Validation of the load collector ratio (LCR) method for predicting the thermal performance from five passive solar test rooms using measured data

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VALIDATION OF THE LOAD COLLECTOR RATIO (LCR) METHOD FOR 
PREDICTING THE THERMAL PERFORMANCE FROM FIVE PASSIVE 
SOLAR TEST ROOMS USING MEASURED DATA

by 

Daniel James Overbey 
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Ball State University 
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A thesis submitted in partial fulfillment 
of the requirements for the

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ABSTRACT

Validation of the Load Collector Ratio (LCR) Method for Predicting the Thermal Performance from Five Passive Solar Test Rooms Using Measured Data

by

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Alfredo Fernández-González, Examination Committee Chair
Associate Professor
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The standard procedure used to analyze buildings that feature passive solar heating strategies is the load collector ratio (LCR) method. This procedure was developed by the Los Alamos National Laboratory between 1977 and 1984. As a result of the LCR method, one will obtain the solar savings fraction (SSF) of the input passive solar building. The SSF is the most widely accepted metric used to evaluate the effectiveness of passive solar heated buildings. The SSF may be defined as the extent to which a building's passive solar feature(s) reduces a building's auxiliary heat requirement relative to a comparable building devoid of passive solar feature(s).

This thesis compares nearly two-years of monitored data collected from five passive solar test rooms in Muncie, Indiana against the performance predicted by the LCR method as well as three other procedures related to passive solar heating analysis developed at the Los Alamos National Laboratory along with the LCR method.

The conclusions of this thesis validate the LCR method with regard to projecting the SSF and auxiliary heat requirements for a range of passive solar heating strategies in a severe winter climate with predominantly cloudy sky conditions.
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NOMENCLATURE

\( A_x \) - Area of considered building component \( x \) (ft\(^2\))

\( A_{c \text{-wall}} \) - Area of opaque east-facing wall (ft\(^2\))

\( A_{\text{floor}} \) (or \( A_F \)) - Floor area of occupiable volume (ft\(^2\))

\( A_{n \text{-door}} \) - Area of north-facing door (ft\(^2\))

\( A_{n \text{-wall}} \) - Area of opaque north-facing wall (ft\(^2\))

\( A_p \) - Projected area of glazing (ft\(^2\))

\( A_{\text{roof}} \) - Area of opaque roof (ft\(^2\))

\( A_{\text{wp}} \) - Area of roofpond (ft\(^2\))

\( A_{s \text{-wall}} \) - Area of opaque south-facing wall (ft\(^2\))

\( A_{s \text{-win}} \) - Area of south-facing window (ft\(^2\))

\( A_{\text{tilt-n}} \) - Area of \( tilted \) north-facing wall (ft\(^2\))

\( A_{\text{tilt-s}} \) - Area of \( tilted \) south-facing wall (ft\(^2\))

\( A_{\text{tilt-win}} \) - Area of \( tilted \) south-facing window (ft\(^2\))

\( A_{tsw} \) - Area of south-facing thermal storage wall (ft\(^2\))

\( A_{w \text{-wall}} \) - Area of opaque west-facing wall (ft\(^2\))

\( \text{ABS} \) - Ratio of monthly total solar radiation absorbed in the building per unit of projected area to that on a unit area of horizontal surface (dimensionless)

\( \text{HOR} \) - Ratio of monthly total solar radiation absorbed in the building to that transmitted through the glazings (dimensionless)

\( ACH \) - Winter air changes per hour due to infiltration (# per hour)

\( ADR \) - Air density ratio (dimensionless)

\( AST \) - Apparent solar time (decimal hours)

\( AZ \) - Azimuth angle (degrees)

\( C \) - Variable C, an interpolation of data related to extraterrestrial solar irradiance; from 2001 ASHRAE Fundamentals Handbook, Chapter 30, Table 7 (dimensionless)

\( c \) - Specific heat (Btu/lb °F)

\( \text{CAP} \) - Total thermal capacitance (Btu/°F)
CAP_{bldg} - Thermal capacitance of the structure, excluding the solar attic (Btu/°F)
CAP_{water} - Thermal capacitance of the roofpond water volume (Btu/°F)
CAP_{rp-sa} - Thermal capacitance of the roofpond structure's solar attic (Btu/°F)
CE_{rp} - Collector efficiency of the roofpond (dimensionless)
CT - Cloud type (dimensionless numerical indicator)
CV - Cloud value (dimensionless)
d - Density (lb/ft^3)
D_{rp} - Depth of roofpond (ft)
D65 - Heating degree-days below a base temperature of 65°F (°F days)
DP - Dew point temperature (°F)
E - The extinction coefficient-thickness product (dimensionless)
E_{clear} - Clear sky emittance (dimensionless)
E_o - Factor of correction for eccentricity in the Earth's trajectory around the sun (dimensionless)
E_{rp} - Emittance of roofpond (dimensionless)
E_{sc} - Extraterrestrial solar constant (W/m^2)
E_{sky} - Sky emittance (dimensionless)
E_{win} - Emittance of south-facing tilted window of solar attic (dimensionless)
ESL - Elevation above sea-level (ft)
ET - The equation of time (decimal minutes)
H - Hourly global irradiation on a horizontal surface (or I) (IP units = Btu/h ft^2; SI units = W/m^2)
H_d - Daily monthly average diffuse radiation (W/m^2)
H_e - Hourly global irradiation on a east-facing surface (IP units = Btu/h ft^2; SI units = W/m^2)
H_o - Instantaneous extraterrestrial solar irradiation on a horizontal surface (W/m^2)
h_o - Coefficient of heat transfer by long-wave radiation and convection at outer surface (Btu/h ft^2 °F)
H_s - Hourly global irradiation on a south-facing surface (IP units = Btu/h ft^2; SI units = W/m^2)
Hs-50 - Hourly global irradiation on a south-facing surface featuring a 50 tilt above the horizon (IP units = Btu/h ft²; SI units = W/m²)

Hs-50-tran - Transmitted hourly global irradiation on a south-facing surface featuring a 50 tilt above the horizon (IP units = Btu/h ft²; SI units = W/m²)

Hs-tran - Transmitted hourly global irradiation on a south-facing surface (IP units = Btu/h ft²; SI units = W/m²)

Hw - Hourly global irradiation on a west-facing surface (IP units = Btu/h ft²; SI units = W/m²)

HDD (or DD) - Heating degree-days (°F days)

HS - Total hemispheric solar radiation incident on a horizontal surface (Btu/ft² day)

Ib - Beam radiation on a horizontal surface (W/m²)

IbT - Beam radiation on a tiled surface (W/m²)

IdT - Diffuse radiation on a tilted surface (W/m²)

IgT - Ground reflected radiation on a tilted surface (W/m²)

Id/I - Diffuse fraction of the total horizontal radiation (dimensionless)

IT - Total radiation on a tilted surface (W/m²)

It - Total irradiation on a horizontal surface (W/m²)

INC - Ratio of monthly total solar radiation incident on a unit area of the glazing plane to that on a unit area of horizontal surface (dimensionless)

HOR - Clarity index; clearness factor; ratio of total radiation on a horizontal surface to extraterrestrial radiation (dimensionless)

Kt - Material thickness (decimal feet)

L-D - Latitude minus midmonth solar declination (degrees)

LAT - Local latitude (decimal ° of arc)

LCR - Load collector ratio (Btu/° day ft²)

LCRs - Load collector ratio for a sunspace (Btu/° day ft²)

LON - Local longitude (decimal ° of arc)

LSM - Local standard time meridian (decimal ° of arc)

LST - Local standard time (decimal hours)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Number of days in a month (days)</td>
</tr>
<tr>
<td>M_open</td>
<td>Mode of operation signifier indicating the roofpond system is <em>open</em> (dimensionless; 1 = yes, 0 = no)</td>
</tr>
<tr>
<td>M_closed</td>
<td>Mode of operation signifier indicating the roofpond system is <em>closed</em> (dimensionless; 1 = yes, 0 = no)</td>
</tr>
<tr>
<td>MT</td>
<td>Mean monthly ambient temperature (°F); calculated as ((T_{min} + T_{max})/2)</td>
</tr>
<tr>
<td>N</td>
<td>Number of window glazings (dimensionless)</td>
</tr>
<tr>
<td>NLC</td>
<td>Net load coefficient (Btu/°F day)</td>
</tr>
<tr>
<td>OC</td>
<td>Number of occupants inside the building (# of occupants)</td>
</tr>
<tr>
<td>Q_aux</td>
<td>Hourly heat need or contribution from auxiliary heat source (Btu/h)</td>
</tr>
<tr>
<td>Q_aux-a</td>
<td>Adjusted heat contribution from auxiliary heat source for the <em>current</em> hour (Btu/h)</td>
</tr>
<tr>
<td>Q_aux-ap</td>
<td>Adjusted heat contribution from auxiliary heat source for the <em>previous</em> hour (Btu/h)</td>
</tr>
<tr>
<td>Q_cond-C</td>
<td>Hourly conductive heat exchange when roofpond glazing is <em>closed</em> (Btu/h)</td>
</tr>
<tr>
<td>Q_cond-O</td>
<td>Hourly conductive heat exchange roofpond glazing is <em>open</em> (Btu/h)</td>
</tr>
<tr>
<td>Q_e-wall</td>
<td>Hourly heat exchange through east-facing wall (Btu/h)</td>
</tr>
<tr>
<td>Q_exchange</td>
<td>Hourly heat exchange between solar attic and occupied volume (Btu/h)</td>
</tr>
<tr>
<td>Q_floor</td>
<td>Hourly heat exchange through floor of occupiable volume (Btu/h)</td>
</tr>
<tr>
<td>Q_h</td>
<td>Monthly hemispheric radiation on horizontal surface (Btu/ft(^2) month)</td>
</tr>
<tr>
<td>Q_he</td>
<td>Monthly extraterrestrial radiation on horizontal surface (Btu/ft(^2) month)</td>
</tr>
<tr>
<td>Q_inf</td>
<td>Hourly heat exchange due to infiltration (Btu/h)</td>
</tr>
<tr>
<td>Q_int</td>
<td>Internal heat gain (Btu/h)</td>
</tr>
<tr>
<td>Q_n-door</td>
<td>Hourly heat exchange through north-facing door (Btu/h)</td>
</tr>
<tr>
<td>Q_n-wall</td>
<td>Hourly heat exchange through north-facing wall (Btu/h)</td>
</tr>
<tr>
<td>Q_net</td>
<td>Net reference load (Btu)</td>
</tr>
<tr>
<td>Q_rad-loss</td>
<td>Hourly radiation loss expression (Btu/h)</td>
</tr>
<tr>
<td>Q_roof</td>
<td>Hourly heat exchange through roof (Btu/h)</td>
</tr>
<tr>
<td>Q_s-wall</td>
<td>Hourly heat exchange through south-facing wall (Btu/h)</td>
</tr>
<tr>
<td>Q_s-win</td>
<td>Hourly heat exchange through south-facing window (Btu/h)</td>
</tr>
</tbody>
</table>
\( Q_{\text{sav}} \) - Solar savings (Btu)

\( Q_{\text{sol}} \) - Hourly transmitted thermal energy due to passive solar strategy (Btu/h)

\( Q_{\text{subt-C}} \) - Sub-total hourly heat exchange when roof pond is \textit{closed} (Btu/h)
(Excludes heat exchange between solar attic and occupiable volume.)

\( Q_{\text{subt-O}} \) - Sub-total hourly heat exchange when roof pond is \textit{open} (Btu/h)
(Excludes heat exchange between solar attic and occupiable volume.)

\( Q_{\text{tilt-n}} \) - Hourly heat exchange through tilted, north-facing wall (Btu/h)

\( Q_{\text{tilt-s}} \) - Hourly heat exchange through tilted, south-facing wall (Btu/h)

\( Q_{\text{tilt-win-C}} \) - Hourly heat exchange through tilted, south-facing window when roof pond system is \textit{closed} (Btu/h)

\( Q_{\text{tilt-win-O}} \) - Hourly heat exchange through tilted, south-facing window when roof pond system is \textit{open} (Btu/h)

\( Q_{\text{total}} \) - Total hourly heat exchange (Btu/h)

\( Q_{\text{total-C}} \) - Total hourly heat exchange when roof pond is \textit{closed} (Btu/h)

\( Q_{\text{total-O}} \) - Total hourly heat exchange when roof pond is \textit{open} (Btu/h)

\( Q_{\text{w-wall}} \) - Hourly heat exchange through west-facing wall (Btu/h)

\( R_b \) - Ratio of beam radiation on a tilted surface to the beam radiation on a horizontal surface (dimensionless)

\( R_d \) - Ratio of diffuse radiation on a tilted surface to the diffuse radiation on a horizontal surface (dimensionless)

\( R_f \) - Ratio of reflected radiation on a tilted surface to the total radiation on a horizontal surface (dimensionless)

\( \text{REFR} \) - Refractive index (dimensionless)

\( \text{RH} \) - Relative humidity (%)

\( S \) - Monthly solar gain (Btu/ft^2 month)

\( S_{\text{e-wall}} \) - Sol-air temperature of east-facing wall (°F)

\( S_{\text{ground}} \) - Sol-air temperature of ground (°F)

\( S_{\text{roof}} \) - Sol-air temperature of roof (°F)

\( S_{\text{tilt-s}} \) - Sol-air temperature of tilted, south-facing wall (°F)

\( S_{\text{s-wall}} \) - Sol-air temperature of south-facing wall (°F)

\( S_{\text{w-wall}} \) - Sol-air temperature of south-facing wall (°F)
<table>
<thead>
<tr>
<th>SC</th>
<th>Shading coefficient (dimensionless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHGC</td>
<td>Solar heat gain coefficient (dimensionless)</td>
</tr>
<tr>
<td>SLR</td>
<td>Solar load ratio (dimensionless)</td>
</tr>
<tr>
<td>SSF</td>
<td>Solar savings fraction (dimensionless)</td>
</tr>
</tbody>
</table>

Ambient outdoor air temperature

\[ T_a \] - (I-P units = °F, used for MPSP simulation models; SI units = °C, used for SOLRAD Model 6.)

Base temperature (°F)

Upper comfort temperature (°F)

Simulated internal air temperature for the current hour (°F)

Adjusted simulated internal air temperature for the current hour (°F) (only relevant to the DG1, DG2, WW, and RP-DG simulation models)

Lower comfort temperature (°F)

Surface temperature of concrete patio upon which the MPSP test cells constructed (°F)

Simulated internal air temperature output for the previous hour (°F)

Thermostat setting (°F)

Minimum sky temperature (°F)

Wind chill temperature (°F)

Total floor area of the structure (ft²)

Tilt angle (degrees)

Total load coefficient (Btu/heating degree day)

Ratio of monthly total solar radiation transmitted through a unit area of glazing to that on a unit area of horizontal surface (dimensionless)

Ratio of monthly total solar radiation transmitted through the glazings to that incident on the glazing plane (dimensionless)

Solar wall steady-state heat transfer coefficient (Btu/ft² °F h)

Overall thermal conductance of east-facing wall (Btu/ft² °F h)

Overall thermal conductance of floor of occupiable volume (Btu/ft² °F h)

Roofpond heat transfer coefficient as heat transfers from below interior to pond (Btu/ft² °F h)
Overall thermal conductance of north-facing door (Btu/ft² °F h)
Overall thermal conductance of north-facing wall (Btu/ft² °F h)
Roofpond heat transfer coefficient as heat transfers from pond to interior below (Btu/ft² °F h)
Overall thermal conductance of roof (Btu/ft² °F h)
Overall thermal conductance of south-facing wall (Btu/ft² °F h)
Overall thermal conductance of south-facing window (Btu/ft² °F h)
Overall thermal conductance of tilted, north-facing wall (Btu/ft² °F h)
Overall thermal conductance of tilted, south-facing wall (Btu/ft² °F h)
Overall thermal conductance of south-facing window (Btu/ft² °F h)
Overall thermal conductance of tilted, south-facing window under the closed condition (Btu/ft² °F h)
Overall thermal conductance of tilted, south-facing window under the open condition (Btu/ft² °F h)
Overall thermal conductance of south-facing Trombé-wall (Btu/ft² °F h)
Overall thermal conductance of west-facing wall (Btu/ft² °F h)
Product of overall thermal conductance and area for exterior envelope component x (Btu/°F h)
Wind velocity (mph)
Air volume inside the building (ft³)
Total solar radiation incident on a vertical surface (Btu/ft² day)
The hour angle (degrees)
Angle at sunrise (degrees)
Angle at sunset (degrees)
Temperature increment due to internal heat generation (°F)
Temperature increment due to solar gains (°F)
Clear winter-day temperature swing (°F)
Surface tilt angle from horizontal (horizontal = 0°; vertical = 90°)
\( \Phi \) - Solar azimuth (degrees)

\( \Phi_{\text{adjust}} \) - Adjusted solar azimuth (positive for afternoon hours and negative for morning hours; degrees)

\( \Psi \) - Surface azimuth (facing east negative; facing west positive)

\( \alpha_{\text{ex-walls}} \) - Surface absorptance of the exterior walls (%)

\( \alpha_{\text{ground}} \) - Surface absorptance of the ground cover (%)

Surface absorptance of the thermal mass. In the case of a direct gain system this refers to the floor and north wall; while in the case of a thermal storage wall system it refers to the thermal storage wall itself (%)

\( \alpha_{\text{roof}} \) - Surface absorptance of the roof (%)

\( \alpha_{\text{ts-wall}} \) - Surface absorptance of the thermal storage wall (%)

\( \beta \) - Solar altitude (degrees)

\( \gamma \) - Surface solar azimuth (degrees)

\( \delta \) - Solar declination (degrees)

\( \eta \) - Day of the year (January 1 = 1, December 31 = 365, except on leap year)

\( \theta \) - Angle of incidence (degrees)

\( \theta_{z} \) - Solar zenith angle (degrees)

\( \rho_{g} \) - Ground reflectance; albedo (%)

\( \sigma \) - Stefan-Boltzman coefficient (5.67E-08 W/m² K⁴)

\( \mathcal{C} \) - Percentage of solar attic thermal mass effectively performs as thermal mass for the adjacent occupiable thermal zone below (dimensionless)
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I would also like to express considerable gratitude to Dr. J. Douglas Balcomb. It is my belief that his contributions to the field of passive solar heating are considerably underappreciated at this juncture. However, I do believe that that will change in the near future.

A special thanks is extended to Ahmet Ugursal and Rita Y. Macias for their dedication to the Muncie Passive Solar Project.

Finally, I would like to thank Robert W. Jones, Robert D. McFarland, William O. Wray, Dennis Barley, Joseph Perry, Jr., Scott Noll, and the other researchers from the Los Alamos National Laboratory and the University of California who dedicated themselves to developing and making accessible the abundant quantity of published resources that are readily accessible to help designers take advantage of our only truly renewable resource—the sun.
DEDICATION

TO GOD

For by the grace given me I say to every one of you: Do not think of yourself more highly than you ought, but rather think of yourself with sober judgment, in accordance with the measure of faith God has given you. Just as each of us has one body with many members, and these members do not all have the same function, so in Christ we who are many form one body, and each member belongs to all the others.

Romans 12:3-5 (NIV)

TO MY WIFE KRISTEN

For her unconditional love and understanding.

TO MY PARENTS AND BROTHER

For their continuous support and encouragement.
CHAPTER 1

INTRODUCTION

The term solar savings fraction (SSF), developed by J. Douglas Balcomb, et al. (1984) is the most widely accepted metric used to evaluate the performance of buildings utilizing passive solar heating strategies (Moore 1993). The SSF may be defined as the extent to which a building's passive solar feature(s) reduces a building's auxiliary heat requirement \( Q_{aux} \) relative to a comparable building devoid of any passive solar feature(s) (Stein, et al. 2006). The standard procedure used to calculate the SSF for a given design scenario is the load collector ratio (LCR) method. Funded by the U.S. Department of Energy by Passive Solar Group Q-11 from 1977 through 1984 (Moore 1993), the Los Alamos National Laboratory (LANL) determined that the primary factor dictating the performance of a passive solar heated building in a particular climate is the ratio of the building's solar aperture to its heat loss (Balcomb, et al. 1984).

Widely accepted as a standard methodology for assessing the potential performance of various passive solar heating design applications, the LCR method has remained unchanged for nearly twenty-five years. The LCR method was designed to help aid and promote the development of passive solar buildings. However, despite the thoroughness of the LCR method and its publication in required architectural textbooks, the architectural and building trade industries have been reluctant to incorporate passive solar heating systems. Rather, mechanical systems are heavily relied upon for thermal control.
While the reasons behind this reluctance to employ passive solar strategies are complex and many, one could speculate that one of the primary reasons is a perceived inadequacy with regard to the SSF predicted by the LCR method. Design professionals have voiced concerns that the SSF expression calculated with the LCR method fails to address issues pertaining to thermal comfort conditions and/or the expected air temperatures and *mean radiant temperatures* (MRT) (Fernández-González 2001). Perhaps a reflection of the primary concerns among designers at the time in which it was developed in the early 1980s, the LCR method is only designed to approximate the quantity of auxiliary energy one could expect to save through the implementation of a passive solar heating strategy. As energy prices dropped in the 1980s and the American society has become more affluent, issues of thermal control have become more important to designers.

In late-2002, Alfredo Fernández-González initiated a research project in which the thermal performance of five passive solar heating strategies (namely the direct gain, Trombé-wall, water-wall, sunspace, and roofpond) were monitored and compared at a research facility in Muncie, Indiana (Fernández-González 2005). Data from five small test cells, each exhibiting a different passive solar heating strategy, were collected for approximately two years—as were simultaneous on-site weather data and thermal performance data from a sixth “reference” test cell devoid of any passive solar heating application. The test cells were operated in *free-running* mode, meaning they were allowed to operate using only the natural physics of heat transfer. Moreover, they did not feature any internal gains (e.g. lights, electrical equipment, etc.) or supplementary heat sources.
The main goal of this research project, referred to as the *Muncie Passive Solar Project* (MPSP), was to identify the potential barriers to achieving thermal comfort when passive solar heating systems are employed in severe winter climates with predominant cloudy sky conditions (Fernández-González 2006). As a result, the test cells were purposely not optimized to achieve thermal comfort. Rather, the test cells were designed to resemble what Fernández-González (2007) has termed "fringe" passive solar applications. The term refers to the rudimentary assemblage of a given passive solar system’s essential features (e.g. south-facing glazing, a certain orientation of thermal mass, etc.) without a thorough knowledge of the system’s optimized design prescriptions. Fringe applications were quite common when many experiments in the field of passive solar heating were being made in the 1970s and 80s. However, these applications often failed, which fostered a negative impression of passive systems held by the lay public.

Despite its deliberately impaired passive solar heating applications, the MPSP was able to demonstrate that such applications could still accomplish energy savings and improved thermal performance. As a result, numerous reports accounting for the thermal performance and economic effectiveness of the test cells based on their first full-year of operation have been published (Fernández-González 2003, 2003a, 2004, 2006; Fernández-González and Ugursal 2005). Among various findings, Fernández-González (2004) determined that a SSF of 100% would be most feasible if a direct or indirect gain strategy were coupled with a roofpond strategy. Thus, after the first heating season, each test cell was modified in hopes of improving its thermal performance. In particular, the sunspace test cell was redesigned as a hybrid passive solar test cell, featuring both a
direct gain and roofpond strategy. This thesis marks the first publication of processed data from these modified test cells.

While each of the passive solar heated test cells exhibited thermal performance characteristics indicating the presence of significant solar heat gains, a precise SSF has never been determined.

Purpose of the Research

The purpose of this study is to evaluate the aptness of the LCR method (Balcomb et al. 1984) for estimating the thermal performance of various passive solar heating strategies. Using computer simulations calibrated against measured data from the MPSP test cells, the actual SSF and $Q_{aux}$ achieved by each of the monitored passive solar test cells are determined. Subsequently, the data validate the results produced by the LCR method for a severe winter climate with predominantly cloudy sky conditions, such as Muncie, Indiana.

Research Question

Throughout the 1970s and 80s, the Los Alamos National Laboratory became the source of some of the most important studies regarding passive solar heating analysis. They developed various methods to aid designers interested in employing passive solar strategies. Chief among these procedures was the LCR method. The research question guiding this thesis refers to the validity of LCR method of passive solar heating analysis. Additionally, three other well-published methods of passive solar heating analysis developed by the LANL will be similarly evaluated in order to further qualify the results.
of this thesis. Specifically, the monthly SLR method, also developed by Balcomb et al. (1984), will be thoroughly analyzed as it predicts both annual and monthly values of SSF and $Q_{aux}$ for passive solar buildings and is purportedly more accurate than the LCR method. Finally, the methods used to estimate average clear winter-day indoor temperatures and clear winter-day indoor temperature swings, developed by Balcomb et al. (1980), will be evaluated.

Significance of the Research

While many professionals involved with the building design community tout the potential benefits of passive solar heating, few contemporary research projects exist to give designers, clients, investors, builders, or legislators a tangible example from which to build confidence or at least confirm suspicions regarding positive or negative performance. The Muncie Passive Solar Project provided one such contemporary example.

While the primary thesis inquiry relates to the LCR method, the conclusions of this thesis will validate both the LCR and SLR method with regard to projecting the SSF and $Q_{aux}$ for a range of passive solar heating strategies in a severe winter climate with predominantly cloudy sky conditions, such as Muncie, Indiana. Thus, the vast body of work relating to both methods provides a foundation from which to promote passive solar heating through appropriate design guidelines, legislature, and/or building code. Furthermore by validating both the LCR and SLR methods, this thesis becomes a useful reference to assist those who would consider utilizing passive solar heating strategies.
CHAPTER 2

REVIEW OF RELATED LITERATURE AND RESEARCH

The principle aim of this chapter is to provide a context from which one may orient the research findings presented in succeeding chapters and ultimately gauge the significance of this thesis. As attested by Dr. J. Douglas Balcomb (1992), one of the nation’s foremost researchers of passive solar heating strategies who has intimately studied passive solar design for over 30 years, the history of solar energy is not unlike that of various other fields in the sense that it is replete with cycles of reinvention and repeated mistakes. He believes that the key to success and timely progress is for each generation to relearn the lessons of the past not through cyclical time-consuming trial and error, but through recourse to the collective wisdom of each generation’s predecessors. It is hoped that readers interested in learning more about passive solar heating may use the relevant literature and research presented below to efficiently recover important resources related to the field.

A Brief History of Passive Solar Heating Systems

Passive solar heating methods have been extensively applied throughout history with great success. Indigenous examples can be found in cultures throughout the world, ranging from the Acoma Indians of the contemporary United States southwest (Moore
1993), to the ancient Greeks (Lechner 2001), to early urban settlements in Saudi Arabia (Moore 1993).

However, it was the ancient Romans who first identified the benefits of using glass to create a heat trap in building interiors. This laid the foundation for the widely accepted passive solar heating strategies employed today (Lechner 2001). Passive solar heating was highly valued by many Roman architects, such as Vitruvius, whose hugely influential treatise regarding architecture contained chapters delineating the implication of the sun's movement on such design matters as the location of rooms and size of apertures (McDonough 2004).

While development and utilization of passive solar heating was relatively stagnant in Europe during the Medieval Ages, Renaissance architects such as Palladio rediscovered the records of Vitruvius. Palladio applied the advice of Vitruvius and employed such principles as facing summer rooms toward the north and winter rooms toward the south. (Lechner 2001).

Throughout the seventeenth and eighteenth centuries in Europe, a revival in solar heating commenced. Initially, stand-alone greenhouses were created to house and maintain exotic vegetation from newly discovered lands. However, as better glass-making techniques were developed and greenhouses were being designed as conservatories—which were attachments to the main buildings, solar heat began to be harnessed for heating living spaces (Lechner 2001). Thus, the embryonic notion of the sunspace passive solar heating strategy had been born.

With the migration of various European populations to the United States, early passive solar heating techniques utilizing glass first appeared in North America. While
early settlements did not display emphatic intentions of utilizing incident solar radiation, the New England “salt box” did frequently reveal a concern for advantageous solar orientation (Lechner 2001). At Monticello, Thomas Jefferson, who was very influenced by both Vitruvius and Palladio, was always aware of solar orientation (McDonough 2004).

For many decades to come, passive solar heating progressed rather slowly. It was not until the 1930s that American architects explored and demonstrated the potential of passive solar design (Lechner 2001). One of the more revered examples of this era was Frank Lloyd Wright’s Jacobs II House (also known as the Solar Hemicycle) (Fernández-González 2001). Architect George Fred Keck was also considered a pioneer in solar design (Lechner 2001).

With the advent of affordable energy and technological innovations in the post-WWII era, architects began to explore new design possibilities presented by mechanical heating, cooling, and ventilation systems (Gissen 2002). For the first time in history, architecture was liberated from the practical constraints imposed by environmental conditions.

Throughout the 1950s and 1960s, energy prices were relatively low. Thus, the affordability of these new-era mechanically conditioned buildings and the fossil fuels used to drive the generators that provided their energy shifted focus away from the passive methods of mitigating the external environmental conditions (Gissen 2002).

As a result of various economic and environmental crises in the 1960s and 1970s, Americans gradually became more aware and concerned about energy use. On the heals of the popular environmental movement catalyzed by Rachel Carson’s 1962 book Silent Spring, enthusiasm in passive, more environmentally benign methods of conditioning
homes began to occur (Balcomb 1992; Gissen 2002). However, the economic fortitude of mechanical systems as a result of low energy prices, as well as their universal design applications, caused interest in passive solar energy to stagnate at a relatively low level.

Beginning in the early 1970s, interest in passive solar design began a cyclical cycle of interest that has continued to this day (Balcomb 1992, 2006). Following a series of public demonstrations advocating environmental sensitivity and responsibility, including the first Earth Day in 1970, entered the oil crisis of 1973. As part of an Arab response to Western aid provided to Israel during the Yom Kippur War, the Organization of Petroleum Exporting Countries (OPEC) dramatically reduced oil exports to the United States (Gissen 2002). By the end of 1974, the average price of crude oil ($12/barrel) had risen to more than quadruple the average price from 1972 (approximately $3/barrel) (Williams 2005). According to the U.S. Department of Energy’s (DOE) Energy Information Administration (2006), the OPEC oil embargo prompted Congress to quickly pass legislature designed to protect American consumers from gasoline shortages and high prices.¹ The federal government also began to heavily invest in alternative energy sources and technologies of all kinds, as the government sought to reduce our nation’s petroleum imports (Gissen 2002). During this time, the U.S. Department of Energy’s Passive Solar Group Q-11 funded what would become the United States’ foremost

¹ According to the DOE’s Energy Information Administration (2006), Congress passed a number of price controls under the Emergency Petroleum Allocation Act. Additionally, the Energy Policy and Conservation Act was intended to increase oil production through price incentives. This act also created the Strategic Petroleum Reserve (SPR) and mandated increased fuel efficiency in automobiles. The EIA contends that the price controls delineated by the Emergency Petroleum Allocation Act were largely considered a failure, thus they were repealed in 1981. WTRG Economics recognizes that while the price controls did reduce the United State’s economic recession resulting from the energy crisis of the early 1970s, they significantly curtailed efforts to lower the national rate of oil consumption. WTRG Economics contends that had the price controls not been in place, the U.S. would have been much less dependent on imports in 1979-1980 when oil prices skyrocketed to an all-time high (Williams 2005).

As chronicled by the DOE’s Energy Information Administration (2006) and WTRG Economics (Williams 2005), throughout the late 1970s, oil prices sky-rocketed. Greatly affected by the Iranian Revolution and the Iran/Iraq War, by 1981 OPEC production was approximately one-quarter lower than it had been in 1978—causing domestic prices to double. As a result, cars became smaller and more efficient. Moreover, estimates indicate that by 1980 over 180,000 passive solar homes had been built across the country (Balcomb 2006). Interest in passive solar energy was at its pinnacle.

By the early 1980s, the energy crisis was resolved in the eyes of policy makers, effectively extinguishing interest and funding in many alternative energy solutions, including passive solar energy (Balcomb 1992). Funding for the Los Alamos National Laboratory’s passive solar program and various other externally-funded passive solar research endeavors dissolved. It became apparent that national interest in passive solar energy was linked to the affordability of imported fossil fuels. Throughout the early 1980s, petroleum prices remained high. Saudi Arabia’s OPEC minister, Sheik Ahmed Zaki Yamani, repeatedly warned other OPEC members that prolonged high prices would lead to a reduction in demand (Williams 2005). Yamani also observed that various methods for achieving greater energy efficiency and alternative energy options were becoming realized in the United States and Western Europe (McDonough 2004).

Moreover, non-OPEC production was on the rise, prompting a freefall in the global
petroleum market (Williams 2005). According to the Energy Information Administration (2006) and WTRG Economics (Williams 2005), throughout the first half of the 1980s, Saudi Arabia attempted to act as a “swing producer” by cutting their production in order to stem falling prices. However, by the end of 1985, Saudi Arabia abandoned this role and increased production. This caused oil prices—and national interest in alternative energy technologies—to dwindle. Consequently, the United States’ economy prospered and national oil consumption grew quickly.

Interest in passive solar energy would not be revived until the 1990s, when concerns regarding the environment, societal sustainability, and national energy vulnerability in the wake of the conflicts in the Middle East began to reemerge (Balcomb 1992). This cycle of interest in passive solar energy was most prevalent in the academic arena and did not rise to the level of significance displayed by the cycles of interest in the late 1970s and early 1980s. This cycle of interest lost momentum as the Asian financial crisis of the late 1990s caused oil prices to fall considerably due to downturns in the Asian economies. Most recently, due to various factors including the War in Iraq, U.S. tensions with Iran, various failures in the U.S. gasoline pipeline infrastructure, an unprecedented rate of industrialization in China, a growing global concern regarding anthropogenic greenhouse gas emissions, and a rapidly expanding “green design” market in the architectural community, there appears to be newfound interest in passive solar energy (U.S. Department of Energy, Energy Information Administration 2006; Williams 2005).
The Effects of Mechanical HVAC Systems on Architectural Design

Despite these waves of interest in passive solar systems and the promising research touting the potential benefits of their application, mechanical heating, cooling, and ventilation systems have continued to prevail as a result of consumer and market familiarity and reasonably affordable energy from nonrenewable fossil fuels. Prior to World War II, radiation—either from stoves, fireplaces, or the sun—was the primary mechanism for delivering heat into buildings. Today, the primary mechanism to deliver and/or remove heat to/from a building is forced convection via central or package-unit HVAC system (Fernández-González 2001). As a result, many design professionals perceive that the greater portion of contemporary architecture is venturing into the pitfall that William McDonough and Michael Braungart (2002) have termed a culture of monoculture by which, under the existing paradigm of manufacturing and development, the diversity and constant flux of climatic forces are treated as an opposing force to be overcome. These forces are often met with an overwhelming counterforce of engineered systems built upon universal design approaches, resulting in less variety and greater homogeneity. A glaring example of this one size fits all approach is the process of manufacturing a typical universal house (McDonough and Braungart 2002). Whether it’s intended for Terre Haute, Indiana or Henderson, Nevada, this process—as well as the final product—is remarkably similar. In both cases, a package-unit HVAC system is installed to simply smother any unfavorable forces brought on the structure by climatic conditions.
The environmental consequences of this current approach to maintaining the thermal quality of our indoor environments have yet to be fully quantified. What is clear and evident is the fact that the United States has been unnecessarily using an abundant amount of non-renewable, high-grade energy sources—much of it to heat the homes we live in. In the latest public release of the Annual Energy Review, the U.S. Department of Energy’s Energy Information Administration (2006) affirms that space heating accounts for approximately 47% of household energy consumption and expenditures by end use. Meanwhile, the technology for utilizing a site’s free and abundant solar income is being vastly underutilized. Dr. J. Douglas Balcomb recently avowed, a combination of energy-efficient design—which entails super insulation and air tightening—and passive solar heating systems can save American homeowners as much as 90 percent of their annual energy expenditures allocated to space heating (Balcomb 2006). The greatest era of interest and application of passive solar heating systems was spurred by an energy crisis, record gas prices, speculative concerns regarding oil shortages and withholdings from hostile nations, Middle East turmoil, and Congressional interest in solutions. Perhaps the time is ripe for a national reinvestment in passive solar heating systems.

A Definition of Passive Solar Heating Systems

At this juncture, it is necessary to establish a clear definition of the term *passive solar heating system*. The word “passive” emphasizes the distinct difference between two fundamental approaches to heating a building. Solar systems that utilize mechanically

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2 These figures can be found in the EIA Annual Energy Review 2005. The figures were derived using data from 2001 and do not include wood.
operated elements, such as fans and/or pumps, are called active solar systems. These systems, which by their own merit are quite valuable, require additional energy (typically in the form of electricity) to operate. Conversely, passive solar systems do not require any form of external energy to operate. Passive solar systems emphasize simple technology and are designed to utilize natural, on-site energy sources and sinks; make judicious use of natural energy flows; and strategically employ the ability of various building materials to collect, store, transfer, and dissipate heat (Haggard and Niles 1980). With the notable exception of the roofpond strategy, whose passive design classification is debatable, every other passive solar heating system consists of two basic design features: a south-facing solar aperture (e.g. a glazed window) for solar energy collection, and thermal mass for heat absorption, storage, and dissipation. Contrary to popular belief, passive buildings do not necessarily require large quantities of glazing. Successful passive heating strategies typically incorporate a calibrated balance of thermal mass and glazing (Mazria 1979).

General Principles for Passive Solar Design

The following passive solar design guidelines are suggested by Balcomb et al. (1984) and should always be considered by any designer seeking to implement passive solar systems into a building project:

Conservation Level – For any passive solar heating application, an overall well-insulated and air-tight building envelope is vital. Unless otherwise constrained by building codes or regional construction practices, employing measures to achieve at
least the conservation factor\(^3\) (CF) suggested for a building's given location can be very advantageous for any passive system (Fig. 2.1).

![Figure 2.1 Conservation Factor (CF) Recommended for Locations in the United States](image)

Source: Balcomb et al. 1984

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\(^3\) Balcomb et al. (1984) developed the conservation factor (CF) method for balancing the levels of conservation (i.e. insulation and building air-tightness) and passive solar features in a building so that any additional construction dollar spent on either feature will yield identical savings. The objective of this procedure is to help designers determine a proportional balance between investments in conservation and in passive solar features. Moore (1993) pointed out that due to the uncertainty of future energy prices, it is impossible to determine an optimum value for conservation. Nonetheless, the CF method provides a reasonable starting point based on a site's climate. In practice, building codes actually dictate a certain level of conservation measures as well. The conservation factor method is beyond the scope of this thesis. However, the CF method is among various procedures provided for passive solar heating design outlined in the Los Alamos National Laboratory's publication titled *Passive Solar Heating Analysis: A Design Manual* (Balcomb et al. 1984).
Distribution of Solar Glazing – For any passive solar heating application (with the exception of the roofpond strategy) solar glazing should be distributed on a space-by-space basis so that each thermal zone features an amount of glazing that is proportional to its heat loss.

Orientation – With the exception of the roofpond strategy, the optimum azimuth orientation of a passive system’s glazing is within 5° of solar (true) south. As the orientation departs from solar south an increasingly severe penalty in thermal performance will occur.

Glazing Tilt – For passive systems featuring glazing, an increase in performance can be achieved by tilting the glazing. While high summer sun angles may pose a problem, during the heating season the optimum tilt is roughly 50° to 65° for the continental United States.

Number of Glazings – For non-roofpond passive systems, the recommended number of glazing layers constituting the solar aperture is dictated by the severity of a location’s winter climate. In most situations, double-glazed windows are a safe assumption.

Night Insulation – Movable night insulation will vastly improve the thermal performance of all passive solar heating systems. The cost effectiveness of night
insulation will vary with the type of passive system. However, even a layer of R4 night insulation can foster incredible thermal performance enhancements.

Classification Schemes

Historically, there are two schemes used to classify passive solar heating systems (Balcomb et al. 1980). Both classification schemes are useful and have the ability to supplement each other. When used in concert, they form an augmentative vocabulary for discussing and analyzing various methods of passive solar heating (Balcomb, et al. 1980).

The first classification scheme is based on the relationship between the means of receiving solar energy, the heat storage, and the heated space. This classification scheme is utilized by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) for their Consumer’s Guide to Energy Efficiency and Renewable Energy (2005). It consists of three categories: 1) direct gain, 2) indirect gain, and 3) isolated gain (Mazria 1979; Balcomb, et al. 1980). Each category is briefly defined below.

Direct Gain

Simply defined, in a direct gain strategy incident solar radiation penetrates the solar aperture and directly enters the heated living space(s). As the transmitted solar radiation strikes various absorbing surfaces, it is converted into thermal energy (heat). The heat is then dispersed throughout the space as it is transferred between various enclosing surfaces and room content (Balcomb, et al. 1980).
Indirect Gain

In the case of indirect gain strategies, incident solar radiation does not directly penetrate into the heated living space(s). Rather, it first strikes the thermal storage (e.g. a concrete wall or a thermally massive roof), where a large percentage of the solar energy is converted into thermal energy and absorbed. The absorbed heat migrates into and throughout the thermal storage material. Eventually, a significant amount of thermal energy is transferred to the living space beyond the thermal storage (Mazria 1979). Thermal storage walls and roofponds are typical examples of this strategy.

