

THERMAL PERFORMANCE LIMITS  
OF SOLAR HEATED BUILDINGS

BY

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## ABSTRACT

Methods to determine and present the thermal performance limits of solar heated buildings are described. Performance limits are calculated by replacing the realistic models of a detailed hourly building energy analysis program with idealized component models. The idealized building models produce thermal performance limits that apply to general classes of buildings and design options.

Generalized results are presented in terms of auxiliary energy savings between design options. Design options are hypothetical (associated with limits of performance), or realistic (associated with the performance of conventional buildings). A specific comparison involving a direct gain building is offered to suggest applications for the use of thermal performance limits. Practical constraints on building design and materials are considered.

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## NOMENCLATURE

Additional nomenclature is defined locally.

$A_c$	Collector area
$A_{esm,p}$	Planar projected area of energy storage material
$A_{esm,s}$	Surface area of energy storage material
$A_o$	Gross wall area of a building
$A_p$	Projected collector area
$A_{p,max1}$	Maximum projected collector area based on building size
$A_{p,max2}$	Maximum projected collector area based on building construction standards
$A_{p,max}$	Maximum of $A_{p,max1}$ and $A_{p,max2}$
$A_w$	Opaque wall area of a building
$d_{esm}$	Thickness of a planar wall
$DD_{yr}$	Annual degree-days
$E_{store}$	Energy stored by a solar heated building
$G_t$	Instantaneous solar radiation incident on a tilted surface
$I_t$	Solar radiation incident on a tilted surface over the period of an hour
LCR	Load collector ratio
NLC	Net load coefficient
$Q_{aux}$	Auxiliary energy input
$Q_{aux,yr,i}$	Auxiliary energy demand for an infinite thermal capacitance building

NOMENCLATURE (continued)

$Q_{aux,yr,z}$	Auxiliary energy demand for a zero thermal capacitance building
$Q_{dump}$	Energy dumped from a building due to insufficient energy storage capacity
$Q_{ex}$	The energy exchanged between energy storage materials and the room air of a building
$Q_{in}$	A controlled energy flow into the room air of a building
$Q_{int}$	Internal energy gains for a building
$Q_{loss,b}$	Building conduction and infiltration energy losses
$Q_{loss,c}$	Solar energy collector losses
$Q_{loss,esm}$	Energy lost from storage to the environment due to a temperature difference
$Q_u$	Useful solar gains delivered to energy storage
SCR	Storage- (to) (projected) collector (area) ratio
SSF	Annual solar savings fraction
$T_a$	Ambient temperature
$T_{bal}$	Room air balance temperature accounting for internal energy gains
$T_{base}$	Base temperature for degree-day calculations
$T_{esm,max}$	Maximum allowable temperature of an energy storage material
$T_r$	Instantaneous room air temperature
$T_{r,set}$	Low thermostat set point temperature
$\Delta T_{esm}$	$(T_{esm,max} - T_{r,set})$
$U_c$	Collector conductance (passive systems)

## NOMENCLATURE (continued)

$U_{c,crit}$	Collector conductance where $A_{p,max1}$ equals $A_{p,max2}$
$U_o$	Gross wall conductance
$U_w$	Opaque wall conductance
$(UA)_b$	Conductance-area product for the total building
$(UA)_w$	Conductance-area product for the opaque walls
$(UA)_r$	Conductance-area product for the roof
$(UA)_f$	Conductance-area product for the floor
$(UA)_i$	Conductance-area product for infiltration
$V_{esm}$	Volume of energy storage material in a building
$(\tau\alpha)$	Transmittance-absorptance product of a solar energy collector
$(\overline{\tau\alpha})$	Monthly-average transmittance-absorptance product of a solar energy collector
.	Above a symbol this denotes an energy rate

## Subscripts

aux	Auxiliary energy
b	Building
c	Collector
esm	Energy storage material
yr	Annual



## CHAPTER 1

### 1. INTRODUCTION

#### 1.1 Overview

What if a solar heated building had infinite capacity to store excess solar gains for use during periods of solar deficiency? Would its performance increase (double? triple?), decrease, or stay the same, relative to a conventional building? Results presented in this thesis concern these questions, and a more general one: "What is the theoretical limit of a hypothetical design option to improve the thermal performance of a conventional solar heated building?" Before these questions can be answered, definitions of terms must be provided. Defining these terms will outline the scope of this thesis.

As used in this thesis, the term 'building' includes those defined by ANSI/ASHRAE/IES standard 90A-1980 [1] as type "A" buildings:

A-1 Detached one- and two-family dwellings

A-2 All other residential buildings, 3 stories or  
or less, including but not limited to multi-family  
dwellings and hotels and motels.

'Buildings' may also apply to such non-residential buildings as greenhouses and airplane hangers. Exact criteria will accompany results. 'Heated' confines this study to analyzing the energy inputs to a building that must be

provided to keep its temperature at a desired level. 'Solar heated' refers to buildings designed to obtain some fraction of their energy input from the sun. Since any building that absorbs sunlight will be solar heated, there will not be a line drawn to distinguish a solar heated building from a non-solar one. Instead, a parameter will be defined to characterize the extent to which a building design infers solar heating.

Three types of systems can deliver solar energy to a building: active, passive, and hybrid. Active systems have solar components that are appended to the building to provide solar heating. Energy is transferred with a working fluid. In passive systems, the solar components are integrated into building design; windows become collectors, and walls become energy storage materials. Hybrid systems combine active and passive features. While this study concentrates on passive systems, several of the concepts presented can be applied to active and hybrid systems.

'Design options' for a solar heated building will be placed into one of two categories: realistic design options, or hypothetical design options. Realistic design options are currently available, and could be used in an actual building. Realistic design options such as double or triple glazed windows can be purchased, and have measureable properties. Hypothetical options are taken into consideration to see their effect on building thermal

performance. A window with zero thermal conductivity would be a hypothetical design option. Hypothetical energy storage material could have infinite thermal conductivity and specific heat. Energy might be withdrawn from this material at an infinite rate, if necessary.

If solar energy input is not sufficient to maintain a desired comfort level, additional energy must come from an auxiliary source. This auxiliary energy is commonly supplied by the purchase and combustion of a nonrenewable fuel. The amount of auxiliary energy required by a building will be used as a measure of 'thermal performance', since this relates directly to the cost that the building owner must pay. Design changes to buildings can be evaluated by noting auxiliary energy savings. The cost of a design change can be compared with the monetary value of the potential energy savings.

'Thermal performance limits' are defined when hypothetical design options replace realistic components or processes. A thermal performance limit must be distinguished from the performance of a building at a practical limit of construction. Consider an existing building, owned and occupied by a single family. The lowest conductance glazing available for this home might be an evacuated window with a conductance of  $0.57 \text{ W/m}^2\text{-C}$  ( $0.1 \text{ ft}^2\text{-h-F/btu}$ ). The performance of a building with these windows would be a practical limit in terms of decreasing

the window conductance. However, the absolute thermal performance limit for this building, in terms of decreasing window conductance, would result from a zero thermal conductance window.

The previous example suggests that one application of knowing thermal performance limits is in their comparison with practical building performance. Such comparisons provide a measure of the potential energy savings of design improvements to solar heated buildings. Thermal performance limits may offer the means to assess the status of current technology, and possibly suggest favorable (or unfavorable) research directions.

Neeper and McFarland [2] evaluated the potential benefits of various improvements to passive solar building materials and heat transfer processes. Among their final conclusions is the statement, "Research leading to practical methods for greatly enhanced heat transfer and/or thermal diode effects between the envelope and the building interior could double the efficiency of passive systems in cold climates." The reader might think this is a general result to be expected of all passive buildings applying these design options in a cold climate. This general conclusion was extrapolated from specific results for a sample building in Caribou, Maine, where a hypothetical vaporizing fluid collector wall had a better performance than a single glazed 0.305 m (1 ft) thick Trombe wall. While to "double the

efficiency" suggests an impressive improvement, the phrase does not make clear how much money this will save, and whether it will be enough money to use the vapor wall instead of a Trombe wall.

## 1.2 Objectives and Organization

The objective of this study is to determine and present thermal performance limits of solar heated buildings. Chapter 2 introduces a method to determine thermal performance limits, after discussing previous research in this area. Parameters to generalize and present limits for solar heated buildings are discussed in Chapter 3. Actual building materials and designs associated with practical limits of performance are also presented. Chapter 4 gives results to answer questions of the type that introduced this thesis. Applications and examples of using thermal performance limits are included in the chapter. A summary and recommendations are offered in Chapter 5.

## CHAPTER 2

### 2. THEORETICAL BASIS OF THERMAL PERFORMANCE LIMITS

The models and equations used to calculate the thermal performance limits of solar heated buildings will be presented in this chapter. Discussion will begin with previous research, and then a new method to calculate thermal performance limits will be presented.

#### 2.1 Previous Research

This section will introduce the concept of thermal performance limits in terms of previous work involving two types of buildings: infinite thermal capacitance buildings, and zero thermal capacitance buildings.

##### 2.1.1 Infinite Thermal Capacitance Buildings

The Un-utilizability design method developed by Monsen, et. al.[3] for passive solar direct gain systems uses the concept of an infinite thermal capacitance building. A building with infinite thermal capacitance is able to store all energy gains in excess of the building losses. The excess energy gains stored within the building can be used to offset auxiliary energy requirements at any time during a month. Month-to-month carry over is not allowed. The annual auxiliary requirement, calculated on a monthly basis,

is given by

$$Q_{aux,yr,i} = \sum_{yr} \left[ \int_{mo} \dot{Q}_{loss,b} dt - \int_{mo} \dot{Q}_{int} dt - \int_{mo} \dot{Q}_u dt \right]^+ \quad (2.1)$$

$\dot{Q}_{loss,b}$  is the rate of conductance losses from the room air to the environment, and includes the losses due to infiltration.  $\dot{Q}_{int}$  is the rate of energy transfer to the room air from interior energy sources such people and appliances.  $\dot{Q}_u$  is the rate that solar gains are delivered to the building interior, where they are stored or used to offset losses.

$\dot{Q}_{loss,b}$  is calculated from the following equation

$$\dot{Q}_{loss,b} = (UA)_b (T_{r,set} - T_a) \quad (2.2)$$

where  $(UA)_b$  is the overall conductance-area product for the building, and includes an effective thermal conductance for infiltration losses. The room set temperature,  $T_{r,set}$ , is used in Equation 2.2 because the room air temperature of an infinite thermal capacitance building is constant at that value. The addition of auxiliary energy prevents the room temperature from dropping below  $T_{r,set}$ , and the infinite energy storage absorbs all energy gains that would raise the room temperature above  $T_{r,set}$ . If the rate of internal gains is constant, the terms  $\dot{Q}_{loss,b}$  and  $\dot{Q}_{int}$  can be combined into a single loss term given by

$$\dot{Q}_{loss,b} - \dot{Q}_{int} = (UA)_b (T_{bal} - T_a) \quad (2.3)$$

where  $T_{bal}$  is the constant balance point temperature accounting for internal gains, and is given by

$$T_{bal} = T_{r,set} - \dot{Q}_{int} / (UA)_b \quad (2.4)$$

The intent of Equation 2.1 is to give the lower limit of auxiliary energy usage, the absolute limit of performance, in terms of increasing the energy storage capacity. Note that Equation 2.1 does not represent the case of seasonal energy storage capacity, since monthly energy carry-over is not allowed. Equation 2.1 also implies there are no rate limitations when removing energy from storage.

### 2.1.2 Zero Thermal Capacitance Buildings

The Un-utilizability method also uses the concept of a zero thermal capacitance building[3]. A zero thermal capacitance building is not able to store excess solar gains for later use. During periods of excess solar gains, it will be necessary to remove energy from the room air to prevent its temperature from rising above  $T_{r,set}$ . This energy must be dumped to the environment at a rate given by

$$\dot{Q}_{dump} = [ \dot{Q}_u + \dot{Q}_{int} - \dot{Q}_{loss,b} ]^+ \quad (2.5)$$

where the plus sign means that only positive values of the expression in brackets are included in  $\dot{Q}_{dump}$ . When energy must be added to the room air to keep its temperature at

$T_{r, set}$ , the energy must come from an auxiliary source at a rate given by

$$\dot{Q}_{aux} = [\dot{Q}_{loss, b} - \dot{Q}_{int} - \dot{Q}_u]^+ \quad (2.6)$$

The annual auxiliary energy requirement of a zero thermal capacitance building is calculated using the following equation

$$Q_{aux, yr, z} = \sum_{yr} \left[ \int_{mo} \dot{Q}_{loss, b} dt - \int_{mo} \dot{Q}_{int} dt - \int_{mo} \dot{Q}_u dt + \int_{mo} \dot{Q}_{dump} dt \right]^+ \quad (2.7)$$

$\dot{Q}_{loss, b}$ ,  $\dot{Q}_{int}$  and  $\dot{Q}_u$  follow the same definitions as in the infinite thermal capacitance case. Mosen[3] presents a method to evaluate  $\dot{Q}_{dump}$  for direct gain systems using utilizability concepts[4,5,6,7]. Utilizability methods allow one to estimate the fraction of the solar radiation incident on a collector that is above a critical level. In the Un-utilizability method, the radiation above the critical level represents energy that cannot be utilized (un-utilizable) and therefore must be dumped.

For the case of the direct gain system, the rate that energy is dumped is given by

$$\dot{Q}_{dump} = [G_t (\tau\alpha) A_c - (UA)_b (T_{bal} - T_a)]^+ \quad (2.8)$$

where  $G_t$  is the instantaneous solar radiation incident on a direct gain collector with area  $A_c$ , and transmittance-absorptance product  $(\tau\alpha)$ [5]. The critical level is obtained by solving Equation 2.8 for  $G_t$  with  $\dot{Q}_{dump}$  equal to zero,

using the daytime value of  $(UA)_b$ . The solar radiation at levels above this critical level must be dumped from the building. Therefore, the monthly-average daily utilizability,  $\bar{\phi}$ , was used to calculate the fraction of the total monthly solar gains that must be dumped, as expressed by the equation below

$$\bar{\phi} = \frac{\int_{m0} \dot{Q}_{dump} dt}{\int_{m0} \dot{Q}_u dt} \quad (2.9)$$

It should be noted, however, that the use of Equation 2.8 to calculate the critical radiation level requires the assumption that heat transfer mechanisms do not limit the rate at which radiant solar gains are converted to sensible heat.

### 2.1.3 Results Using Previous Work

Erbs[8] presents a method to calculate annual auxiliary energy requirements of zero and infinite thermal capacitance passively heated buildings using the concepts described above. Erbs' method requires climatic input of monthly-average daily values of ambient temperature and solar radiation. The calculations were performed for a direct gain passive solar building with the characteristics given in Table 2.1. The results of the calculations are given in Table 2.2.

Table 2.1 Characteristics of a Solar Heated Building

---

Location: Madison, Wisconsin	
Solar Collector: Passive Direct Gain	
South Facing Vertical	
$A_c = 20 \text{ m}^2$	(215 ft <sup>2</sup> )
$(\tau\alpha) = 0.70$	
Building Loss Coefficient: $(UA)_b = 300 \text{ W/C}$ (569 Btu/h-F)	
Internal Energy Gains: $\dot{Q}_{int} = 1000 \text{ W}$ (3412 Btu/h)	
Room Set Temperature: $T_{r,set} = 20 \text{ C}$ (68 F)	
Balance Temperature: $T_{bal} = 16.7 \text{ C}$ (62 F)	

---

**Table 2.2 Annual Auxiliary Heating Requirements for  
the Building Described in Table 2.1,  
Calculated by Erb's Method**

**Monthly Auxiliary Requirements (GJ)**

Month	No Solar	Zero Thermal Capacitance	Infinite Thermal Capacitance
Jan.	20.15	16.71	16.01
Feb.	16.46	12.90	11.95
Mar.	14.94	11.09	9.45
Apr.	6.42	4.75	2.29
May	2.78	2.48	0.00
June	0.76	0.75	0.00
July	0.35	0.35	0.00
Aug.	0.76	0.75	0.00
Sep.	1.69	1.62	0.00
Oct.	5.35	4.27	0.78
Nov.	11.14	8.99	7.76
Dec.	16.38	14.04	13.49
YEAR	97.17	78.71	61.73

A plot of monthly auxiliary energy versus monthly degree-days is given in Figure 2.1. The curve fits are approximate and are intended to convey qualitative information. This figure shows the limits of performance for the solar heated building described in Table 2.1. The best possible performance, excluding the case of seasonal storage, is given by the infinite thermal capacitance with no monthly carry over. The worst performance results from the case when solar energy cannot be used to offset the auxiliary requirement. The difference in annual energy requirements for these two cases is 35.4 GJ. Assuming a delivered cost of \$10/GJ for auxiliary energy, the maximum yearly savings for all energy storage and heat transfer design improvements would be 354 dollars. Notice that for large values of degree-days, the auxiliary energy requirement for the zero thermal capacitance building is nearly equal to the infinite thermal capacitance case.

It is impossible to build houses with zero or infinite thermal capacitance. There are also practical ranges of heat transfer rates between energy storage materials and room air. Realistic construction methods and materials would define sets of practical limit lines falling between the absolute limits given in Figure 2.1. These practical limits would give a better estimate of the maximum possible auxiliary energy savings. One of the objectives of this thesis is to determine the thermal performance limits for

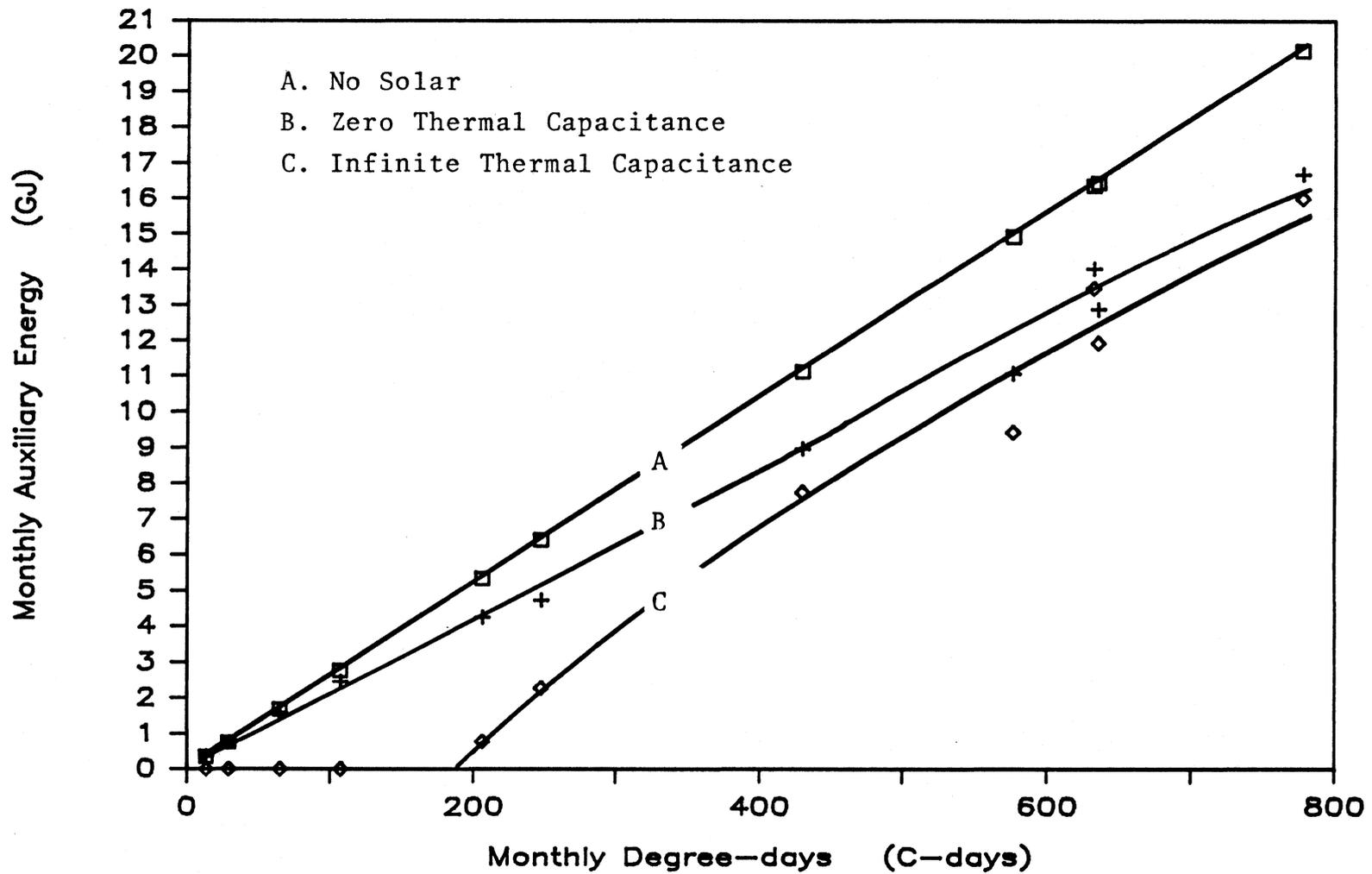


Figure 2.1 Thermal Performance Limits of the Solar Heated Building of Table 2.1, by Erbs' Method

buildings which have finite energy storage capacity and heat transfer rates. A method to calculate the thermal performance of buildings with combinations of practical and hypothetical characteristics will be presented in the next section.

## 2.2 Calculation Method for Thermal Performance Limits

A method to calculate the thermal performance limits for zero, finite, and infinite thermal capacitance buildings will be presented. Buildings having finite heat transfer rates between energy storage and room air are considered in the analysis. A building model is developed which idealizes the performance of building components and energy transfer processes. The model is intended to replace the realistic building component models used in detailed hourly computer simulations. By combining idealized models with the realistic models of an hourly building energy analysis program, one will be able to define thermal performance limits according to the definition given in the first chapter.

The idealized building model is developed using the energy system diagram shown in Figure 2.2. The diagram represents the process of collection, storage, and delivery of solar energy to building. Although Figure 2.2 resembles a schematic diagram for active systems, the resulting energy balance equations will apply to passive and hybrid systems. Thermal performance limits will result from controlling

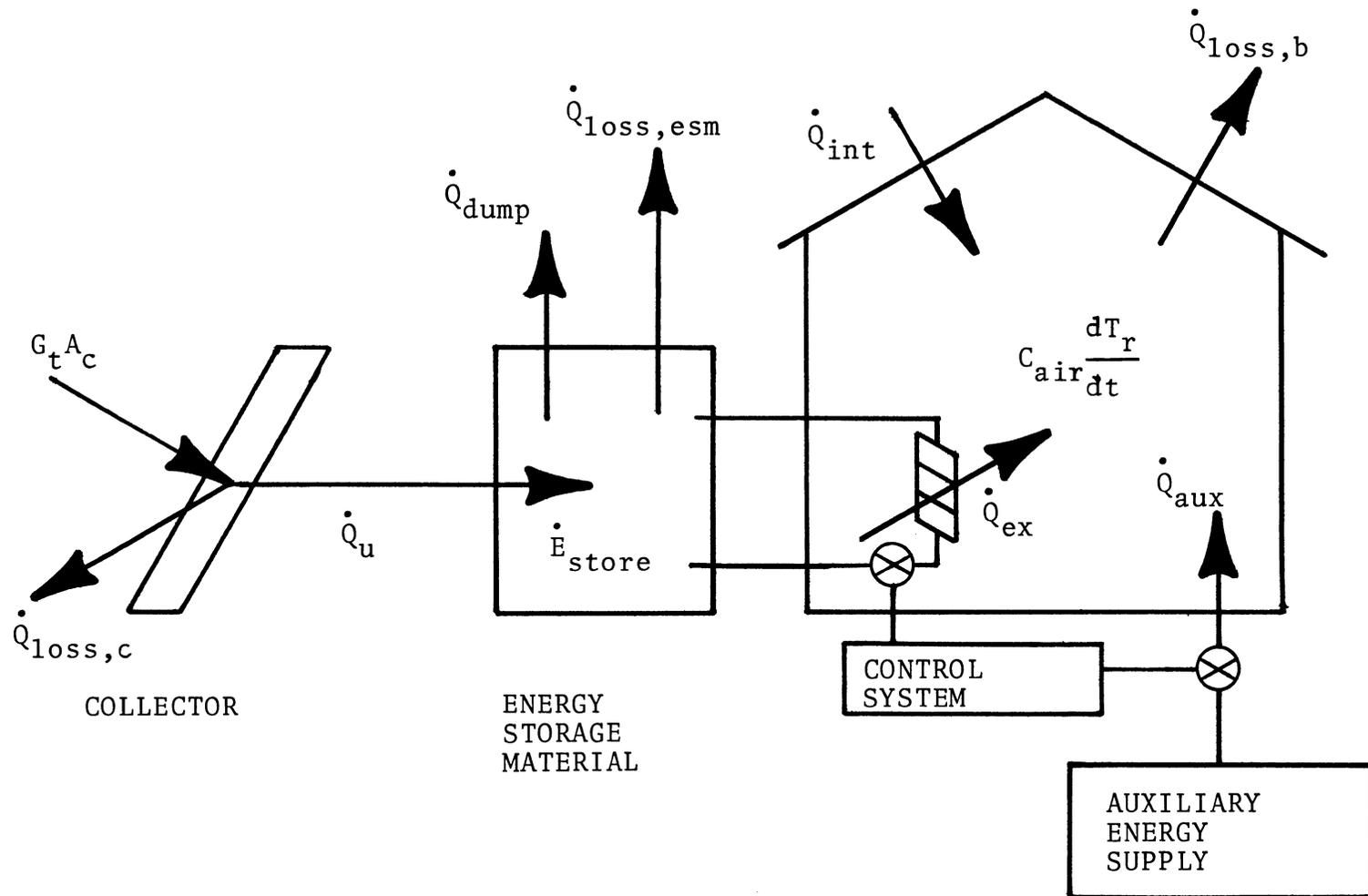


Figure 2.2 Energy System Diagram for a Solar Heated Building

energy exchanges, and by specifying maximum values for energy balance terms.

