7,449) PAR(19)
        WRITE(7,451) PAR(20)
        WRITE(7,520)
        WRITE(7,560)
        WRITE(7,570)
        DO 500 M=1,12
        FF=100.0*FSUN(M)
        WRITE(7,600) MON(M,1),MON(M,2),QLOAD(M),QDHW(M),QSUN(M),FF,QAUX(M)
  500   CONTINUE
        FFF=100.0*TOTS/(TOTL+TOTW)
        WRITE(7,600) MON(13,1),MON(13,2),TOTL,TOTW,TOTS,FFF,TOTA
  510   GOTO 110
  520   FORMAT("    ")
  560   FORMAT(" MONTH",9X,"HEATING",8X,"DHW",7X,"SOLAR",5X,"PERCENT",5X,
     1  "BACKUP")
```

```
570  FORMAT(16X,"DEMAND",6X,"DEMAND",6X,"SUPPLY",6X,"SOLAR",7X,"HEAT")
600  FORMAT(1H ,2A5,3F12.0,1F10.3,1F12.0)
650  FORMAT("     ACTIVE CHARGE/PASSIVE DISCHARGE THERMAL",
    1 " PERFORMANCE"//)
700  STOP
     END
```

FORT WORTH, TEXAS
33
358 252 212 67 29 0 0 0 11 53 165 323
7.0 9.7 12.1 17.7 21.5 26.9 30.1 28.7 23.6 19.5 13.7 8.0
8840 12000 16620 17340 21200 24720 25150 23200 19190 14440 10830 8650
ALBUQUERQUE, NM
35
524 419 361 187 79 20 1 4 39 162 356 504
1.4 3.4 6.8 12.6 18.6 22.9 25.5 24.0 19.5 14.1 6.5 2.1
11120 15270 19790 25990 29320 30120 28220 26190 22200 18120 13290 10780
FRESNO, CALIFORNIA
36.8
373 243 183 134 61 19 4 8 31 96 223 386
6.3 9.7 13.0 15.2 20.0 24.5 27.6 26.0 22.8 17.6 11.0 5.9
7610 11730 18050 24030 28410 30880 30740 27230 22970 16520 10340 6480
CAPE HATTERAS, NC
35.3
324 302 236 99 25 0 0 0 7 44 171 313
7.9 7.5 10.7 15.6 19.7 24.0 25.9 25.6 23.2 18.7 13.2 8.3
8170 11090 14460 19750 22260 23260 21550 19130 17100 13310 10190 7240
NASHVILLE,TENNESSEE
36.1
428 357 277 143 52 7 1 2 22 125 244 422
4.5 5.7 9.6 14.7 19.8 24.0 25.7 24.9 21.9 15.7 10.4 4.7
6280 9180 13400 17720 19530 23070 21780 19960 16100 12060 7840 5790
OMAHA, NEBRASKA
41.4
767 622 448 201 61 19 2 3 82 191 413 637
-6.4 -3.9 3.9 12.2 18.8 22.5 24.8 24.1 17.5 13.0 4.8 -2.2
7520 10570 13460 17140 22730 24780 23420 21250 15820 11470 7760 5970
WASHINGTON, DC
39
591 496 378 193 85 31 3 12 32 161 312 483
-7.4 0.6 6.3 12.8 17.5 21.1 24.4 23.5 20.7 13.8 8.1 2.7
6910 9230 13400 16830 19420 21470 19490 19300 14900 11150 7680 5550
BISMARCK, ND
46.8
915 793 642 412 188 78 22 27 181 351 604 886
-11.2 -10.0 -2.4 4.7 13.0 17.7 21.6 22.5 13.2 7.1 -1.8 -10.3
5370 8900 12750 16570 21130 23620 24840 21440 15000 9960 5780 4530
MEDFORD,OREGON
42.4
466 396 363 268 203 75 40 50 102 228 362 509
3.3 4.2 6.7 9.5 12.6 18.6 21.9 21.1 17.8 11.8 6.3 1.9
4520 8150 12890 18060 23110 26450 28700 24300 18200 11130 5880 3280
MADISON, WISCONSIN
43
829 681 626 297 158 49 16 43 94 250 479 683
-8.4 -6.0 -1.9 8.7 14.6 19.6 22.1 20.0 16.8 10.5 2.4 -3.7
5910 9130 13760 15700 19320 21280 21750 19870 15160 9820 5810 4280