Isolated Gain

This strategy is similar to an indirect gain strategy in the sense that both strategies separate the point of thermal energy collection from the heated living space. However, in the case of the isolated gain strategy, there is a distinct thermal separation between the thermal storage and the heated space. This is typically accomplished via insulation or physical separation (Balcomb, et al. 1980). The most common application of this strategy is the natural convective loop system (Mazria 1979).

The second classification scheme, which is more prevalent and has been adopted here for discussion purposes, identifies passive system types according to their physical configuration. This scheme consists of five categories: 1) direct gain, 2) thermal storage wall, 3) sunspace, 4) thermal storage roof, and 5) convective loop systems (Balcomb, et al. 1980). In the succeeding sections of this chapter, a description of each of the five categories will be explained in detail.
Direct Gain System

The simplest and most commonly encountered approach to passive solar heating is the direct gain system (Mazria 1979; Lechner 2001; Stein et al. 2006). As defined above, in a direct gain system short-wave solar radiation directly enters a space via south-facing windows. Once it has entered the space, long-wave thermal energy (heat) is greatly retained, causing a greenhouse effect within the interior space (Lechner 2001). The thermal mass present within the space—typically in the form of exposed masonry, concrete, or water—is critical because it absorbs and retains heat for a significant amount of time (Mazria 1979). Depending on the amount of thermal mass in the space, the solar gains serve either the immediate heating needs of the interior or are stored in the massive elements to meet heating needs that will arise later (Balcomb et al. 1984).

As illustrated in Figure 2.2, a direct gain system typically features several crucial elements in addition to the key features of south-facing glass and thermal mass. As previously mentioned, an overall well-insulated and air-tight building envelope is important to any passive heating system (Balcomb et al. 1984). Movable insulation panels are often employed to help reduce nighttime radiant heat loss through the solar aperture. They help to curtail the interior’s diurnal temperature swings and maintain a higher daily average interior air temperature. Additionally, they address the cool surface temperature of the solar glazing, which at night can greatly lower the mean radiant temperature4 (MRT) of the interior—causing occupant discomfort (Moore 1993).

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4 On page 90 of Mechanical and Electrical Equipment for Buildings, Tenth Edition, Stein et al. (2006), define the term mean radiant temperature, “the uniform temperature of an imaginary surrounding enclosure in which radiant transfer from the human body would equal the radiant heat transfer in the actual nonuniform enclosure.” The authors go on to clarify that MRT is a calculated variable and cannot be directly measured. One of the calculation approaches defined in this publication was employed to monitor the MRT of the Muncie Passive Solar Project’s various test cells (Fernández-González 2006)
Passive Solar Heating: Direct Gain

Figure 2.2  Diagrammatic Section of a Direct Gain System
Illustration by Daniel J. Overbey
Historically, the most influential example of a direct gain system was the ‘Sunscoop’ residence, which was built in 1974 on the outskirts of Santa Fe, New Mexico. This house was designed and occupied by David Wright. A pure application of the direct gain strategy, the Sunscoop implemented south-facing glass, internal mass (in the form of 14-inch adobe walls and brick flooring), an exterior insulated envelope (via 2-inch polyurethane rigid foam), an overhang, and night insulation to minimize nighttime heat loss. The house features a minimal amount of non-south glazing. Its heating performance was very impressive. Using a supplemental woodstove for auxiliary heat, the Sunscoop typically required less than one cord of wood annually (Moore 1993).

Recommended Design Guidelines

In addition to the general design principles mentioned previously, Balcomb et al. (1984) outlined a number of recommended design guidelines specifically addressing direct gain systems, including the following:

*Mass distribution* – For a given quantity of thermal mass, it is typically recommended that the mass be spread over largest area possible within the direct gain space. A minimum mass-to-glazing ratio of 6:1 is advised. According to the *line-of-sight* rule, if the point where direct beam radiation first strikes within a room can been seen from a mass surface, then the mass is considered to be *radiatively coupled* and thus quite effective for heat storage. *Convectively coupled* mass is not visible from the point where direct beam radiation first strikes within the room, however it is still located within the direct gain space and can exchange heat via air convection. Convectively coupled mass is only one-fourth as effective as radiatively coupled mass.
Mass thickness – Per pound, thinly sectioned mass is more effective than a thicker section. With regard to masonry materials, thicknesses beyond 4 inches become significantly less effective than the mass closer to the surface. For wood, due to its reduced conductivity, the corresponding thickness is approximately 1 inch.

Internal mass storage walls – Assuming equal access to solar heat, internal partition walls, per unit of masonry, are more effective than external walls. This is due to the fact that both sides of the internal partition can transfer heat. Masonry partition walls are most effective when they are located between two direct gain spaces.

Use of color – In general, lightweight objects should be light in color. Typically, only thermally massive floors in direct gain spaces should be dark in color. It is recommended that walls and ceiling surfaces be light in color in order to reflect sunlight throughout the space before it is absorbed.

Surface coverings – Any insulating cover positioned over thermal mass decreases the heat storage effectiveness and thermal performance of the direct gain system. It is recommended that all surface coverings within a direct gain space have good thermal contact with the mass (meaning no air gaps) and an R-value less than 0.1 ft² °F h/Btu. An R-0.4 surface covering can decrease the heat storage effectiveness by about 50%.

Heat storage – When hollow-core concrete masonry units are employed for heat storage, it is recommended that a high-density block be selected. The cores should be
grout solid. If brick is used, one should specify a dense brick. When considering 4-inch thicknesses, face brick or pavers are approximately 36% more effective than common brick (24% more effective in 2-inch thicknesses).

*Floor materials* – Concrete or brick flooring materials are strongly recommended. If insulation is specified under the flooring, it should be covered with no less than 4 inches of mass. However, a mass thickness beyond 6 inches is virtually irrelevant.

*Limits on direct gain glazing* – It is recommended that direct gain glazing be limited in order to prevent large diurnal temperature swings. In general, limits are 7% of the floor area for low-mass buildings and 13% of floor area for high-mass buildings.

**Reference Design Characteristics**

For analytical purposes, Balcomb et al. (1984) have divided direct gain buildings into two broad groups: 1) high-mass, direct gain building and 2) low-mass, suntempered buildings. Suntempered buildings typically use solar gains immediately in order to offset daytime heating loads. The abovementioned direct gain design guidelines may be relaxed considerably when utilizing suntempered applications of the direct gain system.

The following table (Table 2.1) details the characteristics of direct gain reference designs. All eleven direct gain systems researched and evaluated by the Los Alamos National Laboratory and presented in *Passive Solar Heating Analysis: A Design Manual* (Balcomb et al. 1984) were derived from various combinations of these reference design parameters.
Table 2.1  Direct Gain Reference Design Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Suntempered Designs</th>
<th>High-Mass Designs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Storage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat capacity (Btu°F ft² of projected area)</td>
<td>10.8</td>
<td>30</td>
</tr>
<tr>
<td>Thickness (inches)</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Mass-to-glazing ratio</td>
<td>20.0</td>
<td>6</td>
</tr>
<tr>
<td>Thermal conductivity, k (Btu/h ft °F)</td>
<td>0.0923</td>
<td>1</td>
</tr>
<tr>
<td>Density, ρ (lb/ft³)</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Specific heat, c (Btu/lb °F)</td>
<td>0.26</td>
<td>0.2</td>
</tr>
<tr>
<td>Solar absorptance of surface</td>
<td>0.3</td>
<td>0.8*</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Number of Glazings</td>
<td>2</td>
<td>2 or 3</td>
</tr>
<tr>
<td>Glazing Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission characteristics</td>
<td>diffuse</td>
<td></td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
<td></td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
<td></td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>0.125*</td>
<td></td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
<td></td>
</tr>
<tr>
<td>Night insulation when used</td>
<td>R9**</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
<td></td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
<td></td>
</tr>
<tr>
<td>Control Range of Room Air (°F)</td>
<td>65 to 75</td>
<td></td>
</tr>
<tr>
<td>Lightweight Absorption Fraction</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Simulates 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**

* Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.

Source: Balcomb et al. 1984

5 According to Stein et al. (2006), thermal conductivity (k) is defined in units of Btu in./h ft² °F. As the units for thermal conductivity listed in this table (Btu/h ft °F) were consistently used by Balcomb et al. (1984), they are used here as well. This is also the case with all other tables used in this thesis that are sourced from Balcomb et al. (1984) in which these units occur.
Thermal Storage Wall:

Trombé-Wall System

A thermal storage wall consists of a south-oriented thermally massive wall which is typically composed of masonry or water, with glazing over its outer surface (Balcomb et al. 1984). In this type of indirect gain system, incident solar radiation transmitted by the glazing is absorbed as heat by the thermally massive wall. After a period of time dictated by the massive properties of the thermal storage wall, heat is transferred to the heated interior space (Balcomb et al. 1980).

Thermal storage wall systems are often classified by the type of thermal mass they utilize: masonry and water. Thermal storage walls consisting of masonry or concrete are defined as Trombé-walls. Systems using sealed containers filled with water are referred to as water-walls (Stein et al. 2006). The former will be considered in this section.

Trombé-walls receive their name from the French engineer Felix Trombé, who in 1967 worked in concert with architect Jacques Michel to construct a passive solar house in Odeillo, France. The house employed a passive solar design using a masonry-based thermal storage wall system. The system consisted of a double-glazed thermal storage wall constructed of concrete, approximately 2 feet in thickness. The exterior surface of the concrete was painted black to encourage maximum solar absorptance. Documented research indicates that approximately 70% of this building's annual heating requirements were supplied by this passive solar system (Mazria 1979).

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6 In rare instances, phase-change materials have been used for thermal storage wall systems (Balcomb et al. 1980).
Passive Solar Heating: Trombé-Wall

Solar gains

Thermal storage mass (masonry or concrete)

Insulated exterior shell

Vents (optional)

South-facing glazing

Figure 2.3 Diagrammatic Section of a Trombé-Wall System
Illustration by Daniel J. Overbey
As depicted in Figure 2.3, the Trombé-wall system should be oriented toward the south. As with other passive solar heating systems, the closer the orientation of the solar aperture is toward true south, the more effectively the system will perform (Balcomb et al. 1984). However, the performance penalty for deviating from solar south is not as severe as with other systems. In fact, for azimuths within 30° of due south, the performance penalty is approximately 4% (Balcomb 1984; Moore 1993).

Conventional Trombé-walls do not feature vents. However, some designers have implemented vents to combat "lag time" inherent with Trombé-wall warming cycles. Vents foster thermocirculation and facilitate a quicker space heating process in the morning due to convective heat transfer. However, a downfall of vented Trombé-walls is the excessive nighttime heat loss due to reverse thermocirculation. To combat this, some designers turn to dampers. Moore (1993) does not recommend vents because they cost more to construct, can promote overheating in the summer, and can lead to dust buildup in the air cavity between the glass and thermal storage wall. Overtime, the dust can significantly reduce the efficiency of the Trombé-wall. Moreover, vented Trombé-walls typically exhibit only a slight improvement in annual heating performance (Moore 1993).

**Recommended Design Guidelines**

In addition to the general design principles mentioned previously, Balcomb et al. (1984) also outlined a number of recommended design guidelines specifically addressing the Trombé-wall system. Designers wishing to implement a Trombé-wall system should always consider the following design issues:
**Vents** – For residential applications, vents are not recommended. The decision to employ vents should be dictated by the necessity to provide more daytime heat. If used in excess, vents can lead to uncomfortably large internal air temperature swings. In practice, the area of each vent should be considered as a percentage of the solar aperture. This percentage is dictated by the system’s *solar savings fraction*.

**Distance between glass and thermal storage wall** – In the case of *unvented* Trombé-walls, the space between the glass and thermal storage wall is not essential. Typically, one inch will suffice. For *vented* Trombé-walls, the need to facilitate unrestricted air movement prompts a suggested minimum clearance of 6 inches.

**Wall thickness** – The optimum thickness for a Trombé-wall varies between 10 and 16 inches. Specific optimum thickness depend on the type of material (i.e. concrete, concrete block, building brick, or adobe), the material’s density, and the presence or absence of vents. For buildings that are occupied only during the day, a smaller thickness may be most appropriate because it will provide heating to the interior space more quickly.

**Solar absorptance** – Trombé-walls are quite sensitive to the solar absorptance of the exterior-facing surface of the thermal storage wall. Very dark colors, preferably black, are recommended.
Selective surfaces – A selective surface, properly adhered to the exterior-facing surface of the thermal storage wall, can be used to improve system performance. Selective surfaces can provide a winter heating performance enhancement nearly as significant as night insulation. However, these surfaces, if not properly shaded in during the cooling season, can exacerbate summer overheating. If a selective surface is utilized, good thermal contact (e.g. no air gaps) is essential. The selective surface should have an R-value no greater than 0.03, a solar absorptance greater than 0.92, and an infrared emittance of less than 0.15.

Reference Design Characteristics

The following table (Table 2.2) details the characteristics of Trombé-wall reference designs (Balcomb et al. 1984). From the characteristics listed below, 21 reference designs for unvented Trombé-walls and their vented counterparts were derived. All 42 Trombé-wall reference designs researched and evaluated by the Los Alamos National Laboratory are delineated in Passive Solar Heating Analysis: A Design Manual (Balcomb et al. 1984).
### Table 2.2 Trombé-Wall Reference Design Characteristics

<table>
<thead>
<tr>
<th>Thermal Storage</th>
<th>Trombé-Wall</th>
</tr>
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<tbody>
<tr>
<td>Thermal conductivity of wall (Btu/h ft °F)</td>
<td>1</td>
</tr>
<tr>
<td>Density, ρ (lb/ft²)</td>
<td>150</td>
</tr>
<tr>
<td>Specific heat, c (Btu/lb °F)</td>
<td>0.2</td>
</tr>
<tr>
<td>Solar absorptance of wall surface</td>
<td>0.95*</td>
</tr>
<tr>
<td>Solar absorptance of selective surface, when used</td>
<td>0.9*</td>
</tr>
<tr>
<td>Infrared emittance of wall surface</td>
<td>0.9</td>
</tr>
<tr>
<td>Infrared emittance of selective surface, when used</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermocirculation Vents</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent area, sum of upper and lower vents, when used</td>
<td>6</td>
</tr>
<tr>
<td>(% of wall area)</td>
<td></td>
</tr>
<tr>
<td>Vertical separation of vents, when used (ft)</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Glazing Properties</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>diffuse</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1, 2, or 3</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>1/8*</td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Night insulation thermal resistance, when used</td>
<td>R9**</td>
</tr>
</tbody>
</table>

| Control Range of Room Air (°F)                        | 65 to 75    |

| Ground Reflectance                                    | 0.3*        |

| Internal Heat Generation                               | none**      |

* Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.

Source: Balcomb et al. 1984
Thermal Storage Wall:

Water-Wall System

One of the least common of all passive solar systems, water-walls (Fig. 2.4) are similar to Trombé-walls with one obvious difference: the thermal storage wall is composed of water rather than concrete or masonry (Stein et al. 2006). In this indirect system, the water is stored in containers made of steel, corrugated galvanized steel culverts, steel drums, or reinforced fiberglass tubes. While Trombé-walls and water-walls exhibit similar performance, water-walls typically outperform Trombé-walls of the same thickness. This difference in performance becomes more pronounced as the amount of thermal storage mass increases (Balcomb et al. 1984). One major design advantage with water-walls is that they can be as specialized as their containers (Stein et al. 2006).

A classic example of the water-wall system is the “Zomehouse” designed by Steve Baer (Mazria 1979; Moore 1993). Overlooking Albuquerque, New Mexico, this house consists of ten connected domes—each of which enclose 200 square feet of floor area (Mazria 1979). Each south-facing wall features double-glazing. Behind the glazing, horizontal steel racks hold a number of black-painted recycled 55-gallon steel water drums which serve as thermal storage. In addition, each south-facing wall is equipped with a bottom-hinged reflector/shutter that can be lowered to horizontal position during the day. When lowered, the upward-facing aluminum surface reflects as much as 50% more radiation onto the passive system’s solar aperture (Moore 1993). The water-wall system kept temperatures inside the Zomehouse between 63°F and 70°F throughout most of the heating season (Mazria 1979). When auxiliary heat was employed, it was in the
Passive Solar Heating: Water Wall

Figure 2.4 Diagrammatic Section of a Water-Wall System
Illustration by Daniel J. Overbey
form of three wood-burning stoves. The Zomehouse typically required only one cord of wood each year (Mazria 1979).

**Recommended Design Guidelines**

In addition to the general design principles mentioned previously, Balcomb et al. (1984) also outlined a number of recommended design guidelines specifically addressing water-wall system. Designers wishing to implement a water-wall system should always consider the following design issues:

*Solar absorptance* – As with the Trombé-wall, a greater wall absorptance improves the system performance. Thus, the exterior of the water containers should be as darkly-colored as possible.

*Selective surfaces* – Use of a selective surface, if properly installed, can improve system performance. The same guidelines outlined for the Trombé-wall should be used here.

**Reference Design Characteristics**

From the characteristics listed in the following table (Table 2.3), 15 water-wall reference designs were derived and researched by Balcomb et al. (1984).
### Table 2.3 Water-Wall Reference Design Characteristics

<table>
<thead>
<tr>
<th>Water-Wall</th>
<th>Thermal Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity of wall (Btu/h ft °F)</td>
<td>infinite&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Density, ( \rho ) (lb/ft&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>62.4</td>
</tr>
<tr>
<td>Specific heat, ( c ) (Btu/lb °F)</td>
<td>1.0</td>
</tr>
<tr>
<td>Solar absorptance of wall surface</td>
<td>0.95*</td>
</tr>
<tr>
<td>Solar absorptance of selective surface, when used</td>
<td>0.9*</td>
</tr>
<tr>
<td>Infrared emittance of wall surface</td>
<td>0.1</td>
</tr>
<tr>
<td>Infrared emittance of selective surface, when used</td>
<td>0.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water-Wall</th>
<th>Thermocirculation Vents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent area, sum of upper and lower vents, when used (% of wall area)</td>
<td>not used</td>
</tr>
<tr>
<td>Vertical separation of vents, when used (ft)</td>
<td>na</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water-Wall</th>
<th>Glazing Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission</td>
<td>diffuse</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1, 2, or 3</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>1/8*</td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Night insulation thermal resistance, when used</td>
<td>R9**</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water-Wall</th>
<th>Control Range of Room Air (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 to 75.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water-Wall</th>
<th>Ground Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3*</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water-Wall</th>
<th>Internal Heat Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>none**</td>
<td></td>
</tr>
</tbody>
</table>

* Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.

Source: Balcomb et al. 1984

As defined by Balcomb et al. (1984) and Moore (1993), a sunspace is a solar collector that serves the dual purpose of providing another useful space capable of serving other building functions. This system is also commonly referred to as "solarium," "atrium," "conservatory," and "sun room." The term "attached greenhouse" has also been used, but can imply an additional plant-growing function.

A sunspace may be described as a direct gain space with the foremost purpose of collecting and delivering thermal energy to adjoining rooms. However, when conditions permit, the sunspace may serve as an occasional living space (Moore 1993).

With regard to solar heating, a sunspace may serve as either an indirect gain or isolated gain system. In the common indirect gain application (Fig. 2.5), heat radiates to the building's interior after it conducts through a common thermal storage wall. In the less typical isolated gain application (Fig. 2.6), heat is transferred to the building interior by convection through vents or other designed openings in an insulated common wall. In the isolated gain application, fans are sometimes employed to assist in the convective heat transfer (Balcomb et al. 1984; Moore 1993).

The principle sunspace glazing is assumed to face as close to solar south as possible. With this in mind, wall locations are referred to by the general cardinal direction they should face (Balcomb et al. 1984).

With regard to geometric composition, there are two basic types of sunspaces. The attached sunspace features a north common wall, which is typically 30-feet wide in the east-west direction. The semienclosed sunspace has three common walls—the north, east,
Figure 2.5 Diagrammatic Section of an Indirect Sunspace System
Illustration by Daniel J. Overbey
Passive Solar Heating: Isolated Gain Sunspace

Solar gains

Insulated building exterior

Insulated common wall with vents (or other designed openings)

South-oriented glazing

Free-standing thermal storage mass

In the isolated-gain sunspace, heat is transferred to the interior by convection through the openings in the common wall.

Figure 2.6  Diagrammatic Section of an Isolated Gain Sunspace System
Illustration by Daniel J. Overbey
and west. These types of sunspaces are usually 24-feet wide in the east-west direction. For both types of sunspaces, the north wall is typically 9-feet high (Balcomb et al. 1984).

The best known application of this system is in the Unit 1, First Village residence located in historic Santa Fe, New Mexico (Balcomb 2006; Lechner 2001; Moore 1993; Stein et al. 2006). The performance of the house was monitored extensively and, as a result, is one of the better understood passive solar buildings. Both the upstairs and downstairs rooms of this two-story house face a large 20-foot high indirect gain sunspace. The sunspace features approximately 400-ft$^2$ of south-facing double-glazing, two-thirds of which is sloped 50°. The sunspace does not feature night insulation. The floor area of the sunspace is triangular, with two adobe walls (each 14-inch thick downstairs, 10-inch thick upstairs) in addition to the south glazing (Moore 1993). The documented performance of the house indicated that it was 89% solar-heated in the 7,000 degree-day Santa Fe climate. During the seven years Dr. Balcomb lived in this structure, the average cost of annual auxiliary heat was $90, compared to neighboring non-solar homes, which averaged $1,000 per year (Balcomb 2006).

**Recommended Design Guidelines**

In addition to the general design principles described above, Balcomb et al. (1984) outlined a number of recommended design guidelines specifically addressing sunspaces. Designers wishing to implement a sunspace system should always consider the following design issues:

*Use of mass* – The use of mass in a sunspace should be dictated by the function of the space. A “lightweight” sunspace is basically an air-heating collector that may be
convectively coupled with spaces intended to be heated. The sunspace will be too hot to inhabit during the day and too cold to inhabit at night. Conversely, a thermally massive sunspace featuring a concrete, masonry, or water common wall will temper its interior temperatures, making it more livable. In all, every direct gain design guideline applies to the sunspace except that a mass-to-glazing ratio of 3:1 is suggested, rather than 6:1.

**Do not glaze the end walls** – The use of glazed east and west walls are not recommended on the basis of both heating and cooling season thermal criteria. Winter heating is decreased in virtually every climate and solar gains during the summer can be devastating. End walls should be insulated and feature perforations as needed for summer cross-ventilation. In some cases, thermally massive end walls with exterior insulation may be appropriate.

**Roof** – The design of the sunspace should provide shade to the internal sunspace mass during the summer, yet allow solar penetration in the winter.

**Common wall** – Sunspaces should be separable from the building’s living space. In other words, any portal between the sunspace and the building’s living space should have the ability to be closed. The common wall is a very effective and convenient location for the thermal mass and it does not need to be insulated. If the common wall does not function as thermal storage, it should consist of lightweight frame construction with insulation that has a minimal R-value of R-10.
Common-wall vents – Not to be confused with the “summer vents” applied to the end walls to promote cross-ventilation, the “common-wall vents” are portals that connect the sunspace to the attached interior spaces intended to be passively heated. Most typically, convection is the primary thermal connection between the sunspace and the adjacent building. Therefore, particular attention should be given to this aspect of the system’s design. The following are guidelines for sizing common-wall vents (all should be closable at night):

a. Doorways (assuming 6-foot 8-inch door sizes) = 10% of projected area.

b. Window openings (assuming 3-foot window sizes) = 15% of projected area.

c. High and low vent pairs (assuming 8-foot separation) = 6% of projected area (combined area of vent pairs).

Summer vents – Vents to the outdoor environment are important to prevent summer overheating within the sunspace. Both cross-ventilation and stack-effect ventilation can be effective. However, prevailing wind direction(s) should always be considered when locating the inlets and outlets. It is recommended that the inlets be situated low on the windward side of the structure, while the outlets should be situated high on the leeward side of the structure. Vent areas should be generous. If necessary, consider forced fan ventilation.

Wall color – In general, the direct gain guidelines regarding wall color apply. However, the following modifications are suggested:
a. If it is determined that light-colored surfaces are reflecting sunlight out of the sunspace, then consider darker colors. Moreover, the color of lightweight objects does not have a significant influence on performance.

b. If the sunspace is being used as a greenhouse, then the surfaces in dark corners should be light-colored in order to improve sunlight for the plants.

Plants and other lightweight objects – Lightweight objects such as furniture and plants tend to rapidly convert solar energy into heat. Because this heat is not being directly transferred to the system’s thermal storage mass, lightweight objects tend to contribute to overheating. Therefore, the annual solar heating capabilities of the sunspace decrease as the total amount of lightweight objects within the sunspace increases.

Reference Design Characteristics

The following table (Table 2.4) details the characteristics of the sunspace reference designs defined by (Balcomb et al. 1984). The fourteen designs treated by the Los Alamos National Laboratory and presented in Passive Solar Heating Analysis: A Design Manual include two types of common wall: masonry and insulated. The masonry common wall is uninsulated, 12-inches in thickness, high-density (with a thermal conductivity of 1.0 Btu/h ft °F and a volumetric heat capacity of 30 Btu/ft^3 °F). The lightweight, insulated common wall corresponds to a frame wall and features a thermal resistance of R-20 (20 h °F ft^2/Btu).
Table 2.4  Sunspace Reference Design Characteristics

<table>
<thead>
<tr>
<th>Sunspace</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Storage Capacity (Btu°F ft²) (per square foot of common wall)</td>
<td></td>
</tr>
<tr>
<td>Masonry wall</td>
<td>30.0</td>
</tr>
<tr>
<td>Water wall</td>
<td>62.4</td>
</tr>
<tr>
<td>Floor</td>
<td>15.0</td>
</tr>
<tr>
<td>Masonry Properties</td>
<td></td>
</tr>
<tr>
<td>Wall thermal conductivity (Btu/h ft °F)</td>
<td>1.0</td>
</tr>
<tr>
<td>Floor thermal conductivity (Btu/h ft °F)</td>
<td>0.5</td>
</tr>
<tr>
<td>Density (lb/ft³)</td>
<td>150</td>
</tr>
<tr>
<td>Specific heat (Btu/lb °F)</td>
<td>0.2</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
</tr>
<tr>
<td>Glazing Properties</td>
<td></td>
</tr>
<tr>
<td>Transmission characteristics</td>
<td>diffuse</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
</tr>
<tr>
<td>Number of layers</td>
<td>2*</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>1/8*</td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Night insulation thermal resistance, when used</td>
<td>R9**</td>
</tr>
<tr>
<td>Control Range (°F)</td>
<td></td>
</tr>
<tr>
<td>Sunspace</td>
<td>45 to 95</td>
</tr>
<tr>
<td>Room</td>
<td>65 to 75**</td>
</tr>
<tr>
<td>Thermocirculation Vents</td>
<td></td>
</tr>
<tr>
<td>Vent area/projected area</td>
<td>0.06</td>
</tr>
<tr>
<td>(sum of both upper and lower vents)</td>
<td></td>
</tr>
<tr>
<td>Height between vents (ft)</td>
<td>8</td>
</tr>
<tr>
<td>Reverse flow</td>
<td>none</td>
</tr>
<tr>
<td>Lightweight Absorption Fraction</td>
<td>0.20</td>
</tr>
<tr>
<td>Simulates effect of solar radiation absorption on lightweight walls or objects by transferring given fraction of transmitted and reflected solar radiation directly to sunspace air.</td>
<td></td>
</tr>
<tr>
<td>Solar Absorptances</td>
<td></td>
</tr>
<tr>
<td>Common wall, lightweight</td>
<td>0.7*</td>
</tr>
<tr>
<td>Common wall, masonry</td>
<td>0.8*</td>
</tr>
<tr>
<td>Water containers</td>
<td>0.9*</td>
</tr>
<tr>
<td>Floor</td>
<td>0.8*</td>
</tr>
<tr>
<td>Other surfaces</td>
<td>0.3*</td>
</tr>
<tr>
<td>Ground Reflectance</td>
<td>0.3*</td>
</tr>
<tr>
<td>Internal Heat Generation</td>
<td>0**</td>
</tr>
<tr>
<td>Opaque wall thermal resistance (h °F ft²/Btu)</td>
<td>R20</td>
</tr>
<tr>
<td>Sunspace infiltration rate (air changes/hour)</td>
<td>0.5*</td>
</tr>
</tbody>
</table>

*  Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.

Source: Balcomb et al. 1984
Thermal Storage Roof System

(Roofpond System)

A thermal storage roof is similar to the thermal storage wall with one obvious difference: the thermal storage mass is located on the building's roof (Balcomb et al. 1982). In the case of thermal storage roof systems, the thermal mass typically consists of plastic bags filled with water. Water was utilized because its superior specific heat versus that of any common building material (Moore 1993). Over time this indirect gain system came to be commonly referred to as the roofpond.

In the typical roofpond application (also known as the “southwest application,” as depicted in Fig. 2.7), a corrugated metal roof deck with a black liner supports a series of clear polyethylene “bags” containing water. The appropriate depth of this enclosed “pond” of water may vary, however typically 4 to 10 inches have been used in practice. The water does not circulate in and out of the bags at any time as the bags are permanently sealed (Fernández-González and Overbey 2006). Unlike the previously defined passive solar heating applications, movable insulation panel is critical to the success or failure of this system (Haggard et al. 1975; Hay 1984; Marlatt 1984; Stein et al. 2006). Due to their location atop a building, roofponds have historically relied on electrically-powered motors and timers to regulate the operation of the movable insulation (Haggard et al. 1975; Haggard and Niles 1980; Marlatt 1985). The necessary operation of these panels calls into question the roofpond system’s purported classification as a passive system. However, since its inception, the roofpond has been defined as a passive system due to the fact that, in theory, the insulation panels could be
Passive Solar Heating & Cooling: Roofpond (Southwest Application)

Solar gains

Movable insulation panels

Water-filled clear polyethylene "bags"

Uninsulated, metal deck structural ceiling/roof

Insulated exterior shell

Figure 2.7 Diagrammatic Section of a Roofpond System (Southwest Application)

Illustration by Daniel J. Overbey
operated manually. After all, the idea of using movable insulation to moderate heat exchange from a roofpond was derived from a somewhat similar use of insulation during an experiment in New Delhi, India in 1954 (Hay 1984). Finally, the roofpond system, similar to the previously defined passive solar systems, typically features an insulated exterior envelope.

The roofpond is a unique system possessing several key advantages over other passive systems. Foremost, it is the only passive solar heating system that has the ability to also provide cooling without any additional system components. Roofponds have displayed the most stable interior temperatures of any passive heating or cooling strategy (Stein et al. 2006). With the thermal mass located on the roof, the orientation of the roofpond is unrestricted (Hay 1984). Since the roofpond consists of water, it possesses an inherent fire safety feature (Marlatt 1985). Due to convective heat transfer within the water bags, heat gains are quickly distributed throughout the roofpond, leading to a very homogenous distribution of heat throughout the floor area covered by the system (Haggard et al. 1975). In 1985, the U.S. Department of Energy released the most thorough and comprehensive investigation of roofponds ever published. The report analyzed the thermal performance of 13 roofpond buildings with various occupancies in different climatic regions (Marlatt 1985). Among various advantages and disadvantages, the report concluded the following:

*Based on test results from several facilities, the roof pond system outperforms any other single passive system in both heating and cooling modes* (Marlatt 1985).
Well-designed roof pond systems can provide, without backup HVAC systems, relatively even indoor temperatures (approximately 60 to 80°F year round) in climates with an outdoor temperature that ranges between 32 and 115°F (Marlatt 1985).

... there appears to be no significant problems associated with local or universal building codes ... all codes and standards can be met to provide a safe and structurally sound dwelling (Marlatt 1985).

Roof pond buildings are not plagued by overheating (Marlatt 1985).

**Roofpond Basics: Heating Mode**

During the daytime hours of the heating season, when solar radiation levels are capable of providing desirable heating energy, the movable insulation panels are retracted and the water bags are exposed to the outdoor environment (Fig. 2.8a). The water stores much of the thermal energy absorbed from the incident solar radiation. Convective heat transfer within the water bags evenly distributes the thermal energy throughout the roofpond. A percentage of this heat is radiated to the occupied space below. In the evening, or whenever solar radiation levels are deemed inadequate for providing desirable heating energy to the system, the movable insulation panels are positioned over the roofpond area in order to limit heat losses to the outdoor environment. Thus, through radiant heat transfer, the thermal energy stored within the roofpond transfers to the
occupied space below until temperature equilibrium is reached between the roofpond and the space below (Brown and DeKay 2000; Haggard et al. 1975; Hay 1984).

Figure 2.8 Diagrammatic Section of a Roofpond Under (a) Heating Mode and (b) Cooling Mode
Source: Ramsey et al. 2000

**Roofpond Basics: Cooling Mode**

Conversely, during the cooling season, the system works in the opposite way (Fig. 2.8b). During the daytime hours or any portion of the day in which the outdoor environment is incapable of siphoning unwanted heat via radiation from the roofpond, the insulation panels are positioned over the water bags in order to reduce heat gains from incident solar radiation and/or the hot outdoor air. As a result, the roofpond will tend to
withdraw heat from the occupied space below as internal gains persist throughout the
day. At night, or whenever the environment is deemed capable of removing unwanted
heat from the system, the movable insulation panels are retracted and the water bags
radiate stored heat toward the sky (Brown and DeKay 2000; Haggard et al. 1975; Hay
1984).

**Roofpond System Types**

There are two basic roofpond system types: 1) the typical *southwest* application and
2) the *north* application. Both types are defined below.

**Roofpond System: Southwest Application**

As mentioned previously, the “southwest” roofpond application uses a flat roof
structure (Fig. 2.7). This is the archetypical roofpond system. It was primarily designed
for hot and dry climates with predominantly clear skies. Thus, the southwest application
has been most often classified as a passive cooling strategy, even though it has the ability
to provide passive solar heating and cooling (Moore 1993; Stein et al. 2006). *Passive
Solar Heating Analysis: A Design Manual* (Balcomb et al. 1984) does not include any
roofpond design guidelines or reference designs. Ken Haggard and Phillip Niles (1980)
and Ken Haggard et al. (1975) provide valuable information regarding the roofpond bags,
movable insulation, roof decks, and other essential system components. In addition to the
generalized features mentioned previously, consider the following design guidelines
provided by the aforementioned sources:

*Metal deck* – The use of thin metal as the ceiling/roof component supporting the
roofpond bags is very important. Metals are much more thermally conductive than
wood and other common non-metal structural elements. Poor thermal conduction would undermine the system’s operation.

*Flat roofing* – The roofpond strategy requires a perfectly flat roof, as opposed to a conventional low-sloped roof, in order to avoid water stress on the roofpond’s water bags. A scupper should be provided to expel rain water.

*Pond bottom liner* – As with typical low-sloped roof construction, a liner will need to be installed between the water bags and the metal deck. In the past, 4-mil black polyethylene has been used with success. Good thermal contact (no air gaps) with the metal deck will maximize the system’s thermal performance.

*Solar absorptance of liner* – The bottom liner needs to be dark in order to foster solar absorptance.

*Movable insulation* – Virtually all roofpond applications prior to 2001 have used customized movable insulation assemblies. It is well documented that this has been a primary source of system operation failure (Givoni 1994). In two recent research projects, an insulated garage door system has been used as the movable insulation component for both southwest and north roofpond test rooms in Las Vegas, Nevada and Muncie, Indiana, respectively (Fernández-González 2006; Fernández-González and Overbey 2006).
A classic example of the southwest roofpond application is the Atascadero House (Haggard 1975). This three-bedroom, single-story, 1192-ft$^2$ home is located in Atascadero, California. Built upon a slab-on-grade, the structure’s exterior walls were constructed of lightweight concrete block and insulated wood framing. In order to accommodate the loads from the roofpond—namely the approximate 62.4 pounds per cubic foot produced by the water—the reinforced concrete slab is slightly deeper than typically necessary for one-story residential construction. The roofpond itself consisted of four 8-foot wide, 38-foot long, 8.5-inch deep clear plastic bags (Marlatt 1984). With regard to performance, the roofpond provided 100% of the Atascadero House’s heating and cooling requirements, keeping indoor temperatures between 66°F and 74°F throughout an entire year of monitorization (Hay 1984; Marlatt 1984; Mazria 1979; Moore 1993). As a result of the roofpond’s superior performance, in 1976 the American Revolution Bicentennial Commission recognized Harold R. Hay, the inventor of the roofpond system, with the only award for “Environment – Solar Energy.” This was one of only 200 awards given on the nation’s 200th anniversary (Hay 1984).

**Roofpond System: North Application**

For northern climates, with more than 4” of snow per year, the roofpond must be applied in a somewhat modified manner. The north application of the roofpond works in much the same way as the southwest application, except the entire roofpond system is housed within an insulated, air-tight attic space featuring south-facing skylights (Fig. 2.9). Unlike the southwest application, this roofpond system’s performance is heavily influenced by the system’s orientation (Fernández-González and Hay 2004).
A designer wishing to employ a north application of the roofpond should consider the following design guidelines provided by Fernández-González and Hay (2004):

*Metal deck* – Just as with the south application, the use of thin metal as the ceiling/roof component supporting the roofpond bags is essential.

*Thermospace* – The north application of the roofpond requires that the entire assembly, including the movable insulation panels, be housed within the attic of a gabled roof. The attic should be as air-tight as possible with the exterior surfaces as well insulated as possible.

*Orientation of attic skylights* – Solar gains are received by the thermospace via south-facing skylights. As with other passive systems, orientation has a critical influence on thermal performance. The skylights should be oriented as close to solar (true) south as possible. They should also feature a slope of at least the location’s latitude + 10°.

*Pond bottom liner* – The floor of the attic must be watertight as if it were a low-sloped roof. This means that a liner will need to be installed between the water bags and the metal deck in the north application as well. As with the south application, good thermal contact (no air gaps) is important.

*Solar absorptance of liner* – As with the southwest application, the bottom liner needs to be dark in order to foster solar absorptance.
Passive Solar Heating & Cooling: Roofpond (North Application)

Solar gains
Movable insulation panels
South-facing glazing
Solar heat storage space ("air-light, insulated attic")
Water-filled clear polyethylene "bags"
Uninsulated, metal deck structural ceiling/roof
Insulated exterior shell

Figure 2.9 Diagrammatic Section of a Roofpond System (North Application)
Illustration by Daniel J. Overbey
Attic drain – It is recommended that the attic floor contains a means of draining standing water that could result from a ruptured roofpond bag.

Movable insulation – While traditional examples of the north application use customized movable insulation assemblies, it is strongly suggested that designers consider using insulated garage door systems. This recommendation stands to reason as numerous mechanically-operated garage door companies have refined their products and services for many years. Fernández-González (2006) has had success utilizing insulated garage door installations for this type of roofpond application.

The first recorded north application of the roofpond system was constructed in St. Paul, Minnesota in 1979. It was a three-bedroom, two-story, 2000-ft² house designed by R. Wischman and J. Larson (Marlatt 1984). Unlike the Atascadero House, this roofpond was 18-inches deep and covered roughly half the floor area (which also featured an atrium). In this application, a series of narrow water bags were mounted between the joists of the insulated, enclosed attic space. Beneath the bags, a 22-gauge steel deck constituted the ceiling for the occupied spaces below. A series of white-painted 3-inch thick rigid insulation panels were mounted to the top of the attic via barn door hinges, and were allowed to swing open. The house’s two-story atrium fostered effective heat distribution (through radiation and convection) throughout the two stories of occupiable spaces. In addition to the roofpond, this house featured a direct gain system (Marlatt 1984).
The thermal performance of this house's passive solar systems and the auxiliary heat usage was monitored. According to Marlatt (1984), the direct gain system contributed 6 to 8°F to the temperature inside the house during the heating season. When the roofpond bags reached 90°F, the upstairs occupiable volume recorded a temperature of approximately 70°F. During the cooling season, exterior overhangs prevented direct beam radiation from reaching the direct gain system's south-facing glazing; while movable insulation panels were automated to help prevent overheating.

Convective Loop System

In a convective loop passive system, a fluid—typically air, but sometimes water—is heated by a sloped, glazed solar collector. This solar collector is often separated from the main structure containing the living spaces. As the fluid medium is heated by thermal energy, natural convection causes this fluid to rise. In turn, the rising heated medium will replace the less-heated medium as it is transferred back to the collector. Thus, a "loop" of convective current is created. In order to provide thermal storage, the heated medium may be circulated through or along thermal storage mass—perhaps a rockbed or a concrete slab. Heat is transferred to the thermal storage mass through conduction (Moore 1993). This system can be quite akin to active systems as fans are often utilized to force the circulation of the "looped" medium (Balcomb et al. 1980).

Most convective loop systems are isolated gain systems. If the convective loop system is to work effectively, the solar collector must be positioned below the thermal storage medium, which is generally below the occupiable space intended to be heated. In certain locations, if a typical convective air loop is utilized, the migration of groundwater
and/or radon gas into the rockbed may be a problematic. Moreover, some researchers have expressed concern regarding the growth of mold in the rockbeds (Moore 1993).

For these reasons, the convective loop system has not been nearly as researched or applied as other passive systems. It is important to recognize the historical significance of this system within the history of passive solar design, though this system is no longer a seriously considered passive solar strategy (Moore 1993). This type of passive solar system was not analyzed in Balcomb et al.'s Passive Solar Heating Analysis: A Design Manual (1984) and was not studied for this thesis.