### 2.2.1 Energy Balances and Control Strategy

An energy rate balance for the collector component gives

$$\dot{Q}_u = G_t A_c - \dot{Q}_{loss,c} \quad (2.10)$$

$G_t A_c$  is the solar radiation incident on the collector, in dimensions of energy per unit time.  $\dot{Q}_{loss,c}$  is the collector loss rate, and  $\dot{Q}_u$  is collected energy that is delivered to energy storage. Equation 2.10 is integrated over an hour to give the total solar energy collected during one hour

$$Q_u = I_t A_c - \int_{\text{hour}} \dot{Q}_{loss,c} dt \quad (2.11)$$

Figure 2.2 presented the energy rate terms for the energy storage material. An energy balance, integrated over an hour, is given by

$$Q_u = E_{store} + Q_{ex} + Q_{dump} + Q_{loss,esm} \quad (2.12)$$

$Q_u$  is the useful energy delivered to storage from the collector.  $Q_{ex}$  is the energy exchanged between energy storage and the room air.  $E_{store}$  is the amount of energy stored during the hour. If a limit is placed on the total amount of energy allowed in storage, it may be necessary to dump the excess energy gains to the environment.  $Q_{dump}$  accounts for dumping energy to the environment.  $Q_{loss,esm}$

accounts for energy lost from storage to the environment due a temperature difference.

The model for the collector-storage system was presented in terms of a single collector and energy storage component. In general, there may be several collectors with various orientations and properties. The total useful energy collected in a single hour is calculated by summing the energy obtained from each collector. The total useful energy collected in an hour may be delivered to several different energy storage components, each with its own energy storage limit. The intent of this analysis is to be able to model perfect storage; therefore, energy will not be dumped to the environment until all energy storage components have reached their energy storage limit. This implies perfect energy exchange between energy storage components.

The room-air energy rate balance, shown schematically in Figure 2.2, is given by

$$\dot{Q}_{in} = C_{air} \frac{dT_r}{dt} + \dot{Q}_{loss,b} - \dot{Q}_{int} \quad (2.13)$$

where  $\dot{Q}_{in}$  represents a controlled energy input to the room air given by

$$\dot{Q}_{in} = \dot{Q}_{ex} + \dot{Q}_{aux} \quad (2.14)$$

A hypothetical control system controls the energy inputs  $\dot{Q}_{ex}$  and  $\dot{Q}_{aux}$  so that  $dT_r/dt$  is always zero. Equation 2.13,

integrated over an hour, reduces to

$$Q_{in} = Q_{loss,b} - Q_{int} \quad (2.15)$$

where the building conductance loss,  $Q_{loss,b}$ , is calculated using  $T_{r,set}$ , as in Equation 2.2.

The control system uses the following strategy:

1. The integrated room-air energy balance, Equation 2.15, is solved for  $Q_{in}$ , the energy transfer required to keep the room temperature at  $T_{r,set}$ .
2.  $Q_{in}$  will positive, negative, or zero:
  - a.) If  $Q_{in}$  is less than or equal to zero, then  $Q_{aux}$  is zero and Equation 2.14 reduces to  $Q_{in} = Q_{ex}$ . A negative value for  $Q_{ex}$  means that energy is transferred from the room air into the energy storage components.
  - b.) If  $Q_{in}$  is greater than zero, then the first choice to supply  $Q_{in}$  will be with energy from storage,  $Q_{ex}$ . Therefore, Equation 2.14 is rearranged to give

$$Q_{aux} = [ Q_{in} - Q_{ex} ]^+ \quad (2.16)$$

The positive sign means that  $Q_{ex}$  will not be any greater than is required to make  $Q_{aux}$  equal to zero. This implies perfect control over the process of removing energy from storage.

The control system insures that the room temperature will always equal  $T_{r,set}$ , the lowest acceptable room temperature. This control strategy is designed to give the minimum auxiliary heating requirement; it may not result in the lowest heating bill if the auxiliary energy costs are time dependent.

### 2.2.2 Annual Energy Calculations

Annual thermal performance limits can be calculated using the models and control strategies presented in the previous section. Variable weather patterns result in some hours requiring auxiliary energy input, and other hours having energy gains in excess of losses. These two situations are used to illustrate the method of forward shifting excess gains to obtain thermal performance limits.

#### Hours with Excess Energy Gains

During some hours of the year, only a part of the solar gains delivered to the energy storage components will be removed to keep the room temperature at  $T_{r,set}$ . The rest of the gains, the excess, is kept in storage. An important aspect of the calculation procedure is keeping a record of the amount of energy stored each hour, and the hour it was stored. If excess energy gains exist for several consecutive hours, a store of energy will build up. This store of energy has the potential to be used during later hours to offset an auxiliary energy requirement. This pattern of energy flows is shown in Figures 2.3 to 2.7 for a

six hour period.

Figure 2.3 shows the units of useful solar energy delivered to storage during each of the first six hours. Figure 2.4 gives the results for the room air energy balance for hours 1 through 6. For hours 1, 2 and 3, the room air requires energy input to maintain a temperature of  $T_{r,set}$ . During hour 6, energy must be removed from the room air. The useful solar gains for each hour were large enough so that  $Q_{in}$  was supplied with energy from storage, as shown in Figure 2.5. The energy history of the energy storage components is given in Figure 2.6. The components have sufficient capacity so that energy is not dumped to the environment. During each of the 6 hours, an excess gain was stored. The integrated energy in storage is shown in Figure 2.7.

#### Removing Energy from Storage

During some hours of the year, the hourly solar gain may not be sufficient to offset the building losses for the hour. However, if energy was stored in the previous hour, it will be removed from storage to reduce the auxiliary requirement. If auxiliary energy is still needed, storage will be searched for excess energy going backward in time, hour by hour, until the storage is empty or the building loss is offset. If the next hour requires energy from this depleted storage, it will be necessary to search farther back in time. This calculation method results in

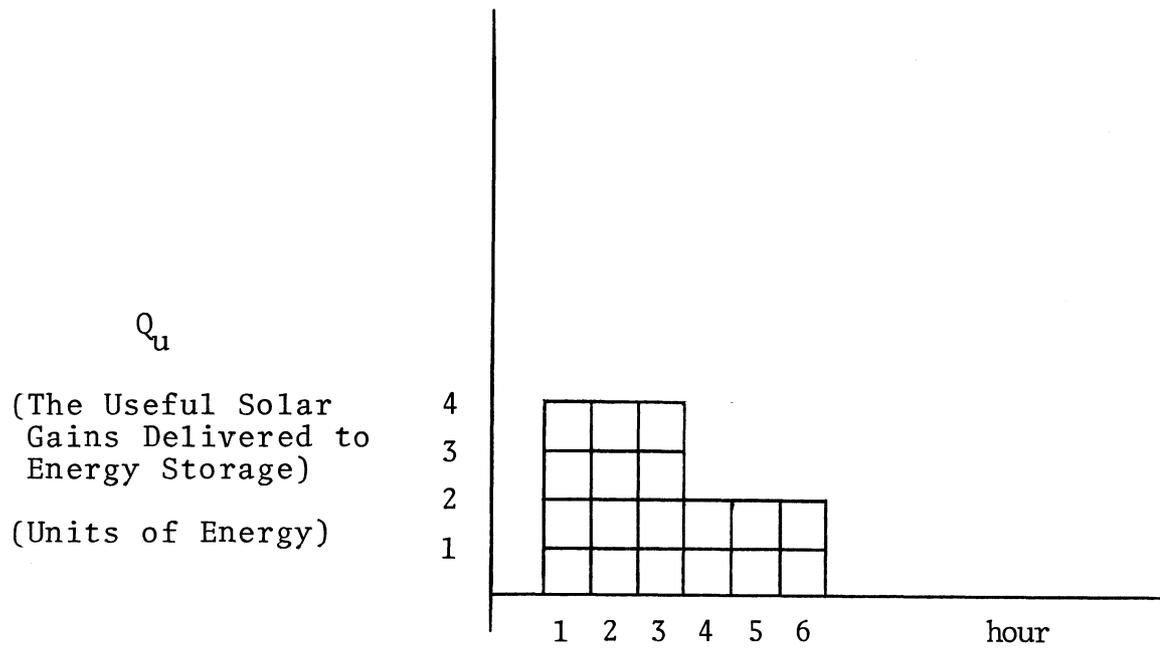


Figure 2.3 Useful Solar Gains are Delivered to Energy Storage During hours 1 Through 6

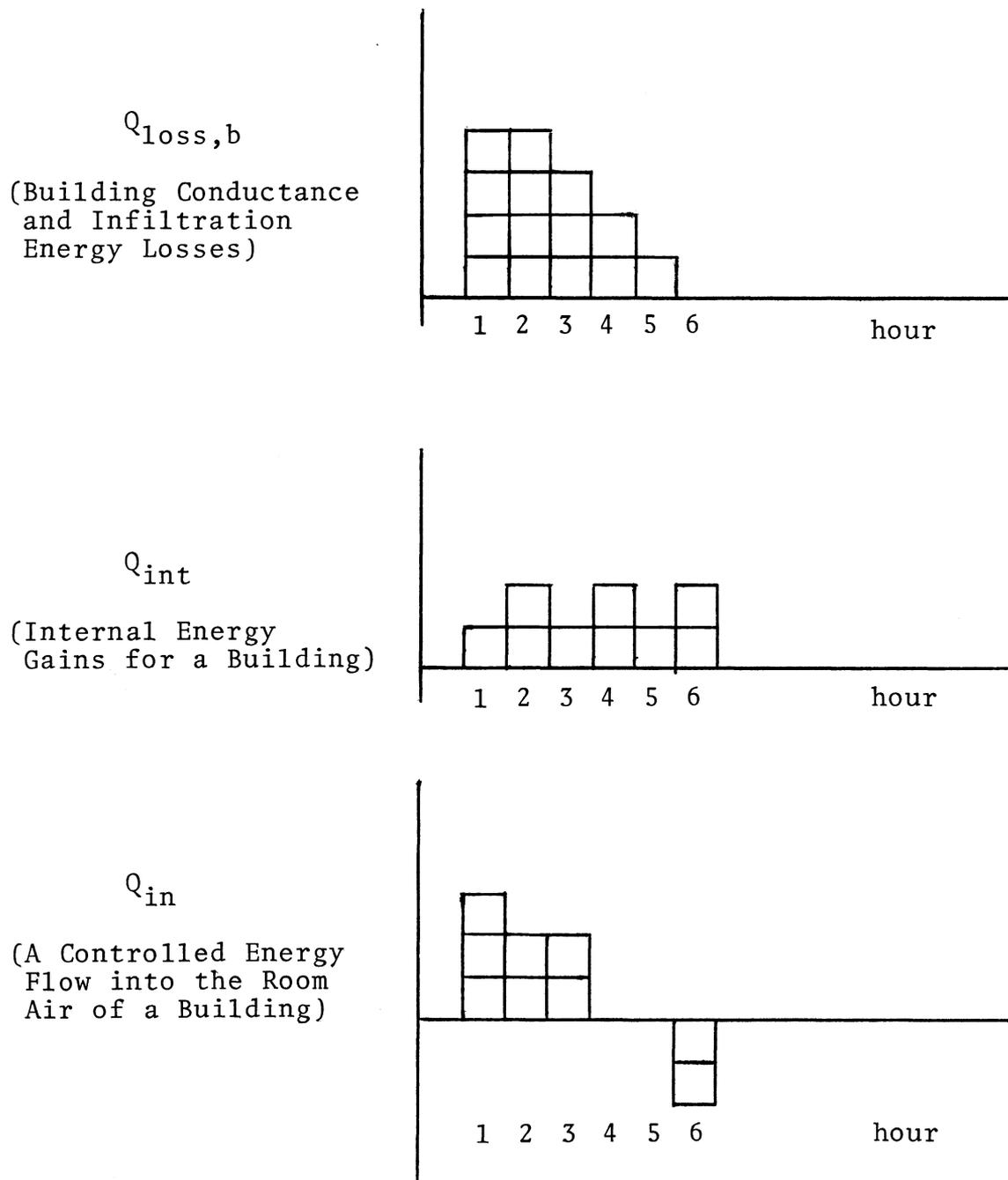


Figure 2.4 Energy Flows for a Solar Heated Building with Controlled Energy Input; from Equation 2.15

$$Q_{in} = Q_{loss,b} - Q_{int}$$

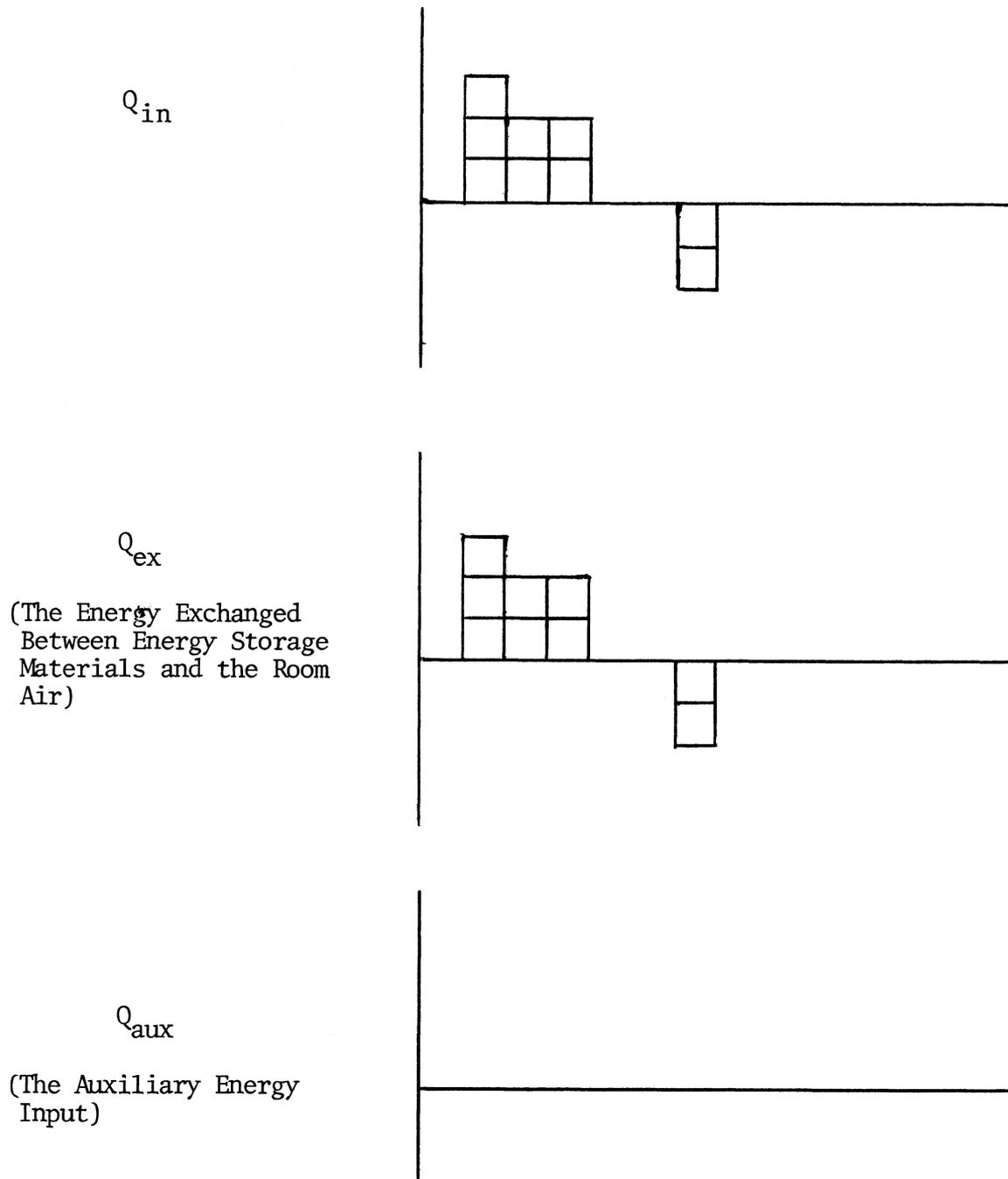


Figure 2.5 Controlled Energy Flows; from Equation 2.14  
 $Q_{in} = Q_{ex} + Q_{aux}$

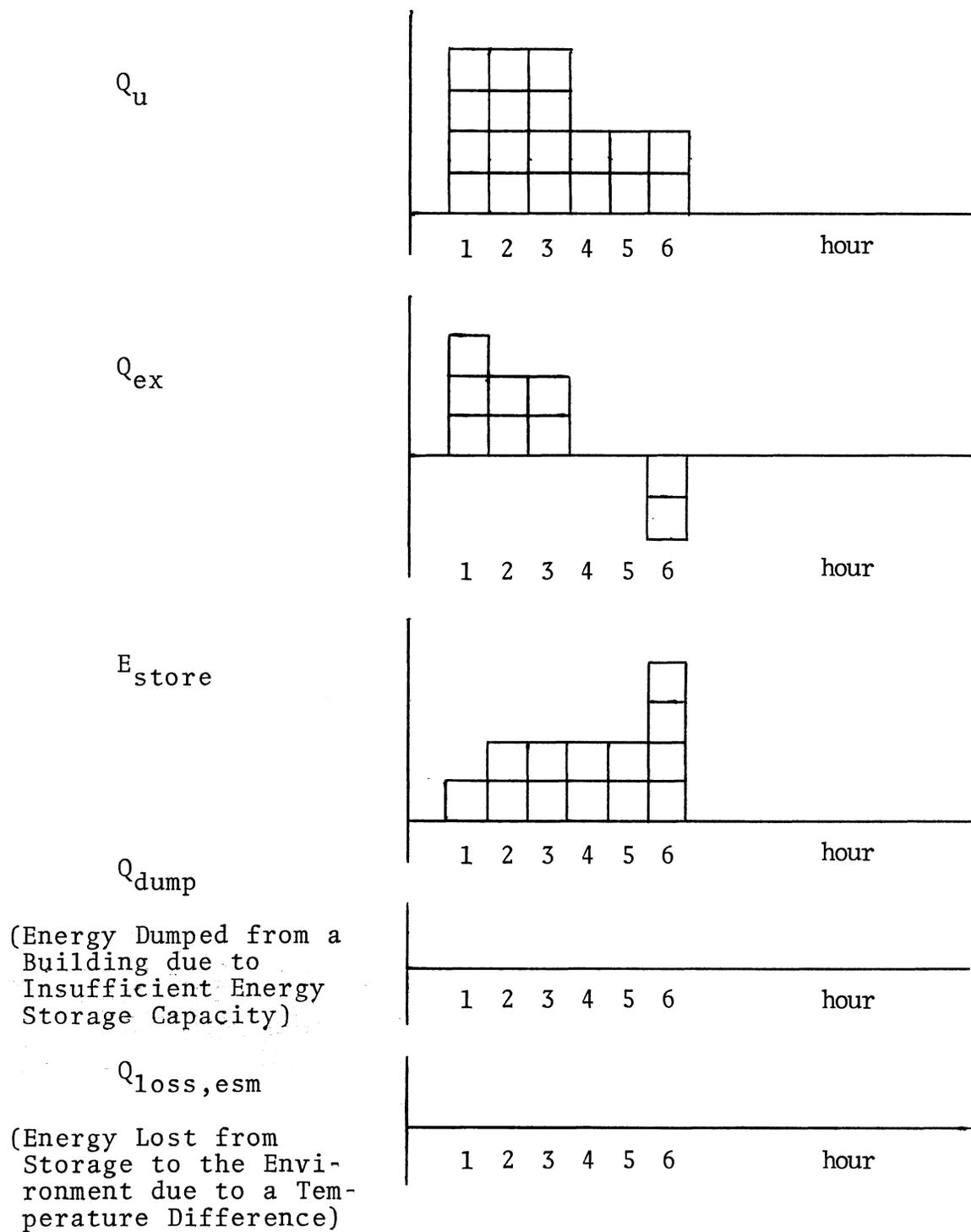


Figure 2.6 Energy Storage Energy Flows; from Equation 2.12  
 $Q_u = E_{store} + Q_{ex} + Q_{dump} + Q_{loss,esm}$

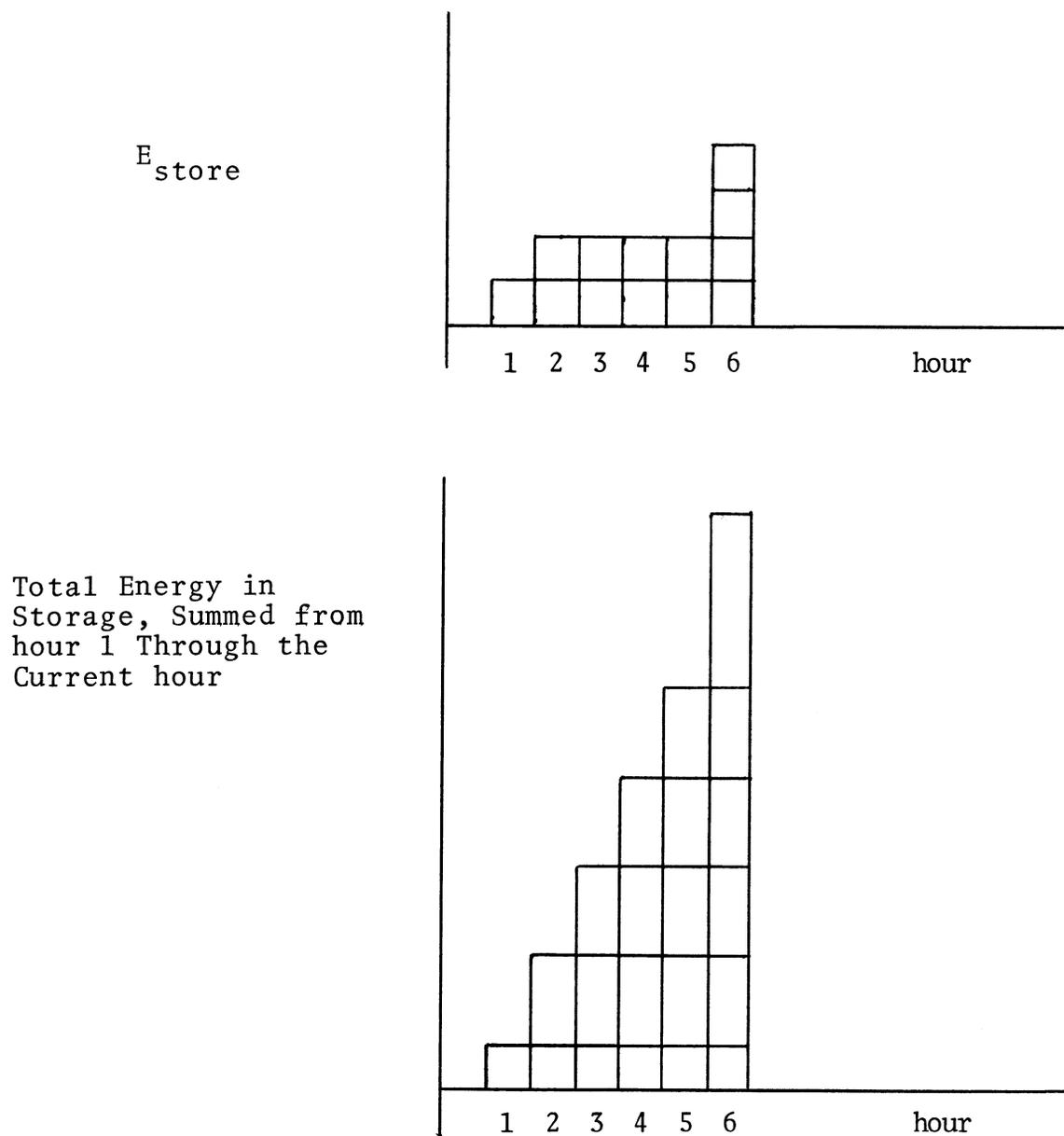


Figure 2.7 Energy Storage History for Periods of Excess Gains

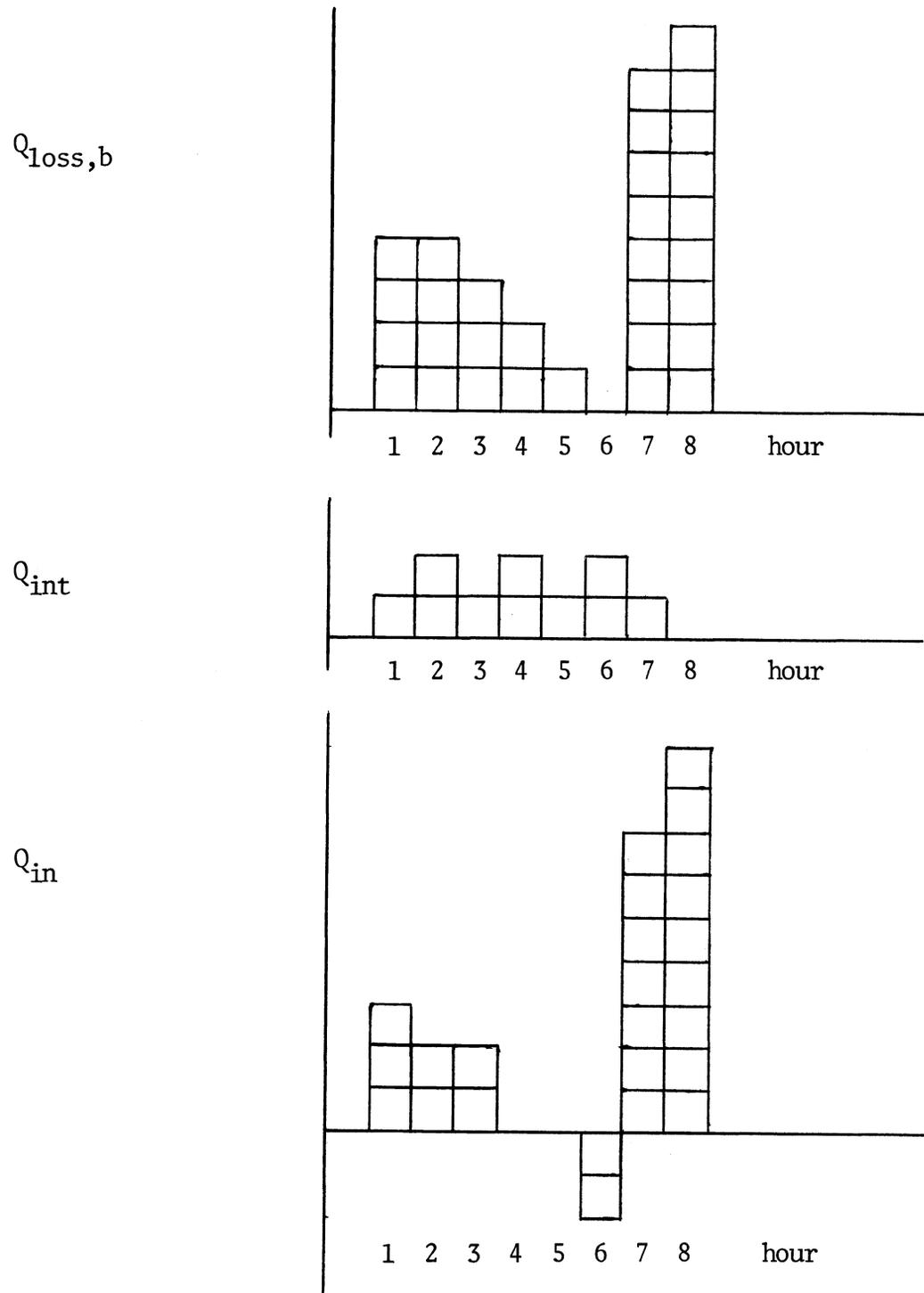
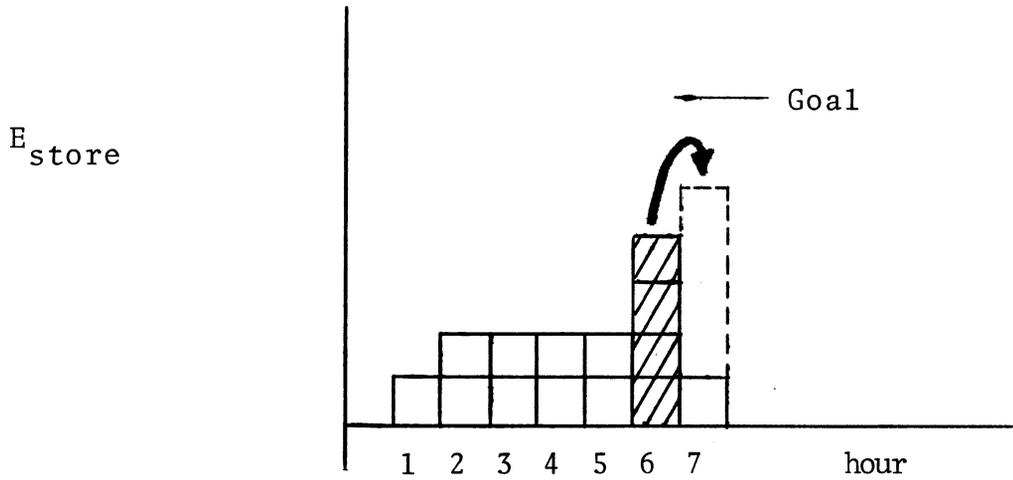
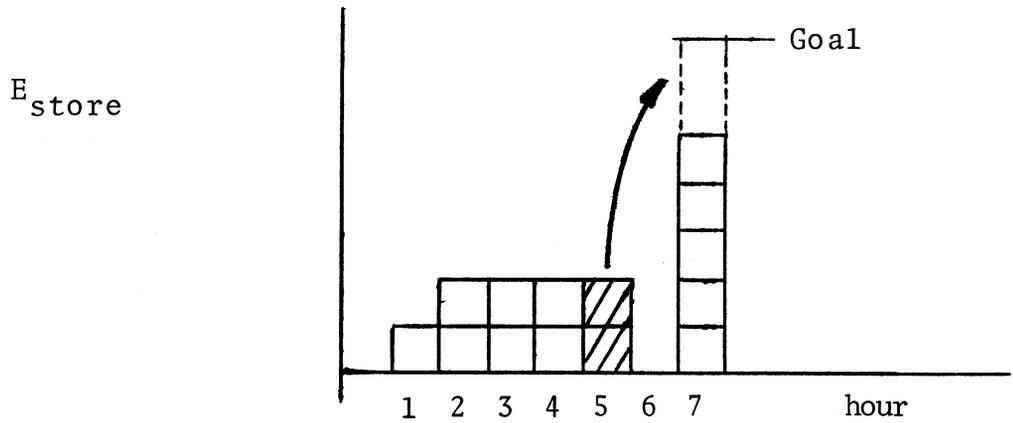