Hybrid Solar Heating Systems

According to Balcomb et al. (1980), a hybrid system simply refers to a passive solar system that is coupled with one or more active and/or passive solar system(s). Typically, passive systems are coupled based on the nature of their operation and performance. Common hybrid systems include a combination of a direct gain and roofpond system as well as the using a sunspace in conjunction with a fan-forced rock bed convective loop system.

Review of Related Research Precedents

The research presented in the succeeding chapters of this thesis is derived from the Muncie Passive Solar Project (MPSP), which consisted of five different passive solar test cells devoted to a side-by-side comparison of passive solar heating strategies from December of 2002 through December of 2004 (Fernández-González 2006). However, the use of experimental test rooms to conduct passive solar research is not new. While over
180,000 passive solar houses and test structures have been built in the United States over
the past seven decades (Balcomb 2006), only a handful have exhibited the design
ingenuity to bolster their value as seminal works that would forever raise the collective
knowledge of passive solar design to new heights. The following are just a few of those
applied research projects that have had a profound influence on the history of passive
solar design in the United States.

**MIT Solar Energy Research Project**

The Massachusetts Institute of Technology (MIT) has had a long an hallowed history
of passive solar design innovation. Funded by Godfrey Lowell Cabot, the first house in
the United States to be completely heated using solar energy was MIT’s *Solar House I*,
completed in 1939 (SOLAR 7 MIT Solar Decathlon Team 2007). According to the U.S.
Department of Energy (2007), Solar House I consisted of two rooms that were heated by
an enormous swimming-pool size solar hot water tank located in the basement of the
structure.

Following this, Cabot’s funding enabled MIT to pursue other passive solar design
endeavors. In 1948, *Solar House II* was constructed as part of the MIT Solar Energy
Research Project. The following year, the house received several design adaptations and
thus became dubbed as *Solar House III*. This prototype was the first to actually be
inhabited. Unfortunately, it was demolished after it caught fire in December of 1955. The
MIT Solar Energy Research Project would continue for several decades and culminated
in the design, construction, and occupation of three more passive solar structures. A
seventh house is scheduled to be completed by end of 2007 (Husmann 2007; SOLAR 7
MIT Solar Decathlon Team 2007).
Hay and Yellott Roofpond Experiment

In 1967 Harold R. Hay and John E. Yellott constructed the first roofpond system at Arizona State University. Located in Phoenix, Arizona, this one room 120-ft² structure provided the first evaluation of the “southwest” roofpond application. The Phoenix prototype was continuously monitored for an entire year. The thermal performance was exceptional— with outdoor ambient air temperatures ranging from subfreezing to 115°F, the roofpond system maintained a range of room temperatures between 68°F and 82°F without the use of supplementary heating or cooling (Hay 1984, 1989; Marlatt 1984). The 100% natural thermal comfort provided by the Phoenix prototype was later confirmed by the Atascadero House, built in 1973 (Haggard et al. 1975; Hay 1989).

Los Alamos National Laboratory Passive Test Cell Experiments


In 1976, the Solar Energy Group initiated the Passive Test Cell Experiments by building and monitoring two side-by-side 5-ft wide by 8-ft deep test rooms—one consisting of a Trombé-wall, the other a water-wall. By the end of 1977, the experiment had expanded significantly, as 14 different test cells were being monitored and analyzed. The Solar Energy Group had amassed a detailed comparative analysis of various passive solar strategies including direct gain, unvented Trombé-wall, water-wall, phase-change wall, and sunspace. As the experiments increased in complexity, auxiliary heating systems and thermostats were added to the cells in 1978. By 1979, the structures were
equipped with measured, forced infiltration that in effect eliminated varying infiltration loads due to varying wind conditions. Extensive amounts of data from each cell were being processed and analyzed to determine performance parameters such as efficiency, solar savings fraction, and the discomfort index. Eventually, validated computer simulation models were developed and employed to build a database of passive solar design performance in various climatic regions throughout the country (Hyde 1981; McFarland 1982; McFarland et al. 1982).

At the end of this research, the multi-volume *Passive Solar Design Handbook* (Balcomb et al. 1980) and *Passive Solar Heating Analysis: A Design Handbook (PSHA)* (Balcomb et al. 1984) were published to provide designers with quantitative tools to aid in the proper sizing of solar glazing, thermal storage, and other components of solar building.

**Pala Passive Solar Project**

A more recent passive solar experiment of considerable scope was the Pala Passive Solar Project (Clinton 1984). Funded by the Southern California Gas Company and the San Diego Gas & Electric Company, with Solar Energy Analysis Laboratory (SEAL) responsible for the project's design and operation, the Pala Passive Solar Project consisted of eight side-by-side test structures that were monitored from early 1981 through mid-1984. Seven of the eight test buildings incorporated a major passive solar design strategy. The one non-solar test building represented “conventional” design and served as a comparison and control building. Included passive solar strategies for this project were the roofpond, direct gain, clerestory direct gain, high-mass concrete walls,
Trombé-wall, water-wall, and attached sunspace (Clinton 1984; San Diego Gas & Electric and Southern California Gas Company 1981).

Results of the Pala Passive Solar Project verified the general effectiveness of passive solar systems in reducing conventional heating requirements. In fact, it was concluded that in a mild climate such as Pala, California the implementation of passive solar systems could save a homeowner 50 to 75% of their annual auxiliary heating costs (Clinton 1984).

Standard Methods of Passive Solar Heating Analysis

As a result of the Passive Test Cell Experiments, Dr. J. Douglas Balcomb and the LANL Solar Energy Group developed a number of procedures to help designers predict the performance of various passive solar systems in variety of different locations throughout the United States (Balcomb et al. 1980, 1984). Foremost among these methods are the load collector ratio (LCR) method and the solar load ratio (SLR) method of determining a passive system’s solar savings fraction (SSF) and auxiliary energy requirements ($Q_{aux}$). In particular, the LCR method has long been considered as the standard procedure by which to determine the SSF—which is the most widely accepted expression of the comparative performance of a passive solar building to a non-solar building (Moore 1993).

Load Collector Ratio (LCR) Method

Over the duration of the Passive Test Cell Experiments, the LANL Solar Energy Group determined that the primary factor dictating the performance of a solar building in any climate is the ratio of the building’s heat loss load to its total area of solar aperture (Balcomb et al. 1984; Moore 1993). The LCR method utilizes this relationship to predict
the annual SSF and \( Q_{aux} \) of a building employing any of a variety of passive solar strategies.

Balcomb et al. (1984) offers a wide range of passive systems and locations to help designers make informed decisions regarding regionally-appropriate passive solar design. Moreover, this reference presents a number of "sensitivity curves" to allow designers to predict the performance of nonstandard passive solar systems.

Please refer to Chapter 4 of this thesis for an explanation of the LCR method.

**Solar Load Ratio (SLR) Method**

The SLR method is a much more time-consuming and detailed method for calculating the SSF and \( Q_{aux} \) of a passive solar building. Whereas the LCR method is most useful at the beginning of the design process, the SLR method was intended to be employed at the end of a project's design development phase—when considerable detail is available for consideration (Balcomb et al. 1984). For this reason, the SLR method is much more flexible with regard to building and climatic data input. In addition, the SLR method provides *monthly* SSF and \( Q_{aux} \) values, rather than annual values. However, due to the complexity of the SLR method, it is not used nearly as much as the LCR method (Moore 1993; Stein et al. 2006). To further qualify the results of this thesis, the SLR method will be analyzed alongside the LCR method.

Please refer to Chapter 4 of this thesis for an overview of the SLR method.

**Other Methods Developed by LANL**

In addition to the LCR and SLR methods, the LANL Solar Energy Group also developed procedures to estimate the average clear winter-day interior air temperature and average clear winter-day diurnal interior air temperature swings of buildings that
utilize passive solar energy. The Los Alamos group also developed a method for estimating the design heat load of a solar building, which is useful for sizing its auxiliary heating system (Balcomb et al. 1980).

Like the LCR method, these procedures are simple and hence useful to designers who wish to obtain quick estimates of passive solar system performance at the design stage of a building project. For more detailed analyses at the design development phase, a plethora of building energy analysis software tools are available that will yield much more reliable performance estimates.

To further qualify the results of this thesis, these methods will also be analyzed—though not to the extent that the closely-related LCR and SLR methods are analyzed. Please refer to Chapter 4 of this thesis for an overview of these methods.
Summary

The fundamentals of passive solar heating and cooling strategies are inextricably rooted in the knowledge of place. Since the very inception of settlement, humans learned to understand their environments and erected structures that controlled climatic influences and provided shelter.

However, with the advent of technologies that have the ability to overpower the outdoor environmental and tailor interior conditions with a click of a button, a new era of architecture materialized in which entire cities could be built with a virtual disregard for a region’s climatic forces.

Today, our nation finds itself in a situation in which much of the off-site energy that enables our buildings to ignore and overpower environmental forces to create comfortable indoor conditions is becoming very pricy and unreliable. The absence of this off-site energy, even for a short period of time, has demonstrated to cause death by freezing or heat exhaustion (Canadian Broadcasting Corporation 2006; Mansfield, 2007).

Fortunately, a sizable body of knowledge exists to help designers who wish to harness free on-site solar energy that is as reliable as a morning’s sunrise. There are numerous types of strategies that utilize on-site solar income and the selection of one strategy over another should be dictated by regional appropriateness and the characteristics of a given location’s climate.

The following chapters will present a study in which the effectiveness of the LCR method and other standard procedures used to conduct passive solar heating analyses are analyzed using measured data from the Muncie Passive Solar Project.
CHAPTER 3

DESCRIPTION OF MPSP

The primary intent of this thesis is to use validated simulation models of the Muncie Passive Solar Project (MPSP) test cells to evaluate the aptness of the LCR method, and three other widely-accepted procedures from Balcomb et al. (1980, 1984) used for passive solar heating analysis, for predicting the thermal performance of various passive solar heating systems located in harsh winter climate with predominantly cloudy conditions. In order to ensure the accuracy of the various simulation models, each model was calibrated against comfort and thermal performance data measured within the MPSP test cells over the duration of the project.

Before proceeding to describe the composition of the various simulation models and the methodology employed to conduct the research published in this thesis, it is necessary to describe the MPSP test facility and the methods by which data were acquired from the project.

Project Overview

Building on previous experimental research in passive solar systems (Balcomb et al. 1984; Clinton 1984; Haggard et al. 1975), the MPSP was meant to identify the potential barriers to achieving thermal comfort when passive solar heating systems are
implemented in a severe winter climate characterized by predominantly cloudy sky conditions during the heating season (Fernández-González 2006).

The MPSP was setup to be a side-by-side comparison between a well-insulated control room or cell devoid of any heating sources and five passive solar test cells featuring the same basic geometry and construction methods. Each cell was monitored in terms of air temperature, mean radiant temperature (MRT), dry-bulb air temperature (DBT), relative humidity (RH), and operative temperature (OT) (Fernández-González 2004). The test cells were constructed and monitored at the Ball State University’s Center for Energy Research/Education/Service (CERES) (Fernández-González 2001). When the MPSP launched in December 2002, the initial setup featured the control cell (CC), a direct gain cell (henceforth identified as direct gain, model 1 or DG1), a Trombé-wall (TW) cell, a water-wall (WW) cell, sunspace (SS) cell, and roofpond (RP) cell featuring a north application of the roofpond system (Fig. 3.1).

After the first eleven months of monitorization (December 2002 through October 2003), the MPSP entered its second phase. In preparation for this phase, each test cell underwent a series of modifications to improve its performance as a result of the observations during the 2002-2003 heating season (Fig. 3.2). The most significant changes were imposed on the DG1 and SS cells. In November 2003, the DG1 cell received a significant increase in thermal mass. The increase was considerable enough to merit a distinction from its former setup. Hence, at this juncture, the DG1 cell was considered as a second direct gain test cell (henceforth identified as direct gain, model 2 or DG2). Between October and December 2003, the SS cell was adapted into the experiment’s only hybrid passive solar test cell. More specifically, the SS cell was
reconstructed to feature both a direct gain strategy and a north application of the roofpond strategy. At this juncture, the test cell became known as the roofpond-direct gain hybrid (RP-DG) cell. In all, seven different passive solar strategies were monitored using five passive solar test cells between December 2002 and August 2004. Please refer to Appendix I for a complete list of experimental modifications and operational irregularities.
Project Goals

In his 2001 proposal, then Resident Researcher and Assistant Professor of Architecture at Ball State University, Alfredo Fernández-González identified the original goals of the MPSP: 1) to determine the thermal characteristics (i.e. air temperatures, mean radiant temperatures, and operative temperatures) of direct (direct gain) and indirect (Roofpond, Trombé-wall, water-wall, and sunspace) passive solar heating systems; and 2) to develop a design guideline to predict the degree of comfort produced by direct and indirect passive heating systems based on monthly mean ambient
temperatures and monthly average global solar radiation. As the project became realized, the additional objective of identifying the potential barriers to achieving thermal comfort when passive solar heating systems are implemented in a severe winter climate characterized by predominantly cloudy sky conditions during the heating season emerged as the primary goal of the project (Fernández-González 2006). In response to this goal, the test cells were intentionally designed with their smaller facades oriented to the north and south and the longer facades facing east and west. This arrangement permitted the study of temperature differences throughout the day (diurnal operative temperature swings) and also simultaneous temperature differences throughout the space (a simultaneous comparison of four points instrumented within each cell to detect variations between the south side and the north side of the test cells) (Fernández-González 2006).

Please note that the test cells were not designed for passive cooling and thus were not well-equipped to achieve comfort during the summer months (Fernández-González 2007).

Macroclimate Summary for Muncie, Indiana

Muncie is located 58 miles northeast of Indianapolis, Indiana. According to DeKay and Meyers (2001), Muncie is located within the “Midwestern & Eastern Temperate Climate Zone.” Locations within this zone are typically very good candidates for passive solar heating strategies due to their rather cold winters. Summers can be very warm and humid, creating significant cooling loads. Precipitation throughout this climate zone can vary significantly from one location to another, but typically rainfall is plentiful.
According to long-term climate normals (Table 3.1) provided by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (1985, 2002), when considering a base temperature of 65°F, Muncie’s heating degree-days (HDD65) radically outweigh its cooling degree-days (CDD65). This lends reinforcement to the presumption that this location is a great candidate for passive solar heating strategies. Moreover, the mean outdoor air temperature for Muncie is below freezing for three months of the year. Mean temperatures are significantly below the base temperature for eight months. Muncie does not have a dry season as rainfall is relatively constant throughout the year.

### Table 3.1 Climate Normals for Muncie, Indiana

<table>
<thead>
<tr>
<th>City</th>
<th>Muncie</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Indiana</td>
</tr>
<tr>
<td>Latitude</td>
<td>40.13N</td>
</tr>
<tr>
<td>Longitude</td>
<td>85.25W</td>
</tr>
<tr>
<td>Elevation</td>
<td>940 ft. above sea level</td>
</tr>
<tr>
<td>Annual HDD base 65°F</td>
<td>6022</td>
</tr>
<tr>
<td>Annual CDD base 65°F</td>
<td>895</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
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<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug.</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Temp. (°F)</td>
<td>16.2</td>
<td>19.4</td>
<td>29.1</td>
<td>39.4</td>
<td>51.3</td>
<td>60.3</td>
<td>64.1</td>
<td>61.9</td>
<td>53.8</td>
<td>41.9</td>
<td>32.5</td>
<td>21.9</td>
<td>41.0</td>
</tr>
<tr>
<td>Max. Temp. (°F)</td>
<td>33.0</td>
<td>37.6</td>
<td>48.4</td>
<td>60.6</td>
<td>71.8</td>
<td>81.0</td>
<td>84.9</td>
<td>82.8</td>
<td>76.3</td>
<td>64.2</td>
<td>50.0</td>
<td>38.1</td>
<td>60.6</td>
</tr>
<tr>
<td>Mean Temp. (°F)</td>
<td>24.4</td>
<td>28.6</td>
<td>38.8</td>
<td>50.0</td>
<td>61.5</td>
<td>70.5</td>
<td>74.5</td>
<td>72.3</td>
<td>64.9</td>
<td>53.1</td>
<td>41.4</td>
<td>30.0</td>
<td>50.7</td>
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<tr>
<td>Precip. (in.)</td>
<td>2.0</td>
<td>2.2</td>
<td>3.1</td>
<td>3.6</td>
<td>4.2</td>
<td>4.3</td>
<td>4.0</td>
<td>3.5</td>
<td>3.0</td>
<td>2.6</td>
<td>3.4</td>
<td>3.0</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Experimental Setup and Data Acquisition

For comparative purposes, each of the six original test cells was constructed using the same building construction methods and materials (i.e. nominal 2x4 wood frame construction, a very widely accepted construction method for residential construction in this United States Midwest region). Additionally, each of the five test cells initially featured identical thermal insulation properties. The floor area of each test cell was 128-ft² (8-ft x 16-ft). However, the actual open floor area differed between test cells as the thermal mass of the each passive solar system was installed.

Each test cell was instrumented using a four-point grid to detect simultaneous variations of air temperature and mean radiant temperature across its floor area (Fig. 3.3). Per structure, each of the four instrumented points featured four sensors (two internal and two external) connected to a HOBO H-8 RH/Temperature 2x data logger (Fig. 3.4). Each equipment bundle was positioned 3.6-ft above the finished floor of each test cell. The two internal sensors were used measure air temperature and relative humidity. The two external sensors were used to record the DBT and the MRT (using a black globe). The DBT was measured using a thermistor positioned above the globe and shielded from direct solar radiation via a white-plastic screen (Fernández-González 2006). Using the recorded DBT and MRT values, the OT was calculated in accordance with


¹ According to ANSI/ASHRAE Standard 55-2004, *operative temperature* is defined as the average of the air temperature and the mean radiant temperature weighted, correspondingly, by the convective heat transfer coefficient and the linearized radiant heat transfer coefficient for the occupant.
Figure 3.3  Four-point grids (with numeric designations) used to monitor the six original test cells. The direct gain (DG1) and sunspace (SS) cells would later become the direct gain, model 2 (DG2) and roofpond-direct gain (RP-DG) hybrid cells, respectively.

Photograph by Alfredo Fernández-González
An on-site weather station was deployed in order to monitor various outdoor environmental parameters, including: air temperature, wind speed and direction, relative humidity, dew point, and global horizontal irradiation (Fernández-González 2006). The weather data proved to be vital for analytical purposes as they provided a record of the simultaneous outdoor conditions during the test cells’ monitorization.

Site-Specific Weather and Insolation Data Summary

As a precursor to the primary research conducted for this thesis, the author developed a series of Microsoft Excel® based software programs designed to convert various solar radiation input values into the simultaneous values for planar surfaces of differing orientations. The *Incident Solar Radiation Converter (SOLRAD) Models* were developed in order to facilitate the thesis presented in this document. There are six models in all, each varying in accuracy and specificity according to the magnitude of the input data.
Following its completion in November 2006, SOLRAD Model 6—the most detailed and accurate of the six models—was used to determine weather and insolation data for the two principal years of the MPSP (2003 and 2004). These values, summarized and tabulated below (Tables 3.2 and 3.3), were necessary to accurately execute the LCR and SLR methods. A brief overview of the SOLRAD Models, as well as a thorough description of SOLRAD Model 6, is provided in Appendix II.

Description of Test Cells

Excluding the passive solar heating components unique to the cells, all six original structures consisted of nominal 2x4 southern pine wood framing at 16” on center (O.C.) with 3-1/2” foil-faced fiberglass insulation infill (R-13). The framing was sheathed with a layer of 2” Super TUFF-R rigid insulation (R-14.4) and T-111 plywood siding. Each cell was painted with a grey paint that has been retroactively determined to have had a light reflectance value (LRV) of approximately 0.25.

Not considering the unique systemic features of the applied passive solar strategies, the floors of the test cells consisted of nominal 2x6 southern pine wood framing at 16” O.C. with 5-1/2” foil-faced fiberglass insulation infill (R-19). A layer of 3/4” plywood over 1/2” APTM foil-faced polyisocyanurate foam sheathing (R-3.3) constituted the interior flooring. Beneath the floor’s framing, a layer of 1/2” treated plywood marked the exterior sheathing of the cells’ floors. However, the test cells did not sit flush with the concrete slab of the CERES patio. Rather, each structure was built atop five evenly spaced 2” x 4” southern pine wood studs oriented along the cells’ long dimension.
Table 3.2 2003 Weather and Insolation Data for Muncie, Indiana

<table>
<thead>
<tr>
<th></th>
<th>HS</th>
<th>VS</th>
<th>MT</th>
<th>D65</th>
<th>Kt</th>
<th>L-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>554</td>
<td>752</td>
<td>24.1</td>
<td>1267</td>
<td>0.43</td>
<td>61.5</td>
</tr>
<tr>
<td>February</td>
<td>740</td>
<td>768</td>
<td>27.9</td>
<td>1039</td>
<td>0.41</td>
<td>53.8</td>
</tr>
<tr>
<td>March</td>
<td>1132</td>
<td>874</td>
<td>44.9</td>
<td>623</td>
<td>0.47</td>
<td>42.6</td>
</tr>
<tr>
<td>April</td>
<td>1406</td>
<td>757</td>
<td>56.7</td>
<td>293</td>
<td>0.45</td>
<td>30.4</td>
</tr>
<tr>
<td>May</td>
<td>1309</td>
<td>552</td>
<td>63.6</td>
<td>89</td>
<td>0.36</td>
<td>21.2</td>
</tr>
<tr>
<td>June</td>
<td>1625</td>
<td>589</td>
<td>71.4</td>
<td>28</td>
<td>0.40</td>
<td>16.9</td>
</tr>
<tr>
<td>July</td>
<td>1660</td>
<td>640</td>
<td>76.3</td>
<td>0</td>
<td>0.43</td>
<td>18.9</td>
</tr>
<tr>
<td>August</td>
<td>1569</td>
<td>767</td>
<td>77.1</td>
<td>0</td>
<td>0.47</td>
<td>26.8</td>
</tr>
<tr>
<td>September</td>
<td>1327</td>
<td>951</td>
<td>66.2</td>
<td>87</td>
<td>0.52</td>
<td>38.4</td>
</tr>
<tr>
<td>October</td>
<td>1033</td>
<td>1086</td>
<td>57.1</td>
<td>270</td>
<td>0.54</td>
<td>50.2</td>
</tr>
<tr>
<td>November</td>
<td>583</td>
<td>776</td>
<td>50.1</td>
<td>462</td>
<td>0.42</td>
<td>59.6</td>
</tr>
<tr>
<td>December</td>
<td>423</td>
<td>638</td>
<td>36.9</td>
<td>872</td>
<td>0.38</td>
<td>63.6</td>
</tr>
<tr>
<td>Year</td>
<td>1113</td>
<td>763</td>
<td>54.3</td>
<td>5030</td>
<td>0.44</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 3.3 2004 Weather and Insolation Data for Muncie, Indiana

<table>
<thead>
<tr>
<th></th>
<th>HS</th>
<th>VS</th>
<th>MT</th>
<th>D65</th>
<th>Kt</th>
<th>L-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>441</td>
<td>506</td>
<td>26.9</td>
<td>1190</td>
<td>0.37</td>
<td>61.5</td>
</tr>
<tr>
<td>February</td>
<td>835</td>
<td>918</td>
<td>34.1</td>
<td>937</td>
<td>0.49</td>
<td>53.8</td>
</tr>
<tr>
<td>March</td>
<td>836</td>
<td>603</td>
<td>46.6</td>
<td>610</td>
<td>0.37</td>
<td>42.6</td>
</tr>
<tr>
<td>April</td>
<td>1452</td>
<td>793</td>
<td>56.7</td>
<td>357</td>
<td>0.48</td>
<td>30.4</td>
</tr>
<tr>
<td>May</td>
<td>1533</td>
<td>639</td>
<td>69.6</td>
<td>90</td>
<td>0.43</td>
<td>21.2</td>
</tr>
<tr>
<td>June</td>
<td>1665</td>
<td>597</td>
<td>73.2</td>
<td>88</td>
<td>0.44</td>
<td>16.9</td>
</tr>
<tr>
<td>July</td>
<td>1637</td>
<td>632</td>
<td>75.5</td>
<td>211</td>
<td>0.44</td>
<td>18.9</td>
</tr>
<tr>
<td>August</td>
<td>1529</td>
<td>727</td>
<td>72.8</td>
<td>7</td>
<td>0.46</td>
<td>26.8</td>
</tr>
<tr>
<td>September</td>
<td>1460</td>
<td>1062</td>
<td>71.7</td>
<td>16</td>
<td>0.56</td>
<td>38.4</td>
</tr>
<tr>
<td>October</td>
<td>880</td>
<td>881</td>
<td>58.3</td>
<td>231</td>
<td>0.46</td>
<td>50.2</td>
</tr>
<tr>
<td>November</td>
<td>476</td>
<td>588</td>
<td>48.4</td>
<td>498</td>
<td>0.35</td>
<td>59.6</td>
</tr>
<tr>
<td>December</td>
<td>501</td>
<td>724</td>
<td>34.5</td>
<td>948</td>
<td>0.43</td>
<td>63.6</td>
</tr>
<tr>
<td>Year</td>
<td>1104</td>
<td>722</td>
<td>55.7</td>
<td>5183</td>
<td>0.44</td>
<td>NA</td>
</tr>
</tbody>
</table>
With the exception of the RP cell, the structures featured a low-sloped roof consisting of nominal 2x6 southern pine wood framing at 16” O.C. with 5-1/2” foil-faced fiberglass insulation infill (R-19). The framing was sheathed with a layer of 2” Super TUFF-R rigid insulation (R-14.4) and a 1/2” layer of plywood. Each test cell’s roof was sheathed with an ethylene propylene diene monomer (EPDM) rubber liner.

As the second phase of the MPSP commenced in the Fall of 2003, each of the test cells received a 2” layer of AP™ foil-faced polyisocyanurate foam sheathing (R-13) to the interior faces of their doors. In addition, some test cells underwent major modifications. Please refer to Appendix I for an exhaustive record of experimental modifications and operational irregularities.

Table 3.4 presents a summary of each of the six original test cells as well as the DG2 and RP-DG test cells featured during the second phase of the experiment. Figure 3.5 depicts a basic test cell floor plan as well as a longitudinal section for each of the six original structures. Figure 3.6 features longitudinal sections of the DG2 and RP-DG cells.

**Control Cell (CC)**

The CC featured no source of heating or significant thermal storage. Thus, the CC cell exhibited a diminutive thermal heat capacity of 287.3 Btu/°F. The cell was devoid of any passive solar system and was meant to perform as a homogeneous thermal environment. Subsequently, it featured little temperature variation among the four instrumented points. Fluctuations in indoor OT values mimicked diurnal temperature swings. However, due to the cell’s high conservation value, exterior temperature extremes were tempered. In short, the CC represented the conditions that would be found in a well-insulated light-frame construction devoid of internal gains.
Table 3.4 Passive Solar Features Specific to All Eight Test Cells

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>DG1</th>
<th>TW</th>
<th>WW</th>
<th>SS</th>
<th>RP</th>
<th>DG2</th>
<th>RP-DG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Floor area (a) ((\text{ft}^2))</td>
<td>128</td>
<td>128</td>
<td>124</td>
<td>121</td>
<td>145</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>Enclosed Volume ((\text{ft}^3))</td>
<td>730.3</td>
<td>739.0</td>
<td>739.0</td>
<td>730.3</td>
<td>843.2</td>
<td>717.2</td>
<td>739.0</td>
<td>783.1</td>
</tr>
<tr>
<td>Experimentally Derived (\text{ACH}^b) ((\text{ACH}_{50} / 20 \text{ R-of-T}))</td>
<td>0.63</td>
<td>0.78</td>
<td>0.75</td>
<td>0.79</td>
<td>0.62</td>
<td>0.84</td>
<td>0.78</td>
<td>0.77</td>
</tr>
<tr>
<td>Experimentally Derived (\text{ACH}) ((\text{HERS R-of-T}))</td>
<td>0.68</td>
<td>0.85</td>
<td>0.81</td>
<td>0.86</td>
<td>0.67</td>
<td>0.91</td>
<td>0.85</td>
<td>0.83</td>
</tr>
<tr>
<td>Net Glazing Area, (A_w) ((\text{ft}^2))</td>
<td>---</td>
<td>43.6</td>
<td>43.6</td>
<td>43.6</td>
<td>90.3</td>
<td>43.6</td>
<td>43.6</td>
<td>DG 30.5 RP 44.4</td>
</tr>
<tr>
<td>Projected Area, (A_p) ((\text{ft}^2))</td>
<td>---</td>
<td>43.6</td>
<td>43.6</td>
<td>43.6</td>
<td>48.4</td>
<td>33.5</td>
<td>43.6</td>
<td>DG 30.5 RP 34.2</td>
</tr>
<tr>
<td>Tilt Angle, TILT ((\text{degrees}))</td>
<td>---</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>50</td>
<td>90</td>
<td>RP 50 DG 90</td>
</tr>
<tr>
<td>Azimuth Angle, AZ ((\text{degrees}))</td>
<td>---</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>RP 0 DG 0</td>
</tr>
<tr>
<td>Base Temp., (T_b) ((\text{°F}))</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>UA Total (c) ((\text{Btu/°F h}))</td>
<td>33.4(^d)</td>
<td>58.5</td>
<td>51.2(^e)</td>
<td>58.0(^f)</td>
<td>59.1</td>
<td>Open 77.0(^g) Closed 50.4</td>
<td>55.4</td>
<td>Open 93.0 Closed 55.6</td>
</tr>
<tr>
<td>Thermal Heat Capacity ((\text{Btu/°F}))</td>
<td>287.3</td>
<td>911.5</td>
<td>941.8</td>
<td>2584.4</td>
<td>769.4</td>
<td>4906.8</td>
<td>1303.2</td>
<td>7603.1</td>
</tr>
</tbody>
</table>

\(a\) Values represent the "open" or "usable" floor area after the thermal storage mass was installed.

\(b\) Values for \(\text{ACH}_{50}\) were obtained using a blower door test, which was conducted on each structure.

\(c\) The method used to calculate the overall coefficient of heat flow (U-factor or U-value) was the parallel-path method as described by ASHREA (2001). Therefore values may appear somewhat different from other published specs regarding the MPSP. Additionally, the values of UA Total presented here utilize the \(\text{ACH}\) values determined by employing the \(\text{ACH}_{50} / 20\) rule-of-thumb.

\(d\) The UA total of the CC was modified after the first phase. During the second phase its value was 30.3 Btu/°F h.

\(e\) The UA total of the TW was modified after the first phase. During the second phase its value was 48.1 Btu/°F h.

\(f\) The UA total of the WW was modified after the first phase. During the second phase its value was 54.9 Btu/°F h.

\(g\) The UA totals of the RP was modified after the first phase. During the second phase its values were 74.1 Btu/°F h (open) and 47.5 Btu/°F h (closed).
Figure 3.5  Basic floor plan and longitudinal sections of the six original test cells.
Illustration by Alfredo Fernández-González, Ahmet Uğursal, and Daniel J. Overbey
Direct Gain, Model 1 (DG1) Cell

The DG1 cell featured a net glazing area of 43.6-ft². The glazing was composed of 1/4-in clear insulated double glazing with a 1/2-in air cavity and an aluminum frame featuring a thermal break. The overall R-Value of the glazing assembly was 1.9 ft² °F h/Btu. Every MPSP test cell featured this type of glazing for its vertical south-facing glazing. The ratio of floor area-to-solar collector area was 2.8:1; while the mass-to-glazing ratio was 2.1:1. The primary thermal storage in this cell consisted of 115 solid concrete blocks (each with a nominal dimension of 8-in x 4-in x 16-in) laid face-up on the floor. The thermal heat capacity of the DG cell was 911.5 Btu/°F.

This DG1 cell featured a direct gain system that most closely resembled reference...
<table>
<thead>
<tr>
<th></th>
<th>Suntempered Ref. Designs</th>
<th>High-Mass Ref. Design</th>
<th>DG1 Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Storage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat capacity (Btu/°F ft² of projected area)</td>
<td>10.8</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Thickness (inches)</td>
<td>0.5</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Mass-to-glazing ratio</td>
<td>20.0</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Thermal conductivity, <em>k</em> (Btu/h ft °F)</td>
<td>0.0923</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Density, <em>ρ</em> (lb/ft³)</td>
<td>50</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Specific heat, <em>c</em> (Btu/lb °F)</td>
<td>0.26</td>
<td>0.2</td>
<td>0.31</td>
</tr>
<tr>
<td>Solar absorptance of surface</td>
<td>0.3</td>
<td>0.8*</td>
<td>0.45</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Number of Glazings</td>
<td>2</td>
<td>2 or 3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Glazing Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission characteristics</td>
<td>diffuse</td>
<td>clear</td>
<td></td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
<td>1.526</td>
<td></td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>0.125*</td>
<td>0.125</td>
<td></td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Night insulation when used</td>
<td>R9**</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
<td>due south</td>
<td></td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td><strong>Control Range of Room Air (°F)</strong></td>
<td>65 to 75</td>
<td>65**</td>
<td></td>
</tr>
<tr>
<td><strong>Lightweight Absorption Fraction</strong></td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Simulates effect of solar radiation absorption on lightweight walls or objects by transferring given fraction of transmitted and reflected solar radiation directly to room air.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ground Reflectance</strong></td>
<td>0.3*</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td><strong>Internal Heat Generation</strong></td>
<td>0**</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

* Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.
*** Since the DG1 cell did not feature mechanical heating, the control range of room air only pertained to the simulation models.

PSHA reference design information source: Balcomb et al. 1984

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design DGB1 from Balcomb et al. (1984). However, as depicted in Table 3.5, the DG1 cell strayed significantly from the reference design properties in terms of heat capacity, mass thickness, mass-to-glazing ratio, thermal conductivity, thermal storage density, the solar absorptance of the thermal storage surface, and glazing transmission characteristics. The aggregate effect of these deviations was a tendency for the DG1 to overheat during clear days. However, in addition, a rather unexpected phenomenon occurred within the test cell. While large operative temperature swings between the day and night were anticipated, the DG1 featured sharp “spikes” in interior air temperature during clearer days, followed by a similarly sharp decrease in interior air temperature. These spikes were more severe during the heating season. This phenomenon will be thoroughly defined in the next chapter.

Trombé-Wall (TW) Cell

The TW cell also featured a net glazing area of 43.6-ft². Like the DG1 cell, it also exhibited a ratio of floor area-to-solar collector area of 2.8:1. The primary thermal storage in this cell was the vented Trombé-wall, which was composed of 109 solid concrete blocks (each with a nominal dimension of 8-in x 4-in x 16-in). The thermal heat capacity of the TW cell was 941.8 Btu/°F. The face of the thermal storage wall was 43.6-ft² and each of the four vents was 1-ft². The vents were kept open throughout the first heating and cooling season. In late December of 2003, the Trombé-wall’s vents became operable as the second phase of the MPSP commenced.

The TW cell’s vented Trombé-wall system most closely resembled reference design

---

DGB1 features a thermal storage capacity of 45 Btu/ft² °F, a nominal mass thickness of 6 inches (for the particular case of \(\rho c = 30 \text{ Btu/ft}^2 \text{ °F} \)), a mass-to-glazing area ratio of 2:1, double glazing, no night insulation, and a solar wall heat loss coefficient of 0.50 Btu/°F h ft².
<table>
<thead>
<tr>
<th></th>
<th>Trombé-Wall Ref. Designs</th>
<th>TW Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Storage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity of wall, k (Btu/h ft °F)</td>
<td>1</td>
<td>0.658</td>
</tr>
<tr>
<td>Density, ρ (lb/ft³)</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Specific heat, c (Btu/lb °F)</td>
<td>0.2</td>
<td>0.31</td>
</tr>
<tr>
<td>Solar absorptance of wall surface</td>
<td>0.9*</td>
<td>0.45</td>
</tr>
<tr>
<td>Solar absorptance of selective surface, when used</td>
<td>0.9*</td>
<td>N/A</td>
</tr>
<tr>
<td>Infrared emittance of wall surface</td>
<td>0.9*</td>
<td>0.9</td>
</tr>
<tr>
<td>Infrared emittance of selective surface, when used</td>
<td>0.1</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Thermocirculation Vents</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vent area, sum of upper and lower vents, when used (% of wall area)</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Vertical separation of vents, when used (ft)</td>
<td>8</td>
<td>5.625</td>
</tr>
<tr>
<td><strong>Glazing Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>diffuse</td>
<td>clear</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
<td>due south</td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
<td>None</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1, 2, or 3</td>
<td>2</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
<td>1.526</td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
<td>0.5</td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>1/8*</td>
<td>1/8</td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
<td>1.5</td>
</tr>
<tr>
<td>Night insulation thermal resistance, when used</td>
<td>R9**</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Control Range of Room Air (°F)</strong></td>
<td>65 to 75</td>
<td>65***</td>
</tr>
<tr>
<td><strong>Ground Reflectance</strong></td>
<td>0.3*</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Internal Heat Generation</strong></td>
<td>none**</td>
<td>none</td>
</tr>
</tbody>
</table>

* Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.
*** Since the TW cell did not feature mechanical heating, the control range of room air only pertained to the simulation models.

PSHA reference design information source: Balcomb et al. 1984
However, as depicted in Table 3.6, the TW cell strayed significantly from the reference design properties in terms of the thermal storage wall’s thermal conductivity and density, the \( \rho \cdot c \cdot k \) product, the solar absorptance of the thermal storage wall’s surface, the overall vent area (as a percentage of the wall), the vertical separation of the vents, and the transmission of the system’s glazing. The TW cell featured relatively small diurnal OT swings and proved to be more thermally stable than the DG1 cell.

Beyond the insulation added to the door of the TW cell in October 2003, in late November 2003 the vents of the Trombè-wall were adapted to become operable. A schedule for opening and closing the vents was suppose to be determined; however, a schedule was never definitively recorded. Nonetheless, due to the proportions of the test cell and the “dry-fitting” of the solid concrete blocks constituting the system’s thermal storage wall (which left many small air gaps), the operation of the vents did not significantly affect the thermal performance of the TW cell. As well, the insulation added to the door did not have a major effect on the cell’s thermal performance. Hence, for this thesis, only the initial configuration of the TW cell was considered for analysis.

**Water-Wall (WW) Cell**

Like the DG1 and TW cells, the WW cell featured a net glazing area of 43.6-ft\(^2\). The primary thermal storage mass was four 5-ft tall, 1.5-ft diameter translucent fiberglass cylinders filled with chlorinated water. The cylinders occupied approximately 7-ft\(^2\) of floor area and a total volume of 35.3-ft\(^3\). Each cylinder contained 66 gallons of water.

---

\[ TWB3 \text{ features a thermal storage capacity of } 30 \text{ Btu/ft}^2 \text{ °F}, \text{ a nominal mass thickness of } 12 \text{ inches (for the particular case of } \rho \cdot c = 30 \text{ Btu/ft}^2 \text{ °F}), \text{ a } \rho \cdot c \cdot k \text{ of } 15 \text{ Btu}^2/\text{°F}^2 \text{ h ft}^3, \text{ double glazing, no night insulation, and a solar wall heat loss coefficient of } 0.19 \text{ Btu/°F h ft}^2. \]
The thermally massive properties of the water gave this test cell a thermal heat capacity of 2,584.4 Btu/°F, a value superior to every test cell except for those featuring roofpond applications.

This test cell featured a water-wall system that most closely resembled reference design WWA4 from Balcomb et al. (1984). However, as depicted in Table 3.7, the WW cell strayed significantly from the reference design properties in terms of the solar absorptance of the water-wall’s surface, the nominal thickness of the water-wall, and the transmission of the glazing. In fact, the WW cell could be considered an incross between a traditional water-wall (indirect gain strategy) and a direct gain strategy due to the fact that the water containers were translucent and featured enough separation between each other to permit indoor air to freely circulate across (Fernández-González 2006). The WW cell’s thermal performance closely resembled that of the DG1 cell. Though they were typically not as severe as those observed within the DG1 cell, the WW cell also exhibited rapid “spikes” in interior air temperature during clear days throughout the heating season. This phenomenon will be expanded upon in the next chapter.

While the interior face of the WW cell’s door did receive the application of 2" AP™ foil-faced polyisocyanurate foam sheathing (R-13) in late October 2003, the effect on thermal performance was not extremely apparent. Thus, only the original configuration of the WW cell was considered for analysis within this thesis.

---

4 WWA4 features a thermal storage capacity of 62.4 Btu/ft² °F, a wall thickness of 12 inches, double glazing, no night insulation, and a solar wall heat loss coefficient of 0.31 Btu/°F h ft².
<table>
<thead>
<tr>
<th></th>
<th>Water-Wall Ref. Designs</th>
<th>WW Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermal Storage</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity of wall (Btu/h ft °F)</td>
<td>infinite</td>
<td>infinite</td>
</tr>
<tr>
<td>Density, ρ (lb/ft³)</td>
<td>62.4</td>
<td>62.4</td>
</tr>
<tr>
<td>Specific heat, c (Btu/lb °F)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Solar absorptance of wall surface</td>
<td>0.95*</td>
<td>0.15</td>
</tr>
<tr>
<td>Solar absorptance of selective surface, when used</td>
<td>0.9*</td>
<td>N/A</td>
</tr>
<tr>
<td>Infrared emittance of wall surface</td>
<td>0.9*</td>
<td>0.9</td>
</tr>
<tr>
<td>Infrared emittance of selective surface, when used</td>
<td>0.1</td>
<td>N/A</td>
</tr>
<tr>
<td>Wall thickness (per reference design, in inches)</td>
<td>12</td>
<td>14.16</td>
</tr>
<tr>
<td><strong>Thermocirculation Vents</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vent area, sum of upper and lower vents, when used</td>
<td>not used</td>
<td>Not used</td>
</tr>
<tr>
<td>(% of wall area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical separation of vents, when used (ft)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Glazing Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>diffuse</td>
<td>clear</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
<td>due south</td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
<td>none</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1, 2, or 3</td>
<td>2</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
<td>1.526</td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
<td>0.5</td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>1/8*</td>
<td>1/8</td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
<td>3</td>
</tr>
<tr>
<td>Night insulation thermal resistance, when used</td>
<td>R9**</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Control Range of Room Air (°F)</strong></td>
<td>65 to 75.</td>
<td>65***</td>
</tr>
<tr>
<td><strong>Ground Reflectance</strong></td>
<td>0.3*</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Internal Heat Generation</strong></td>
<td>none**</td>
<td>none</td>
</tr>
</tbody>
</table>

* Indicates properties that can be varied in the monthly SLR method.
** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.
*** Since the WW cell did not feature mechanical heating, the control range of room air only pertained to the simulation models.

PSHA reference design information source: Balcomb et al. 1984
Sunspace (SS) Cell

With regard to the design guidelines from Balcomb et al. (1984), the SS cell featured a very atypical sunspace application. At 769.4 Btu/°F, the SS cell featured the smallest thermal heat capacity of any passive solar test cell. An indirect gain system in nature, the attached sunspace featured a total floor area 19.2-ft² (open floor area of 16.5-ft²). Above the finished floor, 23 solid concrete blocks (each with a nominal dimension of 8-in x 4-in x 16-in) were placed with their faces upward. The 20.4-ft² common wall was composed of 54 additional concrete blocks. The sunspace’s net glazing area was 90.3-ft². The total enclosed volume of the sunspace was 113.7-ft³.

As mentioned above, the sunspace strategy did not adhere to many of the basic design recommendations for such a system. Foremost, the common wall’s vents in this instance consisted of a single 8.51-ft² void in the thermal storage wall. This equated to 8.8% of the entire 96.8-ft² thermal storage wall assembly (including the wood framing). In addition, the opening could not be closed. Counting both the facing and convectively coupled opposite side of the thermal storage wall, the mass-to-glazing ratio was 0.64:1 rather than the recommended 3:1 by Balcomb et al. (1984). The sunspace also featured glazed end walls. Subsequently, the SS cell performed as (and may be more accurately described as) a direct gain system with an unusually high proportion of solar collector area.

At the author’s discretion, the SS cell was not included in this thesis. This decision was based on the author’s contention that the sunspace’s atypical configuration nullified its qualification as a demonstrable sunspace application with regard to the methods for passive solar heating analysis examined for the purposes of this thesis. However, the entire collection of recorded data from the SS cell has been processed by the author in
accordance with the data recorded from the other test cells for the purposes of this thesis. A complete collection of processed data from any test cell is available upon request.

**Roofpond (RP) Cell**

The RP cell featured a north application of the roofpond strategy. The system closely adhered to the recommended design guidelines defined in Chapter 2. As pictured in Figure 3.7, the system consisted of an 8-in deep roofpond supported by a metal deck topped with a black liner. The roofpond spanned the entire open floor area (128-ft²) of the occupiable volume below. The water volume was contained within two permanently-sealed clear polyethylene bags. The assembly was housed within a thermospace featuring a 43.6-ft² skylight facing true (solar) south. In response to a historical tendency for the roofpond’s movable insulation panels to malfunction, Fernández-González (2006) chose to employ the refined technology of automated garage door assemblies. Thus, the RP cell featured an insulated (R-9.3) Thermacore® garage door system.

At 4,906.8 Btu/°F, the RP cell featured, by far, the highest thermal heat capacity among the five original passive solar test cells. As a result, the RP cell was the most thermally stable in terms of both time and heat distribution to the occupiable volume below. Among the five original test cells, the RP cell displayed the most thermal stability during both the nighttime and extended periods of overcast sky conditions.

While the interior face of the RP cell’s door did receive the application of 2" AP™ foil-faced polyisocyanurate foam sheathing (R-13) in late October 2003, the effect of the insulation on thermal performance was not exceedingly apparent. However, in November 2003, the RP cell received a second layer of batt insulation on the interior faces of the walls of the structure’s occupiable volume. This increase in insulation did have a
significant effect on thermal storage. However, with regard to this thesis, these modifications were only considered for validating the simulation models. Aside from this purpose, only the original configuration of the RP cell was considered for this thesis.

**Direct Gain, Model 2 (DG2) Cell**

In November of 2003, the DG1 cell was significantly modified. In addition to the 2" AP™ foil-faced polyisocyanurate foam sheathing (R-13), which had been added to the interior face of every test cell’s door in late October 2003, the number of solid concrete blocks (each with a nominal dimension of 8-in x 4-in x 16-in) within the DG1 cell was
increased from 115 to 181. While the ratio of floor area-to-solar collector area for the DG2 cell remained at 2.8:1, the mass-to-glazing ratio was increased from 2.1:1 to 3.4:1. As a result, the cell’s thermal heat capacity increased from 911.5 Btu/°F to 1,303.2 Btu/°F. These changes altered the thermal performance of the DG1 cell significantly. Thus, at this point in the test cell’s monitorization, it could be considered as a different test cell altogether. Therefore, the adjusted DG1 cell will henceforth be referred to as the direct gain, model 2 (DG2) cell.

While it could still be compared with the aforementioned DGB1 reference design from Balcomb et al. (1984), the DG2 cell’s modified direct gain system was arguably more comparable with DGCl.\(^5\) However, as depicted in Table 3.8, the DG2 cell still strayed significantly from DGCl in terms of heat capacity, mass-to-glazing ratio, thermal conductivity, thermal storage density, the solar absorptance of the thermal storage surface, and glazing transmission characteristics. Similar to the DG1 cell, the aggregate effect of these deviations caused a tendency for the DG2 cell to overheat during clear days. As with the DG1 and WW cells, the DG2 cell also displayed a tendency to sharply increase in interior air temperature during clearer days—especially in the winter. This was followed by a similarly sharp decrease in interior air temperature. Again, this phenomenon will be thoroughly defined in the next chapter.

\(^5\) DGCl features a thermal storage capacity of 60 Btu/ft\(^2\) °F, a nominal mass thickness of 4 inches (for the particular case of pc = 30 Btu/ft\(^2\) °F), a mass-to-glazing area ratio of 6:1, double glazing, no night insulation, and a solar wall heat loss coefficient of 0.50 Btu/°F h ft\(^2\).
Table 3.8 Properties of PSHA Reference Designs vs. Direct Gain, Model 2 (DG2) Cell

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat capacity (Btu/°F ft² of projected area)</td>
<td>10.8</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Thickness (inches)</td>
<td>0.5</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Mass-to-glazing ratio</td>
<td>20.0</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Thermal conductivity, ( k ) (Btu/h ft °F)</td>
<td>0.0923</td>
<td>1</td>
<td>0.658</td>
</tr>
<tr>
<td>Density, ( \rho ) (lb/ft³)</td>
<td>50</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Specific heat, ( c ) (Btu/lb °F)</td>
<td>0.26</td>
<td>0.2</td>
<td>0.31</td>
</tr>
<tr>
<td>Solar absorptance of surface</td>
<td>0.3</td>
<td>0.8*</td>
<td>0.45</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Number of Glazings

<table>
<thead>
<tr>
<th>Glazing Properties</th>
<th>All Direct Gain Ref. Designs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission characteristics</td>
<td>diffuse</td>
</tr>
<tr>
<td>Infrared emittance of surface</td>
<td>0.9</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.526</td>
</tr>
<tr>
<td>Extinction coefficient (per inch)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Thickness of each pane (inches)</td>
<td>0.125*</td>
</tr>
<tr>
<td>Air gap between layers (inches)</td>
<td>0.5*</td>
</tr>
<tr>
<td>Night insulation when used</td>
<td>R9**</td>
</tr>
<tr>
<td>Orientation</td>
<td>due south*</td>
</tr>
<tr>
<td>Shading</td>
<td>none*</td>
</tr>
</tbody>
</table>

Control Range of Room Air (°F)

| Lightweight Absorption Fraction       | 0.2                         | 0.2 |
| * Simulates 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

| Ground Reflectance | 0.3* | 0.3 |

Internal Heat Generation

| Internal Heat Generation | 0** | 0 |

* Indicates properties that can be varied in the monthly SLR method.

** Indicates properties that can be varied in both the annual LCR method and the monthly SLR method.

*** Since the DG2 cell did not feature mechanical heating, the control range of room air only pertained to the simulation models.

PSHA reference design information source: Balcomb et al. 1984

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Roofpond-Direct Gain (RP-DG) Hybrid Cell

As mentioned earlier in this chapter, between October and December 2003, the SS cell underwent major design modifications. Far beyond the insulation added to the test cell’s door, the entire passive solar heating strategy was changed. After analyzing the results from the first heating season of the MPSP, Fernández-González (2003 and 2004) concluded that a 100% passive solar heated building could be realized in a harsh winter climate with predominantly cloudy skies conditions, such as Muncie, if certain passive solar heating strategies were coupled—namely, a roofpond and direct gain strategy. Therefore, the SS cell’s passive solar system was completely disassembled as the test cell was reconstructed to feature both a roofpond and direct gain strategy. The resulting roofpond-direct gain (RP-DG) cell was the MPSP’s first and only hybrid passive solar heating strategy (Fig. 3.8). The RP-DG cell offered the research team a unique opportunity to monitor both strategies in isolation (via the DG2 and RP cells) and in concert with each other (via the RP-DG cell).

At 7,603.1 Btu/°F, the RP-DG cell exhibited the highest thermal heat capacity of any test cell monitored at the MPSP test facility. The RP-DG cell featured a 12-in roofpond assembly. The roofpond’s thermospace contained 44.4-ft\(^2\) of 1/8” low-e double glazing (CLR LE). As opposed to the 43.6- ft\(^2\) of glazing featured by the DG1 and DG2 cells, the RP-DG cell’s direct gain system only exhibited 30.5-ft\(^2\) of south-facing 1/8” uncoated double glazing. The RP-DG cell’s occupiable volume featured 110 solid concrete blocks (many salvaged from the sunspace and each exhibiting a nominal dimension of 8-in x 4-in x 16-in). The framing of the RP-DG cell featured spray-in-place polyisocynene insulation infill (R-13) rather than foil-faced fiberglass batt insulation (R-19). Though the

89
R-value of the polyicynene insulation was significantly less than the batt insulation, the expanded foam insulation drastically reduced infiltration. Thus, the polyicynene proved to be a more effective insulation product. Unlike the DG1 or DG2 cell, the direct gain system of the RP-DG featured movable insulation in the form of 1/2" AP™ foil-faced polyisocyanurate foam sheathing (R-3.3). According to Fernández-González (2004), the movable insulation was manually operated such that during the heating season it was
opened 45 minutes after sunrise and closed 45 minutes before sunset. During the cooling
season, this schedule was reversed.

As a result of the coupled systems, the RP-DG cell exhibited a thermal performance
superior to any other test cell in the MPSP. However, with both solar systems requiring
automated or manual operation of movable insulation, this test cell is the least passive
among the monitored structures.

Synopsis of Previously Published Findings

Various published works have disclosed a number of findings from the MPSP. In
2003, Fernández-González confirmed the verisimilitude of using full-scale prototypes,
such as those employed for the MPSP, in order to study thermal comfort in passive solar
buildings. Over the course of four years (2003 to 2006), Fernández-González (2003,
2004, and 2006) has also published various results from the MPSP regarding the test
cells’ comfort and thermal performance during the heating season (Fig. 3.9). Data from
the RP cell were used to construct and validate a Microsoft Excel® based software
program called RP_Performance, which allows users to modify relevant parameters that
influence the thermal performance of roofponds featuring a north application. The
software also provides an estimated SSF for the input roofpond strategy (Fernández-
González 2004). Finally, an economic analysis of the six original test cells revealed that
every featured passive system except for the roofpond has a payback period of 30 years
or less. However, in terms of thermal comfort, the roofpond, which could also provide
cooling during the summer months, performed superiorly to the other five test cells
during the considered heating season (Fernández-González and Uğursal 2005).
Current Status of Project

In the Spring of 2005, the MPSP was officially discontinued. The test cells were disassembled. An extensive collection of photographs documenting the test cells' construction and operation is archived at the UNLV NEAT Lab. A full list of published works regarding the MPSP is available through Alfredo Fernández-González.

Figure 3.9 Maximum and minimum extreme and average outdoor dry-bulb air temperatures and coinciding operative temperatures inside the six original test cells.

Illustration by Daniel J. Overbey
Adapted from Fernández-González 2006

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Summary

In order to best understand the research presented within this document, a thorough description of the MPSP is necessary.

In short, the MPSP was meant to identify the potential barriers to achieving thermal comfort when passive solar heating systems are implemented in a severe winter climate characterized by predominantly cloudy sky conditions. The project consisted of a side-by-side comparison between a well-insulated reference “control” test cell and five passive solar test cells, each featuring the same basic geometry and construction methods. Between December 2002 and August 2004, each test cell was monitored in terms of air temperature, mean radiant temperature (MRT), dry-bulb air temperature (DBT), relative humidity (RH), and operative temperature (OT). However, over the course of the experiment, the test cells underwent a series of modifications. While some modifications were relatively minor, two test cells underwent significant changes. Following these modifications, the two heavily altered structures were treated as entirely new passive solar test cells. Thus, the MPSP eventually monitored seven different passive solar heating systems using only five test structures. The test cells considered for this thesis were: the control cell (CC); the direct gain, model 1 (DG1) cell; the direct gain, model 2 (DG2) cell; the Trombé-wall (TW) cell; the water-wall (WW) cell; the roofpond (RP) cell; and the roofpond-direct gain (RP-DG) hybrid cell. The sunspace (SS) cell was not considered for this thesis, although in anticipation of future study the author did process and catalog the experimental data from the SS cell in accordance with the processed data from the test cells that were considered for this thesis.
In order to fulfill the purposes of this thesis, the thermal performance of the considered MPSP test cells must have been compared against the values predicted by the LCR method as defined by Balcomb et al. (1984). From such a comparison, one could then draw conclusions regarding the aptness of the LCR method for estimating the thermal performance of various passive solar heating strategies in a harsh winter climate with predominantly cloudy sky conditions.

The LCR method was designed to delineate \textit{annual} thermal performance. While they were monitored for nearly two years, the thermal performance of the MPSP test cells was not recorded continuously. Gaps in measured data ranged between a few hours to several days. Additionally, every cell endured modifications, system irregularities, and malfunctions to some degree. In order to conduct a useful comparison between the thermal performance of the MPSP test cells and the predicted performance values from the LCR method, a full year of continuous thermal performance data is required from each of the test cells. Furthermore, the test cell data must be devoid of systemic modifications, irregularities, or malfunctions. As a result, thermal performance simulation models were used to provide such data.

With regard to the accuracy of the simulation models, measured data from each of the considered MPSP test cells were used to calibrate and eventually validate the output from
the simulation models. The models were used to emulate the thermal performance of every considered MPSP test cell over the course of their two primary years of monitorization (2003 and 2004). Each two-year simulation run was conducted as if each test cell did not receive any physical modifications nor endure any systemic irregularities or malfunctions.

Following the completion of the validated, two-year simulation runs, four test cells were subjected to the LCR method. The results from both the simulation models and the LCR method were then compared.

In order to further qualify the results of this study, the MPSP test cells were also subjected to the SLR method as defined by Balcomb et al. (1984). This method entails much more complexity. However, it is meant to yield more accurate results than the LCR method (Balcomb et al. 1984).

Finally, in route to the conclusions of this thesis, two additional commonly referenced methods used to evaluate the potential performance of various passive solar heating strategies were compared against the test cells’ simulated thermal performance: 1) the method for estimating average clear winter-day indoor temperatures and 2) the method for estimating clear winter-day indoor temperature swings. Both of these procedures were developed by Balcomb et al. (1980).

The following chapter will describe the four methods applied for the purposes of this study. Then, this chapter will outline the procedure by which the validation study of the LCR method was conducted.
Description of the Annual LCR Method

The following procedural narrative outlines the Load Collector Ratio (LCR) method based on Balcomb et al., *Passive Solar Heating Analysis* (1984), published by ASHRAE. This publication (referred to below as PSHA) provides an extensive variety of passive solar heating systems as well as a vast collection of location listings from which to draw necessary input data required to execute the method. The publication also features an ample collection of “sensitivity curves” that allows individuals to predict the performance of nonstandard passive solar heating systems. In all, this publication brings to fruition a large portion of the extensive research conducted at the Los Alamos National Laboratory by the United States’ foremost passive solar research outfit between 1977 and 1984. Hence, Balcomb et al. (1984) resonates to this day as perhaps the premiere resource for passive solar heating design.

The LCR method yields a predicted annual solar savings fraction (SSF) and auxiliary heat requirement ($Q_{aux}$) for buildings featuring one or more passive solar heating systems.

According to Balcomb et al. (1984), the procedure for executing the annual LCR method may be broken down into the following 7 steps:

1. Select an appropriate reference design.
2. Calculate the net load coefficient, NLC.
3. Determine the projected area of glazing, $A_p$.
4. Calculate the load collector ratio, LCR
5. Determine the base temperature and the annual heating degree-days.
6. Look up the annual SSF in the LCR tables for a project’s specified location.
7. Compute the annual auxiliary heat requirement, $Q_{aux}$.
In turn, each step will be considered. Please be aware that in order to execute the LCR method, one must have access to the resources published in Balcomb et al. (1984). Also, users may find the *Net Load Coefficient and Annual LCR Method Worksheet* particularly useful. This worksheet has been reproduced in Appendix VII. Also note that the author of this thesis has designed a Microsoft Excel® based version of this worksheet. This digital worksheet is available upon request from the UNLV Natural Energies Advanced Technologies Laboratory. The primary advantage of using the digital worksheet is the elimination of many of the calculations asked of the user when executing the LCR method using the original worksheet provided in PSHA.

**Step 1: Select an Appropriate Reference Design**

First, determine the location at which the considered building is located and choose a reference design that most closely coincides with the considered building. Use PSHA Appendix 3 to obtain weather and insolation data for a city that most closely relates to the location of the considered building. A summary of all 94 reference designs considered within Balcomb et al. (1984) is available in PSHA Appendix 5. If the passive system employed by the considered building significantly deviates from the most relevant reference design, the sensitivity data presented in PSHA Appendix 2 may be utilized. Provisions for scenarios in which multiple reference designs are combined into the same building are delineated in Balcomb et al. (1984).

**Step 2: Calculate the Net Load Coefficient**

The NLC is similar to the TLC, except the heat loss through the solar wall is excluded from the calculations.
Please note that with the exception of ACH and ADR, the notations featured in this table are not presented in this document's nomenclature.

Source: Balcomb et al. 1984

With regard to the NLC, the LCR method typically considers a structure’s exterior envelope in terms of seven basic elements. The building elements, notation, and formulas used by Balcomb et al. (1984) to execute NLC computations are listed below in Table 4.1. The formulas featured are approximations of the procedure presented in ASHRAE 1981 Handbook of Fundamentals (Balcomb et al. 1984).

The NLC may be computed using the following formula from Balcomb et al. (1984):

\[
NLC = 24 \left[ (UA)_w + (UA)_r + (UA)_g + (UA)_p or b or f + (UA)_f \right]
\]

Individuals who are designing a passive solar building may consider the following intermediate step as described by Stein et al. (2006). Using the value arrived at using the following formula, one may check a building’s overall heat loss rate against the overall heat loss criteria as listed in Table 4.2.
Table 4.2  Maximum Overall Heat Loss Criteria

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 1000</td>
<td>9</td>
<td>7.6</td>
</tr>
<tr>
<td>1000 – 3000</td>
<td>8</td>
<td>6.6</td>
</tr>
<tr>
<td>3000 – 5000</td>
<td>7</td>
<td>5.6</td>
</tr>
<tr>
<td>5000 – 7000</td>
<td>6</td>
<td>4.6</td>
</tr>
<tr>
<td>Over 7000</td>
<td>5</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Source: Stein et al. 2006, which was reproduced from Balcomb et al. 1980

Btu/DD ft² = NLC/Af

Step 3: Determine the Projected Area of Glazing

According to Balcomb et al. (1984), the projected area (Aₚ) is defined as the sum of the net glazing area of the a passive system that projects on to a single vertical plane that has the same azimuth as the passive system's principal azimuth.

Step 4: Calculate the Load Collector Ratio

As defined by Balcomb et al. (1984), the LCR is the quotient of the NLC and the Aₚ:

LCR = NLC/ Aₚ

Step 5: Determine the Base Temperature and the Annual Heating Degree-Days

To begin this step, the TLC must be calculated. The TLC is defined by Balcomb et al. (1984) as the steady-state load, or heat loss, of a considered building per degree of inside-
versus-outside temperature difference for a given day. While the TLC may be calculated using the standard procedures outlined in the ASHRAE 1981 *Handbook of Fundamentals*, for the purposes of the LCR method, the TLC may be calculated using the following simplified equation:

\[ TLC = NLC + 24 U_c A_p \]

The product \( U_c A_p \) relates to the steady-state load coefficient of the solar wall. Values of \( U_c \) for all 94 reference designs are listed in PSHA Appendix 5. If more than one passive solar system is employed by the considered structure, then the summation of every system's \( U_c A_p \) product should be used.

Next, the base temperature must be determined. The base temperature (\( T_b \)) is defined by Balcomb et al. (1984) as a fixed temperature, typically 65°F, against which the ambient outdoor air temperature is compared. Other base temperatures may be used. The standard formula for computing the \( T_b \) is listed in PSHA as follow:

\[ T_b = T_{set} - Q_{int} / TLC \]

Finally, the *annual total* of heating degree-days for the considered building’s location must be calculated. According to Balcomb et al. (1984), the number of HDD for any particular day may be determined using the following formula:

\[ HDD = T_b - T_a \]
Monthly and annual HDD totals for base temperatures of 50°F, 55°F, 60°F, 65°F, and 70°F are available for a considerable number of locations in PSHA Appendix 3. As HDD information is commonly recorded for various base temperatures, one may also draw on any number of the many climate data resources available throughout the country.

**Step 6: Look Up Annual SSF in LCR Tables**

At this juncture, a predicted value of annual SSF may be determined using the LCR tables listed in PSHA Appendix 1.

Please look up the SSF value corresponding to the reference design specified in Step 1, the LCR value determined in Step 4, and the \( T_b \) calculated in Step 5. If the considered building’s LCR falls between two tabulated values, interpolate linearly between the listed values to determine the building’s predicted annual SSF. As well, use linear interpolation if the \( T_b \) falls between the two tabulated values (55°F and 65°F). In the event that both the LCR and \( T_b \) fall between tabulated values, calculate the SSF for both 55°F and 66°F, then interpolate between these two values of SSF based on the \( T_b \) (Balcomb et al. 1984).

**Step 7: Compute Annual Auxiliary Heat Requirement**

Finally, the predicted value of annual \( Q_{aux} \) (in mega Btu/year) may be calculated using the following formula from Balcomb et al. (1984):

\[
Q_{aux} = NLC \cdot DD \cdot (1 - SSF) \times 10^6
\]
Description of the Monthly SLR Method

The following procedural narrative outlines the Solar Load Ratio (SLR) method based on *Passive Solar Heating Analysis: A Design Manual*, by Balcomb et al. (1984). As with the LCR method, PSHA provides a collection of indispensable resources for any individual planning to employ this method. The SLR method is considerably more complex than the LCR method. Hence, only a general description of the method will be presented here within. The SLR method was designed to be utilized toward the end of design development, as it considers much more detail regarding the exact configuration of the passive solar building at hand. Unlike the LCR method, which supplies annual estimates, the SLR method provides a month-by-month estimate of the thermal performance of a passive solar building for an entire year. It was meant to be used to confirm the sizing and placement of various solar features and/or expose flaws in an structure’s current design configuration. Whereas the LCR method requires the use of sensitivity curves in order to adjust the predicted SSF and $Q_{aux}$ results for systems that significantly deviate from a particular reference design, the SLR method allows users to account more directly for many of these design deviations—thus, reducing or eliminating the number of necessary sensitivity analyses (Balcomb et al. 1984).

According to Balcomb et al. (1984), the procedure for executing the annual LCR method may be broken down into the 13 procedural steps as described below. This procedure is written under the assumption that the reader has access to the *Monthly SLR Method Worksheet* and the supplementary *Solar Gain Worksheet* from Balcomb et al. (1984). In order to facilitate the general understanding of the SLR method, a reproduction of each worksheet is included in Appendix VII. Please note that the author
of this thesis has designed Microsoft Excel® based versions of both worksheets, which serve to eliminate many of the calculations asked of the user when executing the SLR method using the worksheets provided in PSHA. These worksheets are available upon request from the UNLV Natural Energies Advanced Technologies Laboratory.

The following is the 13-step procedure for using the Monthly SLR Method Worksheet as described by Balcomb et al. (1984):

1. Fill in the information regarding the reference design and project location.
2. Enter into the Data block the values of NLC, A_p, and LCR.
3. Enter into the Data block, as needed, the values of \( L C R_s, A, B, C, D, G, H, \) and \( R \).
   Please note that where a value is not required for the particular reference design, the allotted space has been marked out (via cross-hatching).
4. Calculate \( L C R_s \cdot H \), if necessary, and enter the value into the Data block.
5. Fill out the Solar Gain Worksheet, then enter the monthly values of \( S \) into the allotted column of the Item block.
6. Enter monthly values of DD for the specified \( T_b \) into the allotted column.
7. Calculate monthly values of SLR and enter the values into the allotted column.
8. For direct gain systems:
   a. Compute the monthly \( F(SLR) \) values.
   b. Compute the monthly SSF and enter into the allotted column.
9. For sunspace or thermal storage wall systems:
   Compute the monthly SSF and enter into the allotted column.
10. Calculate the monthly values of \( Q_{net} \) and enter into allotted column.
   Please note that the formula for \( Q_{net} \) printed at the head of the allotted column.
converts \( Q_{\text{net}} \) into millions of Btu per month (or Mega Btu/mo). A summation of the column will produce the Annual \( Q_{\text{net}} \). Please enter this value in the allotted cell of the Item block.

11. Calculate the monthly values of \( Q_{\text{sav}} \) and enter them into the allotted column. A summation of the column will produce the Annual \( Q_{\text{sav}} \). Please enter this value in the allotted cell of the Item block.

12. Calculate the Annual SSF and enter the value into the allotted cell of the Item block.

In turn, each step will be considered below. However, please be aware that this chapter only offers a very broad description of the SLR method. A comprehensive description would be extremely lengthy and is not essential to this document. The purpose of the description delineated below is to provide readers with a general understanding of what the SLR method entails. If one wishes to apply the SLR method, please consult Balcomb et al. (1984) for a comprehensive description of the method as well as a complete collection of vital published resources.

**Monthly SLR Method Worksheet Procedure – Step 1**

First, utilizing PSHA Appendix 5, Tables A5-2 through A5-6, users must select the reference design that most closely resembles that which is employed by the building design in consideration. Users must also specify the location of the project and retrieve the necessary weather and insolation data. If no other resource is available, one may consult PSHA Appendix 3 to obtain pertinent data from the city that most closely relates to the project’s location.
Monthly SLR Method Worksheet Procedure – Step 2

Next, users must input the values of NLC, \( A_p \), and LCR for the project into the allotted cells within the *Data* block of the Monthly SLR Worksheet. If these values are not known, the user may implement the procedure described within the LCR method. Balcomb et al. (1984) provides the *NLC Worksheet* to facilitate this process.

Monthly SLR Method Worksheet Procedure – Step 3

Using the data provided by PSHA Appendix 5, Tables A5-7, 8 and 9, this step requires that users to enter the values of \( \text{LCR}_a \), \( A \), \( B \), \( C \), \( D \), \( G \), \( H \), and \( R \) for the project’s most closely related reference design into the spaces provided within the *Data* block. Please be aware, however, if the building’s passive heating system deviates from its related reference design significantly, it may be necessary to manually compute \( \text{LCR}_a \) using procedure outlined in PSHA Chapter 11. Please note that depending on which reference design is specified, certain variables will not be required. These values will be identified on the *Data* block via cross-hatching over their designated cells. It should also be noted that after the release of *Passive Solar Heating Analysis: A Design Manual* (Balcomb et al. 1984), the Los Alamos National Laboratory issued a supplementary publication entitled *Passive Solar Heating Analysis: Supplement One* (Balcomb et al. 1987). The supplement details the SLR correlation coefficients for 81 unique direct gain reference designs. This new collection of correlation data was intended to replace the nine direct gain reference designs listed in PSHA Appendix 5. Balcomb et al. (1987) felt that the original nine reference designs did not provide enough options for the designer to adequately analyze the effects of certain decisions regarding the design of a direct gain system. Be aware that the SLR correlation coefficients for the 81 updated direct gain
reference designs (C, D, H, LCRs, Uc, and EHC/Ag) are unlike those of the original nine
direct gain reference designs (A, B, C, D, G, and R). Notice that the published data for the
updated direct gain reference designs utilize the same SLR correlation coefficients as
those used by sunspaces and thermal storage wall systems. Therefore, the coefficients
from the 81 updated direct gain reference designs must be entered into the Data block on
the same row designated for TW, WW, and SS strategies.

Monthly SLR Method Worksheet Procedure – Step 4

If necessary, the product of $LCR_s \times H$ should be calculated and entered into the
allotted cell within the Data block.

Monthly SLR Method Worksheet Procedure – Step 5

At this point, the user must complete the Solar Gain Worksheet from Balcomb et al.

First, users need to specify the following parametric input values regarding the
considered project: TILT, AZ, E, N, and REFR. For thermal storage wall systems, the
surface absorptance of the thermal storage wall ($\alpha_{ss-wall}$) must be specified. For direct gain
and sunspace systems, the following values need to be specified: $\alpha_m$, $\alpha_o$, system floor-to-
ceiling height, system wall-to-wall depth, system wall-to-wall width, system glazing
length, $HGT$, $XTOP$, $WDTH$, and $Z$.

The values $HGT$, $WDTH$, $XTOP$, and $Z$ are ratios to the height of the sunspace and are
calculated as defined below:

\[
HGT = \frac{\text{height}}{\text{height}} = 1
\]

\[
WDTH = \frac{\text{width}}{\text{height}}
\]
$XTOP = \text{depth/height}$

$Z = \text{glazing length/height}$

Next, the solar noon zenith angle at midmonth (LAT-DEC) must be input for each month of the year. Values of LAT-DEC for a variety of cities are listed in PSHA Appendix 3. However, this data may be calculated for any site using the location’s LAT and the following formula from Balcomb et al. (1984):

$$DEC = 23.45 \sin \left( \frac{360 \left( 284 + \eta \right)}{365} \right)$$

Values of $\eta$ for midmonth are listed below in Table 4.3:

<table>
<thead>
<tr>
<th>Table 4.3 Value of $\eta$ for Midmonth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Jan</td>
</tr>
<tr>
<td>Feb</td>
</tr>
<tr>
<td>Mar</td>
</tr>
<tr>
<td>Apr</td>
</tr>
<tr>
<td>May</td>
</tr>
<tr>
<td>Jun</td>
</tr>
<tr>
<td>Jul</td>
</tr>
<tr>
<td>Aug</td>
</tr>
<tr>
<td>Sep</td>
</tr>
<tr>
<td>Oct</td>
</tr>
<tr>
<td>Nov</td>
</tr>
<tr>
<td>Dec</td>
</tr>
</tbody>
</table>

Source: Balcomb et al. (1984)
Next, monthly values of $K_T$ must be determined. If the information listed in PSHA Appendix 3 does not suffice, users may use insolation data for a specific location to compute monthly $K_T$ values using the following equation from Balcomb et al. (1984):

$$K_T = \frac{Q_h}{Q_{hc}}$$

If $Q_h$ and/or $Q_{hc}$ data is not available, users may consult PSHA Chapter 9 for calculation procedures which may be used to determine these variables.

Next, the Solar Gain Worksheet requires monthly values of $HS$. If this information has not been recorded on-site, and if the information provided in PSHA Appendix 3 does not suffice, users may consult the Renewable Resource Data Center (RReDC) for additional resources.¹

The Solar Gain Worksheet also requires the value of $A_o/A_p$. This is a simple calculation using two easily obtained values relating the design of the considered passive solar building.

Finally, monthly values of solar gain ($S$) may be computed. The basic formula from Balcomb et al. (1984) is as follows:

$$S = M (A_o/A_p) HS (\text{INC/HOR}) (\text{TRN/INC}) (\text{ABS/TRN})$$

---

¹ The RReDC is supported by the National Center for Photovoltaics (NCPV). In addition, the RReDC is managed by the Department of Energy’s Office of Energy Efficiency and Renewable Energy. The RReDC is maintained by the Electric Systems Center at the National Renewable Energy Laboratory.
For passive solar buildings that conform closely to a reference design, Balcomb et al. (1984) provides a number of simplified procedures for calculating $S$. These procedures can save users considerable amounts of time. However, depending on the degree to which a particular building deviates from a reference design, users may need to spend a significant amount of time and effort retrieving information from PSHA Chapter 9 and Appendix 4 necessary to calculate monthly $S$ values. If enough insolation and building design data is available to the user, monthly values of $(\text{INC/HOR})$ and $(\text{TRN/INC})$ may be calculated manually without the aid of the published resources contained within PSHA.

Once the Solar Gain Worksheet has been completed, the monthly values of $S$ should be transferred to the allotted column within the *Item* block of the Monthly SLR Worksheet.

**Monthly SLR Method Worksheet Procedure – Step 6**

Next, the monthly values of DD for the specified $T_b$ should be entered into the allotted column of the *Item* block. This information may be calculated from available weather data for a specific location. Otherwise, DD information for several base temperatures is presented for a large number of cities in PSHA Appendix 3.

**Monthly SLR Method Worksheet Procedure – Step 7**

At this juncture, the solar load ratio may be calculated. The key formula, as defined by Balcomb et al. (1984), is presented in PSHA Chapter 8 and at the top of the Monthly SLR Method Worksheet. The formula, which may differ depending on which reference design is specified, is defined as follows:
For direct gain systems:

\[ \text{SLR} = \frac{(S/DD)}{(LCR + G)} \]

For sunspaces and thermal storage wall systems:\(^2\)

\[ \text{SLR} = \frac{(S/DD - LCR \cdot H)}{LCR} \]

**Monthly SLR Method Worksheet Procedure – Step 8**

This step only pertains to users employing one of the nine direct gain reference designs defined by Balcomb et al. (1984) in PSHA.

First, the monthly values of \( F(\text{SLR}) \) must be computed using either the key formula presented in PSHA Chapter 8 and at the top of the Monthly SLR Method Worksheet or the graphs presented in PSHA Appendix 5, Figures A5-19 through A5-21.

The key formula as defined by Balcomb et al. (1984) reads as follows:

\[
\begin{align*}
\text{If } \text{SLR} < R, \text{ then: } F(\text{SLR}) &= A \text{ SLR} \\
\text{Otherwise: } F(\text{SLR}) &= B - C \exp(-D \text{ SLR})
\end{align*}
\]

Second, the user must compute the monthly SSF using the key formula presented in PSHA Chapter 8 and at the top of the Monthly SLR Method Worksheet. The formula is defined as follows:

\[
\begin{align*}
\text{If } \text{SLR} < R, \text{ then: } F(\text{SLR}) &= A \text{ SLR} \\
\text{Otherwise: } F(\text{SLR}) &= B - C \exp(-D \text{ SLR})
\end{align*}
\]

\(^{2}\) This formula should also be used if the building’s direct gain system is modeled after any of the 81 direct gain systems listed in *Passive Solar Heating Analysis: Supplement One* (Balcomb et al. 1987).
\[
SSF = 1 - (1 + \frac{G}{LCR}) \left[ 1 - F(SLR) \right]
\]

Once the monthly SSF values have been calculated, they should be transferred to the allotted column within the *Item* block of the Monthly SLR Method Worksheet.

**Monthly SLR Method Worksheet Procedure – Step 9**

This step pertains to users employing either one of the sunspace or thermal storage wall reference designs defined by Balcomb et al. (1984) or one of the 81 direct gain reference designs defined by Balcomb et al. (1987). This step entails that the user calculates the monthly SSF values for the considered building and transfers the values to the allotted column within the *Item* block of the Monthly SLR Method Worksheet. For this step, the key formula used to compute the monthly SSF values is presented in PSHA Chapter 8 and at the top of the Monthly SLR Method Worksheet. Alternatively, users may also consult the graphs presented in PSHA Appendix 5, Figures A5-1 through A5-18. The formula for computing the monthly SSF values reads as follows:

\[
SSF = 1 - C \exp(-D \text{ SLR})
\]

**Monthly SLR Method Worksheet Procedure – Step 10**

For this step, the net reference load must be computed and transferred to the allotted column within the *Item* block of the Monthly SLR Method Worksheet. The formula for computing \( Q_{net} \) is presented within the worksheet as well as PSHA Chapter 8. The formula, as defined by Balcomb et al. (1984), reads as follows:
$Q_{\text{net}} = NLC \text{ DD} \, 10-6$

Please note that the formula converts the monthly $Q_{\text{net}}$ values into units of Mega Btu/month (or 1,000,000 Btu/month).

**Monthly SLR Method Worksheet Procedure – Step 11**

The eleventh step of the procedure requires that users calculate monthly values of $Q_{\text{sav}}$ using the following formula from the Monthly SLR Method Worksheet as well as PSHA Chapter 8 (Balcomb et al. 1984):

$$Q_{\text{sav}} = Q_{\text{net}} \times \text{SSF}$$

Once the monthly values of $Q_{\text{sav}}$ have been calculated, they should be transferred to the allotted column within the *Item* block of the Monthly SLR Method Worksheet. The annual value of $Q_{\text{sav}}$ is simply the summation of all twelve monthly values. This value should also be transferred to its designated cell within the *Item* block of the Monthly SLR Method Worksheet.

**Monthly SLR Method Worksheet Procedure – Step 12**

In this step, users calculate the monthly values of $Q_{\text{aux}}$ using the following formula from the Monthly SLR Method Worksheet and PSHA Chapter 8 (Balcomb et al. 1984):

$$Q_{\text{aux}} = Q_{\text{net}} \times (1 - \text{SSF})$$
Once the monthly values of $Q_{aux}$ have been calculated, they should be transferred to the allotted column within the *Item* block of the Monthly SLR Method Worksheet. The annual value of $Q_{aux}$ is simply the summation of all twelve monthly values. This value should also be transferred to its designated cell within the *Item* block of the Monthly SLR Method Worksheet.

**Monthly SLR Method Worksheet Procedure – Step 13**

Finally, users are asked to compute the annual SSF for the considered building using the key formula from PSHA Chapter 8. The formula is defined by Balcomb et al. (1984) as follows:

\[
\text{annual SSF} = \frac{\text{annual } Q_{sav}}{\text{annual } Q_{net}}
\]

Once the annual SSF value has been calculated, it should be transferred to the allotted cell within the *Item* block of the Monthly SLR Method Worksheet.

This concludes the basic procedure for executing the Monthly SLR Method Worksheet.

**Description of the Method Used to Estimate Average Clear Winter-Day Indoor Temperatures**

The following procedure from Balcomb et al. (1980) is used to estimate how much higher, versus the outdoor air temperature, the average indoor air temperature will be within a passively heated building on a clear winter-day.
After several consecutive clear-day conditions, the 24-hour average temperature inside the building will stabilize. It is good design practice to size solar collection glazing to raise the 24-hour average indoor air temperature into a comfortable range on a clear January day. Otherwise, the passive heated building will likely overheat on such days (Balcomb et al. 1980).

According to Balcomb et al. (1980), the average temperature achieved is the sum of three temperatures:

1. The average ambient outdoor air temperature ($T_a$) for January
2. A temperature increment due to internal heat gains ($\Delta t_{\text{internal}}$)
3. A temperature increment due to solar gains ($\Delta t_{\text{solar}}$)

Values of $T_a$ for any month are very common and may be acquired through any number of available climatological databases.

According to Stein et al. (2006), $\Delta t_{\text{internal}}$ may be calculated using the following formula:

$$\Delta t_{\text{internal}} = \frac{\text{total internal gains (Btu/day)}}{\text{TLC}}$$

In order to determine $\Delta t_{\text{solar}}$, one must use the appropriate graph from Figure 4.1, which was reproduced from Stein et al. (2006). This figure pertains to systems without night insulation. If the systems were to employ night insulation, the $\Delta t_{\text{solar}}$ would be larger (Balcomb et al. 1980).
Figure 4.1  Graphs of $\Delta t$ solar:

a) $\Delta t$ solar for vented Trombe-wall, direct gain, and water-wall; and

b) $\Delta t$ solar for unvented Trombe-wall.