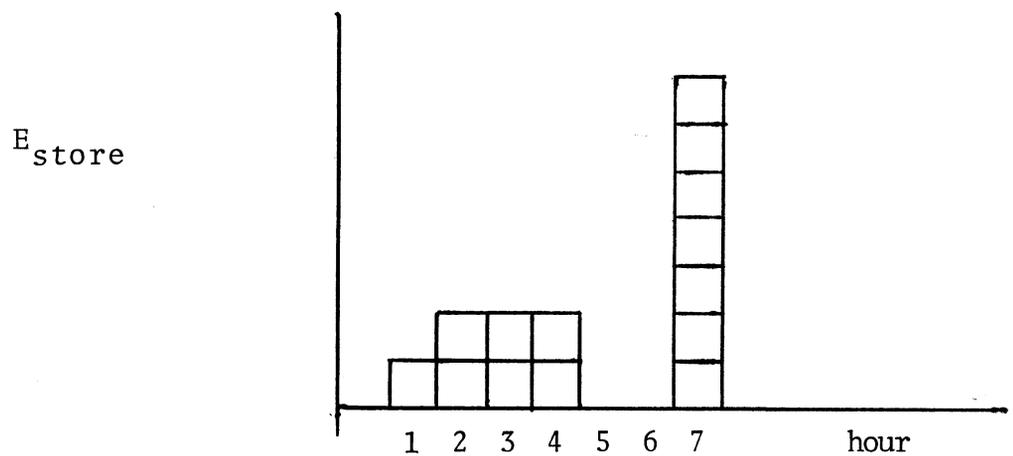
Figure 2.8 Large Losses in hours 7 and 8 Create a Large Demand for Energy from Storage



(a) Stored Excess Gains are Available for Shifting



(b) Forward Shifting Continues



(c) Seven Units of Energy are Available for Removal During hour 7

Figure 2.9 (a,b,c) The Forward Shifting of Excess Gains

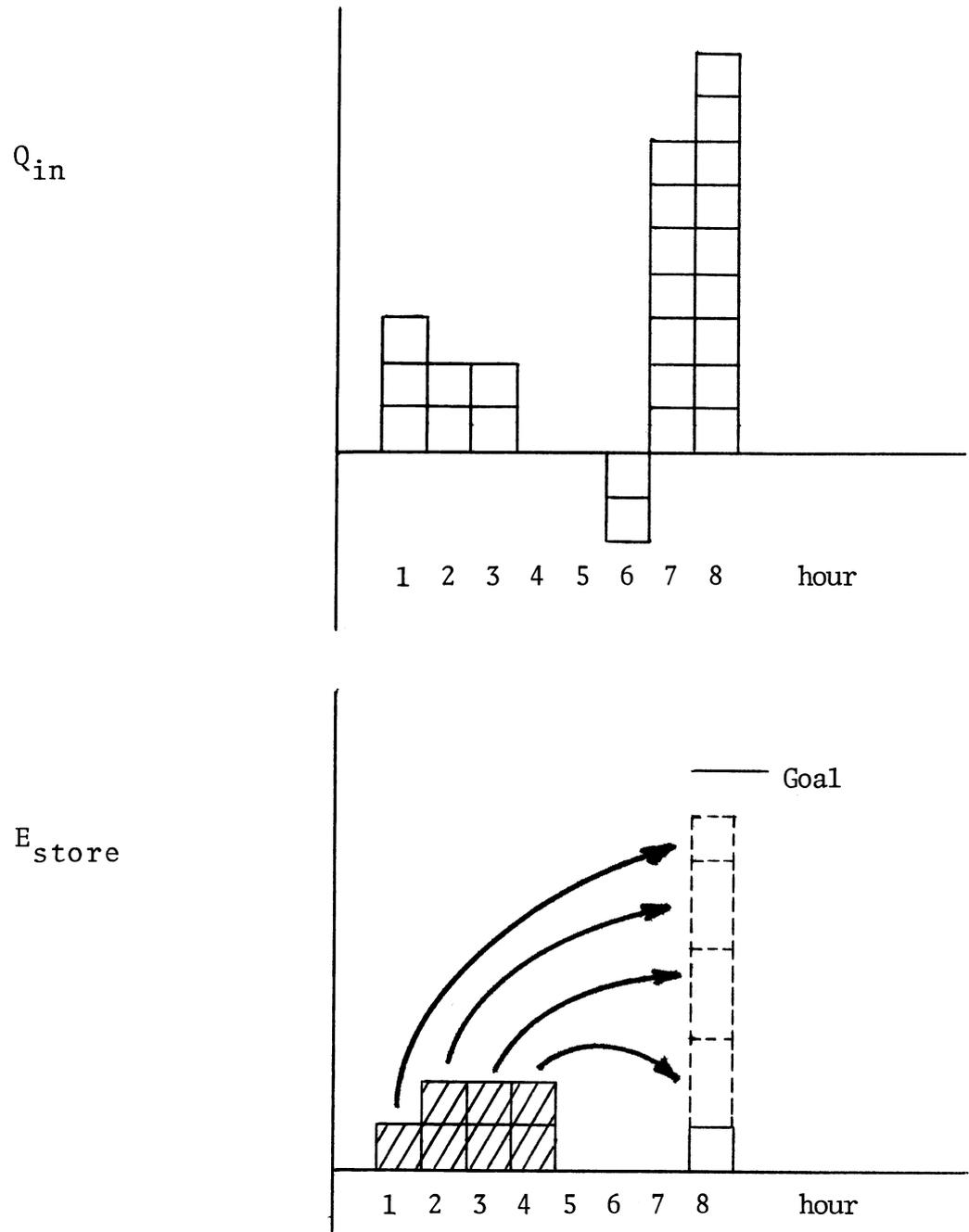


Figure 2.10 A Demand for Stored Energy During hour 8 is Placed on a Depleted Energy Reserve

forward shifting of excess energy gains. The process is demonstrated in Figures 2.8 through 2.10 as a continuation of the example given in Figures 2.3 through 2.7.

Figure 2.8 shows a two hour extension of Figure 2.4 where increased losses have led to a large value for  $Q_{in}$ . Useful solar gain resulted in one unit of energy being temporarily placed in storage at hour 7, however, seven units of energy need to be removed to avoid the use of auxiliary energy. Since previous hours have recorded excess gains, these will be used to offset  $Q_{in}$ . Checking back to hour 6, the excess gains for that hour are forward shifted to hour 7, as shown in Figure 2.9(a). Forward shifting continues, Figure 2.9(b), until seven units of energy are available for removal (Figure 2.9(c)). The shifted gains are removed from storage, and auxiliary energy is not required. Hour 8 requires nine units of energy from an energy storage depleted by the demands of hour 7 (Figure 2.10). Excess gains are forward shifted as in hour 7, but the search now extends farther back in time. Eventually, the storage reserve is empty, and one unit of auxiliary energy must be provided.

The example of Figures 2.3 through 2.10 suggests methods to characterize performance limits of buildings which combine realistic and hypothetical design options. The stored excess gains did not decay by leaking energy to the environment; they were allowed to remain in storage for

several hours before being forward shifted and removed. The storage time of excess gains will be used to characterize a hypothetical design option. The storage time limit is the number of hours an excess gain is perfectly stored to be available for removal from storage. An excess gain is lost to the environment after it has been in storage longer than the storage time limit. This energy loss corresponds to the term  $Q_{\text{loss,esm}}$  of Equation 2.10. The storage time limit can be any integer hour length between 1 hour and 8760 hours. To define an infinite thermal capacitance based on not allowing month-to-month carry over, the storage time limit is set at 720 hours. A storage time limit of 1 hour means that energy will only be available to offset auxiliary energy during the hour it is delivered to storage.

In the example of Figures 2.3 to 2.10, there was no limit on the energy removed from storage to offset the energy requirement of the room air. Practical heat transfer rates are modelled by placing a limit on the amount of energy removed from storage in a given hour. The rate limitation for energy transfer between the energy storage components and the room air is given by

$$\text{Rate Limit} = \frac{[Q_{\text{ex,max}}]^+}{1 \text{ hour}} \quad (2.17)$$

and has dimensions of energy per unit time. Energy can be transferred between storage and the room air at any rate less than or equal to the rate limit. A rate limit greater

than the building loss rate for the coldest hour of the year is considered to be infinite. Finite rate limits define the maximum rate that energy will be removed from storage for realistic design options.

Figure 2.7 gave the total accumulated energy in storage calculated at the end of each hour. The total energy accumulated in storage is the sum of the excess gains over a number of hours equal to the storage time limit, and includes the current hour. The summation takes place after the energy in storage has had the opportunity to be shifted and removed from storage during the current hour. Since energy in storage longer than the storage time limit is lost to the environment, the sum need only be over the number of hours equal to the storage time limit. A limit on this sum allows finite amounts of perfect energy storage in a building. If the amount of energy in storage is greater than the energy storage capacity limit, the overflow must be dumped to the environment. Dumping begins with the excess gain that has been in storage the longest time, and includes the current hour if necessary. Any energy storage capacity limit greater than the annual building losses is considered to be infinite. Zero energy storage capacity defines the lower limit. Finite values of the energy storage capacity limit describe the practical limits of realistic energy storage design options. The energy storage capacity limit

is calculated from

$$\text{Energy Storage Limit} = \sum_{\text{all energy storage components}} [E_{\text{store,max}}]_i \quad (2.18)$$

where

$$[E_{\text{store,max}}]_i = [V_{\text{esm}}(\text{Energy Storage Density})]_i \quad (2.19)$$

A FORTRAN program has been written to perform the energy balance equations according to the forward shifting of excess gains method used in the idealized building model described above. A program listing appears in Appendix A. Since calculations are done on an hourly basis, time varying patterns for internal energy generation rates and building conductances can be used.

Annual calculations begin with hour 1 corresponding to midnight to 1 am on the first of August. A starting length period extends the number of hours equal to the storage time limit back into July to establish the accumulated energy reserves. The starting length calculations follow the same procedure as the annual calculations, except that energy is removed from storage only as far back as the hour (8760 - storage time limit + 1). The effect of a starting length on annual heating load calculations is reduced by starting in the middle of summer.

The forward shifting process removes excess gains from storage with a "last in-first out" strategy over the storage time limit. A "first in-first out" strategy was investigated and was found to result in slightly lower auxiliary energy requirements. The "last in-first out" method was chosen because it follows the strategy that the longer energy has been in storage, the more likely it will be lost to the environment rather than removed to offset a load.

### 2.2.3 Preliminary Results

The purpose of the idealized building model is to calculate the minimum auxiliary energy usage for a solar heated building. A preliminary view of results using the idealized building model will be presented. A realistic model will be used to determine the useful solar gains.

TRNSYS [9] is a modular system simulation program which will provide the realistic building component models to combine with idealized building models. SOLMET Typical Meteorological Year (TMY) data provides the hourly weather data input[10]. The incident solar radiation on each collection device is calculated using the TRNSYS Type 16 Radiation Processor. TRNSYS contains several collector component models which will calculate useful solar gains. The Type 35 Window with Variable Insulation component was used to simulate passive direct gain energy collection.

Table 2.3 gives a description of a direct gain passive solar heated building. A plot of annual auxiliary energy versus the storage time limit is given in Figure 2.11. The rate limit used for this figure is 200 KW, and is effectively infinite. The energy storage capacity limit for this example is calculated from Equations 2.18 and 2.19 using the data of Table 2.3.

$$E_{\text{store,max}} = (4.0)(2000)(5.0) = 40.0 \text{ MJ}$$

The auxiliary energy for infinite thermal capacitance appears on Figure 2.11 as the case of energy storage capacity limit equal to 250 GJ. Figure 2.11 shows that nearly all the stored energy gains are used within 12 to 24 hours after the excess gains occur.

A plot of annual auxiliary energy versus energy storage capacity limit is given in Figure 2.12. For this building, the minimum auxiliary requirement shows relatively little change as the energy storage limit is increased beyond 160 MJ.

Figure 2.13 is a plot of annual auxiliary energy versus rate limit. For the energy storage limit of 40.0 MJ, the curve for the storage time of 720 hours is nearly coincident with the 12 hour curve. For the this example, there is relatively little change in the auxiliary requirement when the rate limit is greater than 5000 W. Notice that the infinite energy storage curve flattens out at a lower rate limit than the zero energy storage curve. This occurs



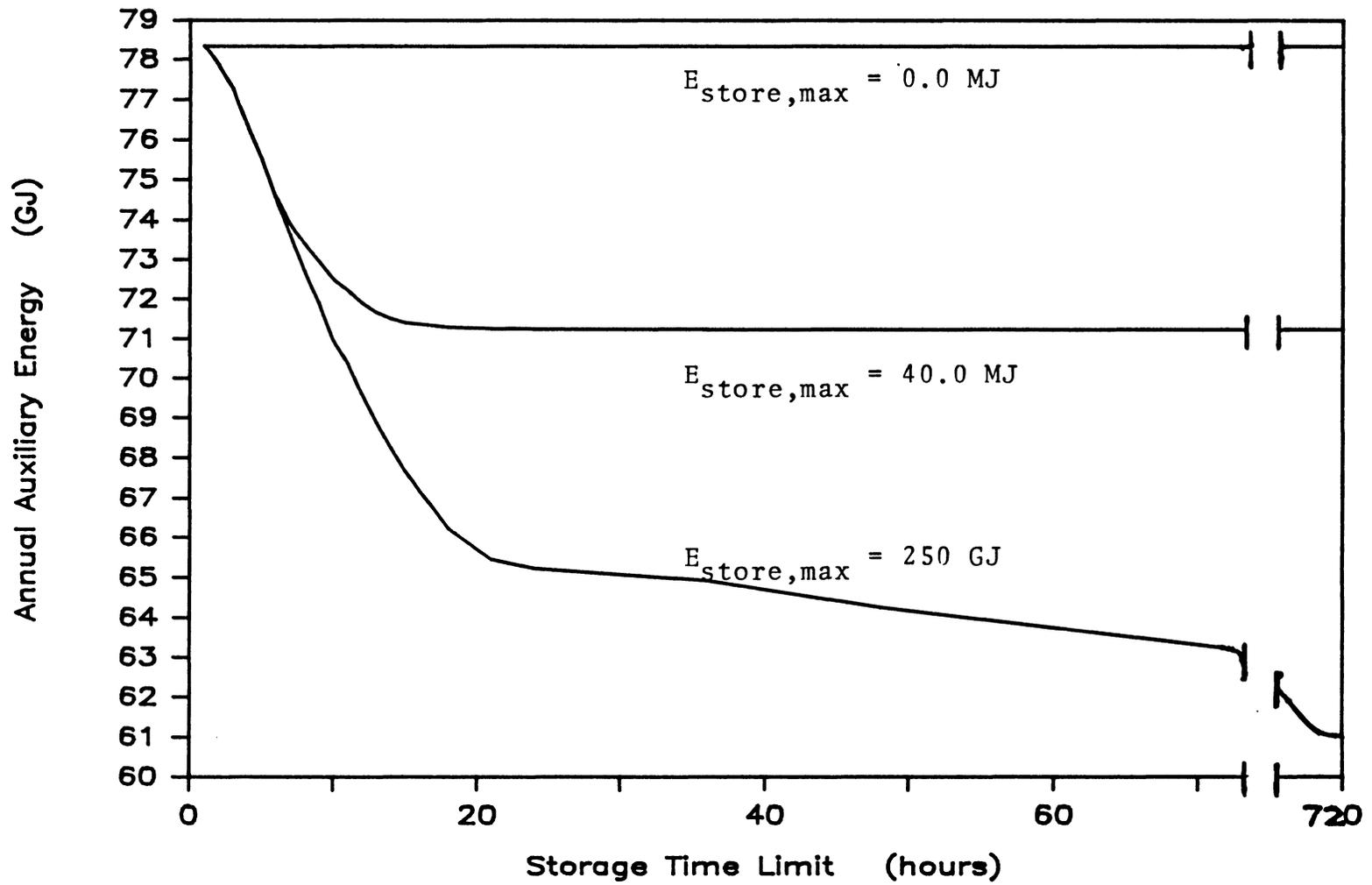


Figure 2.11 Auxiliary Heating Energy Required by the Building Described in Table 2.3

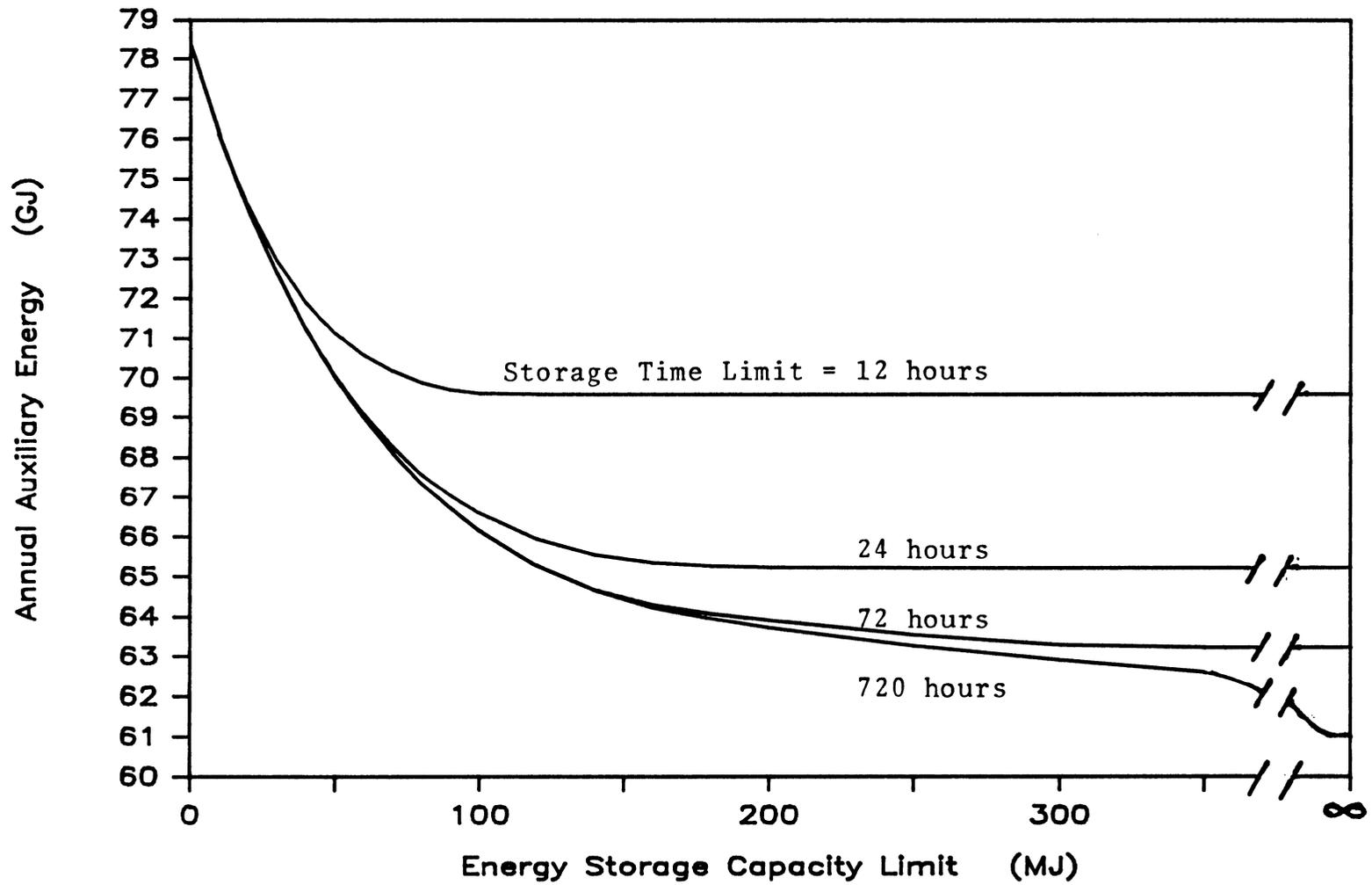


Figure 2.12 Auxiliary Heating Energy Required by the Building Described in Table 2.3

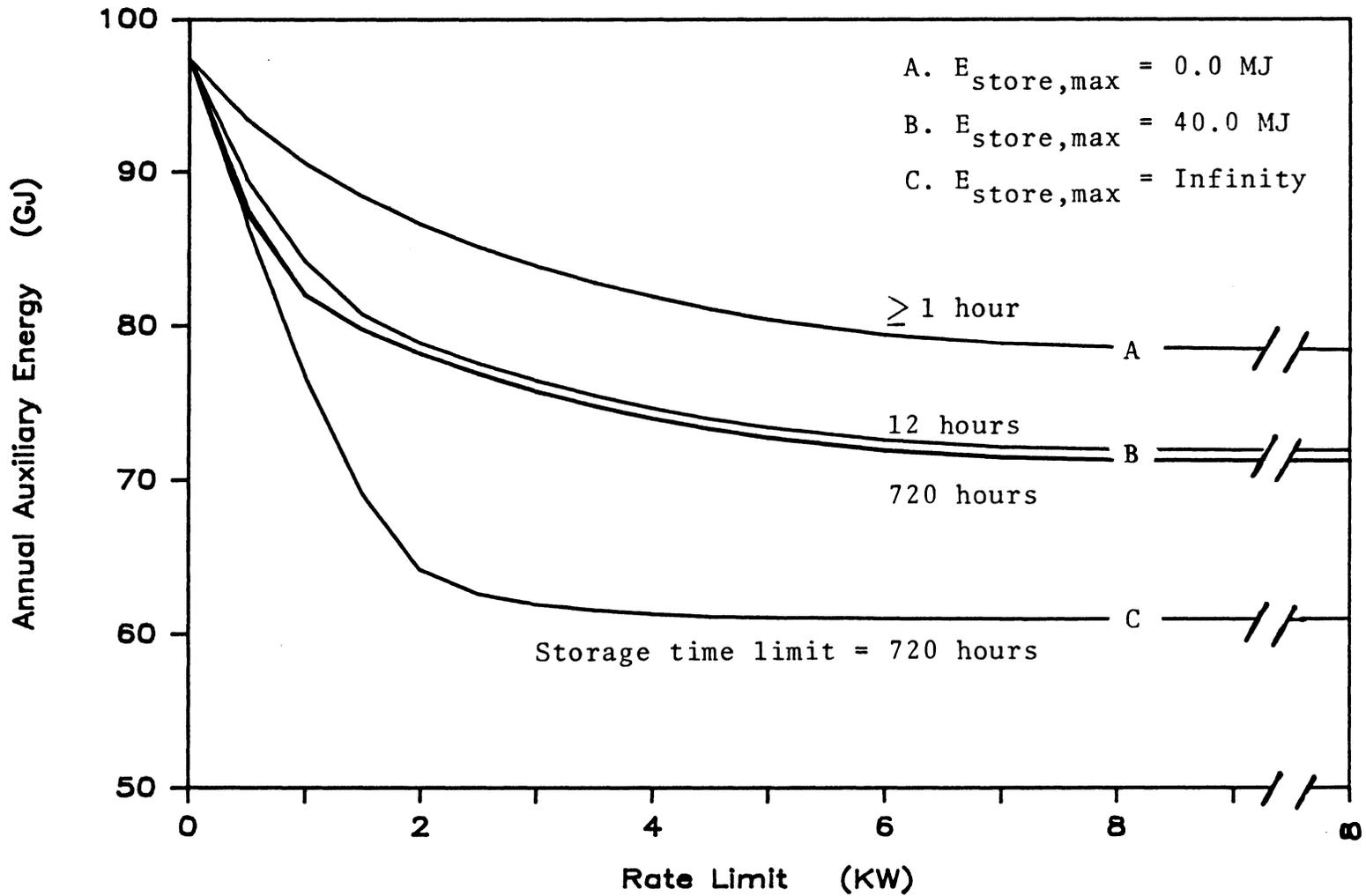


Figure 2.13 Auxiliary Energy Required by the Building Described in Table 2.3

because the energy that is not removed from storage due to rate limitations during cold days can be stored for use at later times.