Source: Stein et al. (2006)
Description of the Method Used to Estimate
Clear Winter-Day Indoor Temperature Swings

The following procedure from Balcomb et al. (1980) is used to estimate the size of
the diurnal temperature swing due to passive solar heating on a clear day in January ($\Delta t$
swing). As passively heated buildings are typically controlled by the sun and the actions
of the occupants, rather than a thermostat, they often exhibit larger daily variations in
indoor air temperature than conventional, mechanically-heated buildings—especially on
clear days (Stein et al. 2006).

Estimated values of $\Delta t$ swing may be determined using the Table 4.4, which was
reproduced from Stein et al. (2006). Please note that the information in this table, which
was transferred from Balcomb et al. (1980), only pertains to reference cases featuring a
thermal mass of 45 Btu/°F per ft² of glazing.

Table 4.4  Indoor Temperature Swing, $\Delta t$ Swing

<table>
<thead>
<tr>
<th>Passive Solar System</th>
<th>$\Delta t$ Swing$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG: mass area / glazing area = 1.5</td>
<td>1.11 x $\Delta t$ solar</td>
</tr>
<tr>
<td>DG: mass area / glazing area = 3</td>
<td>0.74 x $\Delta t$ solar</td>
</tr>
<tr>
<td>DG: mass area / glazing area = 9</td>
<td>0.37 x $\Delta t$ solar</td>
</tr>
<tr>
<td>WW</td>
<td>0.39 x $\Delta t$ solar</td>
</tr>
<tr>
<td>TW, vented for 3% of wall area</td>
<td>0.65 x $\Delta t$ solar</td>
</tr>
<tr>
<td>TW, unvented</td>
<td>0.15 x $\Delta t$ solar</td>
</tr>
</tbody>
</table>

$^a$ These swings are based on a thermal storage mass capacity of 45 Btu/ft² °F; $\Delta t$ solar can be found in Fig. 4.1.

Source: Stein et al. 2006

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Validation of the LCR Method Using
Data from the MPSP

The process by which the LCR method was evaluated and validated using data from the Muncie Passive Solar Project is illustrated below.

Below, each of the major databases, calculation steps, and applied procedures will be briefly defined. More detailed information may be obtained from Appendices II, III, IV, V, and VI.

Please note that the methods used to estimate average clear winter-day indoor temperatures and temperature swings were applied as completely separate, yet complimentary, analyses and were omitted from the flowchart below (Fig 4.2) as they did not influence the validation of the LCR method.

*Passive Solar Heating Analysis (PSHA)*

The procedure by which the LCR and SLR methods were conducted is defined within *Passive Solar Heating Analysis: A Design Manual* by Balcomb et al. (1984). The process by which the Solar Gain procedure was executed was derived from this resource as well. PSHA also provides a number of resources necessary to conduct each of these methods, including: LCR tables, sensitivity data, weather and insolation data, solar radiation coefficients, and SLR correlations. The Microsoft Excel® based worksheets used to execute the Solar Gain calculations, LCR method, and SLR method were modeled after worksheets and other information published within PSHA.
Figure 4.2 Flowchart Illustrating the Methodology Used to Validate the LCR Method

Illustration by Daniel J. Overbey
LCR Method Excel® Worksheet

The LCR Method Excel® Worksheet was modeled after the *Net Load Coefficient and Annual LCR Method Worksheet* published by Balcomb et al. (1984). The Excel® file was developed by this author for the UNLV Natural Energies Advanced Technologies Laboratory during the last semester prior to this thesis. It utilizes the same procedure as outlined in the worksheet developed by Balcomb et al. (1984). However, the Excel® worksheet eliminates the calculations required of users who utilize the published worksheet. The Excel® worksheet only requires users to input a small range of data regarding the considered building’s physical characteristics. For the purposes of this thesis, specific data were input from the Specs & UA Calculations Worksheet.

![Figure 4.3 Screenshot of LCR Method Excel® Worksheet](image)

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The Solar Gain Procedure Excel® Worksheet was modeled after the Solar Gain Worksheet published by Balcomb et al. (1984). Like its published counterpart, this worksheet typically requires users to draw on a number of resources provided in PSHA, especially with regard to the incident (INC/HOR), transmitted (TRN/INC), and absorbed (ABS/TRN) fractions. However, if measured weather and insolation data were available, they should be used instead. The Excel® worksheet does provide users with a number of valuable tables from PSHA that, in many cases, may spare users from consulting the various appendices of Balcomb et al. (1984).

Figure 4.4 Screenshot of Solar Gain Procedure Excel® Worksheet
SLR Method Excel® Worksheet

The SLR Method Excel® Worksheet was modeled after the SLR Worksheet published by Balcomb et al. (1984). As the SLR method entails many complex calculations, the Excel® worksheet is a very valuable tool that has the ability to save users a considerable amount of time by eliminating many of the calculation steps.

Like its published counterpart, the SLR Method Excel® Worksheet requires several pieces of information derived from the appendices of PSHA. Moreover, the SLR Method Excel® Worksheet requires users to input several pieces of data regarding the considered building's physical characteristics. For the purposes of this thesis, specific data were input from the Specs & UA Calculations Worksheet.

Figure 4.5  Screenshot of SLR Method Excel® Worksheet
Specs & UA Calculations Worksheet

The Specs and UA Calculations Worksheet is an Excel® based document used to determine the various pieces of information regarding each MPSP test cell’s physical characteristics required by the simulation models and the various procedures from Balcomb et al. (1980, 1984) related to this thesis. This file draws on documentation conducted prior this thesis. All prior documentation was evaluated for accuracy. For instances in which inaccurate documentation was suspected, analyses were conducted to verify the correct values.
Test Cell Input Files

During test cell monitorization, data were collected every 5-minutes. However, the various simulation models developed for this thesis were designed to receive hourly data. Thus, measured data from each test cell’s collection of data loggers were processed and organized into cell-specific input files. As each input file constituted the database for its related simulation model, it also contained pertinent measured weather and insolation data, as well as converted data from SOLRAD Model 6. Like the measured data from the test cells, the measured weather and insolation data were also recorded in 5-minute intervals and needed to be processed into hourly data.

Please refer to Appendix II for detailed information regarding SOLRAD Model 6.

![Figure 4.7 Screenshot of the DG1 Test Cell Input File](image-url)
Simulation Models

The MPSP simulation models are a series of Excel® based thermal performance simulation models that employ documented formulas in order to simulate the thermal performance of the MPSP test cells. Specifically, by using various input data the MPSP simulation models were designed to simulate the hourly indoor air temperature of the considered test cells both with and without an auxiliary heat source.

A thorough description of the MPSP simulation models, including a detailed formulaic narrative for each model, is provided in Appendix III. In addition, pertinent correlation tables and monthly thermal performance summaries are provided in Appendices IV and V, respectively.
Summary File

A comprehensive summary file was used to ultimately evaluate the aptness of the LCR method. Within the summary file, measured data, simulated data, and predicted values from both the LCR and SLR methods have been brought together for analytical purposes. The summary file also features a breakdown of each test cell’s thermal performance (both measured and simulated) over the entire two-year simulation period.

Please refer to Appendix VI for monthly and annual breakdowns of each test cell’s simulated thermal performance compared against the predicted performance values from both the LCR and SLR methods.

Figure 4.9 Screenshot of the DG1 Test Cell Input File
Summary

The annual LCR method, developed by Balcomb et al. (1984), is a widely published method of estimating the thermal performance of buildings incorporating passive solar heating systems. It was designed to be very user friendly and is frequently cited in a number of architectural text books. Using published correlation tables, the LCR method predicts the annual SSF and $Q_{aux}$ likely to be incurred by a passively heated building.

The monthly SLR method, also developed by Balcomb et al. (1984), is a less popular yet more specific method of estimating the thermal performance of buildings incorporating passive solar heating systems. Rather than predicting only annual values, the SLR method also predicts monthly values of SSF and $Q_{aux}$. According to Balcomb et al. (1984), the SLR method is designed to be more accurate than the LCR method.

The method used to estimate average clear winter-day indoor temperatures and the method used to estimate clear winter-day indoor temperature swings, both developed by Balcomb et al. (1980), may be used to determine a general estimate of how a passively heated building would perform after several consecutive days of clear sky conditions during the heating season.

In order to fulfill the purposes of this thesis, thermal performance data was required from each of the studied test cells from the MPSP. However, the test cells, while monitored regularly over the course of two years, did not record two continuous years of data from which to conduct a direct comparison with the annual LCR method. Thus, a thermal simulation model had to be built for each of the considered test cells. As well, an entire methodology had to be developed in order to properly validate the LCR method using data from the MPSP.
CHAPTER 5

FINDINGS OF THE STUDY

The findings of this thesis focus on the effectiveness of the four methods of passive solar heating analysis presented within this document: 1) the *load collector ratio* (LCR) method, 2) the *solar load ratio* (SLR) method, 3) the method used to estimate a passive solar building's average clear winter-day indoor temperature, and 4) the method used to estimate the average clear winter-day indoor temperature swing ($\Delta t$ swing). In addition, key observations outside the original scope of the study will be described in order to further qualify the findings of this study as well as provide a foundation from which future studies may be realized.

The Effectiveness of Four Widely Accepted Methods of Analyzing Passive Solar Heating Systems

The ultimate goal of this study was to draw conclusions regarding the aptness of the *load collector ratio* (LCR) method for predicting the thermal performance of passively solar heated buildings via the *solar savings fraction* (SSF) and required auxiliary heat ($Q_{aux}$). En route to the study's findings, a rigorous evaluation of the more detailed *solar load ratio* (SLR) method for determining a passively heated building's SSF and $Q_{aux}$ was also deemed to be necessary. In order to further qualify the results of this thesis, two other widely accepted methods used to assess the potential performance of passive solar heating strategies were also evaluated: the method used to estimate average clear winter-day...
day indoor temperatures and the method used to estimate average clear winter-day indoor temperature swings ($\Delta t_{swing}$). All of these methods were developed by the same group at the Los Alamos National Laboratory (Balcomb et al. 1980, 1984).

A summary of the results produced by each of the four methods of predicting the thermal performance of passively solar heated buildings is provided below. Additionally, a direct comparison of their predicted values for various MPSP test cells to data derived from the test cells' monitorization is also produced.

The LCR Method

Ultimately, this study concludes that despite their major deviations from the reference designs, the LCR method was reasonably adequate for predicting the annual solar savings fraction (SSF) for passively heated buildings in harsh winter climates with predominantly overcast sky conditions. While the deviation by the LCR method from the simulated results becomes somewhat large in several instances, it should be noted that every design deviated from their respective reference designs considerably. The TW cell had the most accurate annual SSF predictions from the LCR method (Table 5.1). Conversely, it was also the TW cell which exhibited the largest discrepancy between the simulated annual $Q_{aux}$ and that which was predicted by the LCR method. From these results, one may begin to draw the following conclusions.

The Los Alamos group determined that the primary factor dictating the performance of a passively solar heated building in a particular climate is the ratio of the total building heat loss load to the area of solar aperture. This ratio constitutes the foundation of the LCR method and appears to adequately facilitate in the estimation of how much better or worse a solar heated building will perform in a climate such as Muncie versus a non-solar
<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG1</td>
<td>DG2</td>
</tr>
<tr>
<td>SSF, LCR Method</td>
<td>-4.5%</td>
<td>4.0%</td>
</tr>
<tr>
<td>SSF, Simulated</td>
<td>2.5%</td>
<td>12.8%</td>
</tr>
<tr>
<td>Deviation by LCR Method</td>
<td>-7.0%</td>
<td>-8.8%</td>
</tr>
<tr>
<td>Qaux, LCR Method (Mega Btu/Yr)</td>
<td>4.49</td>
<td>3.77</td>
</tr>
<tr>
<td>Qaux, Simulated (Mega Btu/Yr)</td>
<td>4.11</td>
<td>3.68</td>
</tr>
<tr>
<td>Deviation by LCR Method (Mega Btu/Yr)</td>
<td>+0.38</td>
<td>+0.09</td>
</tr>
</tbody>
</table>

heated building, especially if the passive system’s design adheres to a published reference design. However, it should be reiterated that the passive systems employed for the MPSP deviated significantly from their related reference designs. Yet, these reference designs are what the LCR tables (published within Balcomb et al. 1984) account for. Thus, in order to properly execute the LCR method, the best available sensitivity data had to be implemented despite the fact that the data were designed for locations considerably
different than Muncie. Despite these handicaps, the predicted annual SSF values were typically within 5.4% of the simulated results and were never more than 8.8% inaccurate.

The nature in which the LCR method consistently overestimated the annual $Q_{aux}$ may suggest that the method's formulas are not complex enough to take other influential aspects (e.g. weather and insolation particularities) into consideration. For the simulated test cell results, the only input values that were not fixed related to weather and insolation data. While further investigation is probably needed, it stands to reason that the degree of deviation in $Q_{aux}$ from one year to the next is somehow related to climatic inputs. Both the LCR method and the simulation models take latitude, elevation, and the site's approximate air density into consideration. However, the simulation models also implement hourly values for ambient air temperature, wind chill temperature, relative humidity, ground albedo (which can change due to snow), the clearness factor ($K_t$), and incident solar radiation. By comparison, the LCR method only takes the site's heating degree-days as climatic input. While this simple input lends to the convenience of the LCR method, it may be somewhat insufficient with regard to clearly depicting the climatic effects on a given passive solar heating system. To illustrate this point, consider the following information: from the standpoint of simply considering heating degree-days below the base temperature (in our case 65°F), January of 2003 and 2004 appear to be quite similar with $H_{65}$ values of 1267 and 1190, respectively. However, as one may conclude from the monthly averages depicted in Table 5.2, January 2004 displayed significantly less solar radiation and atmospheric clearness. Moreover, despite similar mean monthly ambient air temperatures, the actual patterns of hourly temperature change per day were quite different between January 2003 and 2004. These differences
Table 5.2  Comparison of January 2003 and January 2004 Climate and Insolation Data

<table>
<thead>
<tr>
<th></th>
<th>January 2003</th>
<th>January 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total hemispheric solar radiation incident on a horizontal surface (Btu/ft² day)</td>
<td>554</td>
<td>441</td>
</tr>
<tr>
<td>Total solar radiation incident on a vertical surface (Btu/ft² day)</td>
<td>752</td>
<td>506</td>
</tr>
<tr>
<td>Mean ambient temperature (°F)</td>
<td>24.1</td>
<td>26.9</td>
</tr>
<tr>
<td>Heating degree-days below the base temperature (65°F)</td>
<td>1267</td>
<td>1190</td>
</tr>
<tr>
<td>Average clearness ratio</td>
<td>0.43</td>
<td>0.37</td>
</tr>
</tbody>
</table>

are most powerfully depicted in the severely different thermal performance exhibited by the RP cell between January 2003 and January 2004.

In short, the LCR method, when used in conjunction with the full array of relevant documented sensitivity data from Balcomb et al. (1984), does appear to convey reasonably accurate predictions of annual SSF one could expect through the implementation of a direct gain, Trombé-wall, or water-wall passive solar heating strategy. However, as it pertains to passive solar heating systems that deviate considerably from the published reference designs and are implemented in severe winter climates with predominantly cloudy sky conditions, the LCR method appears to be somewhat less accurate, yet still reasonably reliable, in predicting precise values of $Q_{aux}$. It is the author's contention that had the MPSP test cells strictly adhered to particular reference designs or had an exhaustive collection of sensitivity data been available for a climate much similar to Muncie (e.g. Fort Wayne, Indiana), the LCR method would have been even more accurate.
The SLR Method

For its considerable increase in complexity, the monthly SLR method did convey more accurate results than the LCR method (Table 5.3).

The increased accuracy of the SLR method may be accounted for by the nature of the method itself, which was considerably more detailed and required more input than the LCR method.

First, the SLR method’s solar gain worksheet considered a much wider range of climatic input (such as heating degree-days, incident solar radiation, the clearness factor, the average monthly solar noon zenith angle, and several monthly ratios based on incident, transmitted, and absorbed solar radiation). This helped combat one of the chief shortcomings of the LCR method, as defined above.

Next, the SLR method possessed the ability to consider a much greater range of design deviations from a related reference design. For instance, within the SLR method, monthly SSF values are heavily influenced by the solar load ratio and various solar load ratio correlation coefficient values published by Balcomb et al. (1984, 1987). These SLR correlation coefficient values have the ability to account for such specific design deviations as the extinction coefficient-thickness product, the number of window glazings, the absorptance of various surfaces, and various types of geometrical deviations.

Unfortunately, in order to successfully execute the SLR method, users must have a much more thorough understanding of the resources provided by Balcomb et al. (1984, 1987), especially if the considered project deviates significantly from its related reference design. However, as a result of the method’s greater complexity, the predicted
Table 5.3  Predicted Performance Using the SLR Method vs. Simulated Performance

<table>
<thead>
<tr>
<th></th>
<th>2003</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG1</td>
<td>DG2</td>
<td>TW</td>
<td>WW</td>
<td>RP</td>
<td>RP-DG</td>
</tr>
<tr>
<td>SSF, SLR Method</td>
<td>5.5%</td>
<td>4.5%</td>
<td>0.6%</td>
<td>8.5%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SSF, Simulated</td>
<td>2.5%</td>
<td>12.8%</td>
<td>-2.4%</td>
<td>8.7%</td>
<td>3.2%</td>
<td>30.6%</td>
</tr>
<tr>
<td>Deviation by SLR Method</td>
<td>+3.0%</td>
<td>-8.3%</td>
<td>+3.0%</td>
<td>-0.3%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Qaux, SLR Method (Mega Btu/Yr)</td>
<td>4.07</td>
<td>3.75</td>
<td>4.70</td>
<td>3.88</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Qaux, Simulated (Mega Btu/Yr)</td>
<td>4.11</td>
<td>3.68</td>
<td>4.32</td>
<td>3.85</td>
<td>4.08</td>
<td>2.92</td>
</tr>
<tr>
<td>Deviation by SLR Method (Mega Btu/Yr)</td>
<td>-0.04</td>
<td>+0.07</td>
<td>+0.38</td>
<td>+0.03</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>2004</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG1</td>
<td>DG2</td>
<td>TW</td>
<td>WW</td>
<td>RP</td>
<td>RP-DG</td>
</tr>
<tr>
<td>SSF, SLR Method</td>
<td>5.4%</td>
<td>4.3%</td>
<td>0.5%</td>
<td>8.1%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>SSF, Simulated</td>
<td>0.9%</td>
<td>7.3%</td>
<td>-5.9%</td>
<td>8.3%</td>
<td>-41.7%</td>
<td>30.3%</td>
</tr>
<tr>
<td>Deviation by SLR Method</td>
<td>+4.9%</td>
<td>-3.0%</td>
<td>+6.4%</td>
<td>-0.2%</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Qaux, SLR Method (Mega Btu/Yr)</td>
<td>4.20</td>
<td>3.87</td>
<td>4.85</td>
<td>4.01</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Qaux, Simulated (Mega Btu/Yr)</td>
<td>3.65</td>
<td>3.42</td>
<td>3.90</td>
<td>3.38</td>
<td>5.22</td>
<td>2.57</td>
</tr>
<tr>
<td>Deviation by SLR Method (Mega Btu/Yr)</td>
<td>+0.55</td>
<td>+0.45</td>
<td>+0.95</td>
<td>+0.63</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

annual SSF values of the considered MPSP test cells were generally more accurate, typically within 5.0% of the simulated results and never more than 8.3% inaccurate. The predicated annual $Q_{aux}$ values were typically within 0.55 mega Btu/year of the corresponding simulated values and never deviated more than 0.95 mega Btu/year.

Monthly breakdowns comparing the predicted thermal performance values from the SLR method to the simulated thermal performance values of the MPSP, as well as
comparisons of the annual SSF and $Q_{aux}$ values from both the LCR and SLR methods to the simulated values of the MPSP are presented in Appendix VI. This appendix also presents a comparison of the simulated monthly and annual thermal performance values of the RP cell to those of the RP-DG cell.

The Method Used to Estimate Average Clear Winter-Day Indoor Temperatures

As described in the previous chapter, a method can be employed to approximate the average indoor air temperature of a passive solar heated building during a typical clear January day.

When applied to the MPSP test cells, the method did not yield acceptably accurate results. As Table 5.4 illustrates, the method consistently overestimated the average indoor temperature for each of the comparable test cells. When compared to simulated monthly averages for January 2003 and 2004, the predicted indoor temperatures were overestimated between 9.1°F and 17.6°F (Fig. 5.1 and 5.2). When compared to a single clear day in January 2003 (23rd) and 2004 (24th), the discrepancies persisted. Theoretically, the single-day comparisons should have yielded the most accurate results.

The discrepancies between the predicted temperatures and the simulated temperatures may have resulted from several factors.

The method, itself, was designed to take three temperature inputs into consideration: the average ambient outdoor air temperature, the temperature increment due to internal gains, and the temperature increment due to solar gains ($\Delta t_{solar}$). However, the MPSP test cells were devoid of any internal gains. Published examples of the method typically utilize some degree of internal heat gain. It is unclear whether the method could actually
Table 5.4 Predicted Performance from the Method Used to Estimate Average Clear Winter-Day Indoor Temperatures vs. Simulated Performance

<table>
<thead>
<tr>
<th></th>
<th>2003 Predicted (°F)</th>
<th>2003 Simulated (°F)</th>
<th>1.23.03 Simulated (°F)</th>
<th>2004 Predicted (°F)</th>
<th>2004 Simulated (°F)</th>
<th>1.24.04 Simulated (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>---</td>
<td>26.5</td>
<td>17.6</td>
<td>---</td>
<td>31.3</td>
<td>29.5</td>
</tr>
<tr>
<td>DG1</td>
<td>59.6</td>
<td>44.0</td>
<td>44.3</td>
<td>62.4</td>
<td>42.3</td>
<td>44.2</td>
</tr>
<tr>
<td>DG2</td>
<td>61.6</td>
<td>43.9</td>
<td>43.2</td>
<td>64.4</td>
<td>42.6</td>
<td>42.0</td>
</tr>
<tr>
<td>TW</td>
<td>58.1</td>
<td>39.6</td>
<td>37.0</td>
<td>60.9</td>
<td>38.8</td>
<td>37.2</td>
</tr>
<tr>
<td>WW</td>
<td>60.1</td>
<td>44.5</td>
<td>43.6</td>
<td>62.9</td>
<td>43.7</td>
<td>42.9</td>
</tr>
<tr>
<td>RP</td>
<td>---</td>
<td>37.3</td>
<td>31.9</td>
<td>---</td>
<td>38.0</td>
<td>33.2</td>
</tr>
<tr>
<td>RP-DG</td>
<td>---</td>
<td>46.7</td>
<td>44.6</td>
<td>---</td>
<td>45.6</td>
<td>43.6</td>
</tr>
</tbody>
</table>

lose accuracy as a result of bypassing the internal gain contributions. However, an absence of internal gains was the reality in the case of the MPSP.

The method’s lack of flexibility and inability to accommodate designs that deviate greatly from the identified design prescriptions published by Balcomb et al. (1980, 1984) may have contributed to the inaccurate results. As stated numerous times, the test cells’ passive solar systems purposely strayed from their related reference designs. The deviations may have been so great that the method’s referenced LCR / Latitude correlations with regard to $\Delta t_{solar}$ may have become inapplicable.

One may hypothesize that the average January 2003 and 2004 air temperatures (24.1°F and 26.9°F respectively) strayed considerably from the region’s normal $T_a$ for January. Yet, the average January outdoor air temperature is 26°F.
Figure 5.1  2003 Predicted Average Clear-Day Temperatures vs. Simulated Results

Figure 5.2  2004 Predicted Average Clear-Day Temperatures vs. Simulated Results
It is also possible that the methodology outlined by the Los Alamos National Laboratory—which was developed in Los Alamos, New Mexico—may not be at apt for estimating \( \Delta t_{solar} \) in climates quite unlike Los Alamos. Case in point, Muncie typically has many more cloudy sky conditions than Los Alamos during the heating season.

The Method Used to Estimate Average Clear Winter-Day Indoor Temperature Swings

The method for estimating the average clear winter-day indoor temperature swing (\( \Delta t_{swing} \)) as a result of utilizing a passive solar heating system was also compared to the applicable MPSP test cells. Developed for designs that feature a thermal storage capacity of 45 Btu/ft\(^2\) °F, this method did not accurately estimate the \( \Delta t_{swing} \) of all but one of the MPSP test cells.

Similar to the previous method, a comparison was made between the predicted results, the average simulated \( \Delta t_{swing} \) for the entire months of January 2003 and 2004, and the simulated \( \Delta t_{swing} \) for a single clear day in January 2003 (23rd) and 2004 (24th). As with the previous method, theoretically, the single-day comparisons should have yielded the most accurate results.

Only the DG1, DG2, and TW cells featured a thermal storage capacity close to 45 Btu/ft\(^2\) °F. Yet, according to the summarized results featured in Table 5.5, the method was only accurate for the TW cell when considering the single-day comparisons. As the mass-to-glazing ratios of the direct gain cells strayed severely from the design prescriptions of Balcomb et al. (1984) and facilitated a tendency to overheat, the single-day comparisons for the DG1 and DG2 cells yielded inaccurate results. As depicted in Figures 5.3 and 5.4, the tendencies of the DG1 and DG2 cells to overheat—especially on
clear days during the heating season—were apparent in the simulated $\Delta t$ swing values for January 23, 2003 and January 24, 2004.

As previously described, the water-wall application featured by the WW cell also prompted a tendency for the cell to overheat. This tendency was also apparent in the single-day comparisons.

Please note that the average simulated $\Delta t$ swing values for the entire months of January 2003 and 2004 are not very suitable for comparison. However, they were included in order to illustrate the difference between a typical $\Delta t$ swing value for January in a climate such as Muncie (which features predominantly cloudy sky conditions during the heating season) and a less typical clear January day.

Table 5.5  
Predicted Performance from the Method Used to Estimate Average Clear Winter-Day Indoor Temperature Swings vs. Simulated Performance

<table>
<thead>
<tr>
<th>Thermal Storage Capacity (Btu/ft$^2$ °F)</th>
<th>Predicted $\Delta t$ swing (°F)</th>
<th>2003</th>
<th></th>
<th></th>
<th></th>
<th>2004</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>--</td>
<td>--</td>
<td>Jan. 2003 Simulated</td>
<td>$\Delta t$ swing (°F)</td>
<td>6.1</td>
<td>5.4</td>
<td>Jan. 2004 Simulated</td>
<td>$\Delta t$ swing (°F)</td>
<td>5.1</td>
</tr>
<tr>
<td>DG1</td>
<td>41.3</td>
<td>28.3</td>
<td>26.9</td>
<td>46.3</td>
<td>17.5</td>
<td>37.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DG2</td>
<td>41.3</td>
<td>22.0</td>
<td>19.4</td>
<td>33.5</td>
<td>12.4</td>
<td>26.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TW</td>
<td>51.1</td>
<td>19.2</td>
<td>13.4</td>
<td>22.2</td>
<td>8.2</td>
<td>18.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td>113.4</td>
<td>11.5</td>
<td>20.5</td>
<td>37.3</td>
<td>10.7</td>
<td>32.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RP</td>
<td>--</td>
<td>--</td>
<td>4.2</td>
<td>5.0</td>
<td>2.8</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RP-DG</td>
<td>--</td>
<td>--</td>
<td>10.1</td>
<td>15.2</td>
<td>6.7</td>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ These swings are based on a thermal storage capacity of 45 Btu/ft$^2$ °F.
Figure 5.3  2003 Predicted Indoor Temperature Swings vs. Simulated Results

Figure 5.4  2004 Predicted Indoor Temperature Swings vs. Simulated Results
MPSP Thermal Performance Comparison
during the Heating Seasons

Perhaps the paramount shortcomings of both the LCR and SLR methods are their
disregard for thermal comfort. These methods focus strictly on energy use. En route to
the ultimate findings of this study, it was discovered that the MPSP test cells—though
purposely featuring passive solar heating systems that were not optimized in order to
identify any potential barriers to achieving thermal comfort (Fernández-González
2006)—still exhibited potential life safety benefits due to their increased number of hours
within the temperature range of passive survivability over the CC throughout the heating
season.

Wilson (1995) uses the term passive survivability to describe a building's ability to
maintain critical life-support conditions in the event of extended loss of power, heating
fuel, or water, or in the event of extraordinary heat spells. Though, never quantitatively
defined, guided by the predicted mean vote (PMV) as defined by ASHRAE (1997), this
study determined internal temperatures between 50 and 85°F to be “survivable” if not
comfortable – thus, this range represented passive survivability.

The fact that the MPSP test cells were not intended to provide passive cooling
beckons that any analysis of the test cells’ thermal performance not include the five
months generally constituting the cooling season for the MPSP during the principal years
2003 and 2004 (May, June, July, August, and September).

Therefore, if one considers the test cells only during the heating seasons (Table 5.6),
several interesting observations can be made.
While the passive solar heated test cells' annual auxiliary energy requirements are comparable to the CC, their percentages of total hours above the $T_{set}$ (65°F) and within the *passive survivability* range a considerably higher than the CC.

These results strongly suggest that the studied passive solar heating strategies possess an inherent safety feature in the face of a prolonged blackout period during the heating season. Muncie often has severe winters. During the 2004-2005 heating season, Muncie withstood a debilitating ice storm that left many homes without electricity for several days as the city's infrastructure was being repaired. In the face of such natural disasters, a passive solar heating system, even if it's not optimized, could offer residents a key advantage in terms of withstanding a potentially life-threatening scenario.

<table>
<thead>
<tr>
<th>Table 5.6 Performance Comparison between Test Cells – Heating Season Only</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
</tr>
<tr>
<td>% Hrs. of Passive Survivability.</td>
</tr>
<tr>
<td>CC</td>
</tr>
<tr>
<td>36.8%</td>
</tr>
<tr>
<td>% of Hrs. Above 65°F.</td>
</tr>
<tr>
<td>CC</td>
</tr>
<tr>
<td>11.2%</td>
</tr>
<tr>
<td>Annual Energy Required, kWh.</td>
</tr>
<tr>
<td>CC</td>
</tr>
<tr>
<td>1,236</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Hrs. of Passive Survivability.</td>
</tr>
<tr>
<td>CC</td>
</tr>
<tr>
<td>37.7%</td>
</tr>
<tr>
<td>% of Hrs. Above 65°F.</td>
</tr>
<tr>
<td>CC</td>
</tr>
<tr>
<td>7.9%</td>
</tr>
<tr>
<td>Annual Energy Required, kWh.</td>
</tr>
<tr>
<td>CC</td>
</tr>
<tr>
<td>1,081</td>
</tr>
</tbody>
</table>
The Potential to Achieve 100% Passive Solar Heating in Muncie, Indiana

All six of the passive solar heated test cells considered for this thesis fell well short of providing 100% of the heat requirements to maintain a minimum indoor air temperature of 65°F. However, the most successful test cell was the Roofpond-Direct Gain (RP-DG) hybrid passive solar test cell, which consistently achieved an annual SSF of approximately 30%. It should be reiterated that the MPSP test cells did not feature any source of internal heat gain or mechanical auxiliary heat. Had any of the passive solar test cells been constructed with more air-tightness and featured additional insulation, its thermal performance could have been improved dramatically. Moreover, had any of the passive solar test cells received even a conservative fraction of the internal gains typically encountered by single-family residences, its thermal performance would have been improved as well. It is conceivable that the RP-DG cell, in particular, could have potentially received all of its auxiliary heat requirements from modest internal gains. In order to understand the extent to which the thermal performance of the RP-DG cell could have been adjusted by such changes, several parametric studies were executed using the RP-DG simulation model. The foremost intent of this investigation was to determine if 100% of the RP-DG cell’s auxiliary heat requirements could have been supplied by a combination of design modifications and realistic internal loads.

**Roofpond-Direct Gain Parametric Examination Summary**

Over the course of the MPSP, January proved to be an exceptionally severe month. The January 2003 and 2004 auxiliary heat requirement \( Q_{aux} \) for the RP-DG was 1,007,923 and 1,048,661 Btu respectively. However, if certain conservation measures

\[142\]
were taken, the auxiliary heat requirements could have been reduced significantly. For illustrative purposes, consider the effect of doubling the insulation of the RP-DG cell. Specifically pertaining to the simulation model, the R-values of the test cell’s 1/2" APTM foil-faced polyisocyanurate foam sheathing, 2" Super TUFF-R insulating sheathing, and polyicynene insulation were doubled. The aggregate effect of which was also assumed to reduce the test cell’s infiltration by 0.10 ACH. Figures 5.5 and 5.6 depict the simulated effect such conservation measures would have had on the RP-DG cell during January of 2003 and 2004. Table 5.7 indicates that the conservation measures reduced the RP-DG cell’s auxiliary heat requirement by 48% for January 2003 and 57% in January 2004.

While the improvements in thermal performance due to the conservation measures were considerable, they would likely not suffice for achieving 100% of the RP-DG cell’s auxiliary heat requirement. However, when both a moderate internal heat gain value of 1,580 Btu/h to compensate for one adult occupant and the average heat produced by incandescent/tungsten halogen lighting in order to provide an interior illuminance of 20 foot-candles evenly throughout the cell is implemented into the test cell, the performance of the RP-DG cell improved dramatically.1 The effect of one adult plus the continuous use of electric lighting in addition to the aforementioned conservation measures is illustrated in Figures 5.7 and 5.8. In January 2003, the RP-DG cell would not require

---

1 The rate of heat gain from one occupant was derived from Stein et al. (2006). Using Table F.8, an activity level defined as “seated, very light work” was assumed for a location defined as “apartments.” Under these conditions, an adult male is assumed to emit 450 Btu/h. A very conservative value of 300 Btu/h was assumed for the described parametric study. The rate of heat gain from electric lighting was derived from Brown and DeKay (2000). Using the figure from Strategy 13, page 14, an interior illuminance of 20 foot-candles was input. Incandescent/Tungsten Halogen lighting was chosen specifically for their low efficiency and subsequently higher heat discharge. Using the figure for Strategy 13, a lighting heat gain of 10 Btu/h ft² of floor area was determined—a particularly low value for the occupancy and lighting types specified. When multiplied by the RP-DG floor area of 128 ft², the total lighting heat gain is determined to be 1280 Btu/h ft². Thus, an internal heat gain value of 1580 Btu/h ft² is employed.

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Figure 5.5  January 2003 RP-DG Cell Thermal Performance after Additional Conservation Measures

Figure 5.6  January 2004 RP-DG Cell Thermal Performance after Additional Conservation Measures

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Table 5.7  Summary of Roofpond-Direct Gain (RP-DG) Parametric Studies

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unadjusted</td>
<td>1,007,923 Btu</td>
<td>1,048,661 Btu</td>
</tr>
<tr>
<td>+ Conservation Measures</td>
<td>481,578 Btu</td>
<td>602,569 Btu</td>
</tr>
<tr>
<td>+ Conservation Measures + Internal Gains</td>
<td>0 Btu</td>
<td>31,997 Btu</td>
</tr>
</tbody>
</table>

mechanical heating to continuously maintain the 65°F thermostat setting, while the January 2004 heat requirements are reduced by 97%.

Ultimately, the parametric studies indicated that a properly designed passive solar heated building, when combined with considerable conservation measures and typical internal heat gains from occupants, lighting, and equipment, may actually be able to achieve 100% of its heating needs in a climate such as Muncie without the aid of a mechanical auxiliary heating system. Considering Muncie’s often harsh winter climate, this information is particularly promising for northern climate regions.
Figure 5.7 January 2003 RP-DG Cell Thermal Performance after Additional Conservation Measures and Internal Gains

Figure 5.8 January 2004 RP-DG Cell Thermal Performance after Additional Conservation Measures and Internal Gains

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Summary

For this study, simulated thermal performance values of the MPSP test cells—as derived from simulation models calibrated against measured data from the test cells—were compared against predicted values from several reputable methods of evaluating the potential thermal performance of passive solar heated buildings. The results of the comparisons ranged considerably. This thesis affirms that both the LCR and SLR methods, when properly applied to passive solar systems that resemble reference designs defined by Balcomb et al. (1984), are reliable for providing a rough estimate of a passive solar heated building’s SSF and $Q_{\text{aux}}$ values in a severe winter climate with predominantly cloudy sky conditions. The other two methods pertaining to the estimation of a passive solar heated building’s average clear winter-day indoor temperature and temperature swing did not yield results that were accurate enough to be relied upon. The study indicated that the inaccuracies of these methods are likely due to their inability to accommodate unique design characteristics and significant deviations from the defined design prescriptions published by Balcomb et al. (1980, 1984).

Even though the MPSP test cells intentionally challenged each passive system’s ability to provide thermal comfort and energy conservation, every passive solar test cell still exhibited considerable life safety potential due to an increased percentage of total hours in which their indoor temperatures were within the range of passive survivability over the CC.

Finally, the study indicated that if a passive solar heated building is properly design and coupled with complimentary passive systems, 100% of the building’s auxiliary heat requirements may be met by heat gains due to the solar system and modest internal gains.
CHAPTER 6

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The results of this thesis reaffirm that the LCR method is suitable for roughly estimating a passive solar heated building’s annual solar savings fraction and auxiliary energy requirement in a severe winter climate characterized by predominantly cloudy sky conditions. Moreover, the results of this thesis also validate the SLR method. Thus, the extensive body of published works from the Los Alamos National Laboratory, among others, citing the LCR and SLR methods is given new relevance and may be relied upon as the foundation for any number of design guidelines or legislature aimed at implementing passive solar heating systems as a way to significantly reduce the auxiliary energy required for space heating in various types of buildings located within a climate similar to that of Muncie, Indiana.

Closing Remarks

A glaring shortcoming of various environmental design guidelines dealing with space heating issues, including the U.S. Green Building Council’s LEED guidelines, is their focus on energy-efficient mechanical space heating systems. Very few environmental design guidelines feature provisions that specifically reward designers for implementing
passive solar heating systems. Understandably, there is much hesitation to embrace systems of space heating that are not easily quantifiable and cannot be packaged with certified information regarding precise energy savings. However, the route to 100% passive solar heating is that which may ultimately enable our built environments to most closely reflect and integrate into their natural context. Passive solar heating systems are based on natural processes of heat collection, conduction, and convection. They use current solar income rather than fossil fuels, which may be considered the Earth’s stored solar energy reserve. As the local climate dictates many design aspects of passive solar heating systems, thus when properly designed they naturally respect diversity. Their performance is dependable and they provide security by virtue of their thermal resilience in the face of severe climatic conditions and/or power outages. As, J. Douglas Balcomb, the seminal force behind the advancements of passive solar design in the United States, recently stated, “As energy becomes more expensive and supplies become unreliable, the question will change from ‘Is it cost effective?’ to ‘What happens if there is a power outage or the supply of natural gas is cut off – will my pipes freeze?’ (Balcomb 2006)”

An analysis of the methods used to estimate a passive solar heated building’s average clear winter-day indoor temperature and diurnal indoor temperature swing revealed a considerable degree of inaccuracy. These results were due to the methods’ inability to accommodate unique design characteristics. Further study regarding these methods is strongly recommended.

1 While passive heating systems may qualify for an Innovation and Design Process (ID) credit within various LEED guidelines, there are currently no specific credits promoting passive solar heating systems in particular.
Finally, this study revealed that even though the MPSP test cells purposely challenged each passive system’s ability to provide thermal comfort and energy conservation, every passive solar test cell still exhibited considerable life safety potential due to the increased hours in which their interior air temperatures were within the range of passive survivability over the CC.

As we, the designers of our built environments, continue to forge paths into the realms of environmental beneficence, energy-efficiency, carbon balancing, and social responsibility, we should make the most of the abundant body of knowledge that precedes us. Passive solar heating is not new. The principles guiding passive systems have been utilized for countless generations prior to our own. It appears that we would be wise to look back to find answers for the future and usher a passive solar comeback.

Recommendations for Further Study

En route to the results of this study, several avenues of future explorations emerged. However, these explorations could be properly executed within the time frame of this thesis and are therefore suggested below as future research directions.

1. Using the data recorded during its monitorization, the Sunspace (SS) test cell should be analyzed and used to develop a SS test cell simulation model. The SS varied greatly from any archetypical reference design and may, in fact, more closely mimic the performance of the Direct Gain test cells. The data recorded during the monitorization of the SS cell has already been processed and is available upon request from Alfredo Fernández-González.
2. The simulation models should be further refined and then applied to all nine cities chosen by the Los Alamos National Laboratory (Balcomb et al. 1984) to represent a wide geographical and climatological sample of major cities in the continental United States. The nine cities are: Albuquerque, New Mexico; Bismarck, North Dakota; Boson, Massachusetts; Ely, Nevada; Madison, Wisconsin; Medford, Oregon; Nashville, Tennessee; Santa Maria, California; and Seattle, Washington. Due to the fact that the Los Alamos National Laboratory conducted most of their experiments in the Los Alamos, New Mexico region, it may be especially advantageous to apply the simulation models to that location and then compare the simulated results to those predicted by the LCR and SLR methods.

3. It would be very advantageous if the MPSP was conducted a second time using test cells strictly designed in accordance with chosen reference designs. By conducting the MPSP again using reference designs, the LCR method could be employed in its purest application.

4. Using the simulation models developed for this thesis, various characteristics of the MPSP test cells could be systematically adjusted in order to determine what characteristics had the most influence on the test cells' thermal performance. Using such information, a thorough thermal performance analysis could be conducted by which the principal goal of the MPSP could be more completely achieved.
APPENDIX I

MPSP ACTIVITY LOG

Over the course of the experiment, the MPSP research team kept an activity log to record experimental modifications and systemic irregularities with regard to the various test cells.

Depicted below is the complete activity log of the MSPS. Please note that the term “HOBO” refers to the Onset Computer Corporation’s HOBO H-8 RH/Temperature 2x data loggers. These devices were simultaneously deployed at various times over the duration of the MPSP. Typically, the data loggers were deployed in “weekly” intervals (typically 6 to 8 days). After each interval, data was downloaded, battery levels were checked, and the devices were redeployed. Each deployment was referred to as a “Launch.” The initial test launch (Launch 001) occurred on Saturday, November 16, 2002 at 12:00 AM. However, the first two launches to occur in succession did not transpire until Launch 002 (which commenced on Friday, December 6, 2002 at 12:00 AM) and Launch 003 (which commenced on Saturday, December 14, 2002 at 12:00 AM). The final launch (Launch 081) began on Friday, July 30, 2004 at 12:00 AM.

Please note that for clarity, some of the entries’ text has been modified.
## Table A1.1  Muncie Passive Solar Project Activity Log

<table>
<thead>
<tr>
<th>Date</th>
<th>Applicable Test Cell(s)</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturday, Nov. 16, 2002</td>
<td><strong>ALL</strong></td>
<td>Test Launch 001 initiated at 12:00 AM. The weather station was also deployed for a test run.</td>
</tr>
<tr>
<td>Friday, Dec. 6, 2002</td>
<td><strong>ALL</strong></td>
<td>Launch 002 began at 12:00 AM. All test cells, as well as the weather station, are operating.</td>
</tr>
<tr>
<td>Saturday, Dec. 14, 2002</td>
<td><strong>ALL</strong></td>
<td>Launch 003 initiated at 12:00 AM, marking the first launch to occur in succession with another launch.</td>
</tr>
<tr>
<td>Friday, Sep. 12, 2003</td>
<td>SS</td>
<td>In the SS cell, the HOBOs (958, 959, 960, and 961) were placed in the same location as usual—3.6-ft (or 43.3 inches above the finish floor).</td>
</tr>
<tr>
<td></td>
<td>SS, WW</td>
<td>The HOBOs 962, 963, 964, and 965 were removed from the WW cell and placed within the SS cell at a height of 2-ft or 24-in above the finish floor, just below the regularly monitored HOBOs within the SS cell.</td>
</tr>
<tr>
<td>Friday, Sep. 26, 2003</td>
<td>RP</td>
<td>At 6:00 PM, the garage door of the RP cell was closed as the system was switched from cooling to heating mode.</td>
</tr>
<tr>
<td>Friday, Oct. 10, 2003</td>
<td>TW, DG1</td>
<td>For Launch 039 (beginning on Oct. 10, 2003), the HOBOs of the TW cell (966, 967, 968, and 969) were removed and placed in the DG1 cell at a height of 2-ft above the finish floor.</td>
</tr>
<tr>
<td></td>
<td>DG1</td>
<td>The DG1 cell HOBOs (970, 971, 972, and 973) were kept at the normal height of 3.6-ft above the finish floor.</td>
</tr>
<tr>
<td>Friday, Oct. 17, 2003</td>
<td>SS, DG1</td>
<td>Retrofiting of the SS cell commenced and the SS cell HOBOs (958, 959, 960, and 961) were removed and placed in the DG1 cell at a height of 2-ft above the finish floor for Launch 040 (beginning on Oct. 17, 2003).</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Date</th>
<th>Cell</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friday, Oct. 17, 2003 (cont.)</td>
<td>SS</td>
<td>All of the “stowaway” HOBOs from CERES were placed in the SS cell until Friday, Oct. 17, 2003.</td>
</tr>
<tr>
<td></td>
<td>WW</td>
<td>For Launch 040 (beginning on Oct. 17, 2003), the HOBOs 962, 963, 964, 965 were returned to the WW cell and placed in their original locations at 3.6-ft above the finish floor.</td>
</tr>
<tr>
<td>Monday, Oct. 20, 2003</td>
<td>RP</td>
<td>From Monday, Oct. 20, 2003 through Thursday, Oct. 23, 2003, the RP cell’s garage door remained continuously shut due to a power outage. It is not certain when the power initially failed.</td>
</tr>
<tr>
<td>Thursday, Oct. 23, 2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Friday, Oct. 24, 2003</td>
<td>RP</td>
<td>The power supply to the RP cell has not been returned.</td>
</tr>
<tr>
<td>Tuesday, Oct. 28, 2003</td>
<td><strong>ALL</strong></td>
<td>This week, between Tuesday, Oct. 28, 2003 and Wednesday, Oct. 29, 2003, insulation was applied to the interior surface of every test cell’s door.</td>
</tr>
<tr>
<td>Wednesday, Oct. 29, 2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thursday, Oct. 30, 2003</td>
<td>RP</td>
<td>The RP cell’s garage door started again.</td>
</tr>
<tr>
<td></td>
<td><strong>ALL</strong></td>
<td>This morning, the <em>Environmental Control Systems</em> class came and visited the test cells just before the data was downloaded. There is a clear temperature increase in every test cell as a result of these visits.</td>
</tr>
<tr>
<td>Friday, Oct. 31, 2003</td>
<td>RP-DG</td>
<td>The “occupiable” space of the RP-DG test cell was finished. The exterior was painted. This space consists of glazing salvaged from the SS test cell. The only remaining tasks are to install the glazing on the roof and then insert/fill the water bags.</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Date</th>
<th>Cell</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wednesday, Nov. 12, 2003</td>
<td>RP-DG</td>
<td>The glazing was installed on the roof of the RP-DG cell.</td>
</tr>
<tr>
<td></td>
<td>RP</td>
<td>Starting with Launch 044 (beginning on Friday, Nov. 14, 2003), the RP cell will feature a second layer of batt insulation on the interior of the “occupiable” space. This insulation was installed today.</td>
</tr>
<tr>
<td>Tuesday, Nov. 18, 2003</td>
<td>DG1, DG2</td>
<td>In the DG1 cell, the number of nominal 8-in x 4-in x 16-in concrete blocks was doubled from 115 to [181]. Henceforth, the DG1 cell is referred to as the DG2 cell. In order to expose the most surface area, half of the blocks were stack on their ends along the east side of the test cell, while the other half were similarly stacked along the west side of the test cell.</td>
</tr>
<tr>
<td></td>
<td>RP</td>
<td>In the RP cell, a leak was discovered. Water was found in between the two layers of batt insulation in the “occupiable” space.</td>
</tr>
<tr>
<td>Thursday, Nov. 20, 2003</td>
<td>TW</td>
<td>On this day, just prior to launching the HOBOs for Launch 045 (beginning on Friday, Nov. 21, 2003), the staff finished the four pieces developed for closing the vents of the TW cell’s thermal storage wall. As soon as the staff develops a schedule for opening/closing the vents, they will begin a scheduled operation of the vents and will record it with within this log.</td>
</tr>
<tr>
<td>Thursday, Nov. 27, 2003</td>
<td>TW, WW, SS, RP, RP-DG</td>
<td>With the exception of the DG2 cell HOBOs (970, 971, 972, and 973), which were left at the usual height of 3.6-ft above the finish floor, all of the HOBOs were sent to the TW cell.</td>
</tr>
<tr>
<td></td>
<td>TW, RP-DG</td>
<td>This week, the RP-DG cell HOBOs (formerly SS cell HOBOs; which are 958, 959, 960, and 961) will be deployed in the upper part of the TW cell at 2-ft below the ceiling.</td>
</tr>
<tr>
<td></td>
<td>TW</td>
<td>The TW cell HOBOs (966, 967, 968, and 969) were deployed at 2-ft above the finish floor.</td>
</tr>
<tr>
<td></td>
<td>TW</td>
<td>The TW cell received the “stowaway” HOBOs.</td>
</tr>
</tbody>
</table>
Wednesday, Dec. 10, 2003  
RP-DG  
The garage door was installed in the RP-DG cell.

Thursday, Dec. 18, 2003  
RP-DG  
The RP-DG cell HOBOs (958, 959, 960, and 961) were launched in the completed RP-DG cell. The HOBOs were placed at the typical height of 3.6-ft above the finish floor. The garage door was set to open at 10:00 AM and close at 3:30 PM.

TW  
The TW cell HOBOs (966, 967, 968, and 969), which had been located at a height of 2-ft (60-cm) above the finish floor, were moved back the typical height of 3.6-ft above the finish floor.

RP  
In the read-out of RP cell HOBOs 957 and 955 for Launch 049 (which began on Thursday, Dec. 18, 2003), no data was found although they appear to have been properly launched. As a result, no Excel files could be created for those two HOBOs.

TW  
For Launch 049 (beginning on Dec. 18, 2003) the TW cell’s vents will be opened at 10:00 AM and closed at 3:30 PM.

Thursday, Jan. 15, 2004  
**ALL**  
For Launch 053 (beginning on Jan. 15, 2004), “stowaway” data will not be recorded because they were returned to CERES. There will not be data for the next Launch at least.

RP-DG, WW  
The doors of the RP-DG and WW cells could not be opened due to frost.

Sunday, May 16, 2004  
RP-DG  
The RP-DG cell’s upper glass was broken.

Monday, May 17, 2004  
RP, RP-DG  
The RP cell HOBOs (954, 955, 956, and 957) and RP-DG cell HOBOs (958, 959, 960, and 961) were downloaded in order to study what happened to the upper glass of the RP-DG cell. These file were named 070(a). Subsequently, they were re-launched as 070(b).
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thursday, May 20, 2004</td>
<td><strong>ALL</strong></td>
<td>Information from all of the HOBOs were downloaded as usual in order to read-out the data from the most recent launch.</td>
</tr>
<tr>
<td></td>
<td><strong>ALL</strong></td>
<td>In all of the test cells, one can observe the impact of the outdoor temperature changes from May 14th through May 15th, 2004.</td>
</tr>
<tr>
<td>Friday, May 21, 2004</td>
<td><strong>ALL</strong></td>
<td>During this week, the staff began to measure the grids established by Alfredo Fernández-González.</td>
</tr>
<tr>
<td>Wednesday, May 26, 2004</td>
<td>CC, DG2,</td>
<td>On May 26, 2004, the staff measured the CC, DG2, TW, and WW cells as illustrated by the charts.</td>
</tr>
<tr>
<td></td>
<td>TW, WW</td>
<td></td>
</tr>
<tr>
<td>Friday, May 28, 2004</td>
<td>RP, RP-DG</td>
<td>During Launch 072 (beginning on May 28, 2004), the staff measured the interior temperatures of the RP and RP-DG cells. The changes that are taking place become clear in the charts. One should especially note the relative humidity.</td>
</tr>
<tr>
<td>Friday, July 20, 2004</td>
<td><strong>ALL</strong></td>
<td>Launch 081 commenced at 12:00 AM.</td>
</tr>
<tr>
<td>Thursday, Aug. 5, 2004</td>
<td><strong>ALL</strong></td>
<td>Launch 081 ended at 9:20 PM, marking the end of test cell monitorization.</td>
</tr>
<tr>
<td>Thursday, Jan. 10, 2005</td>
<td>WEATHER</td>
<td>At 4:00 PM, the weather station was shutdown, marking the end of on-site weather data recording.</td>
</tr>
<tr>
<td></td>
<td>STATION</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX II

DESCRIPTION OF SOLRAD MODEL 6

The *Incident Solar Radiation Converter (SOLRAD) Models* are a series of six Microsoft Excel® based software programs that can be used to convert various solar radiation input values into equivalent values adjusted for planar surfaces of differing orientations. With guidance from Alfredo Fernández-González, director of the Natural Energies Advanced Technologies Laboratory (NEAT Lab) at the University of Nevada, Las Vegas (UNLV), the author developed these models as a precursor to the primary research conducted for this thesis. The six SOLRAD models are numbered in terms of specificity (and accuracy), with Model 1 being the most generic (and least accurate) and Model 6 being the most specific (and most accurate). *Please note that all six models use SI units.* Every SOLRAD model is available through the UNLV NEAT Lab.

Following its completion in November 2006, SOLRAD Model 6 was used to calculate weather and insolation data for the two principal years of the MPSP (2003 and 2004).

Below, all six SOLRAD models are briefly described. Following the descriptions, a formulaic narrative of SOLRAD Model 6 is provided.
Overview of SOLRAD Model 1

This model uses formulas derived from the 2001 ASHRAE Fundamentals Handbook to approximate the average hourly values of direct, diffuse, and reflected radiation for an entire day of a specified month. It also calculates transmitted values for each type of radiation based on a specified glazing type. Unlike the more advanced SOLRAD models, this model does not require any site specific radiation data. Users need only to specify the month of consideration, the number of days within that particular month, local latitude, local longitude, local standard time meridian (LSM), surface azimuth, surface tilt angle (from the horizon), extraterrestrial solar constant, ground reflectance, glazing type, and three parametric inputs from Chapter 30, Table 7 of ASHRAE (2001). Please note that results from SOLRAD Model 1 are typically the most inaccurate among the six models.

Figure A2.1  Screenshot of SOLRAD Model 1, Version 1.0

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Overview of SOLRAD Model 2

Model 2 is similar to Model 1; however Model 2 also requires an input value for the mean daily global irradiation on a horizontal surface. This value is readily available for a variety of locations in the United States via the Solar Radiation Data Manual for Buildings (NREL 1995). This manual, also commonly referred to as the blue book, was produced by the National Renewable Energy Laboratory's Analytic Studies Division under the Resource Assessment Program, which is funded and monitored by the U.S. Department of Energy's Office of Solar Energy Conversion. After inputting the proper monthly value for the mean daily global irradiation on a horizontal surface, Model 2 will approximate all 24 hourly values for an average day of the specified month. Model 2 will also provide equivalent transmitted radiation values for a specified glazing type.

**Figure A2.2** Screenshot of SOLRAD Model 2, Version 1.0

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Overview of SOLRAD Model 3

Model 3 is significantly more advanced than Models 1 or 2. Using formulas derived from a number of reputable published works, Model 3 possesses the ability to convert input hourly incident solar radiation values for a horizontal surface into the simultaneous incident solar radiation values for a surface of any tilt and/or azimuth at the same location. Model 3 can also provide equivalent transmitted radiation values for a specified glazing type. In addition to the inputs required by Models 1 and 2, this software requires hourly horizontal global irradiance data and daily input values related to extraterrestrial solar irradiance as defined by or interpolated from values of "C" listed in Chapter 30, Table 7 of ASHRAE (2001). The hourly horizontal irradiance data must be submitted in complete 24-hour intervals.

![Screenshot of SOLRAD Model 3, Version 1.0](image)

Figure A2.3  Screenshot of SOLRAD Model 3, Version 1.0

<table>
<thead>
<tr>
<th>LAT for March</th>
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<th>March 2</th>
<th>March 3</th>
<th>March 4</th>
<th>March 5</th>
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<th>March 7</th>
<th>March 8</th>
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<th>March 10</th>
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</tr>
</thead>
<tbody>
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<td>313.0°</td>
<td>313.0°</td>
<td>313.0°</td>
<td>313.0°</td>
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<td>313.0°</td>
<td>313.0°</td>
</tr>
</tbody>
</table>

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SOLRAD Model 4

This model is similar to Model 3, except that it uses additional input data to provide more accurate values. In addition to the input data required by Model 3, this processor requires hourly data for the ambient outdoor air temperature and relative humidity. Similar to the hourly horizontal global irradiance data, the outdoor air temperature and relative humidity data must be submitted in complete 24-hour intervals. However, as a result of the additional input, the values produced by Model 4 are considerably more accurate than those of Model 3.

Figure A2.4 Screenshot of SOLRAD Model 4, Version 1.0

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SOLRAD Model 5

Model 5 differs from Models 3 and 4 in the sense that it does not require complete 24-hour periods of hourly horizontal global irradiance values. Rather, this model can convert individual hourly input values.

One downfall of this model is its tendency to occasionally overestimate the incident solar radiation received during late-day, low-sun angle conditions. These issues have been addressed, however, and Model 5 is currently available under the much improved Release Version 1.2.

Figure A2.5  Screenshot of SOLRAD Model 5, Version 1.2
SOLRAD Model 6

Model 6 is the most sophisticated of the SOLRAD models. Similar to Model 5, it has the ability to convert individual hourly values of hourly horizontal global irradiance into simultaneous values for a surface of any tilt and/or azimuth at the same location. To address the inaccuracies of Model 5, SOLRAD Model 6 utilizes additional input data. Beyond the hourly horizontal global irradiance data, Model 6 also requires coinciding hourly ambient outdoor air temperature and relative humidity data.

As Model 6 was developed in concert with the closely-related Model 5, it is also currently available under Release Version 1.2.

![Screenshot of SOLRAD Model 6, Version 1.2](image-url)

Figure A2.6   Screenshot of SOLRAD Model 6, Version 1.2
As SOLRAD Model 6m Version 1.2 was employed for the purposes of this thesis, the remainder of this appendix delineates the process and equations utilized by Model 6. Please note that SOLRAD Model 6 is available through the UNLV NEAT Lab.

Formulaic Narrative of SOLRAD Model 6

The following section delineates a complete account of the formulas used within SOLRAD Model 6. This formulaic narrative may be used as a guide to help users understand the procedure by which this Model 6 processes various input data to determine hourly values of $K_t$, $I_{BT}$, $I_{dT}$, $I_{gT}$, and $I_T$, and equivalent transmitted hourly values of $I_{bT}$, $I_{dT}$, $I_{gT}$, and $I_T$.

*Please note that this program uses SI units.* This decision was dictated by the resources drawn upon to build the SOLRAD models, which were mostly published in SI units.

**Required Input Data**

In order to execute SOLRAD Model 6, users must provide several parametric inputs as well as three to four types of hourly data.

In addition to the hourly input data required by the program, SOLRAD Model 6 requires several parametric input values. To begin, the model requires three parameters regarding geographic information: LAT, LON, and LSM. Additionally, the program requires two pieces of information regarding the surface of consideration: $\psi$ and $\Sigma$. The user must also input two values related to the radiation data: $E_{ac}$ and $\rho_g$. This value of $\rho_g$ acts as a default value that will be overridden by any hourly $\rho_g$ data entered into the model. In order for the program to understand when the simulation period begins, the
user must define the initial value of \( \eta \). Finally, in the prompts provided in the *MAIN worksheet*, values of \( C \) must be provided for every day in which the user inputs hourly data. Values of \( C \) should be input consecutively, regardless of gaps in the hourly data.\(^1\) Values of \( C \) for every day of the year are provided on the *C worksheet* within SOLRAD Model 6. Be aware that if the hourly data is for a leap year, users must obtain values of \( C \) from the next day in succession for every day after February 28.

In addition to the parametric input values required by the program, SOLRAD Model 6 was designed to receive up to four types of input data—three of which are required. The three required hourly input data are: OT, RH, and I. The model can also receive hourly values of \( \rho_g \), which upon entry will replace the specified default value of \( \rho_g \). The hourly \( \rho_g \) data become especially useful when the ground reflectance is altered as a result of snow coverage or a change in the landscape.

**Solar Geometry Calculations**

The solar geometry calculations begin by mathematically determining the AST based on Equation 10 from Chapter 30 of the *2001 ASHRAE Fundamentals Handbook*:

\[
AST = LST + ET/60 + (LSM - LON)/15
\]

The LST is determined by converting the time of the day into decimal hours, such that 12:00 AM = 0.00, 1:00 AM = 1.00 ... 11:00 PM = 23.00.

---

\(^1\) The daily values of \( C \) defined in the *C worksheet* of SOLRAD Model 6 have been interpolated from values listed in Table 7 of Chapter 30 of the *2001 ASHRAE Fundamentals Handbook.*
The ET is determined by employing the following equation from Rosenthal (1993):

\[ ET = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \]

In this instance, \( B = \frac{360\degree}{(\eta - 81)/364} \) if \( \sin \) and \( \cos \) have arguments in degrees. If \( \sin \) and \( \cos \) have arguments in radians, then \( 2\pi (\eta - 81)/364 \).

Due to the Earth's equatorial plane being tilted at an angle of 23.45° to the orbital plane, the solar declination angle varies over the course of the year. Thus, \( \delta \) is calculated using the following formula from the ASHRAE (2001):

\[ \delta = 23.45 \sin\left\{ \frac{360 (284 + \eta)}{365} \right\} \]

In order to determine the sun's location at hourly intervals, the program must calculate the solar altitude (\( \beta \)) above the horizon as well as the solar azimuth (\( \Phi \)) measured from the south. To accomplish this, the hour angle must be determined. The formula for \( W_s \) was derived from ASHRAE (2001) and is as follows:

\[ W_s = 15(\text{AST} - 12) \]

The next two equations are also from ASHRAE (2001) and relate \( \beta \) and \( \Phi \) to the previously determined values of \( \text{LAT} \), \( \delta \), and \( W_s \):

\[ \sin \beta = \cos \text{LAT} \cos \delta \cos W_s + \sin \text{LAT} \sin \delta \]
\[
\cos \Phi = \frac{\sin \beta \sin \text{LAT} - \sin \beta}{\cos \beta \cos \text{LAT}}
\]

One should note that the hourly values of \( \Phi \) are adjusted such that the solar azimuth is positive for afternoon hours and negative for morning hours.

Using \( \Phi \) and \( \psi \), the program then needs to determine \( \gamma \) using the following equation from ASHRAE (2001):

\[
\gamma = \Phi - \psi
\]

Following these calculations, the program determines \( \theta \). For any surface, the incident angle \( \theta \) is related to \( \beta, Y, \) and \( \Sigma \) by the following equation from ASHRAE (2001):

\[
\cos \theta = \cos \beta \cos Y \sin \Sigma + \sin \beta \cos \Sigma
\]

For some analyses, it may be advantageous to know \( W_{sr} \) and \( W_{ss} \). In anticipation of such analyses, SOLRAD Model 6 calculates both \( W_{sr} \) and \( W_{ss} \) using the following formulas from Salgado et al. (1992):

\[
W_{sr} = \text{acos}(-\tan \text{LAT} \tan \delta)
\]

\[
W_{ss} = - W_{sr}
\]
Building off of Spencer (1971), the factor of correction for eccentricity in the Earth's trajectory around the sun \((E_o)\) is calculated using the following formula from Iqbal (1984):

\[
E_o = 1 + \{ 0.033 \cos[(360\times N)/365] \}
\]

Next, the \(H_o\) is calculated using a formula published by Orgil and Hollands (1977):

\[
H_o = E_{sc} \times E_o \times [\cos LAT \times \cos \delta \times \cos W_s + \sin LAT \times \sin \delta]
\]

Following this step, \(K_T\) is calculated according to Salgado et al. (1992):

\[
K_T = H / H_o
\]

After all previous calculations have taken place, SOLRAD Model 6 uses the following correlations to determine the diffuse fraction of the total horizontal radiation, \((I_d/I)\) from *Horizontal Radiation Mode 5* of the *TRNSYS 13.1 Type 16 Solar Radiation Processor* (Klein et al. 1990):

- Interval: \(0 < K_T < 0.3\)
- Constraint: \((I_d/I) < 1.0\)

\[
(I_d/I) = 1.000 - 0.232 \times K_T + 0.0239 \times \sin \beta - 0.000682 \times T_a + 0.0195 \times \frac{RH}{100}
\]
Interval: $0.3 < K_T < 0.78$
Constraint: $0.1 < (I_d/I) < 0.97$

$$(I_d/I) = 1.329 - 1.716 K_T + 0.267 \sin \beta - 0.00357 T_a + 0.106 \left(\frac{RH}{100}\right)$$

Interval: $0.78 < K_T$
Constraint: $0.1 < (I_d/I)$

$$(I_d/I) = 0.426 K_T - 0.256 \sin \beta + 0.00349 T_a + 0.0734 \left(\frac{RH}{100}\right)$$

Though the correlation from *Horizontal Radiation Mode 5* is activated within SOLRAD Model 6, the program also has the correlation from *Horizontal Radiation Mode 4* built into the program. With minor adjustments, the *Mode 4* correlation may be used instead of the correlation from *Mode 5*. However, Klein et al. (1990) acknowledges that the *Mode 4* correlation is a simplified version of the correlation from *Mode 5*.

According to Fernández-González (2007), $H_d$ may be calculated using the following formula:

$$H_d = H \ast (I_d/I)$$

In the case of SOLRAD Model 6, $I_i$ and $H$ may be considered as one in the same, as we are only considering *hourly* intervals. Thus, $I_b$ is calculated using the following formula from Salgado et al. (1992):

$$I_b = 1 - I_d$$
Next, the various radiation values must be adjusted for the specified surface orientation while negative values (which equates to an absence of solar radiation) are removed. To begin, the ratio of beam radiation on a tilted surface to the beam radiation on a horizontal surface ($R_b$) is equated using the following formula from Klein et al. (1990):

$$R_b = \cos \theta / \cos \theta_z$$

According to Salgado et al. (1992), $\cos \theta_z$ may be replaced with $\sin \beta$. For reasons relating to mathematical accuracy, the later variable is used primarily. However, when a value of $R_b$ is greater than 10, the former value is used to calculate $R_b$.

The cosine of the solar zenith angle is determined using the following equation from Klein et al. (1990):

$$\cos \theta_z = \sin \delta \sin \text{LAT} + \sin \text{LAT} \cos \delta \cos W_s$$

Using $R_b$, the program determines the $I_{bT}$ via the following formula from Klein et al. (1990):

$$I_{bT} = I_b \cdot R_b$$

The beta-testing of SOLRAD Model 6 revealed that during conditions in which $\beta$ was between -5° and 10°, a computational error occasionally occurred in which an hourly...
value of $I_{dT}$ was severely overestimated. Investigations into the matter revealed that the equations used to calculate $R_b$ are not well equipped for conditions in which $\beta$ is near the horizon. As such conditions lend only a minute amount of direct beam radiation, this error was easily fixed by programming all values of $\beta$ between -5° and 10° to be substituted with a value of 10°.

Next, the ratio of diffuse radiation on a tilted surface to the diffuse radiation on a horizontal surface ($R_d$) is determined using the following equation from Klein et al. (1990):

$$R_d = 0.5 (1 + \cos \beta)$$

From this, SOLRAD Model 6 calculates $I_{dT}$ using the following formula from Klein et al. (1990):

$$I_{dT} = I_d * R_d$$

Klein et al. (1990) also provides a formula to determine the ratio of reflected radiation on a tilted surface to the total radiation on a horizontal surface ($R_r$). SOLRAD Model 6 uses this formula, which reads as follows:

$$R_r = 0.5 (1 - \cos \beta) \rho_g$$
The equation used by SOLRAD Model 6 to determine $I_{gT}$ is derived from the *2001 ASHRAE Fundamentals Handbook*. The formula reads as follows:

$$I_{gT} = I_{bT} (C + \sin\beta)\rho_g * (1 - \cos\gamma)/2$$

According to Klein et al. (1990), once the hourly values for $I_{bT}$, $I_{dT}$, and $I_{gT}$ have been calculated, $I_T$ is determined via the summation of these three values:

$$I_T = I_{bT} + I_{dT} + I_{gT}$$

Since it is often useful to have the transmitted values for $I_{bT}$, $I_{dT}$, $I_{gT}$, and $I_T$ through a particular type of glazing, SOLRAD Model 6 also determines hourly values of transmitted $I_{bT}$, $I_{dT}$, $I_{gT}$, and $I_T$ through a specified glazing system. Version 1.2 of SOLRAD Model 6 enables users to specify one of seven types of glazing:

- 1/8” uncoated single glazing (CLR)
- 1/8” uncoated double glazing (CLR CLR)
- 1/8” low-e (e = 0.2) double glazing (LE CLR)
- 1/8” low-e (e = 0.2) double glazing (CLR LE)
- 1/8” low-e (e = 0.05) double glazing (LE CLR)
- 1/8” uncoated triple glazing (CLR CLR CLR)
- 1/8” low-e (e = 0.2) triple glazing (CLR CLR LE)
Each programmed glazing system exhibits specifications as listed in Chapter 30, Tables 4 and 13 of the 2001 ASHRAE Fundamentals Handbook. Using the center-of-glazing SHGC values for incident angles of 0°, 40°, 50°, 60°, 70°, 80° and diffuse conditions as listed in Chapter 30, Table 13 of ASHRAE (2001) for the specified glazing system, SOLRAD Model 6 uses interpolation to determine the SHGC for every degree of θ from 0° through 90° (plus the diffuse value). In turn, SOLRAD Model 6 uses these values of SHGC to determine the transmitted hourly values of \( I_{bT}, I_{dT}, I_{gT}, \) and \( I_T \) based on the coinciding hourly \( \theta \).

Finally, the computed values of \( K_T, I_{bT}, I_{dT}, I_{gT}, \) and \( I_T \), as well as the transmitted \( I_{bT}, I_{dT}, I_{gT}, \) and \( I_T \), are communicated to the user of the program. Within the MAIN worksheet, \( K_T, I_{gT}, \) and \( I_T \) are presented explicitly. As well, the input \( H \) data and output \( I_T \) data are plotted on a chart in order to graphically communicate the results. The chart depicts values over the entire duration of the maximum 31-day period of consideration.
APPENDIX III

DESCRIPTION OF MPSP SIMULATION MODELS

In order to fulfill the purposes of this thesis, the thermal performance of the considered MPSP test cells must be compared against the values predicted by the LCR method as defined by Balcomb et al. (1984). From such a comparison, one could then draw conclusions regarding the aptness of the LCR method for estimating the thermal performance of various passive solar strategies in a harsh winter climate with predominantly cloudy sky conditions.

However, the LCR method was designed to predict annual thermal performance. While they were monitored for nearly two years, the thermal performance of the MPSP test cells were not recorded continuously. Gaps in measured data ranged between a few hours to several days. Additionally, every cell endured modifications, system irregularities, and malfunctions to some degree. In order to conduct a useful comparison between the thermal performance of the MPSP test cells and the predicted performance values from the LCR method, a full year of continuous thermal performance data was required from each of the test cells. Furthermore, the test cells had to operate devoid of systemic modifications, irregularities, or malfunctions. Therefore, thermal performance simulation models were built in order to provide such data.

The simulation models were used to emulate the thermal performance of every considered MPSP test cell over the course of their two primary years of monitorization.
Each two-year simulation run was conducted as if each test cell did not receive any physical modifications nor endure any systemic irregularities or malfunctions. With regard to the accuracy of the simulation models, measured data from each of the considered MPSP test cells were used to calibrate the output from the simulation models.

The following appendix provides a detailed formulaic narrative for each of the MPSP thermal simulation models. Each narrative outlines the procedures and published formulas employed by the various models, as well as other pertinent information regarding the development of the models. Following these narratives, the accuracy and validity of the simulation models are demonstrated.

Description of MPSP Simulation Models

The MPSP simulation models are a series of Microsoft Excel® based thermal performance simulation models that employ documented formulas in order to simulate the thermal performance of the MPSP test cells. Specifically, by using various input data the MPSP simulation models were designed to simulate the hourly indoor air temperature of the considered test cells both with and without an auxiliary heat source. Essentially, there are seven simulation models—one for every test cells except the SS cell. However, the RP and RP-DG simulation models feature a supplemental eighth simulation model solely devoted to the thermal performance of the roofpond system and its integral thermospace (known as the RP-T simulation model). The RP and RP-DG simulation models only consider the components of the test cells below the level of the ceiling. Thus, they are necessarily coupled with copies of the RP-T model as the occupiable
volume and thermospace are, in fact, two separate thermal zones that must be independently simulated. The hourly heat exchange between the thermal zones is determined and implemented by each simulation model.

Below, a detailed formulaic narrative is given for each of the simulation models. Please observe that each simulation model was carefully calibrated. Following the narratives, the validity of the simulation models will be demonstrated.

Formulaic Narrative of the Control Cell (CC) Simulation Model

The CC simulation model served as the basic model from which the rest of the models were built. Therefore, the proceeding formulaic narrative is the most comprehensive description among all of the formulaic narratives featured in this chapter. The subsequent narratives for the various passive solar test cells' simulation models will make frequent reference to the CC simulation model's narrative. Even though a complete account of every implemented formula will be disclosed for each narrative, many characteristics of the CC simulation model that reoccur within the rest of the simulation models may not be as thoroughly delineated in the subsequent narratives. Rather, such characteristics are delineated within the succeeding narratives in a generalized fashion. As a result, readers are urged to read the following formulaic narrative before proceeding to that of another simulation model presented in this chapter.

Unlike the SOLRAD models, which were based on SI units for international usage, every MPSP test cell simulation model uses I-P units. This decision was influenced by the critical resources drawn upon to build the simulation models. Most of these resources
were published using I-P units. Therefore, all of the equations presented below use I-P units.

**Required Input Data**

In order to execute the CC simulation model, a number of parametric inputs as well as several forms of hourly data were provided.

With regard to parametric input values, the CC simulation model required the following: $A_{n\text{-wall}}$, $A_{s\text{-wall}}$, $A_{c\text{-wall}}$, $A_{w\text{-wall}}$, $A_{roof}$, $A_{floor}$, $A_{n\text{-door}}$, $U_{n\text{-wall}}$, $U_{s\text{-wall}}$, $U_{e\text{-wall}}$, $U_{w\text{-wall}}$, $U_{roof}$, $U_{floor}$, $U_{n\text{-door}}$, $TA$, $VOL_{air}$, $ACH$, $OC$, $Q_{\text{int}}$, $SC$, $\alpha_{c\text{-walls}}$, $\alpha_{roof}$, $CAP$, $ESL$, and $T_{\text{set}}$.

The various values of area for the CC exterior envelope were derived from cataloged field measurements and data, as well as construction drawings. This prior documentation was also relied upon for the value of $TA$, $VOL_{air}$, and $CAP$.

The various overall thermal conductance values relating to the CC exterior envelope were derived using the parallel path method as defined by ASHRAE (2001).

The initial $ACH$ value used by the CC simulation model was calculated after using the HERS rule-of-thumb and the $ACH_{50}$ value obtained after a blower door test. During the calibration of the simulation model, an adjustment was made to this value based on related measured data. The verisimilitude of the adjusted $ACH$ value is lent by the accuracy of the CC simulation model.

The $OC$ was set to zero for the CC simulation model. This value was applied consistently to every model.

---

1 According to the 2001 *ASHRAE Fundamentals Handbook*, the parallel path method enables an average $U$-value of an exterior envelope component featuring two or more different assemblies (e.g. the frame and infill areas of a stud wall) to be calculated by first determining the $U$-values of each assembly, then multiplying each value times the fraction of the component each assembly constitutes. The summation of these products will yield the average $U$-value of the component in consideration.
As with every simulation model, the CC model was also devoid of any internal heat sources. Therefore, $Q_{\text{int}}$ was set to 0 Btu/h.

The exterior walls of the CC were painted a fairly dark grey. While the $\alpha_{\text{ex-walls}}$ value was never specifically recorded, calibration studies indicated that the value was 0.73. The same paint was applied to every test cell; thus this value was consistently applied to all of the simulation models. The $\alpha_{\text{roof}}$ value exhibited by the CC (which was cloaked with an EPDM liner) was similarly determined to be 0.93. Every test cell featured the same type of liner; thus this value was consistently applied to all of the simulation models.

While Muncie's general elevation is considered to be 940-feet, the site-specific ESL was determined to be 935-feet. This value is later used to determine the ADR.

The $T_{\text{set}}$ for every test cell simulation model was set to 65°F. This value was set continuously throughout the two-year simulation run.

In addition to the parametric input values, the CC simulation model required several forms of hourly data. From the on-site weather station, the following hourly data are required: $T_s$, $T_{\text{ws}}$, RH, DP, and $V_{\text{wind}}$. Since the MPSP test cells were set atop a concrete patio, hourly values of $\rho_g$ were assumed to be the 0.3 unless snow coverage was recorded by the National Climate Data Center’s (2007) Muncie weather station at Ball State University—in which case, an hourly $\rho_g$ value of 0.7 was assumed. From SOLRAD Model 6, hourly data for the following were required: $K_T$, $H$, $H_s$, and $H_w$.

Please note, the simulation model also received measured performance data from the CC itself, but the data were only used for comparative purposes. They did not factor into the simulation model's algorithm.
Air Density Ratio Calculations

As with all of the simulation models, the CC model calculated the ADR by employing the following equation derived from the trendline depicting the ADR for different elevations as published on page 3-2 of Balcomb et al. (1984):

\[
ADR = -0.0321 \left( \frac{ESL}{1000} \right) + 1
\]

Capacitance Calculations

In order to obtain the most accurate simulation possible, the value for CAP was determined using a separate worksheet dedicated to calculating the cell’s capacitance. This worksheet was added to and utilized by every test cell simulation model.

According to Stein et al. (2006), the thermal capacity (Btu/ft\(^3\) °F) of any material may be determined via the product of its density and specific heat. Using recorded measurements, each component’s capacitance (Btu/°F) was determined using the following formula:

\[
CAP_{\text{component}} = d \cdot c \cdot A_x \cdot L
\]

This process was repeated for every material in the test cell with thermal mass. Finally, the total capacitance was determined via a summation of the CAP values from each of the thermally massive components within the test cell:

\[
CAP_{\text{total}} = \text{Sum of} \ CAP_{\text{components}}
\]
Total Load Coefficient Calculations

The TLC was calculated using the following equation from Moore (1994):

\[ TLC = 24 \times U_{A_{\text{total}}} \]

The \( U_A \) values were determined by multiplying the area and overall thermal conductance value of each exterior building component (e.g. \( U_{A_{s\text{-wall}}} = U_{s\text{-wall}} \times A_{s\text{-wall}} \)). The one exception to this method is the \( U_A \) value for infiltration (\( U_{A_{\text{inf}}} \)). This variable was calculated using the following equation from Balcomb et al. (1984):

\[ U_{A_{\text{inf}}} = 0.018 \times V_{OL_{\text{air}}} \times ACH \times ADR \]

Sol-Air Temperature Calculations

Next, the simulation model calculated hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the CC. Obviously, hourly sol-air temperatures for the test cell’s horizontal roof and vertical south-facing surface were determined. However, since the CC was situated to the west of the remaining test cells, sol-air temperatures for the cell’s vertical west-facing surface were also calculated. Additionally, sol-air temperatures for the horizontal ground surface surrounding the test cell were calculated. As described in the previous chapter, the test cells were propped off of a concrete patio by nearly 2 inches. During the calibration of
the simulation models it became apparent that the sol-air temperature of the concrete
patio had a significant impact on the thermal performance of the CC.

According to ASHRAE (2001), the sol-air temperature is the temperature of the
outdoor air which, in the absence of radiation changes, provides the identical rate of heat
entry into the surface as would the combination of incident solar radiation, the radiant
energy exchange with the sky as well as various other outdoor surroundings, and the
convective heat exchange with the outdoor air. Thus, the following simplified equations
from ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces: \[ S_x = T_a + \left( \frac{\alpha x H_x}{h_o} \right) - 7^\circ F \]

For vertical surfaces: \[ S_v = T_a + \left( \frac{\alpha x H_v}{h_o} \right) \]

The value of \( \alpha_x \) depended on the surface being considered (e.g. \( \alpha_{ex-wall} \), \( \alpha_{roof} \), or \( \rho_g \)).

Similarly, the hourly value of \( H_x \) depended on which surface was being considered
(e.g. \( H, H_s, \) or \( H_w \)).

According to ASHRAE (2001) and Stein et al. (2006), it is common practice to
assume that \( h_o \) is 3.0 Btu/h ft\(^2 \) \(^\circ F\). All of the simulation models made this assumption.

The \( S_x \) had to be calculated for four different surfaces, thus the program used the
previously identified variables to calculate \( S_{s-wall}, S_{w-wall}, S_{roof}, \) and \( S_{ground} \).

**CERES Patio Surface Temperature Calculation**

During the calibration phase of the simulation models’ development, it was
discovered that the patio of Ball State University’s Center for Energy

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Research/Education/Service (CERES), atop which the test cells were erected, was having an unanticipated effect on the test cells' thermal performance. The CERES patio is situated atop an enclosed conditioned space.

After a meticulous process of reverse engineering, the author, under the guidance of Professor Alfredo Fernández-González, has managed to distill the affect of the CERES patio into a single equation which implemented two unique variables. This equation was necessarily applied to every simulation model. *Please note that this was a very unusual and site-specific characteristic of the simulation models. If any of the simulation models were to be applied to a different environment, users should eliminate or otherwise disable this step within the models. Rather, the hourly heat exchange through the floor may be calculated in a regular fashion, as described by Balcomb et al. (1984) or Stein et al. (2006).*

The employed formula for determining the surface temperature of the concrete patio upon which the MPSP test cells were constructed ($T_{\text{patio}}$) was as follows:

$$T_{\text{patio}} = S_{\text{ground}} + x(y - S_{\text{ground}})$$

The variables $x$ and $y$ related to the conditioning of the spaces below the CERES patio. As information regarding the conditioning of the spaces below the patio was not recorded, the heat transfer through the patio and the subsequent effect on the thermal performance of the test cells was unpredictable. Nonetheless, monthly values for variables $x$ and $y$ were reverse engineered during the calibration studies. Please refer to Table A3.1 for a list of the monthly values of $x$ and $y$. Please note that these values were
unique to the specific year and month listed. It is suggested that future research endeavors regarding the MPSP investigate this issue more thoroughly to understand the effect of the CERES patio more thoroughly. At this time, the above mentioned formula and the values listed below adequately compensated for the effect of the patio on the test cells within the thermal simulation models.