The idealized building model will be used in this thesis to calculate the thermal performance limits of buildings with zero, finite, or infinite thermal capacitance. Since the method requires hourly data, it can be used only for locations where such data is available. The work of Monsen[3] and Erbs[8] allow the performance of zero and infinite capacitance buildings to be calculated using monthly-average data. A comparison of Erbs' method with the idealized building model for the zero and infinite thermal capacitance cases of the building of Table 2.3 is outlined below:

	Erbs' Method	Idealized Building Model	
$Q_{aux,yr,z}$	= 78.7	78.4	(GJ)
$Q_{aux,yr,i}$	= 61.7	61.0	(GJ)

## CHAPTER 3

## 3. PRESENTATION OF THERMAL PERFORMANCE LIMITS

It will be useful to present annual thermal performance limits for passive solar buildings that are generalized for various building constructions. Generalizing will be done using parameters from the Solar Load Ratio (SLR) method as described in Passive Solar Heating Analysis, A Design Manual [11]. A brief description of the generalizing parameters is given in Section 3.1. Practical values of these parameters are discussed in Section 3.2.

## 3.1 Generalizing Parameters

Solar heated buildings can be characterized by the load collector ratio [11], LCR, which is given by

$$\text{LCR} = \text{NLC}/A_p \quad (3.1)$$

NLC is the net load coefficient, and is equal to the overall building conductance-area product,  $(UA)_b$ , minus the conductance-area product for the passive solar energy collector. The projected area,  $A_p$ , of a direct gain window, Trombe wall, or water wall solar collector equals the net glazing area,  $A_c$ . The load collector ratio provides a measure of the extent to which a building design infers solar heating.

Energy storage capacity is expressed by the storage-collector ratio, SCR, which is the ratio of the energy

storage capacity limit to the projected collector area.

$$\text{SCR} = \text{Energy Storage Limit} / A_p \quad (3.2)$$

The limit of energy storage capacity is used because this study is concerned with the limits of thermal performance.

When considering a design option for a building, the effect on performance can be measured by the auxiliary energy savings. The energy savings of an option over a base design has a monetary value, and this value can be compared with the cost of the option. The auxiliary energy savings will be used to present the potential of design options to improve the performance of solar heated buildings.

The thermal performance of solar heated buildings is often expressed as a solar fraction, or, in the case of the SLR method, an annual solar savings fraction[11], SSF. Annual auxiliary energy requirements are related to the solar savings fraction by

$$Q_{\text{aux, yr}} = \text{NLC DD}_{\text{yr}} (1 - \text{SSF}) \quad (3.3)$$

$\text{DD}_{\text{yr}}$  are the annual degree-days at a constant base temperature,  $T_{\text{base}}$ , where the base temperature is equal to the balance point temperature given by Equation 2.4. Solar savings fractions are related to auxiliary energy savings by the following equation

$$\begin{aligned} Q_{\text{aux, yr, B}} - Q_{\text{aux, yr, O}} & \quad (3.4) \\ & = [\text{NLC DD}_{\text{yr}} (1 - \text{SSF})]_{\text{B}} - [\text{NLC DD}_{\text{yr}} (1 - \text{SSF})]_{\text{O}} \end{aligned}$$

where 'B' represents the base design, and 'O' represents the optional design. If comparisons are made between buildings which have the same net load coefficient, Equation 3.4 can be simplified to the form of Equation 3.5

$$\begin{aligned}
 Q_{\text{aux,yr,B}} - Q_{\text{aux,yr,O}} & \quad (3.5) \\
 & = \text{NLC} [ \text{DD}_{\text{yr}} (1 - \text{SSF})_{\text{B}} - \text{DD}_{\text{yr}} (1 - \text{SSF})_{\text{O}} ]
 \end{aligned}$$

When comparisons are made between buildings which also have the same balance temperatures, Equation 3.5 reduces to

$$Q_{\text{aux,yr,B}} - Q_{\text{aux,yr,O}} = \text{NLC} \text{DD}_{\text{yr}} (\text{SSF}_{\text{O}} - \text{SSF}_{\text{B}}) \quad (3.6)$$

Solar savings fractions calculated with the idealized building model were investigated. For the case of infinite rate limit and constant balance temperature, different building constructions with equivalent LCR's and SCR's were found to have the same solar savings fraction. This was found to apply at various values of the storage time limit. This means that the auxiliary energy savings calculated with Equation 3.6 will be a unique value for a given load collector ratio, directly proportional to the net load coefficient. When the rate limit is not effectively infinite, different buildings which have the same load collector ratios but different net load coefficients have different solar savings fractions.

## 3.2 Practical Considerations

This section presents examples of building materials and construction methods which lead to practical ranges for the generalizing parameters. Values of the load collector ratio and storage-collector ratio will be examined which relate to passive solar heated buildings.

### 3.2.1 The Load Collector Ratio

A lower limit to LCR in terms of practical building construction will establish a practical limit to the thermal performance of a solar heated building. The load collector ratio is defined as the ratio of the net load coefficient to the projected glazing area. The ranges of these two terms will be investigated for the case of an ASHRAE type A-1 building. It will first be necessary to establish the range of building geometries to be considered.

#### Building Geometry and Orientation

The geometry for the one family dwelling will be limited to a rectangular parallelepiped of one or two stories in height. Length to width ratios for the floor are limited to 2:1 and 1:1. The minimum floor area allowed is 80 m<sup>2</sup> (861 ft<sup>2</sup>). The height of each story is 2.5 m (8.2 ft). The floor and wall thicknesses are neglected. Buildings are oriented with the longer wall facing due south. Solar collector glazing is allowed only on the south facing wall; the east, west, and north walls have no windows.

### The Net Load Coefficient

The net load coefficient should be minimized to decrease the load collector ratio. The net load coefficient is calculated as the sum of the building component conductance-area products, excluding the solar collector. The following equation is used in this study to calculate the net load coefficient

$$NLC = (UA)_w + (UA)_r + (UA)_f + (UA)_i \quad (3.7)$$

where the conductance-area products are as follows

$(UA)_w$  is for the opaque exterior wall component

$(UA)_r$  is for the roof component

$(UA)_f$  is for the floor component

$(UA)_i$  is for the infiltration component

The conductance-area product for the walls is based on the three types of frame wall construction described in Table 3.1. The 1981 ASHRAE Handbook of Fundamentals gives details for calculating the total conductance for built-up frame walls.[12]

The conductance-area product for the roof will be based on 0.3 m (12 inch) fiberglass batt insulation. The total resistance of the roof is 7.04 C m<sup>2</sup>/W (40 h ft<sup>2</sup> F/Btu) giving a total conductance of 0.142 W/C m<sup>2</sup> (0.025 Btu/h ft<sup>2</sup> F).

The conductance-area product for the floor corresponds to unheated slab on grade construction with 0.076 m



(3 inches) of rigid foam perimeter insulation with a total resistance of 2.22 m<sup>2</sup> C/W (12.6 ft<sup>2</sup> h F/Btu). Equation 3.8 is an approximation to the procedure for calculating the heat loss from unheated slab floors given in the 1981 ASHRAE Handbook of Fundamentals, and is taken from Passive Solar Heating Analysis. [11]

$$(UA)_f = \frac{1.271 P_f}{(R_f + 0.8806)} \quad (3.8)$$

where  $P_f$  is the perimeter of the floor measured in meters, and  $R_f$  is the thermal resistance of the perimeter insulation, (m<sup>2</sup>-C/W).

The infiltration conductance-area product is calculated using the air change method [12,13] by

$$(UA)_i = \rho c_p V \dot{N} \quad (3.9)$$

where  $\rho$  and  $c_p$  are for outdoor air,  $V$  is the volume of the air in the building, and  $\dot{N}$  is the number of air changes per hour. A value of 1/2 air change per hour is used for infiltration.

#### The Projected Solar Glazing Area

Solar collector projected glazing area should be maximized to obtain small values of the load collector ratio. The maximum south facing projected glazing area is limited by either of the following:

1. By the total area of the south facing wall of the building

2. By compliance with building standards which place a limit on the conductance for the gross wall area

The projected glazing area limit due to the area of the south facing wall is given by

$$A_{p,max1} = L_b H_b \quad (3.10)$$

where  $L_b$  is the length of the south facing wall, and  $H_b$  is the total wall height for one or two stories. Glazing area will not be lost due to window framing, shades, or overhangs. The projected glazing area limit due to compliance with building standards will be evaluated using ANSI/ASHRAE/IES building standard 90A-1980[1].

ASHRAE standard 90A-1980 places a limit on the conductance for the gross area of the exterior walls. The conductance limit is given as a function of degree-days at an 18 C or 65 F base temperature. In this study, the gross wall conductance corresponding to the value given by the ASHRAE standard will be calculated by

$$U_o = \frac{(U_w A_w) + (U_c A_p)}{A_o} \quad (3.11)$$

where:

$U_o$  is the average conductance of the gross wall area

$A_o$  is the gross area of the exterior walls

$U_w$  is the conductance of the opaque walls

$A_w$  is the opaque wall area

$A_p$  is the projected area of the solar collector

$U_c$  is the average conductance, over the projected area of the solar collector, between the room air and the ambient air

The wall areas  $A_o$ ,  $A_w$ , and  $A_p$  are related by the following equation

$$A_o = A_w + A_p \quad (3.12)$$

Standard 90A-1980 also specifies values for the overall roof conductance and the unheated slab floor perimeter insulation. If the constructed roof or floor conductance-area products are less than the standard specifications, ASHRAE allows the conductance through the exterior walls to be increased provided that the overall conductance-area product for the building does not exceed the value resulting from conformance to the standard. By combining this information with Equations 3.11 and 3.12, the maximum allowable projected glazing area based on compliance with ASHRAE 90A-1980 is given by

$$A_{p,max2} = \frac{[(U_{o,s} - U_{w,a}) A_o] + [(UA)_{r,s} - (UA)_{r,a}] + [(UA)_{f,s} - (UA)_{f,a}]}{(U_c - U_w)} \quad (3.13)$$

where the subscript 's' refers to a conductance-area product with the conductance given by ASHRAE 90A-1980, and the subscript 'a' refers to the conductance based on the actual building construction.

If the conductance across solar collector,  $U_c$ , is greater than the wall conductance,  $U_w$ , then decreasing  $U_c$  will allow larger projected glazing areas. However, the collector size is limited by the area of the south facing wall, so that the maximum projected glazing area is given by

$$A_{p,max} = \min [ A_{p,max1}, A_{p,max2} ] \quad (3.14)$$

Equation 3.14 is expressed qualitatively by Figure 3.1. The critical collector conductance,  $U_{c,crit}$ , is the conductance where  $A_{p,max1} = A_{p,max2}$ . As the collector conductance is decreased below  $U_{c,crit}$ , the maximum collector area remains constant, therefore, the load collector ratio remains constant for constant net loss coefficients. The lowest values for  $U_{c,crit}$ , in terms of the constraints of this study, correspond to the 2 story, 80 m<sup>2</sup> floor area dwelling with a length to width ratio of 2 and a frame wall resistance of 2.20 m<sup>2</sup> C/W (12.2 ft<sup>2</sup> h F/Btu). These values are presented in Figure 3.2 as a function of annual degree-days (base 18.3 C). Glazing materials with conductances less than the values given in Figure 3.2 will have maximum collector areas limited by building geometry, and therefore the minimum load collector ratio will not depend on location.

Existing and hypothetical glazing design options offer a range of possible collector conductance values. Examples of various glazing types are given in Table 3.2 [12,14,15].

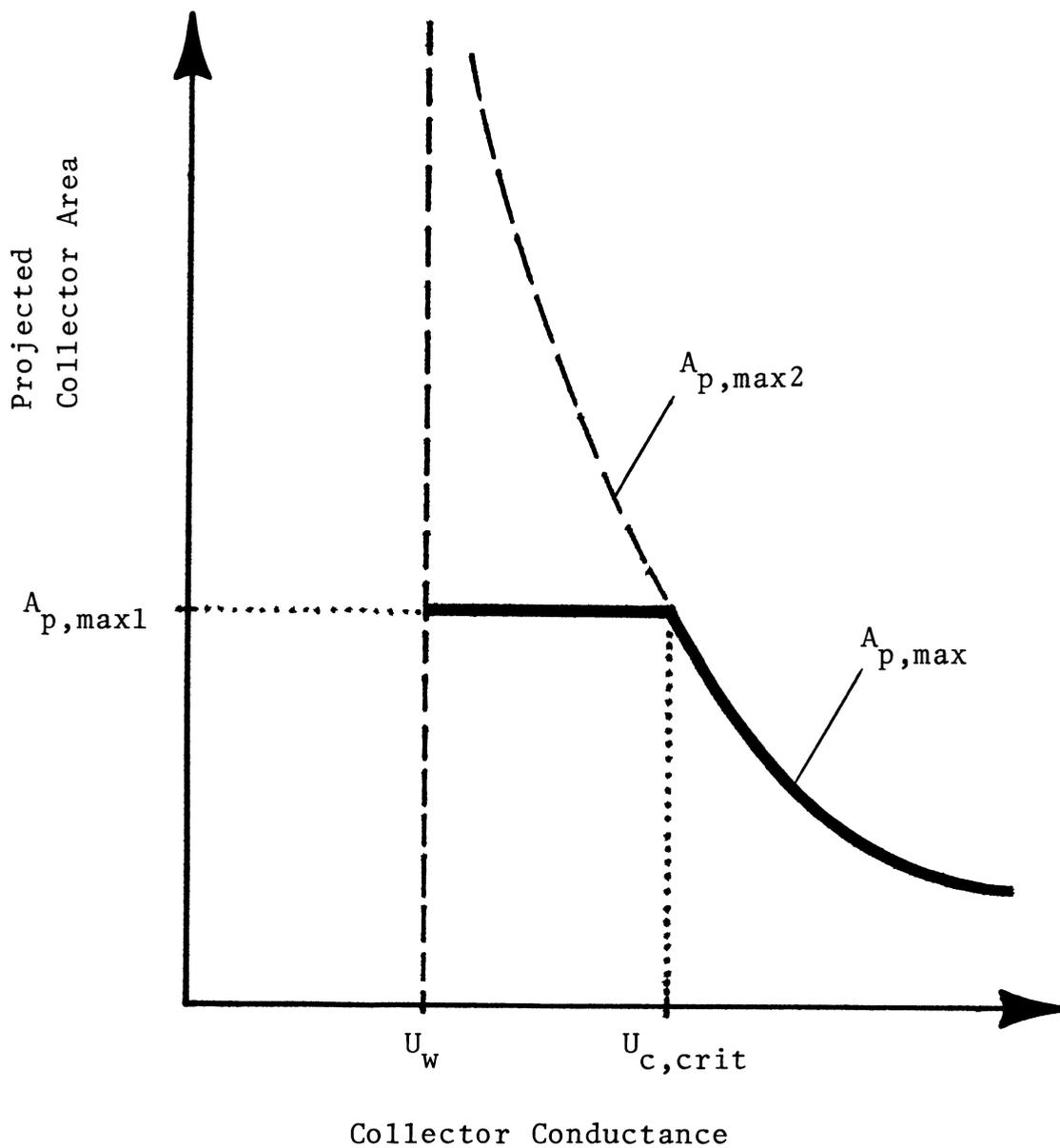


Figure 3.1 Maximum Passive Solar Collector Area,  $A_{p,max}$  as Limited by Building Geometry ( $A_{p,max1}$ ), or Building Construction Standards ( $A_{p,max2}$ )

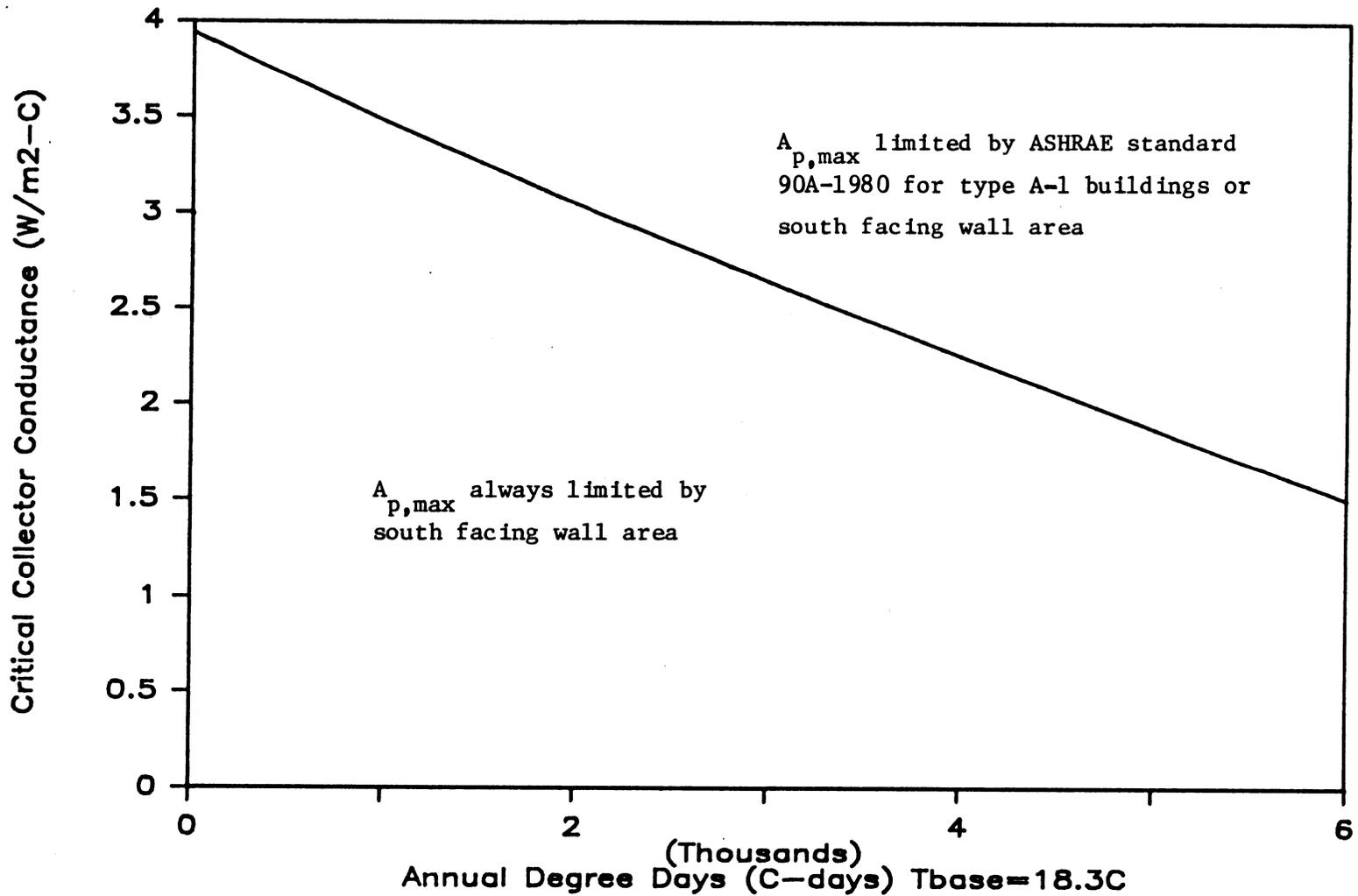


Figure 3.2 Minimum Values for the Critical Collector Conductance,  $U_{c,crit}$ , in Terms of the Practical Constraints of this Study

Table 3.2 Five Examples of Passive Collector Glazing for an ASHRAE Standard 90A-1980 Type "A" Building

Glazing Description	Overall Resistance	Overall Conductance	Shading Coefficient
	m <sup>2</sup> -C/W (ft <sup>2</sup> -h-F/Btu)	W/m <sup>2</sup> -C (Btu/ft <sup>2</sup> -h-F)	
1. Double 3 mm (1/8 in) Glass 13 mm (1/2 in) air space [12]	0.36 (2.0)	2.8 (0.49)	0.88
2. Triple 3 mm (1/8 in) Glass 13 mm (1/2 in) air space [12]	0.56 (3.2)	1.8 (0.31)	0.80
3. Aerogel between 3 mm (1/8 in) glass at 16.5 mm (0.65 in) spacing [14]	1.0 (5.7)	1.0 (0.18)	0.80
4. 3 mm (1/8 in) glass at 13 mm (1/2 in) evacuated spacing with heat mirror film [15]	1.8 (10.0)	0.57 (0.10)	0.80
5. Zero Conductance Glazing	Infinity	Zero	0.80

Since the vacuum and aerogel glazings are developing technologies, they will use the solar transmittance of the triple glazed windows, as will the zero conductance glazing.

From Figure 3.2 it is seen that for all locations having fewer than 5200 C-days (9360 F-days, base 65 F) the triple glazed, aerogel, and vacuum glazing types will result in the same maximum collector area.

The following figures present the lower limits for the load collector ratio based on the examples of building construction and design discussed above. Figures 3.3 through 3.6 apply to dwellings meeting the following conditions:

1. ASHRAE 90A-1980 type A-1 buildings
2. Annual degree-days less than 5200 C-days  
(9360 F-days) ( $T_{base} = 18.3\text{ C (65 F)}$ )
3. Collector conductance less than or equal to  
1.8 W/m<sup>2</sup> C (0.31 Btu/ft<sup>2</sup> h F)
4. Collector oriented due south
5. No east, west, or north wall glazing area
6. Roof resistance of 7.04 m<sup>2</sup> C/W  
(40 ft<sup>2</sup> h F/Btu)
7. Unheated slab on grade floor with 0.076 m  
(3.0 in) of rigid foam perimeter insulation
8. Infiltration of 1/2 air change per hour

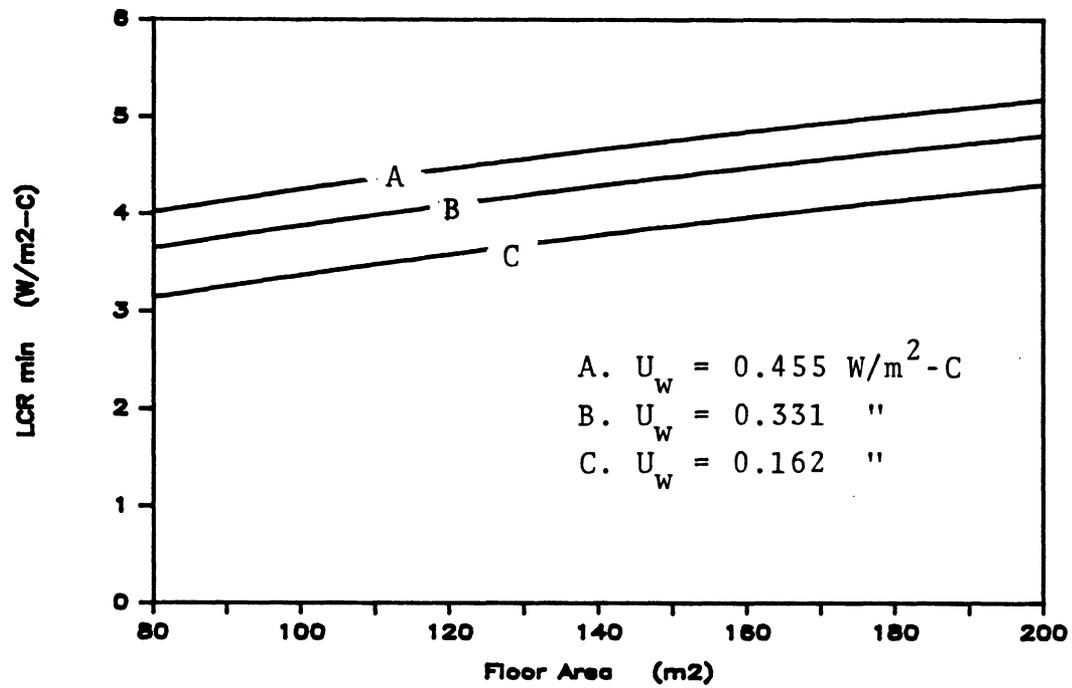


Figure 3.3 L:W = 1, 1 Story

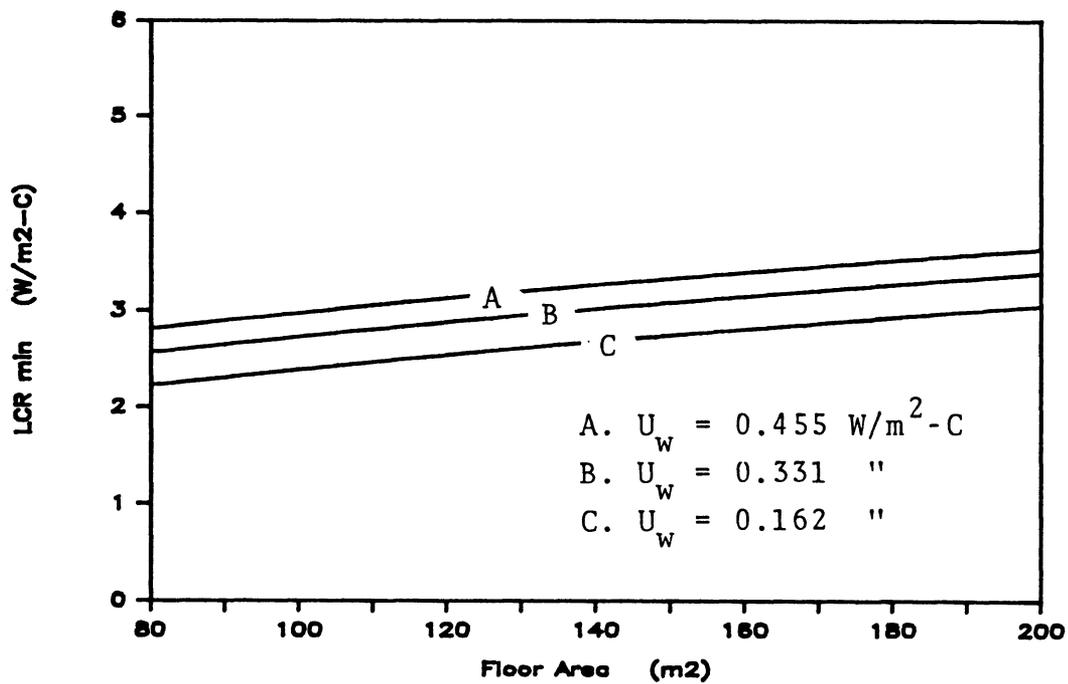


Figure 3.4 L:W = 2, 1 Story

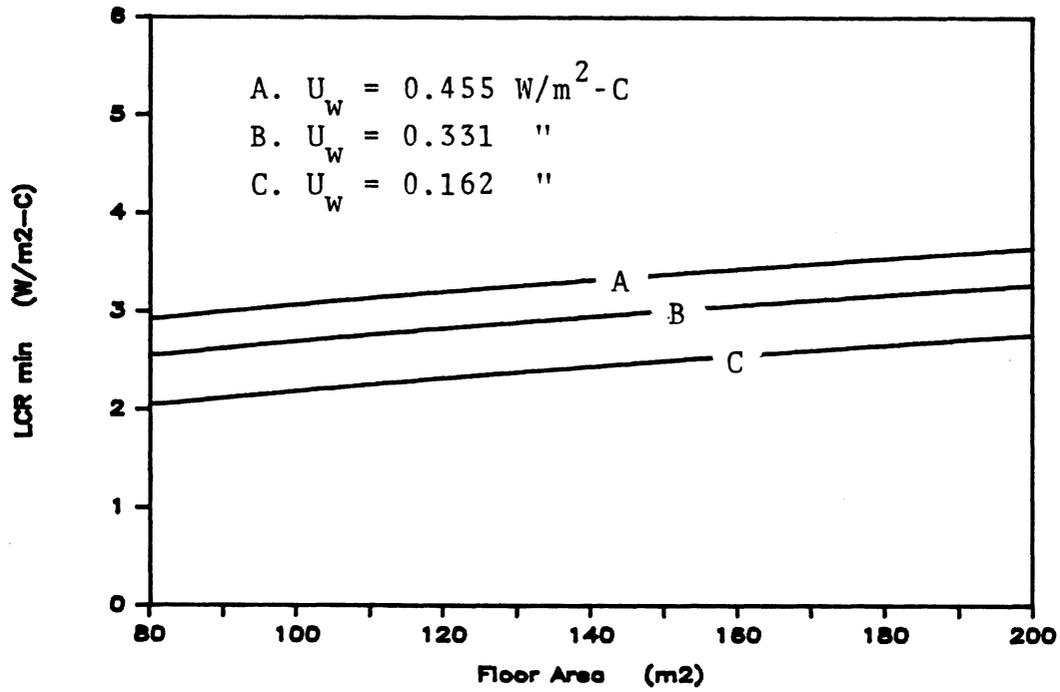


Figure 3.5 L:W = 1, 2 Stories

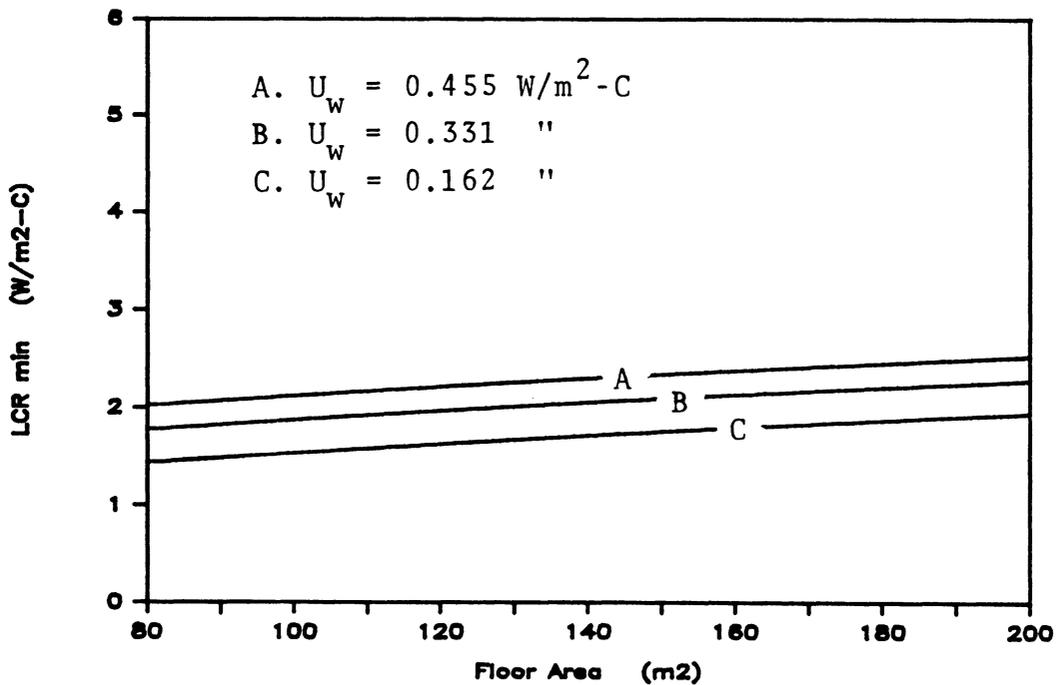


Figure 3.6 L:W = 2, 2 Stories

### 3.2.2 The Storage-Collector Ratio

The focus of this section is to relate values of SCR to actual building materials and design. Using definitions from Chapter 2, SCR is defined as

$$\text{SCR} = (1/A_p) \sum_{\text{all energy storage components}} (E_{\text{store,max}})_i \quad (3.15)$$

where the energy storage capacity limit of a component is given by

$$E_{\text{store,max}} = V_{\text{esm}} (\text{Energy Storage Density}) \quad (3.16)$$

so that the storage to collector ratio for each type of energy storage material is given by

$$\text{SCR} = \left[ d_{\text{esm}} \right] \left[ \frac{A_{\text{esm,p}}}{A_p} \right] (\text{Energy Storage Density}) \quad (3.17)$$

The volume of the energy storage component has been replaced by the product of  $d_{\text{esm}}$  and  $A_{\text{esm,p}}$ , where  $d_{\text{esm}}$  is the total thickness of an energy storage component with projected planar area  $A_{\text{esm,p}}$ . Although some energy storage components may be used in the form of cylindrical columns or other shapes, the equivalent plane wall thickness,  $d_{\text{esm}}$ , will be convenient for comparing various energy storage materials. The limits and ranges of the three bracketed terms of Equation 3.17 will be examined to determine values of SCR for various materials.

Two methods of energy storage will be considered: sensible energy storage, and solid to liquid phase change energy storage. The energy storage density of sensible storage is given by the following equation

$$\text{Energy Storage Density} = \rho c (T_{\text{esm,max}} - T_{\text{r,set}}) \quad (3.18)$$

which corresponds to the energy storage capacitance limit. Phase change energy storage will include both sensible and latent energy storage. The energy storage density of a phase change material that completely melts is given by

$$\begin{aligned} \text{Energy Storage Density} = \\ \rho [c_s (T_m - T_{\text{r,set}}) + \lambda + c_l (T_{\text{esm,max}} - T_m)] \end{aligned} \quad (3.19)$$

where

- $\rho$  is the density of the material evaluated at  $T_{\text{esm,max}}$
- $c_s$  is the specific heat of the solid material
- $T_m$  is the melting temperature
- $\lambda$  is the latent heat of fusion
- $c_l$  is the specific heat of the liquid material

The thermal properties of sensible energy storage materials are given in Table 3.3. The energy storage densities are given in terms of the temperature difference ( $T_{\text{esm,max}} - T_{\text{r,set}}$ ). Table 3.3 also gives thermal properties for sodium sulfate decahydrate,  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ , a

Table 3.3 Properties of Energy Storage Materials

Energy Storage Material	$T_{esm,max} - T_{r,set}$ ( $\Delta T_{esm}$ ) C	Energy Storage Density MJ/m <sup>3</sup>
<b>Concrete:</b>	5.0	10.1
$\rho_c = 2010 \text{ KJ/m}^3\text{-C}$	10.0	20.1
	15.0	30.2
<b>Water:</b>	5.0	20.9
$\rho_c = 4180 \text{ KJ/m}^3\text{-C}$	10.0	41.8
	15.0	62.7
<b>Na<sub>2</sub>SO<sub>4</sub> · 10H<sub>2</sub>O:</b>	15.0	377.0
$\rho = 1330 \text{ KG/m}^3$		
$c_s = 1.92 \text{ KJ/KG-C}$		
$c_l = 3.26 \text{ KJ/KG-C}$		
$\lambda = 251 \text{ KJ/KG}$		
$T_m = 32 \text{ C}$		

phase change energy storage material [16]. The maximum allowable energy storage density of  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  is based on a room temperature of 20 C (68 F) and maximum material temperature of 35 C (95 F).

The following values of the energy storage to projected glazing area ratio,  $A_{\text{esm},p}/A_p$ , will be used in this study:

$$A_{\text{esm},p}/A_p = 1, 3, \text{ and } 6$$

When calculating the limiting auxiliary energy usage using the idealized building model of Chapter 2, the effectiveness of a material to store energy does not depend on  $A_{\text{esm},p}/A_p$  or on the thickness of a material. All energy storage material is perfectly effective.

Figures 3.7 through 3.9 give the storage-collector ratio as a function of the storage material thickness for sensible energy storage materials selected from Table 3.3. Figure 3.10 gives SCR versus  $d_{\text{esm}}$  for the phase change energy storage material.

The practical limits to the thickness of perfect energy storage are based on the volume of energy storage material allowed in a building. Energy storage materials occupy livable space, and therefore have economic limits based building costs. Figure 3.11 gives the energy storage limit per percent of building volume allowed for energy storage, in terms of a building having a height per story of 2.5 meters with the sensible storage materials of Table 3.3.

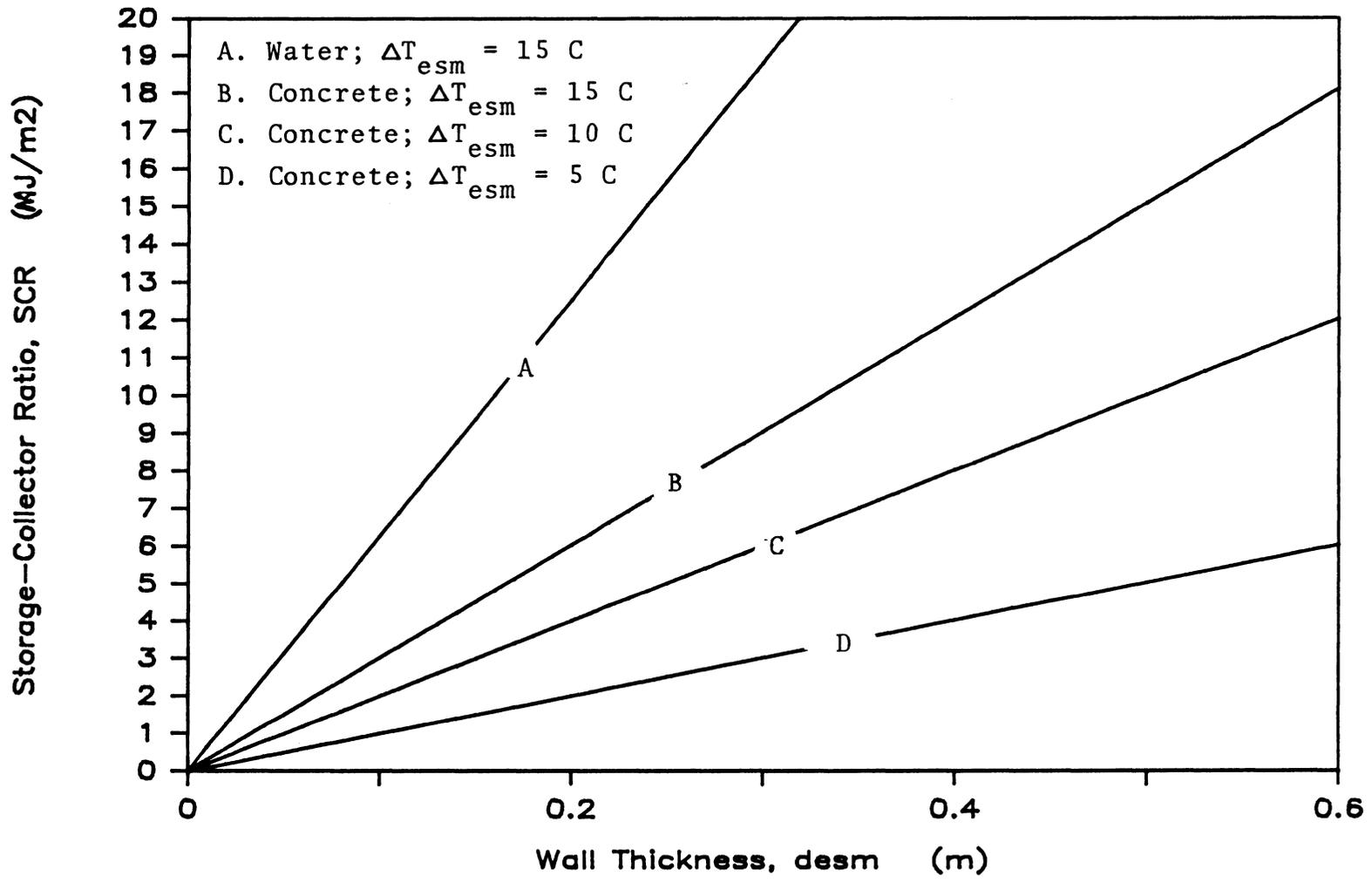


Figure 3.7 Sensible Energy Storage with  $A_{esm,p}/A_p = 1$

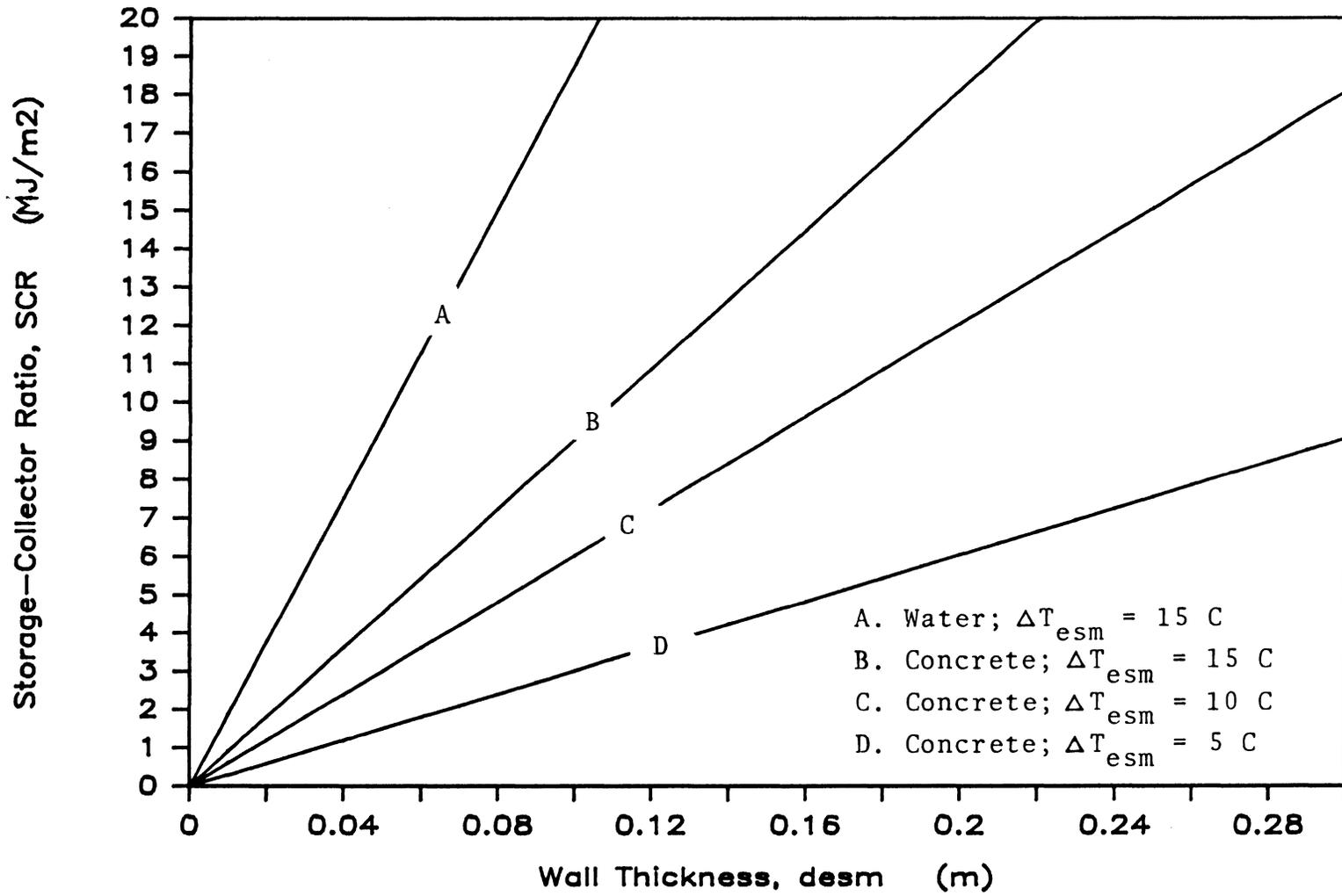


Figure 3.8 Sensible Energy Storage with  $A_{esm,p}/A_p = 3$

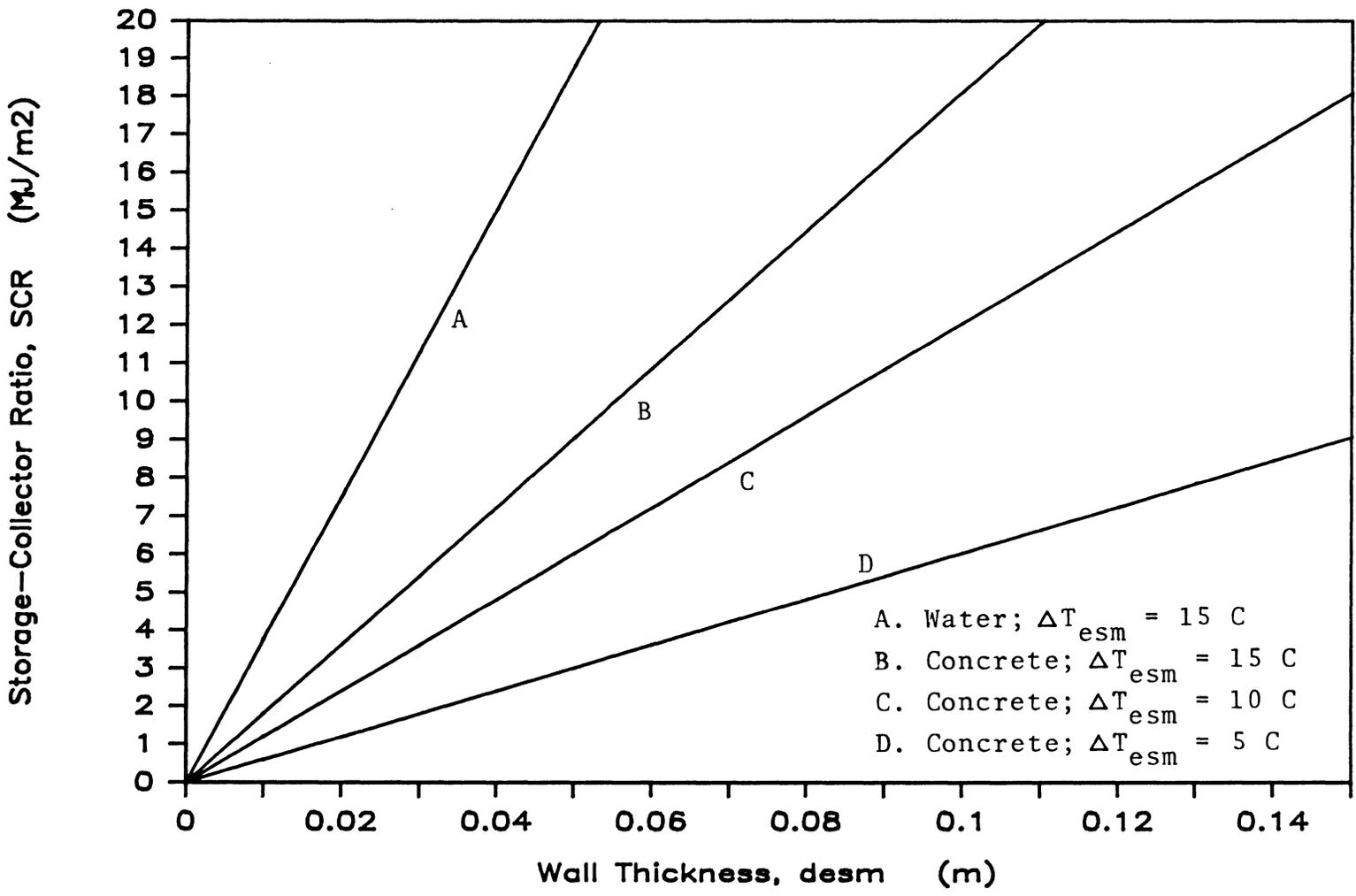


Figure 3.9 Sensible Energy Storage with  $A_{esm,p}/A_p = 6$

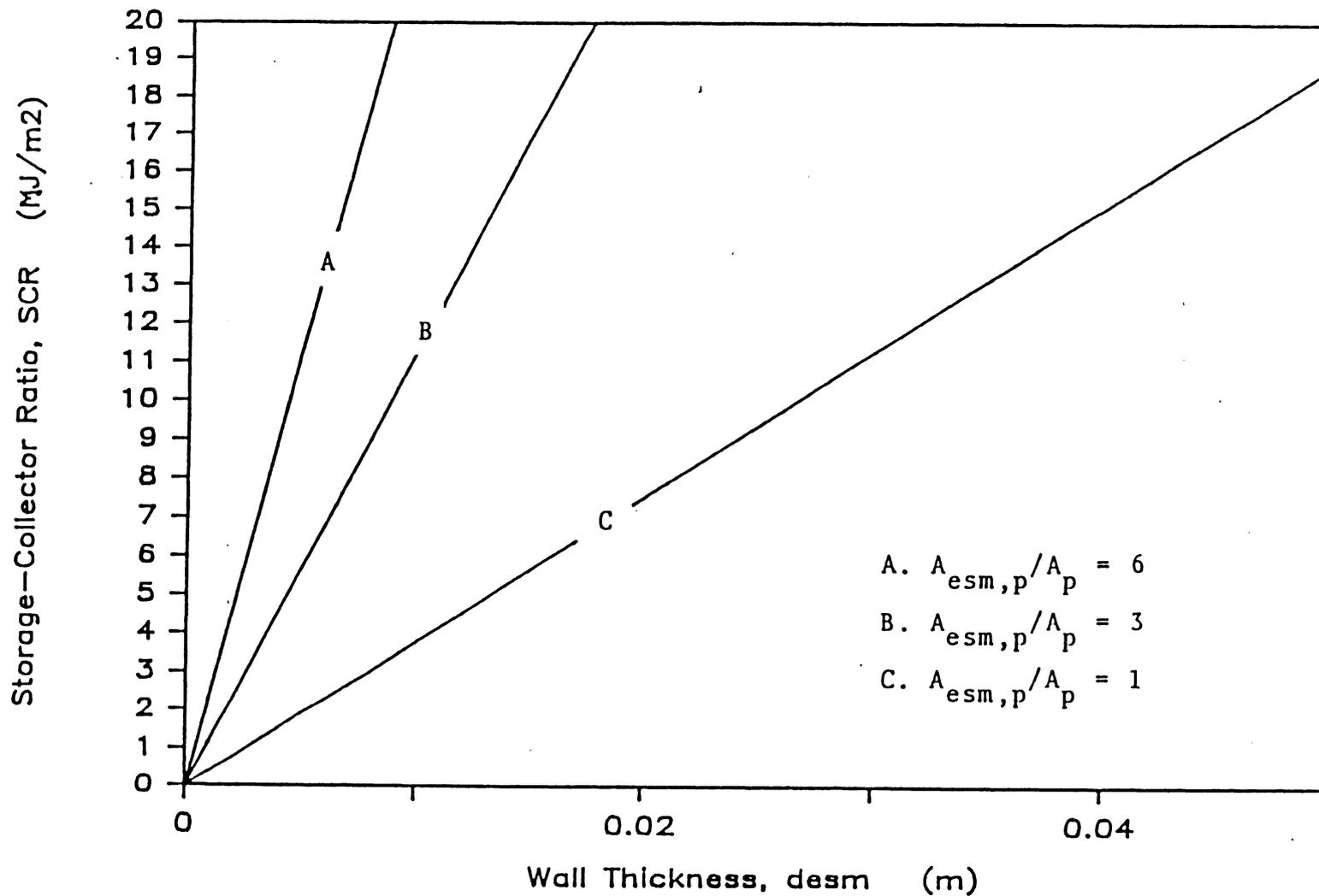


Figure 3.10 Phase Change Energy Storage Based on  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  with  $T_{esm,max} = 35 \text{ C}$ , and  $T_{r,set} = 20 \text{ C}$

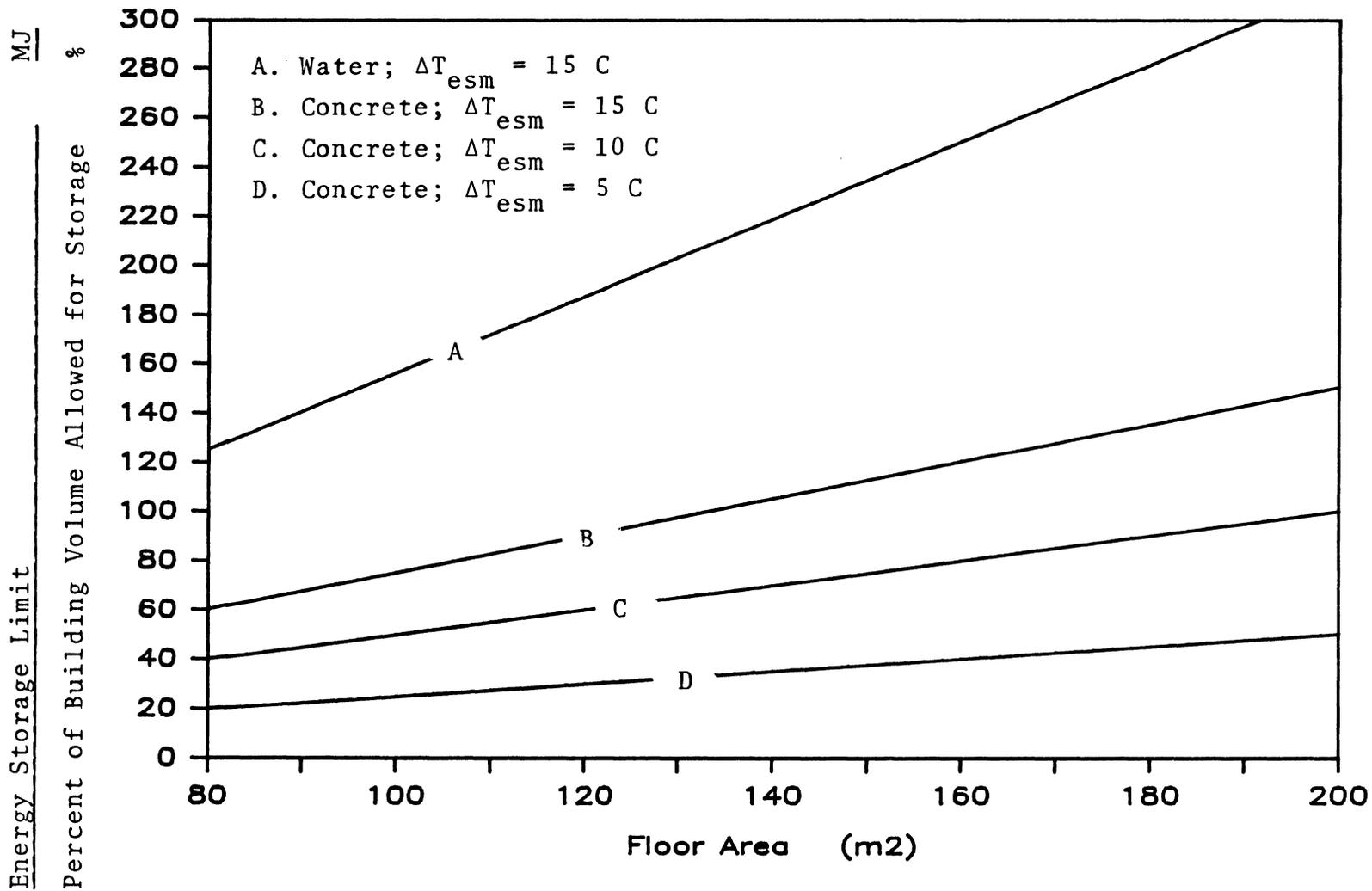


Figure 3.11 Energy Storage Limited by the Space it Occupies



## CHAPTER 4

### 4. RESULTS AND APPLICATIONS

Recall the question that introduced Chapter 1: "What is the theoretical limit of a hypothetical design option to improve the thermal performance of a conventional solar heated building?" The purpose of Chapter 4 is to provide answers to that question, using the work presented in Chapters 2 and 3. The results are presented in terms of the auxiliary energy savings of a building design relative to a reference load. Two different reference loads will be used:

1. The auxiliary load for the non-solar components of a building (net reference load)
2. The auxiliary energy requirement of a conventional direct gain building.