<table>
<thead>
<tr>
<th>Month</th>
<th>2003 Values</th>
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<tr>
<td>January</td>
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<td>1.00</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>February</td>
<td>0.60</td>
<td>0.40</td>
<td>35</td>
<td>45</td>
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<tr>
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<td>1.00</td>
<td>1.00</td>
<td>40</td>
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</tbody>
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* Speculative values based on the previous year's data and/or observable trends.

**Hourly Heat Exchange Calculations**

Once the above mentioned calculations had taken place for a considered hour, the CC simulation model proceeded to calculate the composite heat exchange through the test cell. Depending on the orientation and nature of a given surface, the exchange was calculated somewhat differently. Therefore, it is necessary to delineate every equation
used to calculate the composite hourly heat exchange below. These equations drew on the
textbook for calculating design heat loss published by Stein et al. (2006). Please note
that the equations listed below were uniquely designed for the CC cell:

\[ Q_{s\text{-wall}} = U_{A_{s\text{-wall}}} \times (T_{prev} - S_{s\text{-wall}}) \]

\[ Q_{n\text{-wall}} = U_{A_{n\text{-wall}}} \times (T_{prev} - T_a) \]

\[ Q_{e\text{-wall}} = U_{A_{e\text{-wall}}} \times (T_{prev} - T_a) \]

\[ Q_{w\text{-wall}} = U_{A_{w\text{-wall}}} \times (T_{prev} - S_{w\text{-wall}}) \]

\[ Q_{n\text{-door}} = U_{A_{n\text{-door}}} \times (T_{prev} - T_a) \]

\[ Q_{floor} = U_{A_{floor}} \times (T_{prev} - T_{\text{pato}}) \]

\[ Q_{roof} = U_{A_{roof}} \times (T_{prev} - S_{\text{roof}}) \]

The \( Q_{inf} \) was similarly calculated as listed below. However, during the calibration of
the MPSP test cell simulation models, the simulation model required the ratio of the
ambient outdoor air temperature to the wind chill temperature \( (T_a/T_{wc}) \) to serve as a
multiplier in order to match the test cell’s measured values. Thus, the following equation:
\[ Q_{\text{inf}} = UA_{\text{inf}} \times (T_{\text{prev}} - T_a) \times (T_a / T_{\text{wc}}) \]

There were no internal gains. Therefore, \( Q_{\text{int}} \) was continuously set to 0 Btu/h.

While subsequent calculations simply drew on the previous hour’s \( T_{\text{int}} \) value for the \( T_{\text{prev}} \) value, the initial hour’s heat exchange calculations required a manually input value for \( T_{\text{int}} \). This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the CC simulation model received either an arbitrary \( T_{\text{prev}} \) value influenced by the actual measured data from the previous hour or the most recently calculated value of \( T_{\text{int}} \), even if the value was not calculated for the previous hour.

For the CC simulation model, the hourly value of \( Q_{\text{total}} \) was simply a summation of the calculated hourly heat exchange values:

\[
Q_{\text{total}} = Q_{\text{s-wall}} + Q_{\text{n-wall}} + Q_{\text{e-wall}} + Q_{\text{w-wall}} + Q_{\text{n-door}} + Q_{\text{floor}} + Q_{\text{roof}} + Q_{\text{inf}} + Q_{\text{int}}
\]

It is important to note that a positive value for \( Q_s \) equated to a loss of heat through the structure. Conversely, a negative value of \( Q_s \) equated to a gain of heat through the structure (i.e. a \( Q_{\text{total}} \) of -500 Btu/h indicated a collective gain of heat by the cell during the hour of consideration and a \( Q_{\text{total}} \) of 500 Btu/h indicated a collective loss of heat by the cell during the hour of consideration).
Hourly Indoor Air Temperature Calculations

The simulated internal air temperature of the CC for any given hour was calculated using the following formula from Professor Alfredo Fernández-González (2007):

$$ T_{int} = \frac{Q_{total}}{CAP} $$

HVAC Simulation Calculations

Once the CC simulation model was calibrated, an amended second version of the simulation model was designed to emulate the energy use and thermal performance influence of an auxiliary heat source within the test cell. Under the guidance of Professor Alfredo Fernández-González, the HVAC-enabled version of the CC simulation model was designed to communicate the effect a thermostat-linked auxiliary heat source would have on $Q_{total}$ on an hourly basis. Please note that auxiliary cooling was never implemented into the models.

There were three basic calculation steps that separated the HVAC-enabled model from the free-running model. The first of which was the modified equation used to calculate $T_{int}$:

$$ T_{int} = \left[ \frac{Q_{total} + Q_{aux-ap}}{CAP} \right] $$

---

2 The mode of operation termed free-running refers to the condition in which the test cell or simulation model operates devoid of internal gains or auxiliary heat.
Next, the hour value of $Q_{aux}$ was calculated using the following formula from Fernández-González (2007):

\[
\text{If } T_{int} < T_{set}, \text{ then: } Q_{aux} = -(T_{set} - T_{int}) \times CAP \\
\text{Otherwise: } Q_{aux} = T_{int}
\]

Finally, the value of $Q_{aux}$ was adjusted ($Q_{aux-a}$) as follows:

\[
\text{If } Q_{aux} > 0, \text{ then: } Q_{aux-a} = 0 \\
\text{Otherwise: } Q_{aux-a} = Q_{aux}
\]

This last step was necessary due to the fact that a mathematically positive value for $Q_{aux}$ simply indicated an absence of auxiliary heat during the current hour and a mathematically negative value of $Q_{aux}$ indicated the degree of utilized auxiliary heat during the current hour. Therefore, only negative values of $Q_{aux}$ were desired.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $Q_{aux-a}$ value for its $Q_{aux-ap}$ value. However, the initial hour’s HVAC-enabled calculations required a manually input value for $Q_{aux-ap}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the HVAC-enabled simulation model received either an arbitrary value for $Q_{aux-ap}$ influenced by the $T_{set}$ input value or the most recently calculated value of $Q_{aux-a}$, even if the value was not calculated for the previous hour.
Formulaic Narrative of the Direct Gain, Model 1 (DG1) and Direct Gain, Model 2 (DG2) Simulation Models

The DG1 and DG2 simulation models were built upon the algorithm of the CC simulation model, amending and adding various formulas in order to emulate the effects of the test cells' direct gain passive solar heating systems.

As with the CC model, the DG1 and DG2 models used I-P units. Again, this was dictated by the critical resources drawn upon to build the simulation models.

**Required Input Data**

In order to execute the DG1 and DG2 simulation models, a number of parametric inputs as well as several forms of hourly data were provided.

With regard to parametric input values, the DG1 and DG2 simulation models required the same variables as the CC model plus additional input values regarding their south-facing windows. Thus, the direct gain simulation models required the following: \( A_{\text{n-wall}}, A_{\text{s-wall}}, A_{\text{e-wall}}, A_{\text{w-wall}}, A_{\text{roof}}, A_{\text{floor}}, A_{\text{n-door}}, A_{\text{s-win}}, U_{\text{n-wall}}, U_{\text{s-wall}}, U_{\text{w-wall}}, U_{\text{roof}}, U_{\text{floor}}, U_{\text{n-door}}, U_{\text{s-win}}, TA, \text{VOL}_{\text{air}}, ACH, OC, Q_{\text{int}}, SC, \alpha_{\text{ex-wall}}, \alpha_{\text{roof}}, \text{CAP}, \text{ESL}, \) and \( T_{\text{set}}. \)

As with the CC model, the various areas of the DG1 and DG2 cells' exterior envelope components were derived from cataloged field measurements, recorded data, and construction drawings. This prior documentation was also relied upon for the value of \( TA, \text{VOL}_{\text{air}}, \) and \( \text{CAP}. \)

As with every simulation model, the various overall thermal conductance values relating to the DG1 and DG2 cells' exterior envelopes were derived using the parallel path method as defined by ASHRAE (2001).
Consistent with the other simulation models, the initial ACH values used in the DG1 and DG2 models were calculated after using the HERS rule-of-thumb and the ACH\textsubscript{50} value obtained after a blower door test. During the calibration of the simulation models, the values of ACH were adjusted in order to better emulate the actual performance of the DG1 and DG2 cells.

To reiterate, the value of OC was fixed at zero. This was consistently applied to every simulation model.

Again, every MPSP test cell was devoid of internal heat sources. Thus, the Q\textsubscript{int} was set to 0 Btu/h.

The exterior walls of the DG1 and DG2 cells were painted with the same grey paint as the CC. Thus, the $\alpha_{\text{ex-walls}}$ value for both DG1 and DG2 was set to 0.73. Both cells also exhibited the same EDPM liner as specified for the CC. Therefore, both models’ value of $\alpha_{\text{roof}}$ was set to 0.93.

Consistent with the other test cells, the ESL was set to 935-feet.

As well, the $T_{\text{set}}$ for both DG1 and DG2 was set to 65°F.

In addition to the parametric input values, the DG1 and DG2 simulation models required much of the same forms of hourly data as the CC simulation model. As with the CC simulation model, the following hourly data, as obtained from the on-site weather station, was required: $T_{\text{a}}$, $T_{\text{wc}}$, RH, DP, and $V_{\text{wind}}$. Please refer back to the CC formulaic narrative for information regarding the hourly values of $p_\infty$. The DG1 and DG2 models also required the following hourly data derived from SOLRAD Model 6: $K_T$, $H$, $H_s$.

However, rather than requiring $H_\infty$ as the CC model did for calculating the hourly $S_{\text{w-wall}}$, the DG1 and DG2 models required $H_{s-tran}$, as the test cells featured south-facing,
unshaded glazing. Please note that hourly input data were consistently applied to every
simulation model.

Please note, the DG1 and DG2 simulation models received measured performance
data (when available) from the test cells themselves. However, as with all of the
simulation models, the data was only used for comparative purposes. The data did not
factor into the simulation models’ calculations.

**Air Density Ratio Calculations**

As with all of the simulation models, the DG1 and DG2 models calculated the ADR
by employing the following equation derived from the trendline depicting the ADR for
different elevations as published on page 3-2 of Balcomb et al. (1984):

\[
ADR = -0.0321 \left( \frac{ESL}{1000} \right) + 1
\]

**Capacitance Calculations**

The DG1 and DG2 simulation models utilized a separate worksheet solely dedicated
to calculating the CAP for both the DG1 and DG2 cells. The worksheet is identical to that
described within the CC model’s formulaic narrative. In fact, the worksheet was utilized
by all of the simulation models.

To reiterate, the worksheet utilized the method of calculating a material’s thermal
heat capacity (Btu/ft^3 °F) as described by in the previous narrative. Using recorded
measurements, each component’s capacitance (Btu/°F) was determined using the
following formula:
This process was repeated for every thermally massive material in the DG1 and DG2 cells. Finally, the total capacitance for each cell was determined via a summation of the CAP values from the cells’ individual thermally massive components:

\[ \text{CAP}_{(\text{total})} = \text{Sum of CAP}_{(\text{components})} \]

**Total Load Coefficient Calculations**

Consistent with the CC model, the DG1 and DG2 models used the following equation from Moore (1994) to calculate the TLC:

\[ \text{TLC} = 24 \times \text{UA}_{\text{total}} \]

The UA values were determined by multiplying the area and overall thermal conductance value of each exterior building component (e.g. \( \text{UA}_{\text{s-wall}} = \text{U}_{\text{s-wall}} \times \text{A}_{\text{s-wall}} \)). The one exception to this method was the UA value for infiltration (\( \text{UA}_{\text{inf}} \)). This variable was calculated using the following equation from Balcomb et al. (1984):

\[ \text{UA}_{\text{inf}} = 0.018 \times \text{VOL}_{\text{air}} \times \text{ACH} \times \text{ADR} \]
Sol-Air Temperature Calculations

Next, the DG1 and DG2 models calculated hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the DG1 and DG2 cells. Specifically, hourly sol-air temperatures for the cells’ horizontal roof and vertical south-facing surfaces were determined. Unlike the CC model, the DG1 and DG2 models did not require sol-air temperature calculations for their vertical west-facing surfaces, as they were adequately shaded by adjacent test cells. However, sol-air temperatures for the horizontal ground surface surrounding the DG1 and DG2 cells had to be calculated. As described in the previous chapter, the test cells were propped off of a concrete patio by nearly 2 inches. During the calibration of the simulation models it became apparent that the sol-air temperature of the concrete patio had a significant impact on the thermal performance of the DG1 and DG2 cells.

As with the CC simulation model, the DG1 and DG2 models utilized the proceeding simplified equations for calculating the sol-air temperatures of both horizontal and vertical surfaces as detailed by ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces: \( S_x = T_a + \left[ \frac{(a_x H_x)}{h_o} \right] - 7^\circ F \)

For vertical surfaces: \( S_x = T_a + \left[ \frac{(a_x H_x)}{h_o} \right] \)

The value of \( a_x \) depended on the surface being considered (e.g. \( a_{\text{ex-walls}} \), \( a_{\text{roof}} \), or \( p_g \)).
Similarly, the hourly value of \(H_x\) depended on which surface was being considered (e.g. \(H\) or \(H_0\)).

According to ASHRAE (2001) and Stein et al. (2006), it is common practice to assume that \(h_o\) is 3.0 Btu/h ft\(^2\) °F. All of the simulation models made this assumption.

In the case of the DG1 and DG2 simulation models, \(S_x\) had to be calculated for three different surfaces: \(S_{\text{wall}}\), \(S_{\text{roof}}\), and \(S_{\text{ground}}\).

**CERES Patio Surface Temperature Calculation**

Please refer to the CC simulation model narrative for an explanation of how the effect of the CERES patio was compensated for within the DG1 and DG2 simulation models. The formula used to determine the surface temperature of the concrete patio upon which the MPSP test cells were constructed (\(T_{\text{patio}}\)) was as follows:

\[
T_{\text{patio}} = S_{\text{ground}} + x(y - S_{\text{ground}})
\]

As described within the CC simulation model’s formulaic narrative, the variables \(x\) and \(y\) related to the conditioning of the spaces below the CERES patio. As information regarding the conditioning of the spaces below the patio was not recorded, the heat transfer through the patio and the subsequent effect on the thermal performance of the test cells was unpredictable. Nonetheless, monthly values for variables \(x\) and \(y\) were reverse engineered during the calibration studies. Please refer back to Table A3.1 for a list of the monthly values of \(x\) and \(y\). Please note that these values were unique to the specific year and month listed.
Hourly Heat Exchange Calculations

Once the above mentioned calculations had taken place for a given hour, the DG1 and DG2 simulation models proceeded to calculate the composite heat exchange through their respective test cells. Depending on the orientation and nature of a given surface, the exchange was calculated somewhat differently. Therefore, it was necessary to delineate every equation used to calculate the composite hourly heat exchange below. These equations drew on the methodology for calculating design heat loss published by Stein et al. (2006). Please note that due to the extreme similarities between the DG1 and DG2 test cells, both direct gain simulation models calculated their respective cell’s hourly heat exchange using the same formulas. Also note that the following series of formulas were uniquely designed for the DG1 and DG2 simulation models:

\[ Q_{s\text{-wall}} = U_{A_{s\text{-wall}}} \times (T_{\text{prev}} - S_{s\text{-wall}}) \]

\[ Q_{n\text{-wall}} = U_{A_{n\text{-wall}}} \times (T_{\text{prev}} - T_{a}) \]

\[ Q_{e\text{-wall}} = U_{A_{e\text{-wall}}} \times (T_{\text{prev}} - T_{a}) \]

\[ Q_{w\text{-wall}} = U_{A_{w\text{-wall}}} \times (T_{\text{prev}} - T_{a}) \]

\[ Q_{s\text{-win}} = U_{A_{s\text{-win}}} \times (T_{\text{prev}} - T_{a}) \]

\[ Q_{n\text{-door}} = U_{A_{n\text{-door}}} \times (T_{\text{prev}} - T_{a}) \]
\[ Q_{\text{floor}} = U A_{\text{floor}} \times (T_{\text{prev}} - T_{\text{patio}}) \]

\[ Q_{\text{roof}} = U A_{\text{roof}} \times (T_{\text{prev}} - S_{\text{roof}}) \]

\[ Q_{\text{inf}} \] was calculated as listed below. However, please note that during the calibration of the MPSP test cell simulation models, the ratio of the ambient outdoor air temperature to the wind chill temperature \( T_{\text{a}}/T_{\text{wc}} \) was required as a multiplier by each model’s hourly \( Q_{\text{inf}} \) calculations in order to match each test cell’s measured performance values. Thus, the following equation:

\[ Q_{\text{inf}} = U A_{\text{inf}} (T_{\text{prev}} - T_{\text{a}}) \times (T_{\text{a}}/T_{\text{wc}}) \]

There were no internal gains. Therefore, \( Q_{\text{int}} \) was continuously set to 0 Btu/h.

While subsequent calculations could simply have drawn on the previous hour’s \( T_{\text{int}} \) value for the \( T_{\text{prev}} \) value, the initial hour’s heat exchange calculations required a manually input value for \( T_{\text{int}} \). This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the DG1 and DG2 simulation models received either an arbitrary \( T_{\text{prev}} \) value influenced by the actual measured data from the previous hour or the most recently calculated value of \( T_{\text{int}} \), even if the value was not calculated for the previous hour.

As the DG1 and DG2 cells featured south-facing glazing as part of their direct gain strategies, their simulation models had to calculate the transmitted radiation through the
glazing. This is accomplished using the following formula from Fernández-González (2007):

\[ Q_{\text{sol}} = m A_{s-win} H_{s-tran} \]

A correction multiplier \( m \) had to be applied to \( Q_{\text{sol}} \) due to the gradual accumulation of particulate matter upon the surface of the south-facing glazing, which subsequently reduced its ability to absorb incident solar radiation. Further analyses indicated that the impact of the glazing's dirtiness was also somewhat affected by the Sun's altitude. Thus, on occasion the value of \( m \) slightly increased or decreased in an unexpected fashion from one month to the next. Table A3.2 lists the monthly values of \( m \) used to correct the value of \( Q_{\text{sol}} \). Please note that the south-facing glass of the MPSP test cells was cleaned in late January 2004.

Finally, the hourly value of \( Q_{\text{total}} \) for the DG1 and DG2 models was calculated via a summation of the previously explained hourly heat exchange values:

\[ Q_{\text{total}} = Q_{s-wall} + Q_{n-wall} + Q_{c-wall} + Q_{w-wall} + Q_{s-win} + Q_{n-door} + Q_{floor} + Q_{roof} + Q_{inf} + Q_{int} + Q_{sol} \]

It is important to note that a positive value for \( Q_x \) equated to a loss of heat through the structure. Conversely, a negative value of \( Q_x \) equated to a gain of heat through the structure (i.e. a \( Q_{\text{total}} \) of -500 Btu/h indicated a collective gain of heat by the cell during the hour of consideration and a \( Q_{\text{total}} \) of 500 Btu/h indicated a collective loss of heat by the cell during the hour of consideration).

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Table A3.2 Scheduled Values of Variable $m$

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<th>Month</th>
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<td>February</td>
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<td>April</td>
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<td>0.88</td>
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<tr>
<td>May</td>
<td>0.90</td>
<td>0.85</td>
</tr>
<tr>
<td>June</td>
<td>0.88</td>
<td>0.85</td>
</tr>
<tr>
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<td>0.80</td>
</tr>
<tr>
<td>August</td>
<td>0.80</td>
<td>0.80</td>
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<tr>
<td>September</td>
<td>0.78</td>
<td>0.78$^b$</td>
</tr>
<tr>
<td>October</td>
<td>0.79</td>
<td>0.79$^b$</td>
</tr>
<tr>
<td>November</td>
<td>0.75</td>
<td>0.75$^b$</td>
</tr>
<tr>
<td>December</td>
<td>0.76</td>
<td>0.86$^b$</td>
</tr>
</tbody>
</table>

$^a$ The south-facing glazing of all of the test cells were cleaned in late January 2004. The exact date of the cleaning was not officially recorded. However, during the calibration of the simulation models, the date was determined to be January 27th.

$^b$ Speculative values based on the previous year’s data and/or observable trends.

Uncorrected Hourly Indoor Air Temperature Calculations

The uncorrected internal air temperature of the DG1 or DG2 cell for any given hour was calculated using the same formula for $T_{int}$ as used by the CC simulation model. The formula was from Professor Alfredo Fernández-González (2007) and read as follows:

$$T_{int} = \frac{Q_{total}}{CAP}$$

The reason that this value of $T_{int}$ was referred to as “uncorrected” within the DG1 and DG2 models was due to an unanticipated phenomenon observed within the direct gain.
test cells during the development of the simulation models. This phenomenon could not be compensated for by the aforementioned equations used to compute hourly heat transfer. An explanation of this phenomenon and the formulas used to compensate for its effect within the DG1 and DG2 simulation models is delineated below.

**Adjusted Hourly Indoor Air Temperature Calculations**

Initially, the DG1 and DG2 simulation models severely underestimated the daytime values for $T_{int}$. According to measured data, unless the hourly values of $K_t$ were considerably low, the direct gain test cells exhibited a rapid increase in the cells' average indoor air temperature that peaked around midday when incident solar radiation was most regular to the cells' south-facing glass. This rapid increase was typically met with a similarly rapid decrease in the cell's average indoor air temperature, which would eventually align itself with the simulated $T_{int}$ values throughout the evening and nighttime hours.

A definitive explanation of this phenomenon has not been concluded. However, a thorough investigation into the discrepancies between the measured and simulated values of $T_{int}$ has lead to the following hypothesis: *While they adequately estimated the heat transfer through the building's exterior shell, the equations used within the simulation models were not complex enough to take into consideration the precise absorption rate exhibited by the interior surfaces directly exposed to transmitted incident solar radiation. Furthermore, low-angle irradiation that struck the data loggers prompted an artificial spike in ambient temperature readings.*

This phenomenon was also observed in the WW and RP-DG cells. However, the spikes were not as severe as those exhibited by the direct gain cells. Figure A3.1 depicts a
computer model of the DG1 cell illustrating the degree to which direct beam radiation could penetrate the structure during the winter. Note that the sun path depicted in this illustration is that of February 1st for Fort Wayne, Indiana. The sun angle pictured is for 12:00 PM. This is the degree of direct beam solar penetration one would also observe in late autumn. Closer to the winter solstice, the penetration would be even more severe.

Due to this phenomenon, a correlation between the hourly south vertical solar irradiation and the absolute difference between the hourly measured and simulated value of $T_{int}$ was observable within the DG1 and DG2 models which compensated for the simulation models' formulaic shortcomings. This correlation data for the DG1 model are illustrated in Figure A3.2; while the correlation data for the DG2 model are illustrated in Figure A3.3. The following equations were derived from 2-order polynomial trendlines calculated using the data depicted in Figures A3.2 and A3.3:

For DG1: $y = (-0.00008 H_s^2) + (0.1052 H_s) + 1.6361$

For DG2: $y = (-0.00003 H_s^2) + (0.0692 H_s) + 1.5135$

These hourly values of $y$ were used to correct the corresponding values of $T_{int}$ via the following equation:

$$T_{int-a} = [T_{int} - (Q_{total} / THC)] + y$$

3 Fort Wayne, Indiana is located approximately 81 miles north-northeast of Muncie, Indiana.
A comparison of Figures A3.4 and A3.5 lends verisimilitude to the correlation defined above, as well as the equation for $T_{int-a}$.

**HVAC Simulation Calculations**

Once the DG1 and DG2 simulation models were calibrated, an amended second version of each simulation model was designed to emulate the energy use and thermal performance influence of an auxiliary heat source within the test cell. Under the guidance of Professor Alfredo Fernández-González, HVAC-enabled versions of the DG1 and DG2 simulation models were built to communicate the effect of a thermostat-linked auxiliary heat source. Please note that auxiliary cooling was never implemented into the models.

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**Figure A3.1** Screenshot of a DG1 Test Cell Computer Model featuring the Sun Path for February 1st

*Software: Ecotect, Version 5.50, 2006 Square One Research Ltd.*

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Figure A3.2  XY Scatter Chart Illustrating the Correlation between the South Vertical Global Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the Direct Gain, Model 1 (DG1) Cell

Figure A3.3  XY Scatter Chart Illustrating the Correlation between the South Vertical Global Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the Direct Gain, Model 2 (DG2) Cell
Figure A3.4  Direct Gain, Model 1 (DG1) Performance Summary for February 2003 in which the Simulated Interior Air Temperature Values were Uncorrected

Figure A3.5  Direct Gain, Model 1 (DG1) Performance Summary for February 2003 in which the Simulated Interior Air Temperature Values were Corrected

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There were three basic calculation steps that separated the HVAC-enabled models from the free-running models. The first of which was the modified equation used to calculate $T_{int}$:

$$T_{int} = \left( \frac{Q_{total} + Q_{aux-ap}}{CAP} \right)$$

Next, the hour value of $Q_{aux}$ was calculated using the following formula from Fernández-González (2007):

If $T_{int} < T_{set}$, then: $Q_{aux} = -(T_{set} - T_{int}) \times CAP$

Otherwise: $Q_{aux} = T_{int}$

Finally, the value of $Q_{aux}$ must be adjusted ($Q_{aux-a}$) as follows:

If $Q_{aux} > 0$, then: $Q_{aux-a} = 0$

Otherwise: $Q_{aux-a} = Q_{aux}$

This last step was necessary due to the fact that a mathematically positive value for $Q_{aux}$ simply indicated an absence of auxiliary heat during the current hour and a mathematically negative value of $Q_{aux}$ indicated the degree of utilized auxiliary heat during the current hour. Therefore, only negative values of $Q_{aux}$ were desired.

While conducting subsequent hourly calculations, the simulation models simply drew on the previous hour's $Q_{aux-a}$ value for the $Q_{aux-ap}$ value. However, the initial hour's
HVAC-enabled calculations required a manually input value for $Q_{aux-ap}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the HVAC-enabled simulation model received either an arbitrary value for $Q_{aux-ap}$ influenced by the $T_{set}$ input value or the most recently calculated value of $Q_{aux-a}$, even if the value was not calculated for the previous hour.

Following these calculations, the adjusted (and final) hourly interior air temperature ($T_{int-a}$) were calculated using the formula for $T_{int}$ as described above.

**Formulaic Narrative of the Trombé-Wall (TW) Simulation Model**

The TW simulation model was built upon the algorithm of the CC simulation model, amending and adding various formulas in order to emulate the effect of the TW cell’s indirect gain passive solar heating system.

As with the CC model, *the TW model used I-P units*. This was dictated by the critical resources drawn upon to build the simulation models, many of which were only published using I-P units.

**Required Input Data**

In order to execute the TW simulation model, a number of parametric inputs as well as several forms of hourly data were needed.

With regard to parametric input values, the TW simulation model required a number of fields that were unlike the CC model. The necessary input values were as follows: $A_{nwall}$, $A_{s-wall}$, $A_{e-walls}$, $A_{w-wall}$, $A_{roofs}$, $A_{floors}$, $A_{n-door}$, $A_{s-win}$, $A_{tsw}$, $U_{n-walls}$, $U_{s-walls}$, $U_{e-walls}$, $U_{w-wall}$,
The various areas of the TW exterior envelope components were derived from cataloged field measurements and data, as well as construction drawings. This prior documentation was also relied upon for the value of TA, VOL-air, and CAP.

Consistent with all of the simulation models, the various overall thermal conductance values relating to the TW exterior envelope were derived using the parallel path method as defined by ASHRAE (2001).

The initial ACH value used in the TW simulation model was calculated after using the HERS rule-of-thumb and the ACH_{50} value obtained after a blower door test. During the calibration of the simulation model, this initial value was adjusted. The verisimilitude of the adjusted ACH value was lent by the accuracy of the TW simulation model's output.

Similar to the other models, the OC was set to zero for the TW simulation model.

As with every simulation model, the TW model was also devoid of any internal heat sources. Therefore, Q_{int} was set to 0 Btu/h.

The exterior walls of the TW cell were painted with the same grey paint as the CC. Thus, the \( \alpha_{\text{ex-walls}} \) value was set to 0.73. The TW cell also exhibited the same EDPM liner as specified for the CC. Therefore, the TW model's value of \( \alpha_{\text{roof}} \) was set to 0.93.

Consistent with the other test cells, the ESL was set to 935-feet.

As well, the T_{set} for the TW simulation model was set to 65°F.

In addition to the parametric input values, the TW simulation model required several forms of hourly data. From the on-site weather station, the following hourly data were
required: $T_s$, $T_{wc}$, RH, DP, and $V_{wind}$. Please refer back to the CC formulaic narrative for information regarding the hourly values of $p_g$. From SOLRAD Model 6, hourly data for the following were required: $K_T$, $H$, $H_s$, and $H_{s-tran}$. Please be aware that hourly input data was consistently applied to every simulation model.

As with the other models, the TW simulation model received measured performance data from the TW cell itself, but the data were only used for comparative purposes. They did not factor into the simulation model’s calculations.

**Air Density Ratio Calculations**

As with all of the simulation models, the TW model calculated the ADR by employing the following equation derived from the trendline depicting the ADR for different elevations as published on page 3-2 of Balcomb et al. (1984):

$$ADR = -0.0321 \left( \frac{ESL}{1000} \right) + 1$$

**Capacitance Calculations**

In order to obtain the most accurate simulation possible, the value for CAP was determined using a separate worksheet dedicated to calculating the cell’s capacitance. This worksheet was added to and utilized by every test cell simulation model.

According to Stein et al. (2006), the thermal capacity (Btu/ft$^3$ °F) of any material may be determined by taking the product of its density and specific heat. Using recorded measurements, each component’s capacitance (Btu/°F) was determined using the following formula:
\[ \text{CAP}_{\text{(component)}} \times d \times A \times L \]

This process was repeated for every material in the TW cell with thermal mass. Finally, the total capacitance was determined via a summation of the CAP values from each of the thermally massive components within the TW cell:

\[ \text{CAP}_{\text{(total)}} = \text{Sum of CAP}_{\text{(components)}} \]

**Total Load Coefficient Calculations**

Consistent with the other simulation models, the TLC of the TW cell was calculated using the following equation from Moore (1994):

\[ \text{TLC} = 24 \times U\text{A}_{\text{total}} \]

The UA values were determined by multiplying the area and overall thermal conductance value of each exterior building component (e.g. \( U\text{A}_{\text{wall}} = U_{\text{wall}} \times A_{\text{wall}} \)). The one exception to this method was the UA value for infiltration (\( U\text{A}_{\text{inf}} \)). This variable was calculated using the following equation from Balcomb et al. (1984):

\[ U\text{A}_{\text{inf}} = 0.018 \times V\text{OL}_{\text{air}} \times \text{ACH} \times \text{ADR} \]
Sol-Air Temperature Calculations

Following the TLC calculations, the TW model calculated hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the TW cell. In this instance, hourly sol-air temperatures for the cell's horizontal roof and vertical south-facing surfaces had to be determined. Unlike the CC model, the TW model did not require sol-air temperature calculations for its vertical west-facing surface, as it is adequately shaded by an adjacent test cell. However, sol-air temperatures for the horizontal ground surface surrounding the TW cell did have to be calculated. As described in the previous chapter, the MPSP test cells were propped off of a concrete patio by nearly 2 inches. During the calibration of the simulation models it became apparent that the sol-air temperature of the concrete patio had a significant impact on the thermal performance of the TW cell.

As with the CC simulation model, the TW model utilized the proceeding simplified equations for calculating the sol-air temperatures of both horizontal and vertical surfaces as detailed by ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces: $S_x = T_a + \left[ \frac{(a_x H_x)}{h_o} \right] - 7^\circ\text{F}$

For vertical surfaces: $S_x = T_a + \left[ \frac{(a_x H_x)}{h_o} \right]$  

The value of $a_x$ depended on the surface being considered (e.g. $a_{\text{ex-walls}}$, $a_{\text{roof}}$, or $\rho_g$).
Similarly, the hourly value of $H_x$ depended on which surface was being considered (e.g., $H$ or $H_s$).

According to ASHRAE (2001) and Stein et al. (2006), it is common practice to assume that $h_o$ is 3.0 Btu/h ft$^2$ °F. All of the simulation models made this assumption.

In the case of the TW simulation model, $S_x$ was calculated for three different surfaces: $S_{wall}$, $S_{roof}$, and $S_{ground}$.

**CERES Patio Surface Temperature Calculation**

Please refer to the CC simulation model narrative for an explanation of how the effect of the CERES patio was compensated for within the TW simulation model. The formula used to determine the surface temperature of the concrete patio upon which the MPSP test cells were constructed ($T_{patio}$) was as follows:

$$T_{patio} = S_{ground} + x(y - S_{ground})$$

The variables $x$ and $y$ related to the conditioning of the spaces below the CERES patio. As information regarding the conditioning of the spaces below the patio was not recorded, the heat transfer through the patio and the subsequent effect on the thermal performance of the test cells was unpredictable. Nonetheless, monthly values for variables $x$ and $y$ were reverse engineered during the calibration studies. Please refer back to Table A3.1 for a list of the monthly values for $x$ and $y$. Please note that these values were unique to the specific year and month listed. It is suggested that future research endeavors regarding the MPSP investigate this issue more thoroughly to understand the effect of the CERES patio more thoroughly. However, the above mentioned formula and
the values listed below adequately compensated for the effect of the patio on the test cells within the thermal simulation models.

**Hourly Heat Exchange Calculations**

Once the above mentioned calculations were completed for a given hour, the TW simulation model proceeded to calculate the composite heat exchange through the test cell. Depending on the orientation and nature of a given surface, the exchange was calculated somewhat differently. Therefore, it is necessary to delineate every equation used to calculate the composite hourly heat exchange below. These equations drew on the methodology for calculating design heat loss published by Stein et al. (2006). Please note that this collection of equations was uniquely designed for the TW cell:

\[
Q_{s\text{-wall}} = UA_{s\text{-wall}} \times (T_{prev} - S_{s\text{-wall}})
\]

\[
Q_{n\text{-wall}} = UA_{n\text{-wall}} \times (T_{prev} - T_a)
\]

\[
Q_{e\text{-wall}} = UA_{e\text{-wall}} \times (T_{prev} - T_a)
\]

\[
Q_{w\text{-wall}} = UA_{w\text{-wall}} \times (T_{prev} - T_a)
\]

\[
Q_{s\text{-win}} = UA_{s\text{-win}} \times (T_{prev} - T_a)
\]

\[
Q_{n\text{-door}} = UA_{n\text{-door}} \times (T_{prev} - T_a)
\]
\[ Q_{\text{floor}} = U A_{\text{floor}} \times (T_{\text{prev}} - T_{\text{patio}}) \]

\[ Q_{\text{roof}} = U A_{\text{roof}} \times (T_{\text{prev}} - S_{\text{roof}}) \]

\( Q_{\text{inf}} \) was calculated as listed below. Please note that during the calibration of the MPSP test cell simulation models, the simulation model required the ratio of the ambient outdoor air temperature to the wind chill temperature \( (T_a/T_{wc}) \) to serve as a multiplier in order to match the test cell’s measured values. Thus, the following equation:

\[ Q_{\text{inf}} = U A_{\text{inf}} \times (T_{\text{prev}} - T_a) \times (T_a/T_{wc}) \]

There were no internal gains. Therefore, \( Q_{\text{int}} \) was continuously set to 0 Btu/h.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s \( T_{\text{int}} \) value for the \( T_{\text{prev}} \) value. However, the initial hour’s heat exchange calculations required a manually input value for \( T_{\text{int}} \). This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the TW simulation model received either an arbitrary \( T_{\text{prev}} \) value influenced by the actual measured data from the previous hour or the most recently calculated value of \( T_{\text{int}} \), even if the value was not calculated for the previous hour.

As the TW cell featured south-facing glazing as part of its indirect gain strategy, the TW simulation model had to calculate the transmitted radiation through the glazing. This was accomplished using the following formula from Fernández-González (2007):
As explained within the DG1 and DG2 formulaic narrative, the correction multiplier $(m)$ has to be applied to $Q_{sol}$ due to the gradual accumulation of particulate matter upon the surface of the south-facing glazing. Please refer back to Table A3.2 for the list of monthly values for $m$ used within the simulation models featuring south-facing glazing.

Finally, the hourly value of $Q_{total}$ for the TW model was calculated via a summation of the previously explained hourly heat exchange values:

$$Q_{total} = Q_{s-wall} + Q_{n-wall} + Q_{e-wall} + Q_{w-wall} + Q_{s-win} + Q_{n-door} + Q_{floor} + Q_{roof} + Q_{inf} + Q_{int} + Q_{sol}$$

It is important to note that a positive value for $Q_x$ equated to a loss of heat through the structure. Conversely, a negative value of $Q_x$ equated to a gain of heat through the structure (i.e. a $Q_{total}$ of -500 Btu/h indicated a collective gain of heat by the cell during the hour of consideration and a $Q_{total}$ of 500 Btu/h indicated a collective loss of heat by the cell during the hour of consideration).

**Hourly Indoor Air Temperature Calculations**

The simulated internal air temperature of the TW cell for the any given hour was calculated using the following formula from Professor Alfredo Fernández-González (2007):

$$T_{int} = Q_{total} / CAP$$
One interesting observation which occurred during the calibration of the TW model using the test cell’s measured thermal performance data was the discovery that the operation of the Trombé-wall’s vents had a negligible effect on the test cell’s thermal performance. This was most likely due to the fact that the thermal storage wall consisted on dry-fitted concrete blocks. The dry-fitting left many small crevices between the blocks which seemingly rendered the operation of the vents inconsequential. Moreover, the vertical orientation of thermal storage wall kept the test cell from exhibiting the interior temperature spikes exhibited by the DG1, DG2, WW, and RP-DG cells on clear days during the heating season.

**HVAC Simulation Calculations**

Once the TW simulation model was calibrated, an amended second version of the simulation model was designed to emulate the energy use and thermal performance influence of an auxiliary heat source within the test cell. Under the guidance of Professor Alfredo Fernández-González, the HVAC-enabled version of the TW simulation model was designed to communicate the effect a thermostat-linked auxiliary heat source would have had on hourly $Q_{total}$ values. Please note that auxiliary cooling was never implemented into any of the models.

There were three basic calculation steps that separated the HVAC-enabled model from the free-running model. The first of which was the modified equation used to calculate $T_{int}$:

$$T_{int} = \frac{(Q_{total} + Q_{aux-ap})}{CAP}$$
Next, the hour value of $Q_{aux}$ was calculated using the following formula from Fernández-González (2007):

\[
\text{If } T_{int} < T_{set}, \text{ then: } Q_{aux} = -(T_{set} - T_{int}) \times \text{CAP} \\
\text{Otherwise: } Q_{aux} = T_{int}
\]

Finally, the value of $Q_{aux}$ had to be adjusted ($Q_{aux-a}$) as follows:

\[
\text{If } Q_{aux} > 0, \text{ then: } Q_{aux-a} = 0 \\
\text{Otherwise: } Q_{aux-a} = Q_{aux}
\]

This last step was necessary due to the fact that a mathematically positive value for $Q_{aux}$ simply indicated an absence of auxiliary heat during the current hour and a mathematically negative value of $Q_{aux}$ indicated the degree of utilized auxiliary heat during the current hour. Therefore, only negative values of $Q_{aux}$ were desired.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $Q_{aux-a}$ value for the $Q_{aux-ap}$ value. However, the initial hour’s HVAC-enabled calculations required a manually input value for $Q_{aux-ap}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the HVAC-enabled simulation model received either an arbitrary value for $Q_{aux-ap}$ influenced by the $T_{set}$ input value or the most recently calculated value of $Q_{aux-a}$, even if the value was not calculated for the previous hour.
Formulaic Narrative of the
Water-Wall (WW) Simulation Model

The WW simulation model was built upon the algorithm of the CC simulation model, amending and adding various formulas in order to emulate the effect of the test cells’ passive solar heating system.

As with the other simulation models, the WW models used I-P units. This was dictated by the critical resources drawn upon to build the simulation models; many of which were only published using I-P units.

**Required Input Data**

In order to execute the WW simulation model, a number of parametric inputs as well as several forms of hourly data were needed.

With regard to parametric input values, the WW simulation model required the same variables as the CC model plus additional input values regarding the south-facing windows exhibited by the WW cell. Specifically, the WW simulation models required the following: $A_{n-wall}$, $A_{s-wall}$, $A_{e-wall}$, $A_{w-wall}$, $A_{roof}$, $A_{floor}$, $A_{n-door}$, $A_{s-win}$, $A_{tsw}$, $U_{n-wall}$, $U_{s-wall}$, $U_{e-wall}$, $U_{w-wall}$, $U_{roof}$, $U_{floor}$, $U_{n-door}$, $U_{s-win}$, $U_{tsw}$, $TA$, $VOL_{air}$, $ACH$, $OC$, $Q_{int}$, $SC$, $a_{ex-walls}$, $a_{roof}$, $CAP$, $ESL$, and $T_{set}$.