The first reference load will be used to present general results. The second reference load will be used to examine practical applications of thermal performance limits.

#### 4.1 A Presentation of Thermal Performance Limits

Thermal performance limits will be calculated using the idealized building model of Chapter 2, in connection with TRNSYS simulation output. The TRNSYS Type 16 solar radiation processor, mode 5, is used to process hourly SOLMET TMY solar radiation data. The Type 35 window model, mode 2, is used to model the solar collector. The collector properties are referenced to Table 3.2. The absorptance of the room to solar radiation is taken as 1 in the idealized case.

Properties of the SLR direct gain reference design DGA1 are given in Table 4.1. The performance of this design will be used to represent a conventional solar heated building. The predicted performance of design DGA1 will be calculated using the SLR method, which is discussed in Appendix B. Both the SLR method and the idealized building model will use SOLMET TMY radiation and ambient temperature weather data.

Table 4.1 Properties of Direct Gain Reference Design  
DGA1, from Passive Solar Heating Analysis,  
A Design Manual[11]

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**THERMAL STORAGE**

Heat Capacity (per unit projected collector area)	0.61	MJ/m <sup>2</sup> -C
Thickness	51.0	mm
Mass-to-glazing area ratio	6	
Thermal conductivity	1.7	W/m-K
Density	2400	kg/m <sup>3</sup>
Specific heat	840	J/kg-K
Solar absorptance of surface	0.8	
Infrared emittance of surface	0.9	

**SOLAR COLLECTOR**

Number of glazings	2	
Transmission characteristics	diffuse	
Infrared emittance of surface	0.9	
Index of refraction	1.526	
Extinction coefficient (per mm)	0.02	
Thickness of each pane	3.2	mm
Air gap between layers	12.7	mm
Orientation	due south	
Shading	none	

CONTROL RANGE OF ROOM AIR 18.3 to 23.9 C

LIGHTWEIGHT ABSORPTION FRACTION 0.2

Simulates the effect of solar radiation  
absorption on lightweight walls or  
objects by transferring given fraction  
of transmitted and reflected solar  
radiation directly to room air

GROUND REFLECTANCE 0.3

INTERNAL HEAT GENERATION 0

#### 4.1.1 General Results

Figure 4.1 shows the limits of the effect of thermal capacitance on the thermal performance of buildings which have the same net load coefficient. The thermal performance limits are based on the following conditions:

1. Control energy flows according to the forward shifting method
2. No rate limitations on energy transfers
3. Storage time limit = 720 hours
4. Storage-collector ratio equal to zero (lowest curve) and infinity (upper curve)

These limits apply to buildings having the following characteristics:

1. Located in Madison, WI
2.  $T_{bal} = 18.3 \text{ C (65 F)}$
3. South facing vertical collector
4. Collector properties corresponding to the double glazed windows of Table 3.2

The limits of performance are presented as auxiliary energy savings relative to the heating load for the non-collector components of the building, that is, relative to a load based on the net load coefficient. All the graphs in this section are based on a net load coefficient of 100 W/C. This value was chosen to scale the auxiliary energy savings to the order of magnitude typical of passive solar

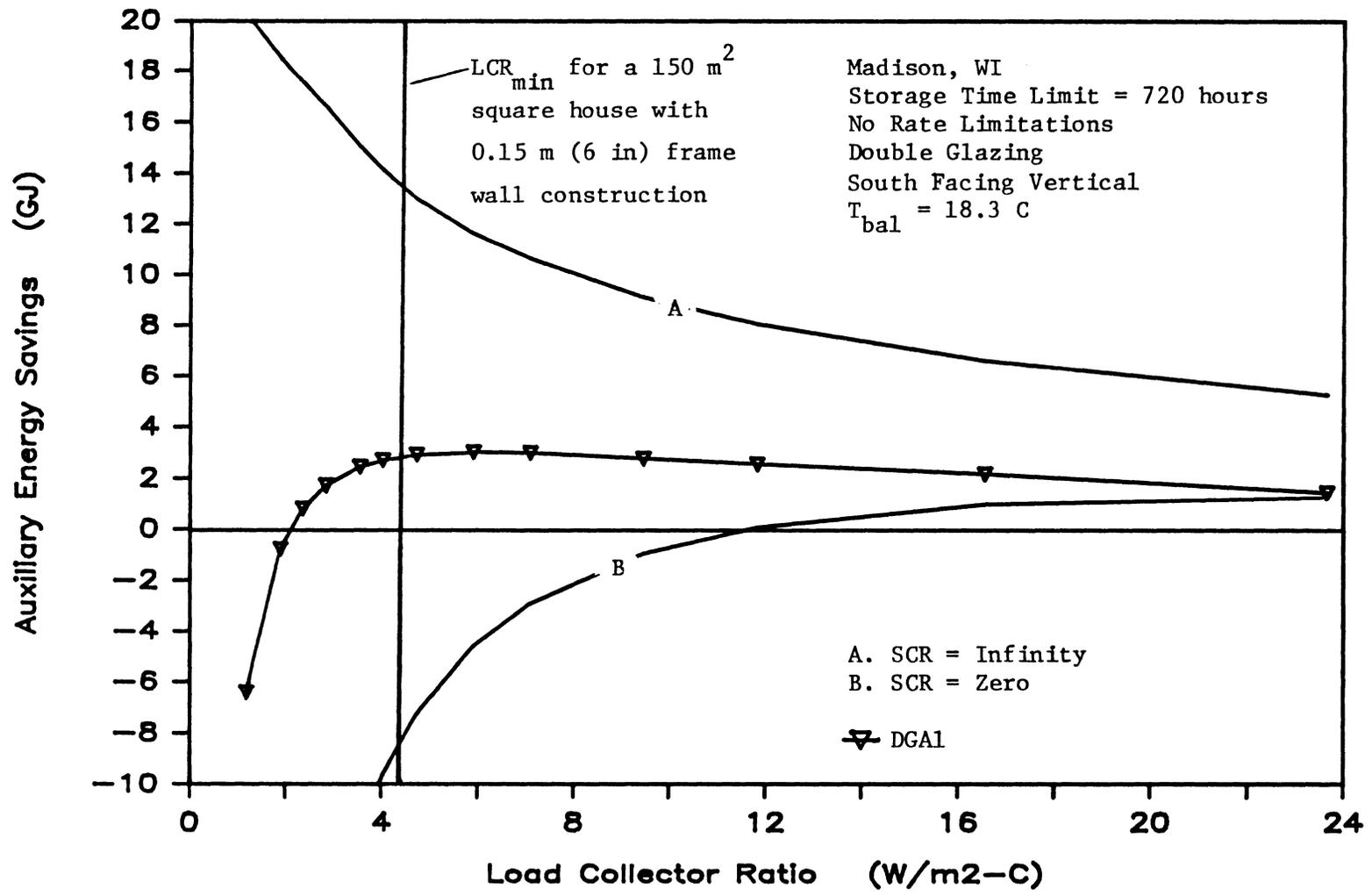


Figure 4.1 Limits of the Effect of Thermal Capacitance on Thermal Performance

buildings. Realistic net load coefficients would commonly fall in the range of 150 W/C to 300 W/C.

When the rate limit is effectively infinite, the limits of auxiliary energy savings were found to be directly proportional to the net load coefficient. For example, Figure 4.1 shows that an infinite capacitance building with  $LCR = 16 \text{ W/m}^2\text{-C}$  and  $NLC = 100 \text{ W/C}$  will save 6 GJ per year, relative to the same building with zero capacitance. The difference in annual auxiliary requirements for these two buildings would be 12 GJ if the net load coefficient were 200 W/C. This example shows that thermal performances can be compared without considering the net reference load. The example also points out that this figure can only be used for comparisons between buildings which have the same net load coefficient.

To examine the effects of hypothetical design options, buildings must be properly characterized. Figure 4.1 shows that the limit of the effect of energy storage capacity on thermal performance depends on the ratio of the building losses to the solar gains. This dependence must be considered when making conclusions about the potential energy savings of hypothetical design options, since all buildings in this range of LCR could be called passive solar buildings. Very low values of LCR are

limited by physical and practical building design, as discussed in Chapter 3. For example, a one story square house with 150 m<sup>2</sup> (1615 ft<sup>2</sup>) of floor area and 0.15 m (6 inch) frame wall construction was defined to have a minimum load collector ratio of 4.4 W/m<sup>2</sup>-C (18.6 Btu/day-ft<sup>2</sup>-F), based on limited south wall area. This minimum value is shown as a vertical line on Figure 4.1. A similar house with a 2:1 length to width ratio would have a minimum LCR of 3.1 W/m<sup>2</sup>-C (13.1 Btu/day-ft<sup>2</sup>-F).

The thermal performance limits shown in Figure 4.1 apply to a general class of buildings. An example of a building that fits the restrictions to Figure 4.1 is SLR reference design DGAl. The performance of design DGAl is shown on this figure by the curve with symbols. The energy savings difference between this curve and the infinite capacitance curve gives the limit of a hypothetical energy storage material to improve the thermal performance of direct gain building DGAl. The SLR method gives the performance of DGAl in terms of a solar savings fraction; the energy savings relative to the net reference load are calculated using the equations of Chapter 3, and by noting that the net reference load corresponds to an SSF of 0. The net reference load provides a convenient reference for mapping the performance of actual buildings on Figure 4.1.

Houses cannot have infinite energy storage capacity. Figure 4.2 repeats Figure 4.1, but includes the limits of performance associated with finite energy storage capacity. Even though the energy storage is finite, excess gains can be perfectly stored for 720 hours and removed without rate limitations. Figure 4.2 shows that the limit of performance improvement with an energy storage capacity limit of 16 MJ per  $m^2$  of collector area is nearly equal to the infinite capacitance performance improvement. Figures 3.7 through 3.10 can be used to relate a storage-collector ratio of 16 MJ/m<sup>2</sup> (1410 Btu/ft<sup>2</sup>) to the energy storage potential of sensible or phase change energy storage materials. For example, Figure 3.10 shows that an SCR of 16 MJ/m<sup>2</sup> could be provided by 42.0 mm (1.65 in) of phase change material with an area equal to the collector area ( $A_{esm,p}/A_p = 1$ ). Figure 4.2 shows that an SCR of 8 MJ/m<sup>2</sup> also provides a close approximation to infinite energy storage capacitance. Figure 3.7 ( $A_{esm,p}/A_p = 1$ ) demonstrates that this energy storage capacity is possible with 0.128 m (5.0 in) of water with a 15 C (27 F) maximum allowable temperature rise, or with 0.265 m (10.4 in) of concrete ( $\Delta T_{esm} = 15$  C). Recall that the storage-collector ratio refers to the upper limit of energy storage capacity that a material must be able to provide; allowing a maximum

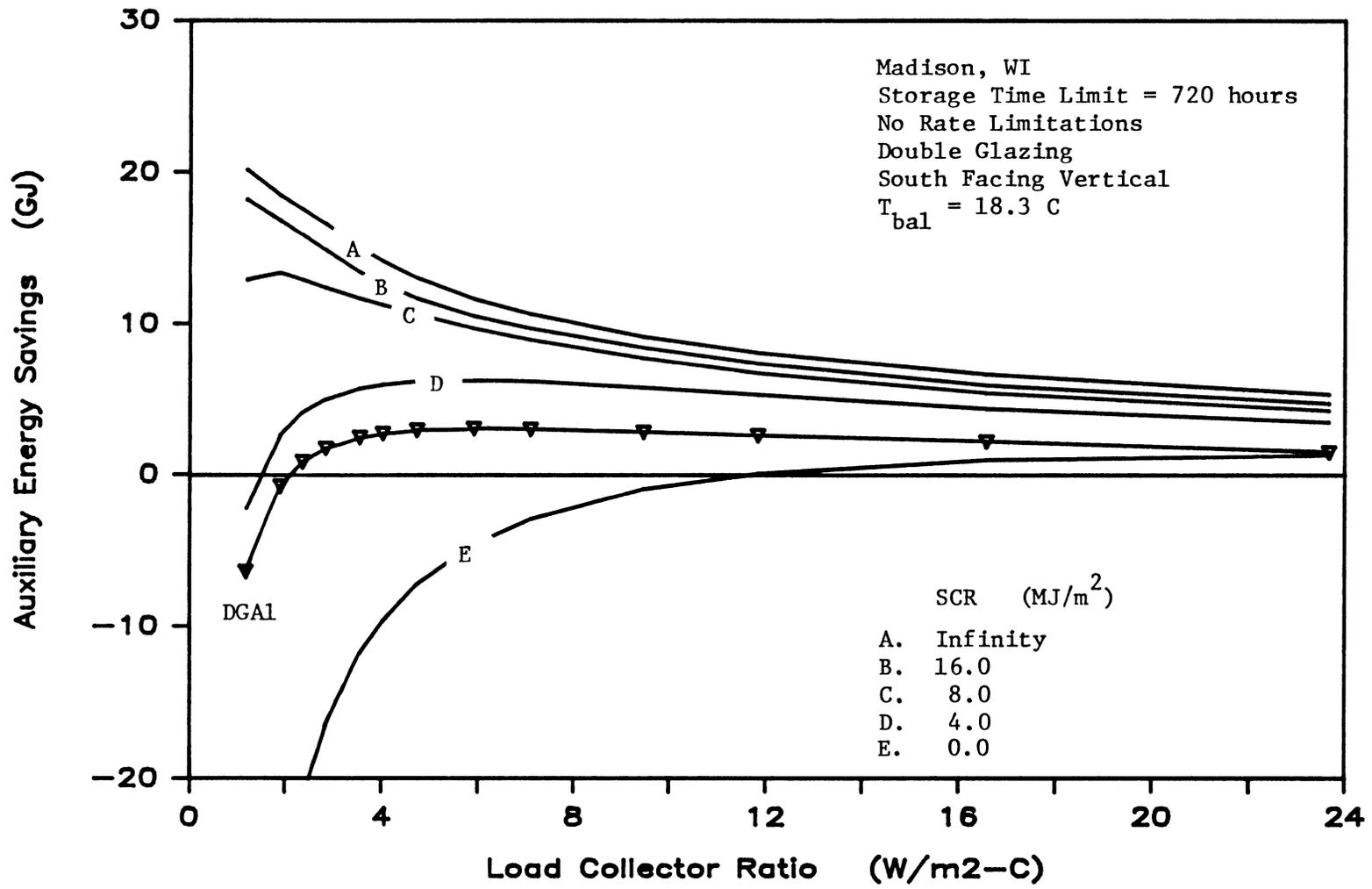


Figure 4.2 Limits of Thermal Performance Associated with Finite Thermal Capacitance

temperature increases beyond 15 C may be reasonable for some systems.

Location differences for thermal performance limits are shown with Figures 4.2, 4.3 and 4.4. Figure 4.3 is the same as Figure 4.2, except that the location is Albuquerque, New Mexico. Figure 4.4 gives results for Seattle, Washington. The effect of energy storage capacity can be assessed by comparing the difference between the zero and infinite thermal capacitance options. Notice that the energy savings between these two cases decreases significantly for all three locations as LCR increases. The greatest effects of capacitance occur in the lower range of LCR, but such buildings do not represent practical design. The energy savings with a storage-collector ratio of 16 MJ/m<sup>2</sup> approximates the infinite capacitance case for all three locations. The energy savings with infinite capacitance stops increasing when LCR is less than 6 W/m<sup>2</sup>-C in Albuquerque because the auxiliary energy requirement is completely offset by solar gains. The difference between the infinite capacitance building and design DGA1 are examined in Section 4.1.2.

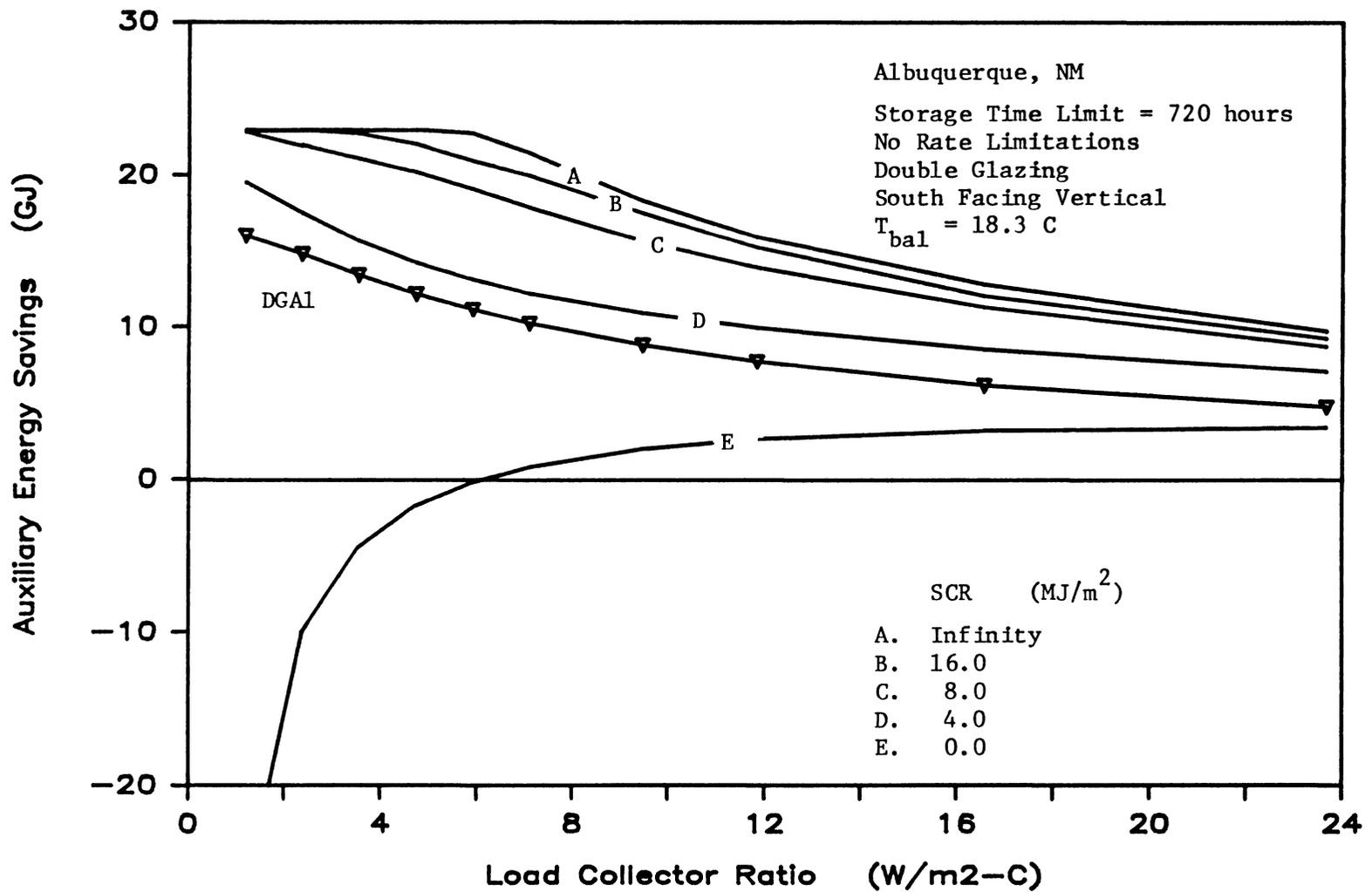


Figure 4.3 Limits of Thermal Performance Associated with Finite Thermal Capacitance

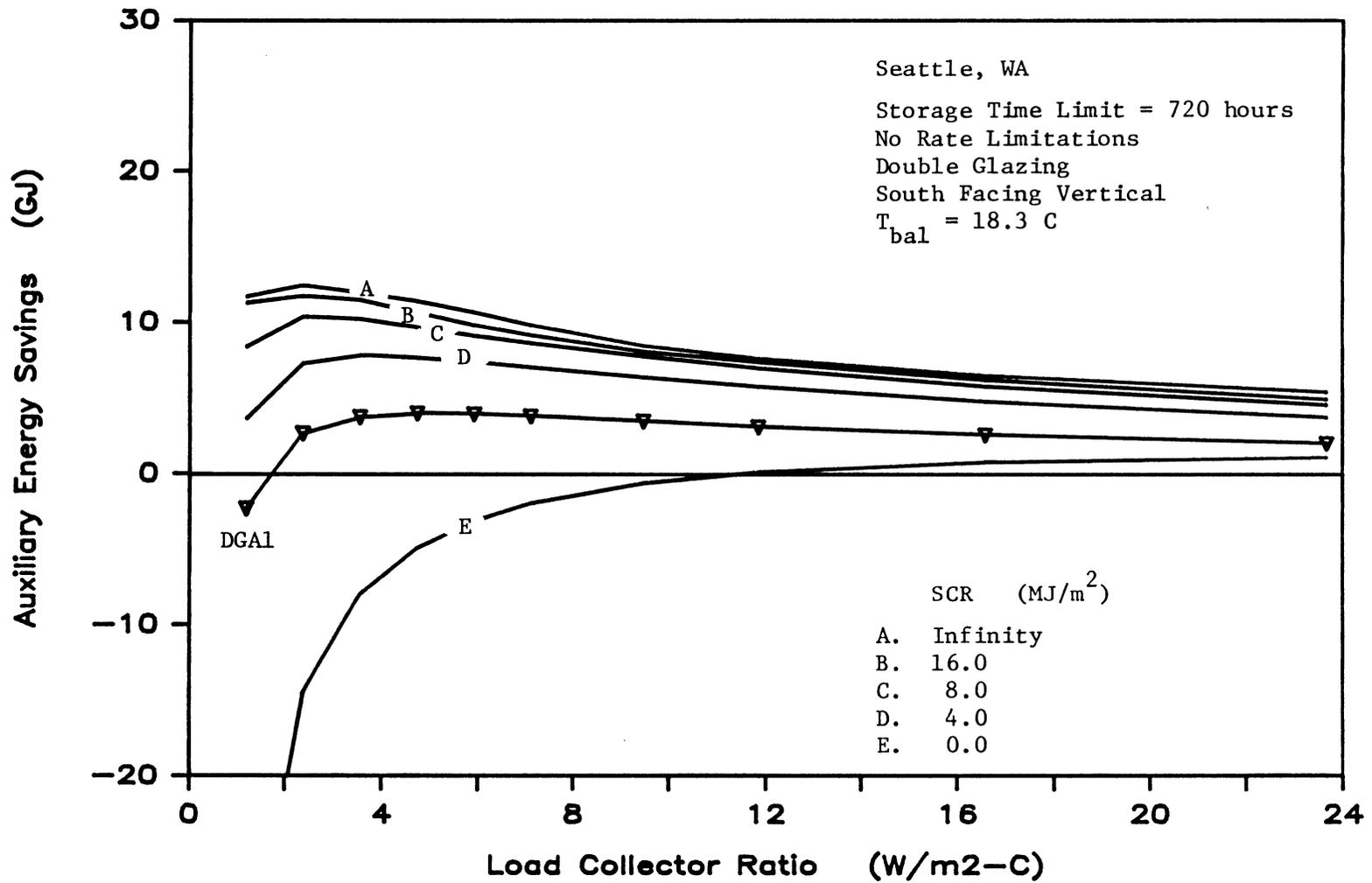


Figure 4.4 Limits of Thermal Performance Associated with Finite Thermal Capacitance

Figure 4.5 is the same as Figure 4.2, except that a low conductance collector is used to calculate the limits of thermal performance, instead of the double glazing. The low conductance collector corresponds to the evacuated glazing of Table 3.2. The performance of design DGA1 is also included on Figure 4.5. The performance of DGA1 can be compared with the low conductance performance limits because both design options have energy savings based on the same reference load. Figure 4.5 shows that the zero thermal capacitance building with the evacuated glazing saves auxiliary energy relative to design DGA1. The effects related to energy storage shown in Figures 4.2 and 4.5 are compared in Figure 4.6. The limit of performance with 4 MJ/m<sup>2</sup> of idealized energy storage more closely approximates the infinite capacitance performance for the evacuated collector than for the double glazed collector.

The previous graphs were based on a storage time limit of 720 hours. Figure 4.7 shows the effect in Madison of reducing the storage time limit to 24 hours. Reducing the storage time limit has the greatest effect on the the infinite thermal capacitance case; however, the effect is small for the practical ranges of the load collector ratio. This conclusion was found to apply to Albuquerque and Seattle. This demonstrates the importance of day-to-day energy carry over compared with month-to-month carry over.

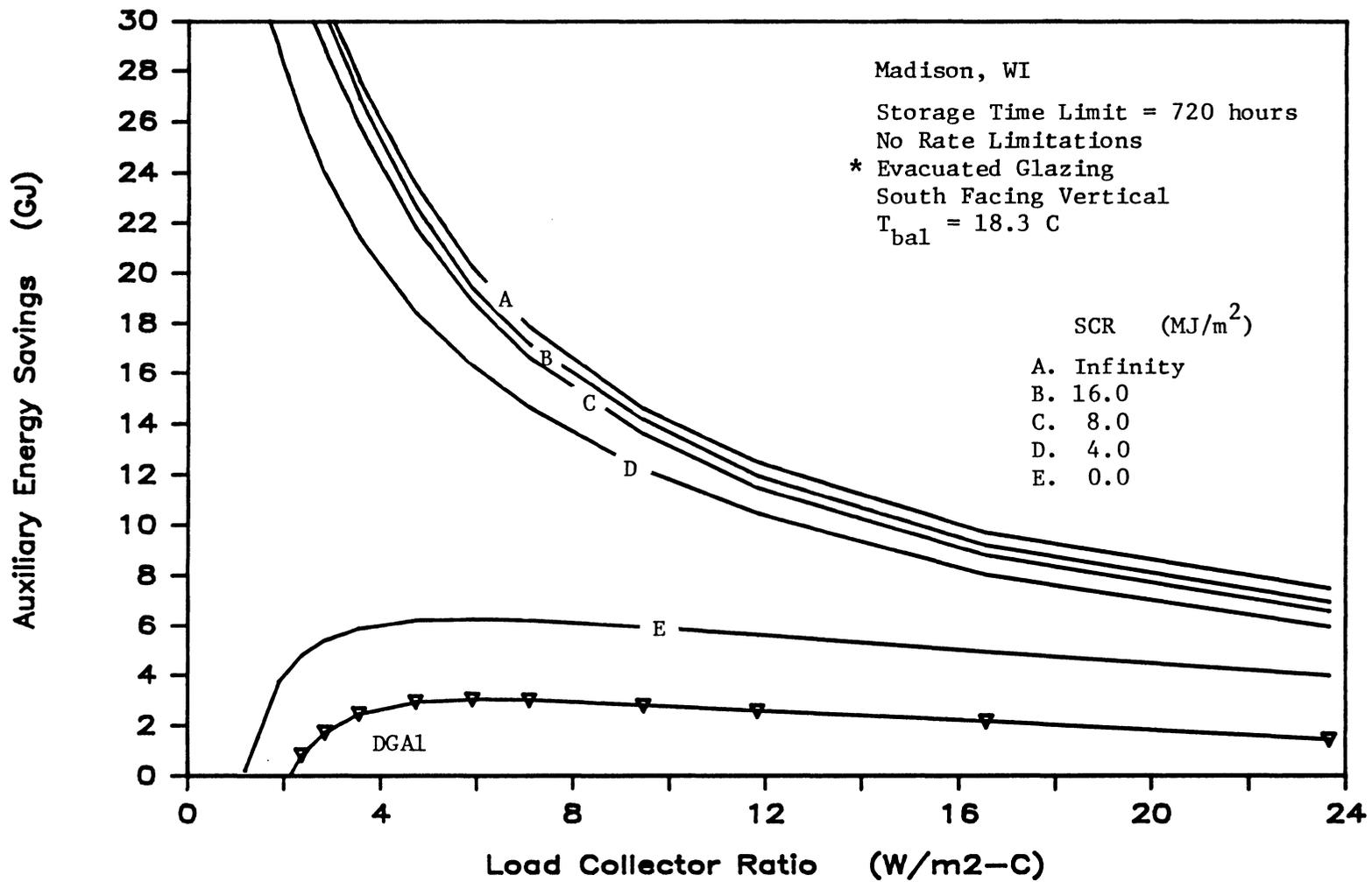


Figure 4.5 Limits of Thermal Performance Associated with Finite Thermal Capacitance and a Low Conductance Collector

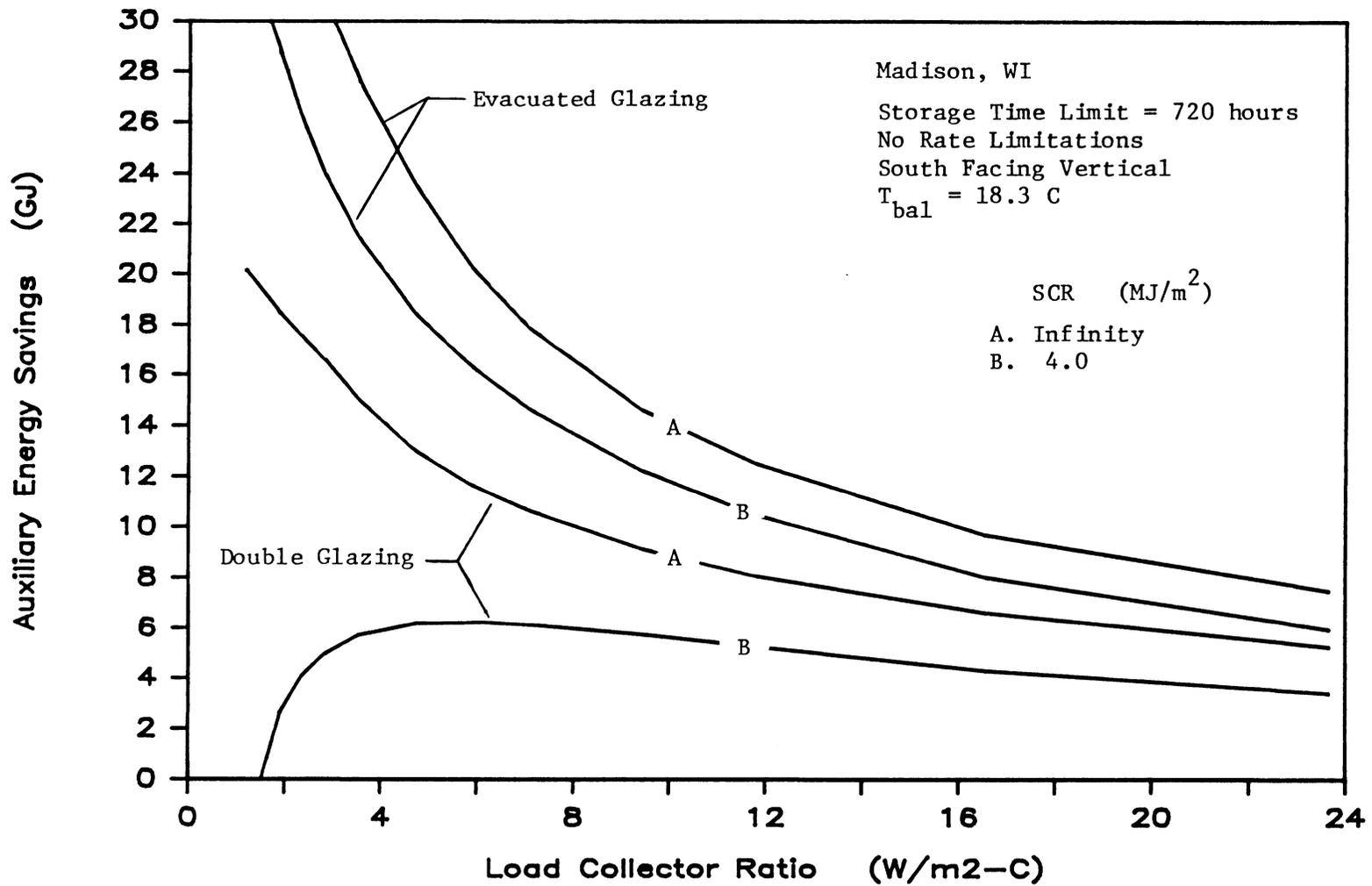


Figure 4.6 The Interaction between Thermal Capacitance and Collector Conductance

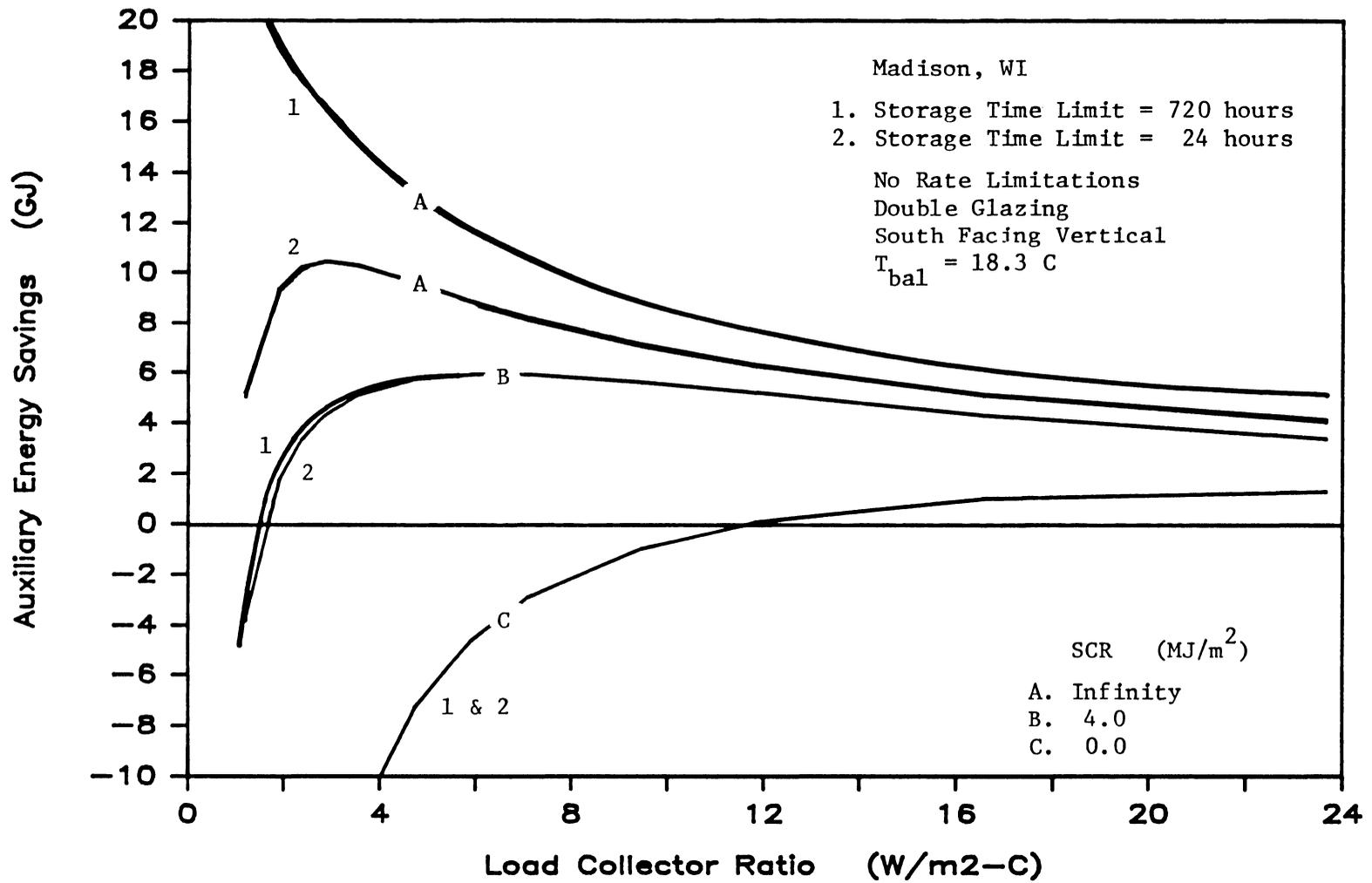


Figure 4.7 The Effect of Reducing the Storage Time Limit on Thermal Performance Limits

#### 4.1.2 Applications

A limit of performance improvement for design DGA1 is given in Figure 4.8 for Madison, Albuquerque, and Seattle. This figure gives the annual auxiliary energy savings, for a building with a net load coefficient of 100 W/C, resulting from the following changes to design DGA1: (1) increase energy storage capacity to infinity, (2) control energy flows according to the forward shifting method, (3) allow excess gains to be perfectly stored for 720 hours, and (4) allow energy to be removed from storage without rate limitations. This figure compares the effect of these design changes to an identical building built in three locations. These results can be generally applied; the curves represent the limit of any method to improve the performance of DGA1 by increasing energy storage capacity (excluding seasonal energy storage).

Figure 4.8 suggests there is little financial incentive to increase the energy storage capacity of design DGA1 in Seattle. As an example, consider a house in Seattle with 140 m<sup>2</sup> (1500 ft<sup>2</sup>) of floor area based on design DGA1. Assume electric heating will supply auxiliary energy at \$0.07/KWh, or \$19.44/GJ. Guidelines in Passive Solar Heating Analysis [11] suggest a load collector ratio of 11.4 W/m<sup>2</sup>-C and a net load coefficient of 134 W/C will approximately yield a life-cycle optimum cost. Figure 4.8

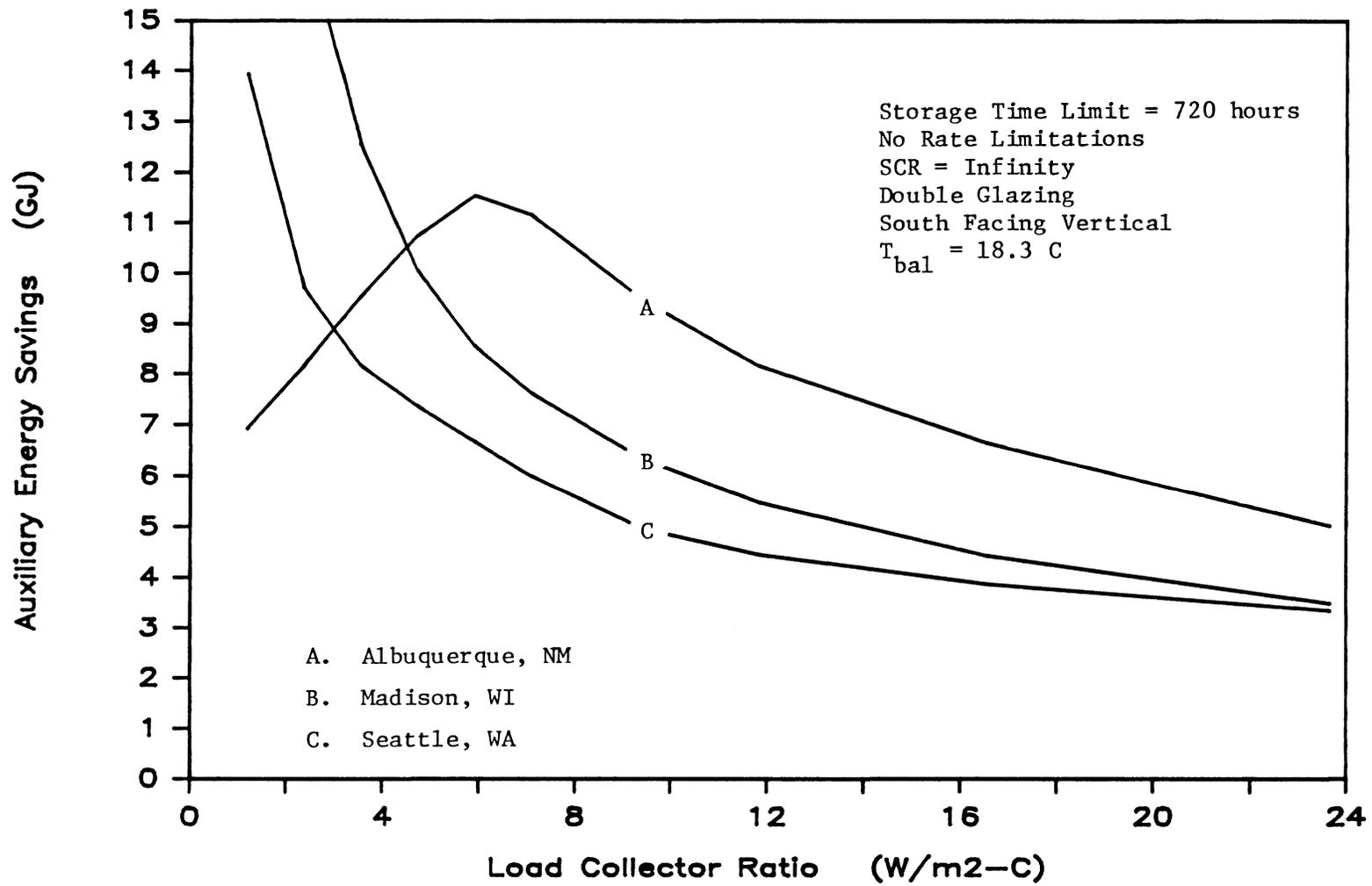


Figure 4.8 The Limit of Infinite Energy Storage Capacity to Improve the Thermal Performance of SLR Reference Design DGA1

shows that 4.5 GJ (per 100 W/C of NLC) of auxiliary energy could be saved per year by adding infinite energy storage capacity, eliminating rate limitations on energy transfer, and reducing storage losses to correspond to a 720 hour storage time limit. This yields a potential annual savings of 117 dollars. Table 4.2 extends this example to Madison and Albuquerque. Table 4.2 shows that different types of houses are typical for different locations, and this will also affect potential energy savings. Results of this type may be useful to the homeowner contemplating the purchase of additional energy storage material in a retrofit situation.

One might decrease the collector conductance to improve the thermal performance of design DGAl, instead of increasing thermal capacitance. Figure 4.9 shows the effect on design DGAl in Madison of using various low conductance glazing types listed in Table 3.2. The curves of Figure 4.9 are based on 4 MJ/m<sup>2</sup> of energy storage which has the idealized thermal characteristics of the energy storage of the Figure 4.2. Even though the energy storage capacity is limited, the performance improvement with the triple glazing is comparable to the infinite energy storage-double glazed collector of Figure 4.2. This suggests that the limits of performance improvement can be applied to choosing between design options.

Table 4.2 Limit of Infinite Energy Storage Capacity to Improve the Performance of SLR Reference Design DGA1

Electric Auxiliary Energy Cost : \$0.07/KWh = \$19.44/GJ

Recommendations for LCR and NLC: Passive Solar Heating Analysis, A Design Manual [11]

	Seattle	Madison	Ablbuquerque
LCR (W/m <sup>2</sup> -C)	11.4	7.1	6.2
NLC (W/C)	134.0	105.0	166.0
Auxiliary Savings per 100 W/C of NLC GJ/(W/C)	4.5	7.6	11.4
Annual Auxiliary Fuel Cost Savings Dollars	117	155	368

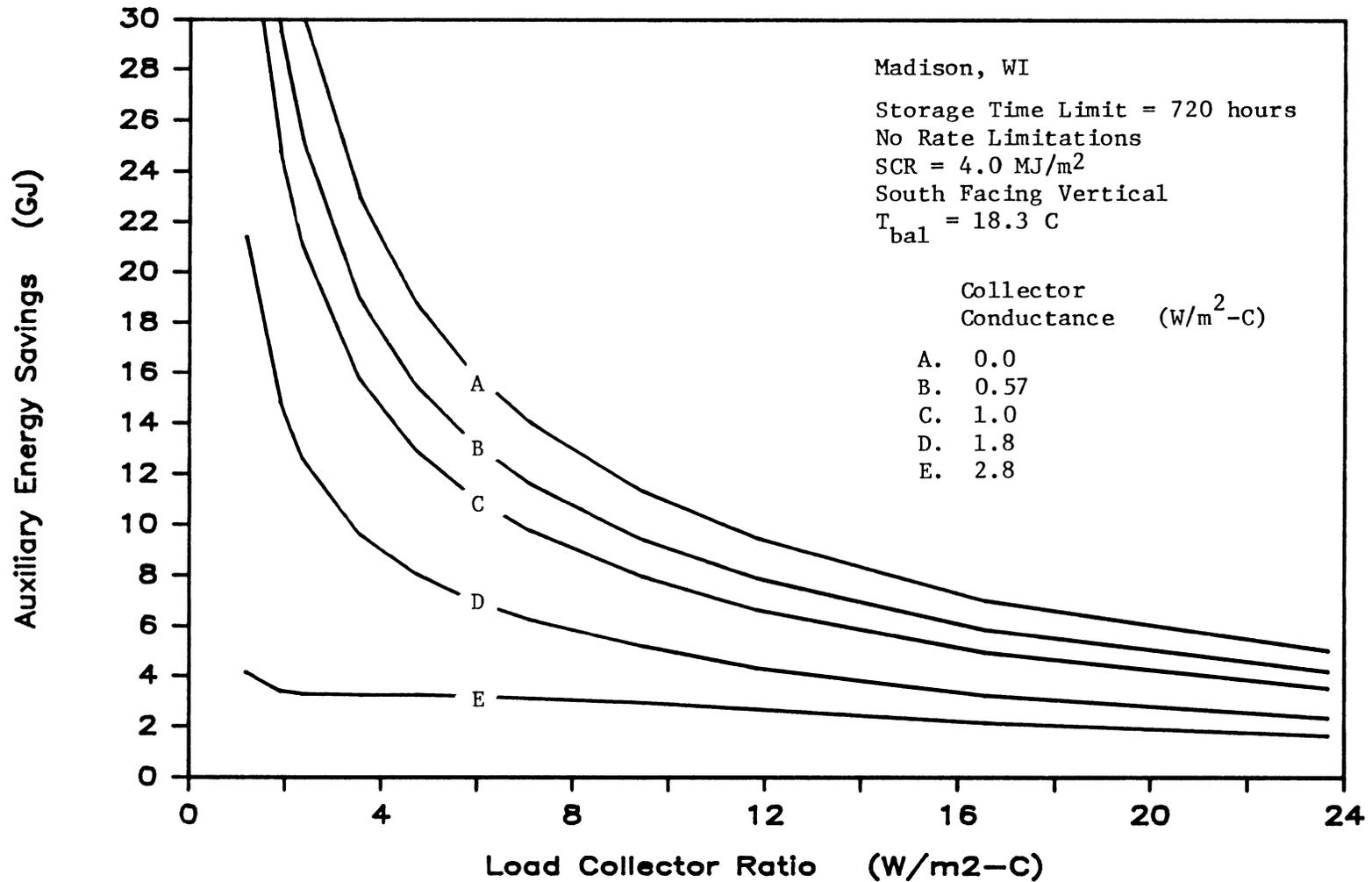


Figure 4.9 The Limit of 4.0 MJ/m<sup>2</sup> of Energy Storage Capacity and Various Low Conductance Glazings to Improve the Thermal Performance of SLR Reference Design DGA1

Curve 'e' of Figure 4.9 can be used to evaluate the energy saving potential from improving the energy transfer characteristics of design DGAl. The performance of DGAl is based on finite energy exchange rates between energy storage materials and between energy storage and the room air. The storage-collector ratio for design DGAl is 3.4 MJ/m<sup>2</sup>. The limit of performance given by curve 'e' is based on perfect control of energy exchanges. Energy exchange rates may be infinite if necessary. Curve 'e' is based on an SCR of 4 MJ/m<sup>2</sup>, which is slightly greater than that of design DGAl. Therefore, the potential energy savings resulting from methods to improve the energy exchange characteristics of design DGAl would be less than the energy savings given by curve 'e', which is small over the range of LCR.

The effect of various design improvements to design DGAl are shown in Figure 4.10. The SLR prediction of performance improvement from doubling the energy storage capacity of design DGAl to 1.22 MJ/m<sup>2</sup>-C is given by the curve "DGC1". The actual effect of adding night insulation is shown with curve "DGA3". The night insulation is in place between the hours of 5:30 P.M. and 7:30 A.M. and has a thermal resistance of 1.585 m<sup>2</sup> C/W (9 ft<sup>2</sup> h F/Btu). This resistance corresponds to

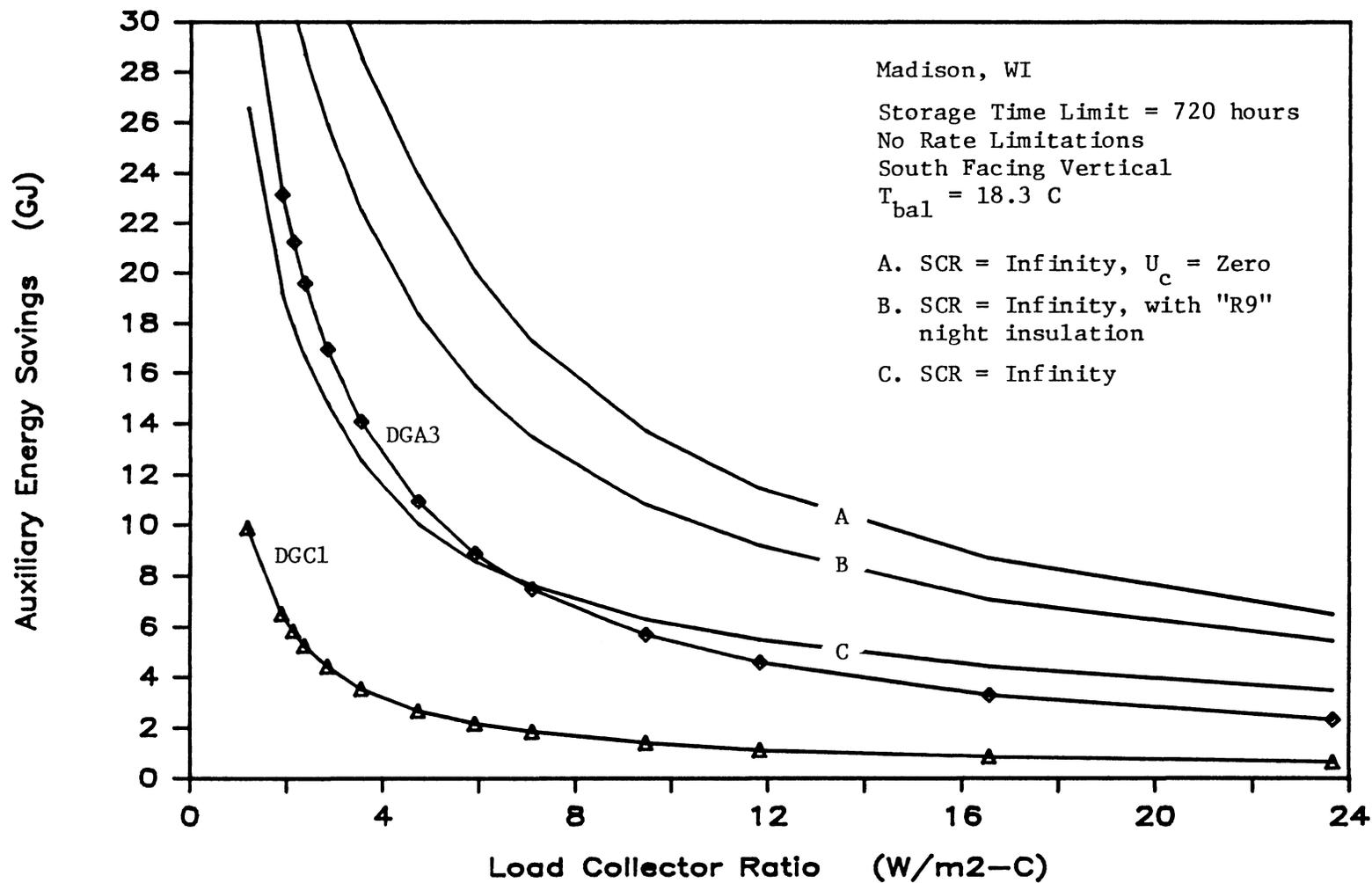


Figure 4.10 The Effect of Various Design Options to Improve the Thermal Performance of SLR Reference Design DGA1

approximately 75 mm (3 in) of fiberglass insulation. The limit of potential improvement from adding night insulation is also shown. An ultimate limit of performance is represented with the zero conductance glazing-infinite thermal capacitance option.

The actual improvement of adding night insulation to DGAl is approximately equal to the performance limit associated with infinite thermal capacitance. This observation suggests a practical use for the knowledge of thermal performance limits; comparison of design options. Consider the choice between adding night insulation or energy storage material to design DGAl. If energy storage is increased by doubling the present materials, the SLR method shows that night insulation will result in greater energy savings. Economic analysis can be carried out to choose the best option. However, if the energy storage is to be increased by adding a newly developed phase change material, evaluation becomes more difficult, since phase change energy storage is not directly considered by the SLR method. It is seen in Figure 4.10 however, that if the phase change material had infinite energy storage capacity, perfect energy exchange capability, no rate limitations and a storage time limit of 720 hours, its performance would be about equal to the actual night insulation option. This knowledge could make economic

decisions possible. In fact, Figure 4.10 shows that for high LCR buildings, the best option may be not changing design DGAl, since even an infinite capacity, zero collector conductance building results in only a modest performance improvement.

The results presented in this section suggest that thermal performance limit information is applicable to the process of designing solar heated buildings. Given a conventional (and perhaps lowest cost) building design and a prediction of its performance, the limit of energy savings from added options can be evaluated from graphs of the type presented in this chapter. Limits would be especially useful when a designer does not have a specific option to check, but rather a category, such as increasing energy storage capacity.

## CHAPTER 5

## 5. CONCLUDING REMARKS AND RECOMMENDATIONS

Precise definitions must accompany a presentation of the thermal performance limits of a solar heated building. The limit of a design option to improve the thermal performance of a building was precisely defined using the potential auxiliary energy savings. It was shown that auxiliary energy savings can vary significantly with building design and location, therefore the load and solar gain characteristics of a building must be specified. Building characteristics were defined using a load collector ratio, and an energy storage to collector area ratio. Practical ranges of these parameters were discussed.

The limits of performance were calculated using an idealized building model. The model and control strategy are not intended to simulate the actual performance of a realistic building, but to calculate a theoretical minimum auxiliary energy requirement. Idealizing energy storage, building losses, energy exchange and control, and auxiliary input gives a performance limit that is calculated from relatively few parameters (given in Appendix A). One can determine the limit of design changes to improve the thermal performance of a building without having to simulate the actual building design.

The general results presented in Section 4.1.1 suggest that the following criteria be considered when evaluating results concerning the potential of design changes to improve building thermal performance:

- \* To what range of load collector ratio and net load coefficient do the results apply?
- \* What type of climate?
- \* Are the ranges of LCR and NLC practical for the climate?
- \* How do the results relate to money saved?
- \* How do monetary savings relate to the cost of implementing the option?
- \* Do the results of a specific improvement apply to the general category of the design change?

The results presented in Section 4.1.2 demonstrated how thermal performance limit information can be applied to the design and analysis of solar heated buildings and building materials. Those with access to hourly weather data can calculate thermal performance limits using the program listed in Appendix A. Where only monthly average weather data is available, the Un-utilizability design method[3] and the work of Erbs[8] provide useful performance limit information.

General conclusions from this work regarding the limits of thermal performance are summarized below.

Buildings having an energy storage capacity greater than 8 MJ per square meter of collector area can approximate the thermal performance of infinite thermal capacitance buildings. This approximation improves as collector conductance decreases or as loss rates from energy storage increase. A storage-collector ratio of 8 MJ/m<sup>2</sup> was shown to be attainable with practical designs using sensible energy storage materials.

Nearly all stored energy gains are used within 24 hours after the excess gains occur. There is little potential to save energy by designing systems to store excess gains for 720 hours rather than 24 hours, especially when energy storage capacity is limited.

Figure 4.9 gave the potential energy savings of design changes to improve the energy exchange characteristics of a typical direct gain building in Madison. The limit of energy savings was less than 4 GJ saved per year for each 100 W/C of net load coefficient.

Continued research in the area of this thesis should involve the following:

- 1) Economics - The limits of energy savings for for design options need to be related to the cost of the option. Specific building materials should be targeted for evaluation.
- 2) Calculation Method - The basic approach presented in Section 2.2 should be extended by replacing portions of idealized building model with realistic building models. This would allow a more detailed separation of effects of various design changes. The modular format of TRNSYS would be particularly useful for such a study.
- 3) Other Systems - The idealized building model (shown in Figure 2.2) was developed to represent active, passive, and hybrid systems. Work should be done to extend the presentation of thermal performance limits to active and hybrid systems.
- 4) Cooling Loads - An analysis which parallels the work in this thesis should be performed for cooling loads.

## APPENDIX A

Program FORXS (FORward shifting of eXceSs gains)

This FORTRAN program uses the forward shifting of excess gains method to calculate the thermal performance limits of a solar heated building, in conjunction with TRNSYS output.

INPUT	UNITS	VARIABLE DESCRIPTION
TITLE	-	Name of Run
AP	m <sup>2</sup>	Projected Collector Area
AZ	degrees	Collector Azimuth (to identify TRNSYS run)
B	degrees	Collector Tilt (to identify TRNSYS run)
IG	-	Identifies Input File for TA & QUPM2
LCR	Btu/F-day-ft <sup>2</sup>	Load Collector Ratio
QI	W	Average Hourly Rate of Internal Gains (may be a vector)
QUPM2	KJ/m <sup>2</sup>	Useful Hourly Solar Gains Delivered to Storage per Square Meter of AP
RINSUL	m <sup>2</sup> -C/W	Resistance of Night Insulation
RLIMIT	W	Rate Limit for Removal of Stored Energy
SS	MJ	Energy Storage Limit
ST	hours	Storage Time Limit
TA	C	Ambient Temperature
TR	F	Room Set Point Temperature
UC	W/m <sup>2</sup> -C	Collector Conductance

```

      INTEGER ST(50),IG(50)
      REAL NLC(50),LCR(50)
      DIMENSION SS(50),ESLIM(50),AUXYR(50),TRSI(50),UC(50)
      DIMENSION AP(50),TR(50),RLIMIT(50),RINSUL(50)
      COMMON/BLK1/ QU(8760),TA(8760),ES(18000),AUX(18000),
&QUPM2(8760)
      CHARACTER TITLE*80
      DATA AUXYR/50*0./

C
      READ(12,501)TITLE
      READ(12,*)QI,AZ,B
      READ(12,*)NUC
      READ(12,*)(UC(IUC),RINSUL(IUC),IG(IUC),IUC=1,NUC)
      READ(12,*)NLCR
      READ(12,*)(LCR(I),I=1,NLCR)
      READ(12,*)NAP
      READ(12,*)(AP(I),I=1,NAP)
      READ(12,*)NTR
      READ(12,*)(TR(I),I=1,NTR)
      READ(12,*)NSS
      READ(12,*)(SS(I),I=1,NSS)
      READ(12,*)NST
      READ(12,*)(ST(I),I=1,NST)
      READ(12,*)NRL
      READ(12,*)(RLIMIT(I),I=1,NRL)

C
      NNLC=NLCR
      NRUNS=NUC*NNLC*NAP*NTR*NST*NRL
      IFLAG=1
      WRITE(17,600)
      WRITE(17,601)TITLE
      WRITE(17,602)QI
      WRITE(17,603)AZ
      WRITE(17,604)B
      WRITE(17,605)

C
C      Convert rate limit to [KJ/h]
C
      DO 201 I=1,NRL
          RLIMIT(I)=3.6*RLIMIT(I)
201  CONTINUE

C
C      Convert room set point temperature to Celcius
C
      DO 202 ITR=1,NTR
          TRSI(ITR)=(TR(ITR)-32.0)/1.8
202  CONTINUE

C
      DO 400 IUC=1,NUC
          IF(IUC.EQ.1) GOTO 301
          IF(IG(IUC).EQ.IG(IUC-1)) GOTO 302

```

```

C
C   FILE "IG(IUC)": Read in 8760 values for ambient
C                   temperature "TA" [C] beginning with
C                   hour one on August first. Then
C                   read in hourly solar energy gain
C                   "QUPM2" [KJ/m2], convert "QUPM2" to
C                   "QU" [KJ].
C       *! NOTE: Data must be ordered to begin with hour
C               one on 8/1
C
301  READ(IG(IUC),*)(TA(I),I=1,8760)
      READ(IG(IUC),*)(QUPM2(I),I=1,8760)
C
302  CONTINUE
      DO 410 IAP=1,NAP
      DO 310 I=1,8760
          QU(I)=AP(IAP)*QUPM2(I)
310  CONTINUE
      UCAP=AP(IAP)*UC(IUC)
      UCNIAP=AP(IAP)/((1.0/UC(IUC))+RINSUL(IUC))
      DO 420 INLC=1,NNLC
      NLC(INLC)=LCR(INLC)*AP(IAP)*0.2366
      DO 430 ITR=1,NTR
      DO 440 IST=1,NST
      DO 450 IRL=1,NRL
C
C-----
C-----
C   Loop 460 varies the size of the storage
C-----
C-----
      DO 460 ISS=1,NSS
C
C   Loop 360 Establishes "AUX" and "ES" for starting
C           length by reaching back into July. Build
C           up accumulation of "ES" energy in storage.
C           SS(ISS) has units [MJ] ESLIM(ISS) has
C           units [KJ]. There is no night insulation
C           during starting length
C
      ESLIM(ISS)=SS(ISS)*1000.0
      DO 360 J=1,ST(IST)
          ES(J)=QU(8760-ST(IST)+J)
          AUX(J)=3.6*(NLC(INLC)+UCAP)*(TRSI(ITR)-
&TA(8760-ST(IST)+J))-3.6*QI
          IF(AUX(J).LT.0.0) THEN
              ES(J)=(-1.0)*AUX(J)+ES(J)
              AUX(J)=0.0
          END IF
          IF(AUX(J).EQ.0.0) GOTO 362
C

```

```

C          Removing energy from storage
C
QEXMAX=RLIMIT(IRL)
QEX=0.0
DO 361 JJ=J+1,2,-1
  IF(ES(JJ-1).EQ.0.0) GOTO 361
  ESOUT=ES(JJ-1)
  QEX=QEX+ESOUT
  SPACE=QEXMAX-QEX
  IF(SPACE.LT.0.0) ESOUT=ES(JJ-1)+SPACE
  ESLO=ES(JJ-1)-ESOUT
  AUX(J)=AUX(J)-ESOUT
  IF(AUX(J).LE.0.0) THEN
    ES(JJ-1)=(-1.0)*AUX(J)+ESLO
    AUX(J)=0.0
    GOTO 362
  ELSE
    ES(JJ-1)=ESLO
    IF(QEX.GE.QEXMAX) GOTO 362
  END IF
361 CONTINUE
362 CONTINUE
C
C          Check energy storage limit
C
SUMES=0.0
DO 363 JJJ=1,J
  SUMES=SUMES+ES(J-JJJ+1)
363 CONTINUE
  SPACE=ESLIM(ISS)-SUMES
  IF(SPACE.LT.0.0) THEN
    DO 364 J4=1,J
      IF(ES(J4).GT.0.0) THEN
        J5=J4
        GOTO 365
      END IF
364 CONTINUE
      J5=J
365 ES(J5)=ES(J5)+SPACE
      IF(ES(J5).LT.0.0) THEN
        DO 367 J6=J5+1,J
          ES(J6)=ES(J6)+ES(J6-1)
          ES(J6-1)=0.0
          IF(ES(J6).GE.0.0) GOTO 360
367 CONTINUE
        END IF
      END IF
360 CONTINUE
C
C-----

```

```

C      This is the beginning of the 8760 hour loop
C-----
C
      IHOURL=0
      DO 368 I=1+ST(IST),8760+ST(IST)
        IF(RINSUL(IUC).EQ.0.0) THEN
          UAC=UCAP
          ES(I)=QU(I-ST(IST))
          GOTO 369
        END IF
        IHOURL=IHOURL+1
        IF(IHOURL.EQ.25) IHOURL=1
        IF(IHOURL.EQ.8.OR.IHOURL.EQ.18) THEN
          UAC=(UCAP+UCNIAP)/2.0
          ES(I)=QU(I-ST(IST))/2.0
          GOTO 369
        END IF
        IF(IHOURL.LE.7.OR.IHOURL.GE.19) THEN
          UAC=UCNIAP
          ES(I)=0.0
          GOTO 369
        END IF
        IF(IHOURL.GE.9.OR.IHOURL.LE.17) THEN
          UAC=UCAP
          ES(I)=QU(I-ST(IST))
          GOTO 369
        END IF
369     AUX(I)=3.6*(NLC(INLC)+UAC)*(TRSI(ITR)-
&TA(I-ST(IST)))-3.6*QI
        IF(AUX(I).LT.0.0) THEN
          ES(I)=(-1.0)*AUX(I)+ES(I)
          AUX(I)=0.0
        END IF
        IF(AUX(I).EQ.0.0) GOTO 371

C
C      Loop 370: Excess energy is removed from storage to
C               offset the auxiliary energy requirement
C
      QEXMAX=RLIMIT(IRL)
      QEX=0.0
      DO 370 J=ST(IST)+1,2,-1
        IF(ES(I-ST(IST)+J-1).EQ.0.0) GOTO 370
        ESOUT=ES(I-ST(IST)+J-1)
        QEX=QEX+ESOUT
        SPACE=QEXMAX-QEX
        IF(SPACE.LT.0.0) ESOUT=ES(I-ST(IST)+J-1)+SPACE
        ESLO=ES(I-ST(IST)+J-1)-ESOUT
        AUX(I)=AUX(I)-ESOUT
        IF(AUX(I).LE.0.0) THEN
          ES(I-ST(IST)+J-1)=(-1.0)*AUX(I)+ESLO
          AUX(I)=0.0
        END IF
      END DO

```

```

        GOTO 371
    ELSE
        ES(I-ST(IST)+J-1)=ESLO
        IF(QEX.GE.QEXMAX) GOTO 371
    END IF
370    CONTINUE
371    CONTINUE
C
C        Checking the energy storage limit
C
        SUMES=0.0
        DO 372 III=1,ST(IST)
            SUMES=SUMES+ES(I-III+1)
372    CONTINUE
        SPACE=ESLIM(ISS)-SUMES
        IF(SPACE.LT.0.0) THEN
            DO 373 I4=1,ST(IST)
                IF(ES(I-ST(IST)+I4-1).GT.0.0) THEN
                    I5=I-ST(IST)+I4-1
                    GOTO 374
                END IF
373    CONTINUE
            I5=I
374    ES(I5)=ES(I5)+SPACE
            IF(ES(I5).LT.0.0) THEN
                DO 375 I6=I5+1,I
                    ES(I6)=ES(I6)+ES(I6-1)
                    ES(I6-1)=0.0
                    IF(ES(I6).GT.0.0) GOTO 376
375    CONTINUE
                END IF
            END IF
C
376    AUXYR(ISS)=AUXYR(ISS)+AUX(I)
C
        IF(ISS.EQ.1) THEN
            QNETH=3.6*NLC(INLC)*(TRSI(ITR)-TA(I-ST(IST)))
            &-3.6*QI
            IF(QNETH.LT.0.0) QNETH=0.0
            QNETYR=QNETYR+QNETH
        END IF
C
368    CONTINUE
C-----
C        This is the end of the annual hour by hour loop
C-----
460    CONTINUE
C
C        FILE 17: Output yearly values for data plotting
C
        IF(IFLAG.EQ.1) WRITE(17,607)NRUNS,NSS

```

```

      IF(IFLAG.EQ.1) WRITE(17,608)
      WRITE(17,609)AP(IAP),NLC(INLC),TR(ITR),ST(IST),
&RLIMIT( IRL)/3600.0
      IF(IFLAG.EQ.1) WRITE(17,610)
      IF(IFLAG.EQ.1) WRITE(17,611)
      WRITE(17,612)QNETYR/1.0E+6,LCR(INLC),UC(IUC),
&RINSUL(IUC),IG(IUC)
      IF(IFLAG.EQ.1) THEN
        WRITE(17,613)
        WRITE(17,614)
        IFLAG=2
      END IF
      DO 350 ISS=1,NSS
        SSF=1.0-AUXYR(ISS)/QNETYR
        WRITE(17,615)ESLIM(ISS)/1000.0,AUXYR(ISS)/1.0E+6,SSF
        SCR=ESLIM(ISS)/AP(IAP)
        WRITE(19,*)LCR(INLC),SSF,SCR
        AUXYR(ISS)=0.0
350    CONTINUE
      QNETYR=0.0
450    CONTINUE
440    CONTINUE
430    CONTINUE
420    CONTINUE
410    CONTINUE
400    CONTINUE
501    FORMAT(A80)
600    FORMAT(' **** PROGRAM FORXS *** Version 8.5.85 **')
601    FORMAT(/,5X,A80)
602    FORMAT(/,' Internal Energy Generation  =',F7.1,' W')
603    FORMAT(/,' Collector Surface Azimuth   =',F7.1,' deg')
604    FORMAT(/,' Collector Surface Tilt     =',F7.1,' deg')
605    FORMAT(/,' *****')
607    FORMAT(I5,' run sets;      # of storage sizes=',I3)
608    FORMAT(/,T5,'AP',T17,'NLC',T30,'TR',T43,'ST',T53,
&'RLIMIT')
609    FORMAT(F7.1,T17,F6.2,T30,F5.2,T43,I3,T53,F5.1)
610    FORMAT(T5,'m2',T17,'W/C',T30,'F',T43,'hrs',T54,'KW',/)
611    FORMAT(T3,'QNET,YR GJ',T16,'LCR, Btu/F day ft2',T38,
&'Ucoll',T50,
&'RINSUL',T60,'FILE')
612    FORMAT(1X,F10.6,T17,F9.1,T37,F6.3,T47,F10.4,T60,I3)
613    FORMAT(/,T7,'STORAGE',T22,'AUXILIARY',T35,'SOLAR
& SAVINGS')
614    FORMAT(T7,'LIMIT MJ',T22,'ENERGY GJ',T35,' FRACTION')
615    FORMAT(T3,F10.2,T20,F10.6,T38,F7.3)
      STOP
      END

```

## APPENDIX B

## The Solar Load Ratio Method

The Solar Load Ratio (SLR) method was developed at the Los Alamos National Laboratory to calculate the auxiliary energy requirements of passive solar buildings. It is based on monthly correlations derived from hourly simulations. The hourly simulations were performed with detailed building models in various locations using the PASOLE[17] computer program. The results of the simulations were used to correlate the monthly solar savings fraction with the solar load ratio, SLR, and several correlation coefficients. Precise definition of the solar load ratio, the ratio of the monthly solar gain to monthly load is defined in Passive Solar Heating Analysis[11]. Balcomb, et. al. [18] report that the mean square deviation for the correlated annual solar savings fraction is typically (+-3%) compared to the hourly simulations. Validation of the PASOLE code is offered by Wray[19] and Klein[20] based on the results of software-software comparisons of PASOLE with other widely used computer models.

Results of the SLR method are given terms of 94 reference building designs which were used in the simulations. The building designs include direct gain, Trombe wall, water wall, and sunspace configurations. Given below is a FORTRAN program to perform the calculations required to predict direct gain reference design performance.

```

INTEGER CITY1,CITY2,CITY3,IG(9)
REAL LCR(50)
DIMENSION S(9,12),ASSF(9,50),DDM(2,12),DDY(2),SI(3,12)
DIMENSION DM(12),A(9),B(9),C(9),D(9),R(9),G(9),ABS(9)
DATA DM/31.,28.,31.,30.,31.,30.,31.,31.,30.,31.,30.
&,31./
DATA A/.5650,.5906,.5442,.5739,.6180,.5601,.6344,
&.6763,.6182/
DATA B/1.009,1.006,.9715,.9948,1.0,.9839,.9887,.9994,
&.9859/
DATA C/1.044,1.065,1.13,1.251,1.276,1.352,1.527,1.4,
&1.566/
DATA D/.7175,.8099,.9273,1.061,1.156,1.151,1.438,
&1.394,1.437/
DATA R/.3931,.4681,.7068,.7905,.7528,.8879,.8632,
&.7604,.899/
DATA G/9.36,5.28,2.64,9.6,5.52,2.38,9.6,5.28,2.4/
DATA ABS/.976,.976,.976,.948,.948,.948,.976,.976,
&.976/
DATA IG/2,3,2,2,3,2,2,3,2/

C
C
C
INPUT LCR=[Btu/F day ft2] TBASE=[F]

READ(12,*)CITY1,CITY2,CITY3
READ(12,*)NLCR
READ(12,*)(LCR(IL),IL=1,NLCR)
READ(12,*)TBASE
IF(TBASE.LT.56.0.AND.TBASE.GT.54.0) ITB=1
IF(TBASE.LT.66.0.AND.TBASE.GT.64.0) ITB=2

C
C
C
C
C
IN FILE "CITY":

"S"      monthly solar gain      [MJ/m2 mo]
"DDM"    monthly degree days     [C-days]
"DDY"    annual heating degree-days [C-days]

C
C
C
C
C
READ(CITY2,*)(SI(2,MO),MO=1,12)
READ(CITY2,*)(DDM(1,MO),MO=1,12)
READ(CITY2,*)(DDM(2,MO),MO=1,12)
READ(CITY2,*)DDY(1),DDY(2)
READ(CITY3,*)(SI(3,MO),MO=1,12)

C
C
C
C
CONVERT SI UNITS TO: S=[Btu/ft2 mo]
                      DDM=[F-day] DDY=[F-day]

DO 101 MO=1,12
DO 102 ID=1,9
S(ID,MO)=SI(IG(ID),MO)*((0.3048)**2)*1000.0/1.055
102 CONTINUE

```

```

DDM(1,MO)=1.8*DDM(1,MO)
DDM(2,MO)=1.8*DDM(2,MO)
WRITE(6,*)DDM(1,MO),DDM(2,MO)
101 CONTINUE
DDY(1)=1.8*DDY(1)
DDY(2)=1.8*DDY(2)
C
DO 201 IL=1,NLCR
DO 202 ID=1,9
SUMN=0.0
DO 203 MO=1,12
IF(DDM(ITB,MO).LE.0.0) THEN
F=1.0
GOTO 204
END IF
SLR=(S(ID,MO)*ABS(ID)/DDM(ITB,MO))/(LCR(IL)+G(ID))
IF(SLR.LT.R(ID)) THEN
F=A(ID)*SLR
ELSE
F=B(ID)-C(ID)*EXP((-1.0)*D(ID)*SLR)
END IF
IF(F.GT.1.0) F=1.0
204 SSF=1.0-(1.0+G(ID)/LCR(IL))*(1.0-F)
SUMN=SUMN+SSF*DDM(ITB,MO)
203 CONTINUE
ASSF(ID,IL)=SUMN/DDY(ITB)
202 CONTINUE
201 CONTINUE
C
WRITE(13,*)'SLR METHOD FOR DIRECT GAIN BUILDINGS'
WRITE(13,*)' '
WRITE(13,601)
WRITE(13,602)TBASE,DDY(ITB)
WRITE(13,603)
DO 301 IL=1,NLCR
WRITE(13,604)LCR(IL)*0.2366,(ASSF(ID,IL),ID=1,9)
301 CONTINUE
601 FORMAT(' ANNUAL SOLAR SAVINGS FRACTION, (%)',/)
602 FORMAT(' Tbase=',F5.1,' F', '(,F6.0,' F-day)',/)
603 FORMAT(' LCR',T10,'DGA1',T17,'DGA2',T24,'DGA3',
&T31,'DGB1',T38,
&'DGB2',T45,'DGB3',T52,'DGC1',T59,'DGC2',T66,'DGC3',/)
604 FORMAT(F8.4,9F7.3)
STOP
END

```

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