As with the CC model, the various areas of the WW cell’s exterior envelope components were derived from cataloged field measurements and data, as well as construction drawings. This prior documentation was also relied upon for the value of $TA$, $VOL_{air}$, and $CAP$. 

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As with every simulation model, the various overall thermal conductance values relating to the WW cell's exterior envelope were derived using the parallel path method as defined by ASHRAE (2001).

Consistent with the other simulation models, the initial ACH value used by the WW model was calculated after using the HERS rule-of-thumb and the ACH\textsubscript{50} value obtained after a blower door test. During the calibration of the simulation models, the values of ACH were adjusted in order to better emulate the actual performance of the WW cell.

To reiterate, the value of OC was fixed at zero. This was consistently applied to every simulation model.

Again, every MPSP test cell was devoid of internal heat sources. Thus, the Q\textsubscript{int} was set to 0 Btu/h.

The exterior walls of the WW cell were painted with the same grey paint as the rest of the test cells. Thus, the $\alpha_{\text{ext-walls}}$ value for the WW model was set to 0.73. The WW cell also exhibited the same EDPM liner as the other test cells. Therefore, the WW model's value of $\alpha_{\text{roof}}$ was set to 0.93.

Consistent with the other test cells, the ESL was set to 935-feet.

As well, the $T_{\text{set}}$ for the WW simulation model was set to 65°F.

In addition to the parametric input values, the WW simulation model also required various forms of hourly data. From the on-site weather station, the following hourly data were required: $T_{\text{s}}$, $T_{\text{wc}}$, RH, DP, and $V_{\text{wind}}$. Please refer back to the CC formulaic narrative for information regarding the hourly values of $\rho_e$. The WW model also required the following hourly data derived from SOLRAD Model 6: $K_T$, $H$, $H_s$, and $H_{s\text{-tran}}$. Please note that the hourly input data were consistently applied to all of the simulation models.
The WW simulation model also received measured performance data (when available) from the WW cell itself. However, as with all of the simulation models, the data were only used for comparative purposes. Measured data did not factor into any of the simulation model’s calculations.

Air Density Ratio Calculations

As with all of the simulation models, the WW model calculated the ADR by employing the following equation derived from the trendline depicting the ADR for different elevations as published on page 3-2 of Balcomb et al. (1984):

\[ ADR = -0.0321 \left( \frac{ESL}{1000} \right) + 1 \]

Capacitance Calculations

The WW simulation model utilized a separate worksheet solely dedicated to calculating the cell’s CAP. The worksheet was identical to that described within the CC model’s formulaic narrative. This worksheet was utilized by all of the simulation models.

Within the worksheet, a material’s thermal heat capacity (Btu/ft\(^3\) °F) was calculated as described by Stein et al. (2006). Using recorded measurements, each component’s capacitance (Btu/°F) was determined using the following formula:

\[ CAP_{(component)} = d \cdot c \cdot A_x \cdot L \]
Next, this process was repeated for every thermally massive material exposed within the WW cell. Finally, the total capacitance was determined via a summation of the CAP values from the cell’s individual thermally massive components:

\[
\text{CAP}_{\text{total}} = \text{Sum of CAP}_{\text{components}}
\]

**Total Load Coefficient Calculations**

Consistent with the other simulation models, the WW model used the following equation from Moore (1994) to calculate the TLC:

\[
TLC = 24 \times U_{A_{\text{total}}}
\]

The UA values were determined by multiplying the area and overall thermal conductance value of each exterior building component (e.g. \(U_{A_{\text{s-wall}}} = U_{s\text{-wall}} \times A_{s\text{-wall}}\)). The one exception to this method is the UA value for infiltration (\(U_{A_{\text{inf}}}\)). This variable was calculated using the following equation from Balcomb et al. (1984):

\[
U_{A_{\text{inf}}} = 0.018 \times V_{\text{OL-air}} \times ACH \times ADR
\]

**Sol-Air Temperature Calculations**

Next, the WW model calculated the hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the WW cell.
In this instance, hourly sol-air temperatures for the WW cell’s horizontal roof and vertical south-facing surfaces had to be determined. Like the DG1, DG2, and TW models, the WW model did not require sol-air temperature calculations for its vertical west-facing surfaces, as it was adequately shaded by adjacent test cells. However, sol-air temperatures for the horizontal ground surface surrounding the WW cell had to be calculated. As described in the previous chapter, the test cells were propped off of a concrete patio by nearly 2 inches. During the calibration of the simulation models, it became apparent that the sol-air temperature of the concrete patio had a significant impact on the thermal performance of the WW cell.

As with the previously described simulation models, the WW model utilized the proceeding simplified equations for calculating the sol-air temperatures of both horizontal and vertical surfaces as detailed by ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces: \[ S_x = T_a + \left( \frac{\alpha_x H_x}{h_0} \right) - 7^\circ F \]

For vertical surfaces: \[ S_x = T_a + \left( \frac{\alpha_x H_x}{h_0} \right) \]

The value of \( \alpha_x \) depended on the surface being considered (e.g. \( \alpha_{ex-walls}, \alpha_{roof}, \) or \( \rho_g \)).

Similarly, the hourly value of \( H_x \) depended on which surface was being considered (e.g. \( H \) or \( H_s \)).

As mentioned earlier, according to ASHRAE (2001) and Stein et al. (2006) it is common practice to assume that \( h_0 \) is 3.0 Btu/h ft\(^2\) \(^\circ\)F. All of the simulation models made this assumption.
In the case of the WW simulation model, $S_x$ had to be calculated for three different surfaces: $S_{\text{wall}}$, $S_{\text{roof}}$, and $S_{\text{ground}}$.

**CERES Patio Surface Temperature Calculation**

Please refer to the CC simulation model narrative for an explanation of how the effect of the CERES patio was compensated for within the WW simulation model. The formula used to determine the surface temperature of the concrete patio upon which the MPSP test cells were constructed ($T_{\text{patio}}$) was as follows:

$$T_{\text{patio}} = S_{\text{ground}} + x(y - S_{\text{ground}})$$

As described within the CC simulation model’s formulaic narrative, the variables $x$ and $y$ related to the conditioning of the spaces below the CERES patio. As information regarding the conditioning of the spaces below the patio was not recorded, the heat transfer through the patio and the subsequent effect on the thermal performance of the test cells was unpredictable. Nonetheless, monthly values for variables $x$ and $y$ were reverse engineered during the calibration studies. Please refer back to Table A3.1 for a list of the monthly values of $x$ and $y$. Please note that these values were unique to the specific year and month listed.

**Hourly Heat Exchange Calculations**

Once the above mentioned calculations had taken place for a considered hour, the WW simulation model proceeded to calculate the composite heat exchange through the WW cell. Depending on the orientation and nature of a given surface, the exchange was calculated somewhat differently. Therefore, it was necessary to delineate every equation
used to calculate the composite hourly heat exchange below. These equations drew on the methodology for calculating design heat loss published by Stein et al. (2006). Please note that the following series of formulas was uniquely designed for the WW simulation model:

\[
Q_{s\text{-wall}} = U_{A_{s\text{-wall}}} \times (T_{prev} - S_{s\text{-wall}})
\]

\[
Q_{n\text{-wall}} = U_{A_{n\text{-wall}}} \times (T_{prev} - T_{a})
\]

\[
Q_{c\text{-wall}} = U_{A_{c\text{-wall}}} \times (T_{prev} - T_{a})
\]

\[
Q_{w\text{-wall}} = U_{A_{w\text{-wall}}} \times (T_{prev} - T_{a})
\]

\[
Q_{s\text{-win}} = U_{A_{s\text{-win}}} \times (T_{prev} - T_{a})
\]

\[
Q_{n\text{-door}} = U_{A_{n\text{-door}}} \times (T_{prev} - T_{a})
\]

\[
Q_{floor} = U_{A_{floor}} \times (T_{prev} - T_{patio})
\]

\[
Q_{roof} = U_{A_{roof}} \times (T_{prev} - S_{roof})
\]

\[Q_{inf}\] was similarly calculated as listed below. However, during the calibration of the MPSP test cell simulation models, the simulation model required the ratio of the ambient
outdoor air temperature to the wind chill temperature \((T_o/T_{wc})\) to serve as a multiplier in order to match the test cell's measured values. Thus, the following equation:

\[
Q_{\text{inf}} = UA_{\text{inf}} \times (T_{\text{prev}} - T_a) \times (T_o/T_{wc})
\]

There were no internal gains. Therefore, \(Q_{\text{int}}\) was continuously set to 0 Btu/h.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour's \(T_{\text{int}}\) value for its \(T_{\text{prev}}\) value. However, the initial hour's heat exchange calculations required a manually input value for \(T_{\text{int}}\). This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the WW simulation model received either an arbitrary \(T_{\text{prev}}\) value influenced by the actual measured data from the previous hour or the most recently calculated value of \(T_{\text{int}}\), even if the value was not calculated for the previous hour.

As the WW cell featured south-facing glazing as part of its passive solar heating strategy, the simulation model also had to calculate the transmitted radiation through the glazing. This was accomplished using the following formula from Fernández-González (2007):

\[
Q_{\text{sol}} = m A_{\text{win}} H_{s\text{-tran}}
\]

A correction multiplier \((m)\) had to be applied to \(Q_{\text{sol}}\) due to the gradual accumulation of particulate matter upon the surface of the south-facing glazing, which subsequently
reduced its ability to absorb incident solar radiation. Further analyses indicated that the impact of the glazing’s dirtiness was also somewhat affected by the Sun’s altitude. Thus, the value of $m$ could slightly increase or decrease in an unexpected fashion from one month to the next. Table A3.2 lists the monthly values of $m$ used to correct the value of $Q_{\text{sol}}$. Please note that the south-facing glass of the MPSP test cells was cleaned in late January 2004.

Finally, the hourly value of $Q_{\text{total}}$ for the WW model was calculated via a summation of the previously explained hourly heat exchange values:

$$Q_{\text{total}} = Q_{\text{s-wall}} + Q_{\text{n-wall}} + Q_{\text{e-wall}} + Q_{\text{w-wall}} + Q_{\text{w-win}} + Q_{\text{n-door}} + Q_{\text{floor}} + Q_{\text{roof}} + Q_{\text{inf}} + Q_{\text{int}} + Q_{\text{sol}}$$

It is important to note that a positive value for $Q_x$ equated to a loss of heat through the structure. Conversely, a negative value of $Q_x$ equated to a gain of heat through the structure (i.e. a $Q_{\text{total}}$ of -500 Btu/h indicated a collective gain of heat by the cell during the hour of consideration and a $Q_{\text{total}}$ of 500 Btu/h indicated a collective loss of heat by the cell during the hour of consideration).

**Uncorrected Hourly Indoor Air Temperature Calculations**

The *uncorrected* internal air temperature of the WW cell for the any given hour was calculated using the same formula for $T_{\text{int}}$ as used by the CC simulation model. The following formula was acquired from Professor Alfredo Fernández-González (2007):

$$T_{\text{int}} = Q_{\text{total}} / \text{CAP}$$
The reason that this value of $T_{\text{int}}$ was referred to as "uncorrected" within the WW model was due to an unanticipated phenomenon observed within the WW cell during the development of the simulation models. This phenomenon was similar to that explained within the DG1 and DG2 formulaic narrative. However, due to the compound effect of the water-wall's superior heat capacity and its higher conductivity, the daily temperature spikes were less severe. \footnote{According to Moore (1994), the thermal storage capacity (density x specific heat x conductivity) of water ($1,059 \text{ Btu}/\text{h} \cdot \text{ft}^2 \cdot \text{°F}$) is superior that of concrete ($362 \text{ Btu}/\text{h} \cdot \text{ft}^2 \cdot \text{°F}$) or brick ($123 \text{ Btu}/\text{h} \cdot \text{ft}^2 \cdot \text{°F}$).}

Adjusted Hourly Indoor Air Temperature Calculations

Similar to the DG1 and DG2 models, the WW simulation model initially underestimated the daytime values for $T_{\text{int}}$ by a significant margin. According to measured data, unless the hourly values of $K_T$ were considerably low, the WW cell exhibited a rapid increase in average indoor air temperature that peaked around midday when incident solar radiation was most regular to the cells' south-facing glass. This rapid increase was typically met with a similarly rapid decrease in the cell's average indoor air temperature, which would eventually align itself with the simulated $T_{\text{int}}$ values throughout the evening and nighttime hours.

As stated within the formulaic narrative for the DG1 and DG2 models, a definitive explanation of this phenomenon has yet to be determined. However, a thorough investigation into the discrepancies between the measured and simulated values of $T_{\text{int}}$ has led to the following hypothesis: \textit{While they adequately estimated the heat transfer through the building's exterior shell, the equations used within the simulation models were not complex enough to take into consideration the precise absorption rate exhibited...}
by the interior surfaces directly exposed to transmitted incident solar radiation.

Furthermore, as described in the DG1 and DG2 model’s formulaic narrative, low-angle irradiation that struck the data loggers prompted an artificial spike in ambient temperature readings.

Due to this phenomenon, a correlation between the hourly global horizontal irradiation and the absolute difference between the hourly measured and simulated value of $T_{int}$ was observable within the WW model which compensated for the model’s formulaic shortcomings. Unlike the correlations relating to the DG1 and DG2 cells, which presented a strong relationship regardless of the time of year; the correlation relating to the WW model exhibited an indisputable seasonal variation. Appendix IV presents a series of monthly charts which utilize both years of WW measured data to lend verisimilitude to the following series of monthly equations used by the WW simulation model to emulate the phenomenon described above. The following equations were derived from the 2-order polynomial trendlines calculated from each the monthly correlation figures presented in Appendix IV:

For January: $y = (0.0004 H_s^2) + (0.0742 H_s) + 2.2004$

For February: $y = (-0.00005 H_s^2) + (0.079 H_s) + 1.5561$

For March: $y = (-0.00008 H_s^2) + (0.0301 H_s) + 1.3711$

For April: $y = (0.00002 H_s^2) + (0.0245 H_s) + 1.5039$
For May: \( y = (-0.00002 H^2) + (0.024 H) + 1.2135 \)

For June: \( y = (-0.000006 H^2) + (0.0166 H) + 1.2717 \)

For July: \( y = (-0.000004 H^2) + (0.0272 H) + 1.2018 \)

For August: \( y = (-0.000005 H^2) + (0.0291 H) - 1.8258 \)

For September: \( y = (-0.00002 H^2) + (0.039 H) + 1.6386 \)

For October: \( y = (-0.00002 H^2) + (0.0614 H) + 2.8085 \)

For November: \( y = (0.0001 H^2) + (0.07 H) + 2.5325 \)

For December: \( y = (-0.0005 H^2) + (0.0705 H) + 1.7576 \)

These values of \( y \) computed from the equations listed above were used to correct the corresponding values of \( T_{int} \) via the following equation:

\[
T_{int-a} = [ T_{int} - (Q_{total} / THC) ] + y
\]
HVAC Simulation Calculations

Once the WW simulation model was calibrated, an amended second version of the model was designed to emulate the energy use and thermal performance influence of an auxiliary heat source within the test cell. Under the guidance of Professor Alfredo Fernández-González, the HVAC-enabled version of the WW simulation model was designed to communicate the effect a thermostat-linked auxiliary heat source would have on $Q_{\text{total}}$ on an hourly basis. Please note that auxiliary cooling was never implemented into the models.

There were three basic calculation steps that separate the HVAC-enabled model from the free-running model. The first of which was the modified equation to calculate $T_{\text{int}}$:

$$T_{\text{int}} = \left[ \frac{(Q_{\text{total}} + Q_{\text{aux-ap}})}{\text{CAP}} \right]$$

Next, the hour value of $Q_{\text{aux}}$ was calculated using the following formula from Fernández-González (2007):

If $T_{\text{int}} < T_{\text{set}}$, then: $Q_{\text{aux}} = -(T_{\text{set}} - T_{\text{int}}) \times \text{CAP}$

Otherwise: $Q_{\text{aux}} = T_{\text{int}}$

Finally, the value of $Q_{\text{aux}}$ had to be adjusted ($Q_{\text{aux-a}}$) as follows:

If $Q_{\text{aux}} > 0$, then: $Q_{\text{aux-a}} = 0$

Otherwise: $Q_{\text{aux-a}} = Q_{\text{aux}}$
This last step was necessary due to the fact that a mathematically positive value for \( Q_{aux} \) simply indicated an absence of auxiliary heat during the current hour and a mathematically negative value of \( Q_{aux} \) indicated the degree of utilized auxiliary heat during the current hour. Therefore, only negative values of \( Q_{aux} \) were desired.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s \( Q_{aux-a} \) value for its \( Q_{aux-ap} \) value. However, the initial hour’s HVAC-enabled calculations required a manually input value for \( Q_{aux-ap} \). This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the HVAC-enabled simulation model received either an arbitrary value for \( Q_{aux-ap} \) influenced by the \( T_{set} \) input value or the most recently calculated value of \( Q_{aux-as} \), even if the value was not calculated for the previous hour.

Following these calculations, the adjusted (and final) hourly interior air temperature \( (T_{int-a}) \) was calculated as defined above.

Foreword to Narratives Regarding the Roofpond (RP) and Roofpond-Direct Gain (RP-DG) Simulation Models

The RP and RP-DG simulation models were considerably more complex than the previously described simulation models as the test cells’ thermospaces were considered as separate thermal zones—thus requiring their own sets of calculations.

In turn, a formulaic narrative relating to the simulation models for both the RP and RP-DG cell’s *occupiable volumes* will be delineated. These narratives will then be
followed by a formulaic narrative relating to the simulation model used to simulate the test cells’ thermospaces—the thermal zones that house their roofponds.

Formulaic Narrative of the Roofpond (RP)

Simulation Model (Occupiable Volume)

The RP model simulated the \( T_{\text{int}} \) of the RP cell’s *occupiable volume*. It did not execute the hourly heat transfer calculations for the cell’s thermospace. Every component of the RP cell from the metal decking (which constituted the ceiling plane) and higher was accounted for by a secondary simulation model solely devoted to the roofpond’s thermospace. This model will be referred to below as the RP-T simulation model.

As with the other simulation models, *the RP model used I-P units*. This was dictated by the critical resources drawn upon to build the simulation models; many of which were only published using I-P units.

**Required Input Data**

In order to execute the RP simulation model, a number of parametric inputs as well as several forms of hourly data were required.

With regard to parametric input values, the RP simulation model required the following: \( A_{n\text{-wall}}, A_{s\text{-wall}}, A_{e\text{-wall}}, A_{w\text{-wall}}, A_{\text{floor}}, A_{n\text{-door}}, U_{n\text{-wall}}, U_{s\text{-wall}}, U_{e\text{-wall}}, U_{w\text{-wall}}, U_{\text{floor}}, U_{n\text{-door}}, T_{\text{A}}, \text{VOL}_{\text{air}}, \text{ACH}, \text{OC}, Q_{\text{ints}}, \text{SC}, \alpha_{\text{ex-wall}}, \alpha_{\text{roof}}, \text{CAP} \) for the non-thermospace components of the RP cell, \( \text{CAP} \) for only the thermospace components of the RP cell, ESL, and \( T_{\text{scf}} \).

As with the other simulation models, the various required values of areas from the RP cell’s exterior envelope were derived from cataloged field measurements and data, as
well as construction drawings. This prior documentation was also relied upon for TA, VOL\textsubscript{air}, and both CAP values.

As with every simulation model, the required overall thermal conductance values relating to the RP cell’s exterior envelope were derived using the parallel path method as defined by ASHRAE (2001).

Consistent with the other simulation models, the initial ACH value used in the RP model was calculated after using the HERS rule-of-thumb and the $ACH_{50}$ value obtained after a blower door test. During the calibration of the simulation models, this initial value of ACH was adjusted in order to better emulate the measured performance of the RP cell.

As with the other simulation models, the values of OC was set to zero.

Consistent with the other models, $Q_{\text{nat}}$ was set to 0 Btu/h.

The exterior walls of the RP cell were painted with the same grey paint as the rest of the test cells. Thus, the $\alpha_{\text{ex-walls}}$ value for the RP model was set to 0.73. The RP cell also exhibited the same EDPM liner as the other test cells. Therefore, the RP model’s value of $\alpha_{\text{roof}}$ was set to 0.93.

Consistent with the other test cells, the ESL was set to 935-feet.

As well, the $T_{\text{set}}$ for the RP simulation model was set to 65°F.

In addition to the parametric input values, the RP simulation model also required various forms of hourly data. From the on-site weather station, the following hourly data were required: $T_a$, $T_{\text{wc}}$, RH, DP, and $V_{\text{wind}}$. Please refer back to the CC formulaic narrative for information regarding the hourly values of $\rho_g$. The RP model also required the following hourly data, which was obtained using SOLRAD Model 6: $K_T$, H, $H_s$, and $H_c$. 

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Please note that any utilized forms of hourly input data were consistently applied to every simulation model.

The RP simulation model also required hourly $Q_{\text{exchange}}$ values from the corresponding roofpond thermospace (RP-T) simulation model.

The RP simulation model also received measured performance data (when available) from the RP cell itself. However, as with all of the simulation models, the data were only used for comparative purposes. Measured data did not factor into any of the simulation model’s calculations.

**Air Density Ratio Calculations**

As with all of the simulation models, the RP model calculated the ADR by employing the following equation derived from the trendline depicting the ADR for different elevations as published on page 3-2 of Balcomb et al. (1984):

$$ADR = -0.0321 \left( \frac{\text{ESL}}{1000} \right) + 1$$

**Capacitance Calculations**

The RP simulation model utilized a separate worksheet solely dedicated to calculating the cell’s CAP. The worksheet was identical to that described within the CC model’s formulaic narrative. This worksheet was utilized by all of the simulation models.

Within the worksheet, a material’s thermal heat capacity ($\text{Btu/lft}^3 \^\circ\text{F}$) was calculated as described by Stein et al. (2006). Using recorded measurements, each component’s capacitance ($\text{Btu/}^\circ\text{F}$) was determined using the following formula:
This process was repeated for every thermally massive material within the RP cell’s occupiable volume. Finally, the total capacitance was determined via a summation of the CAP values from the cell’s individual thermally massive components:

\[ \text{CAP}_{\text{total}} = (\text{Sum of CAP of non-thermospace components}) + (\text{CAP of thermospace}) \]

Please notice that the final value of CAP took into consideration the percentage of the thermal mass constituting the thermospace that effectively performed as thermal mass for the RP cell’s occupiable volume. The value of \( C \) was unique to each cell featuring a thermospace. In the case of the RP model, the value of \( C \) was 0.05. The values of \( C \) were determined during the calibration of the RP-T model using measured data from the relevant test cells.

**Total Load Coefficient Calculations**

Consistent with the other simulation models, the RP model used the following equation from Moore (1994) to calculate the TLC:

\[ \text{TLC} = 24 \times U_A_{\text{total}} \]

With the exception of the UA value for infiltration, the UA values were determined by first multiplying the area and overall thermal conductance value of each exterior building component (e.g. \( U_A_{\text{wall}} = U_{\text{wall}} \times A_{\text{wall}} \)). However, unlike the other thermal
simulation models mentioned thus far, the RP model’s UA values (except for infiltration) required a multiplier in order to correctly emulate heat flow conditions through the RP cell’s envelope. The multipliers were developed via reverse engineering based on relevant measured data from the test cell. After completing a thorough analysis, the following hypothesis has been determined: While they adequately estimate the heat transfer through the building’s conventionally constructed exterior shell, the equations used within the simulation models were not complex enough to take into consideration the dynamic effect by which the roofpond facilitates or hampers heat flow throughout the test cell’s occupiable volume or how the roofpond’s influence correlates with the ambient outdoor air temperature. Please note that the manipulated values as a result of the multiplier were not considered during the TLC value calculations.

The corrective multiplier for every UA value (except for infiltration) was determined on an hourly basis and was calculated as follows:

For exterior wall components: If $T_a > f$, then: $g = 1.43$
Otherwise: $g = 2.50$

For exterior the floor component: If $T_a > f$, then: $g = 1.11$
Otherwise: $g = 1.67$

In this instance, $f$ was the U-value threshold temperature and $g$ was the multiplier applied to the appropriate value of UA. Table A3.3 lists the monthly U-value threshold temperatures used for the RP simulation model. Please be aware that the multiplier
Table A3.3  Scheduled Values of U-Value Threshold Temperature, \( f \)

<table>
<thead>
<tr>
<th>Month</th>
<th>2003 Values</th>
<th>2004 Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>70°F</td>
<td>40°F</td>
</tr>
<tr>
<td>February</td>
<td>70°F</td>
<td>70°F</td>
</tr>
<tr>
<td>March</td>
<td>70°F</td>
<td>55°F</td>
</tr>
<tr>
<td>April</td>
<td>70°F</td>
<td>70°F</td>
</tr>
<tr>
<td>May</td>
<td>80°F</td>
<td>70°F</td>
</tr>
<tr>
<td>June</td>
<td>100°F</td>
<td>85°F</td>
</tr>
<tr>
<td>July</td>
<td>110°F</td>
<td>95°F</td>
</tr>
<tr>
<td>August</td>
<td>90°F</td>
<td>95°F</td>
</tr>
<tr>
<td>September</td>
<td>85°F</td>
<td>85°F(^a)</td>
</tr>
<tr>
<td>October</td>
<td>70°F</td>
<td>70°F(^a)</td>
</tr>
<tr>
<td>November</td>
<td>75°F</td>
<td>75°F(^a)</td>
</tr>
<tr>
<td>December</td>
<td>50°F</td>
<td>50°F(^a)</td>
</tr>
</tbody>
</table>

\(^a\) Speculative values based on the previous year's data and/or observable trends.

described here only pertained to the RP and RP-DG simulation models. If these simulation models were to be used for a different time or location, a more thorough understanding of what prompts this multiplier must be obtained.

The UA value multiplier did not pertain to the UA value for infiltration (UA\(_{\text{inf}}\)). This variable was calculated using the following equation from Balcomb et al. (1984):

\[
UA_{\text{inf}} = 0.018 \times V_{\text{OAIr}} \times ACH \times ADR
\]

**Sol-Air Temperature Calculations**

Next, the RP model calculated hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the RP cell's
exterior shell below the roofpond. In this instance, hourly sol-air temperatures had to be determined for the cell’s vertical south-facing wall \( (S_{\text{s-wall}}) \) as well as its vertical, east-facing surface \( (S_{\text{e-wall}}) \), as the RP cell did not have an adjacent test cell on its east side. Additionally, sol-air temperatures for the horizontal ground surface \( (S_{\text{ground}}) \) surrounding the RP cell had to be calculated. As described previously, during the calibration of the simulation models, it became apparent that the sol-air temperature of the concrete patio had a significant impact on the thermal performance of the RP cell.

As with the previously described simulation models, the RP model utilized the proceeding simplified equations for calculating the sol-air temperatures of both horizontal and vertical surfaces as detailed by ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces: 
\[
S_x = T_a + \left[ \frac{(\alpha_x H_x)}{h_o} \right] - 7^\circ F
\]

For vertical surfaces: 
\[
S_x = T_a + \left[ \frac{(\alpha_x H_x)}{h_o} \right]
\]

The value of \( \alpha_x \) depended on the surface being considered (e.g. \( \alpha_{\text{ex-walls}}, \alpha_{\text{roof}}, \text{or } \rho_g \)). Similarly, the hourly value of \( H_x \) depended on which surface was being considered (e.g. \( H, H_s, \text{or } H_c \)).

As mentioned earlier, according to ASHRAE (2001) and Stein et al. (2006) it is common practice to assume that \( h_o \) is 3.0 Btu/h ft\(^2\) °F. All of the simulation models made this assumption.
CERES Patio Surface Temperature Calculation

Please refer to the CC simulation model narrative for an explanation of how the effect of the CERES patio was compensated for within the RP simulation model. The formula used to determine the surface temperature of the concrete patio upon which the MPSP test cells were constructed \( (T_{\text{patio}}) \) was as follows:

\[
T_{\text{patio}} = S_{\text{ground}} + x(y - S_{\text{ground}})
\]

As described within the CC simulation model’s formulaic narrative, the variables \( x \) and \( y \) related to the conditioning of the spaces below the CERES patio. As information regarding the conditioning of the spaces below the patio was not recorded, the heat transfer through the patio and the subsequent effect on the thermal performance of the test cells was unpredictable. Nonetheless, monthly values for variables \( x \) and \( y \) were reverse engineered during the calibration studies. Please refer back to Table A3.1 for a list of the monthly values of \( x \) and \( y \). Please note that these values were unique to the specific year and month listed.

Hourly Heat Exchange Calculations

Once the above mentioned calculations had taken place for a considered hour, the RP simulation model proceeded to calculate the composite heat exchange through the RP cell below the roofpond. Depending on the orientation and nature of a given surface, the exchange was calculated somewhat differently. Therefore, it is necessary to delineate every equation used to calculate the composite hourly heat exchange below. These equations draw on the methodology for calculating design heat loss published by Stein et
al. (2006). Please note that the following series of formulas was uniquely designed for the RP simulation model:

\[
Q_{s\text{-wall}} = UA_{s\text{-wall}} \times (T_{\text{prev}} - S_{s\text{-wall}})
\]

\[
Q_{n\text{-wall}} = UA_{n\text{-wall}} \times (T_{\text{prev}} - T_a)
\]

\[
Q_{e\text{-wall}} = UA_{e\text{-wall}} \times (T_{\text{prev}} - S_{e\text{-wall}})
\]

\[
Q_{w\text{-wall}} = UA_{w\text{-wall}} \times (T_{\text{prev}} - T_a)
\]

\[
Q_{n\text{-door}} = UA_{n\text{-door}} \times (T_{\text{prev}} - T_a)
\]

\[
Q_{\text{floor}} = UA_{\text{floor}} \times (T_{\text{prev}} - T_{\text{patio}})
\]

\(Q_{\text{inf}}\) was similarly calculated as listed below. However, during the calibration of the MPSP test cell simulation models, the simulation model required the ratio of the ambient outdoor air temperature to the wind chill temperature \((T_a/T_{wc})\) to serve as a multiplier in order to match the test cell’s measured values. Thus, the following equation:

\[
Q_{\text{inf}} = UA_{\text{inf}} \times (T_{\text{prev}} - T_a) \times (T_a/T_{wc})
\]

There were no internal gains. Therefore, \(Q_{\text{int}}\) was continuously set to 0 Btu/h.
While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $T_{int}$ value for its $T_{prev}$ value. However, the initial hour’s heat exchange calculations required a manually input value for $T_{int}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the RP simulation model received either an arbitrary $T_{prev}$ value influenced by the actual measured data from the previous hour or the most recently calculated value of $T_{int}$, even if the value was not calculated for the previous hour.

As the ceiling of the RP cell’s occupiable volume was the metal decking supporting the roofpond system and its integral thermospace, $Q_{roof}$ did not need to be calculated. Rather, the heat exchange with the roofpond system, $Q_{exchange}$, was taken into consideration. The algorithm to determine $Q_{exchange}$ was rather complex, thus it was calculated using an entirely separate simulation model which ultimately interacted with the RP model. This separate model will be expanded upon later in this chapter.

Finally, the hourly value of $Q_{total}$ for the RP model was calculated via a summation of the previously explained hourly heat exchange values:

\[
Q_{total} = Q_{s-wall} + Q_{n-wall} + Q_{e-wall} + Q_{w-wall} \\
+ Q_{n-door} + Q_{floor} + Q_{exchange} + Q_{inf} + Q_{int}
\]

It is important to note that a positive value for $Q_x$ equated to a loss of heat through the structure. Conversely, a negative value of $Q_x$ equated to a gain of heat through the structure (i.e. a $Q_{total}$ of -500 Btu/h indicated a collective gain of heat by the cell during
the hour of consideration and a $Q_{\text{total}}$ of 500 Btu/h indicated a collective loss of heat by
the cell during the hour of consideration).

**Hourly Indoor Air Temperature Calculations**

The simulated internal air temperature of the RP cell’s occupiable volume for the any
given hour was calculated using the following formula from Professor Alfredo
Fernández-González (2007):

$$T_{\text{int}} = \frac{Q_{\text{total}}}{C A P}$$

**HVAC Simulation Calculations**

Once the RP simulation model was calibrated, an amended second version of the
simulation model was designed to emulate the energy use and thermal performance
influence of an auxiliary heat source within the test cell. Under the guidance of Professor
Alfredo Fernández-González, the HVAC-enabled version of the RP simulation model
was designed to communicate the effect a thermostat-linked auxiliary heat source would
have on $Q_{\text{total}}$ on an hourly basis. Please note that auxiliary cooling was never
implemented into the models.

There were three basic calculation steps that separate the HVAC-enabled model from
the free-running model. The first of which was the modified equation used to calculate
$T_{\text{int}}$:

$$T_{\text{int}} = \frac{(Q_{\text{total}} + Q_{\text{aux-ap}})}{C A P}$$
Next, the hour value of $Q_{aux}$ was calculated using the following formula from Fernández-González (2007):

$$\text{If } T_{\text{int}} < T_{\text{set}}, \text{ then: } Q_{\text{aux}} = -(T_{\text{set}} - T_{\text{int}}) \times \text{CAP}$$

Otherwise: $Q_{\text{aux}} = T_{\text{int}}$

Finally, the value of $Q_{aux}$ had to be adjusted ($Q_{aux-a}$) as follows:

$$\text{If } Q_{\text{aux}} > 0, \text{ then: } Q_{\text{aux-a}} = 0$$

Otherwise: $Q_{\text{aux-a}} = Q_{\text{aux}}$

This last step was necessary due to the fact that that a mathematically positive value for $Q_{aux}$ simply indicated an absence of auxiliary heat during the current hour and a mathematically negative value of $Q_{aux}$ indicated the degree of utilized auxiliary heat during the current hour. Therefore, only negative values of $Q_{aux}$ were desired.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $Q_{aux-a}$ value for its $Q_{aux-ap}$ value. However, the initial hour’s HVAC-enabled calculations required a manually input value for $Q_{aux-ap}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the HVAC-enabled simulation model received either an arbitrary value for $Q_{aux-ap}$ influenced by the $T_{\text{set}}$ input value or the most recently calculated value of $Q_{aux-as}$, even if the value was not calculated for the previous hour.
Formulaic Narrative of the Roofpond-Direct Gain (RP-DG) Simulation Model (Occupiable Volume)

The RP-DG simulation model built off of the RP model. The primary programming variation between the two was the direct gain component which was integrated into the RP-DG model.

As with the other simulation models, the RP-DG model used I-P units. This was dictated by the critical resources drawn upon to build the simulation models; many of which were only published using I-P units.

Corrected Erroneous Input

It should be clearly identified that the RP-DG model’s final simulation runs contained two incorrect parametric input values. The first erroneous input value was the incorrect specification for the vertical, south-facing glazing of the RP-DG cell’s direct gain strategy. The glass was input as 1/8-inch uncoated double glazing with a 1/2-inch air gap and aluminum framing with a thermal break. However, in reality, the glass was 1/8-inch low-e double glazing with the coating on the third surface of the glazing assembly. The air gap was still 1/2-inch and the framing still consisted of aluminum and featured a thermal break. This information affected the $H_{s-tran}$ data from SOLRAD Model 6.

The second erroneous input value affected the integrated RP-T simulation model. The roofpond depth was input as 8-inches when in reality it was 12-inches. This information affected the CAP value of the roofpond system. Thus, the thermospace’s heat exchange with the occupiable volume below would be significantly different.
However, one should note that these errors were compensated for within the simulation models. Specific details regarding this matter are provided later in this narrative.

**Required Input Data**

In order to execute the RP simulation model, a number of parametric inputs as well as several forms of hourly data are required.

Similar to the RP model, the RP-DG required the following parametric input values: $A_{n\text{-wall}}, A_{s\text{-wall}}, A_{c\text{-wall}}, A_{w\text{-wall}}, A_{\text{floor}}, A_{n\text{-door}}, U_{n\text{-wall}}, U_{s\text{-wall}}, U_{c\text{-wall}}, U_{w\text{-wall}}, U_{\text{floor}}, U_{n\text{-door}},\ TA,\ VOL_{\text{air}},\ ACH,\ OC,\ Q_{\text{int}},\ SC,\ \alpha_{\text{ex-walls}},\ \alpha_{\text{roof}},\ CAP$ for the non-thermospace components of the RP cell, $\text{CAP}$ for only the thermospace components of the RP cell, ESL, and $T_{\text{set}}$.

In addition, however, the RP-DG model also required a value for $A_{s\text{-win}}$ and two values for $U_{s\text{-win}}$ (one value for when the movable insulation was placed directly behind the south-facing glazing and one value for when the insulation was removed).

As with the other simulation models, the various required values of areas from the RP-DG cell's exterior envelope were derived from cataloged field measurements and data, as well as construction drawings. This prior documentation was also relied upon for $TA,\ VOL_{\text{air}},$ and both CAP values.

As with every simulation model, the required overall thermal conductance values relating to the RP-DG cell's exterior envelope were derived using the parallel path method as defined by ASHRAE (2001).

Consistent with the other simulation models, the initial $ACH$ value used in the RP-DG model was calculated after using the HERS rule-of-thumb and the $ACH_{50}$ value obtained after a blower door test. During the calibration of the simulation models, the
initial value of ACH was adjusted in order to better emulate the measured performance of the RP-DG cell.

As with the other simulation models, the values of OC was set to zero.

Consistent with the other models, $Q_{int}$ was set to 0 Btu/h.

The exterior walls of the RP-DG cell were painted with the same grey paint as the rest of the test cells. Thus, the $\alpha_{ex-walls}$ value for the RP-DG model was set to 0.73. The RP-DG cell also exhibited the same EDPM liner as the other test cells. Therefore, the RP-DG model’s value of $\alpha_{roof}$ was set to 0.93.

Consistent with the other test cells, the ESL was set to 935-feet.

As well, the $T_{set}$ for the RP-DG simulation model was set to 65°F.

In addition to the parametric input values, the RP-DG simulation model also required various forms of hourly data. From the on-site weather station, the following hourly data were required: $T_a$, $T_{wc}$, RH, DP, and $V_{wind}$. Please refer back to the CC formulaic narrative for information regarding the hourly values of $\rho_g$. The RP-DG model also required the following hourly data, which was obtained using SOLRAD Model 6: $K_T$, $H$, $H_v$, $H_e$, and $H_{s-tran}$. Please note that all hourly input data was consistently applied to every simulation model.

The RP-DG simulation model also required hourly $Q_{exchange}$ values from the corresponding roofpond thermospace (RP-T) simulation model.

The RP-DG simulation model also received measured performance data (when available) from the RP-DG cell itself. However, as with all of the simulation models, the data were only used for comparative purposes. Measured data did not factor into any of the simulation model’s calculations.
Air Density Ratio Calculations

As with all of the simulation models, the RP-DG model calculated the ADR by employing the following equation derived from the trendline depicting the ADR for different elevations as published on page 3-2 of Balcomb et al. (1984):

\[ \text{ADR} = -0.0321 \left( \frac{\text{ESL}}{1000} \right) + 1 \]

Capacitance Calculations

The RP-DG simulation model utilized a separate worksheet solely dedicated to calculating the cell’s CAP. The worksheet was identical to that described within the CC model’s formulaic narrative. This worksheet was utilized by all of the simulation models.

Within the worksheet, a material’s thermal heat capacity (Btu/ft² °F) was calculated as described by Stein et al. (2006). Using recorded measurements, each component’s capacitance (Btu/°F) was determined using the following formula:

\[ \text{CAP}_{\text{component}} = d \cdot c \cdot A \cdot L \]

Next, this process was repeated for every thermally massive material within the RP-DG cell’s occupiable volume. Finally, the total capacitance of the cell was determined via a summation of the CAP values from the cell’s individual thermally massive components:

\[ \text{CAP}_{\text{total}} = \text{Sum of CAP}_{\text{non-thermospace components}} + \text{CAP}_{\text{of thermospace}} \]
Please notice that the final value of CAP took into consideration the percentage of the thermal mass constituting the thermospace that effectively performed as thermal mass for the RP-DG cell’s occupiable volume. The value of \( C \) was unique to each cell featuring a thermospace. In the case of the RP-DG model, the value of \( C \) was 0.25. The values of \( C \) were determined during the calibration of the RP-T model using measured data from the relevant test cells.

**Total Load Coefficient Calculations**

Consistent with the other simulation models, the RP-DG model used the following equation from Moore (1994) to calculate the TLC:

\[
TLC = 24 \times UA_{\text{total}}
\]

The RP-DG model had to conduct the TLC calculations twice—once with the direct gain system “closed” (indicating that the movable insulation was positioned directly behind the cell’s vertical, south-facing glazing) and once with the direct gain system “open” (indicating that the movable insulation was not in place behind the glazing).

With the exception of the UA value for infiltration, the UA values were determined by first multiplying the area and overall thermal conductance value of each exterior building component (e.g. \( UA_{\text{wall}} = U_{\text{wall}} \times A_{\text{wall}} \)). However, like the RP model, the RP-DG model’s UA values (except for infiltration) required the same multiplier described in the RP model’s narrative in order to correctly emulate heat flow conditions through the test cell’s envelope. Please refer to the RP model’s narrative for a more detailed
explanation of why this multiplier was necessary. Also note that the multiplier was not factored into the TLC calculations.

To reiterate, the corrective multiplier for every UA value (except for infiltration) was determined on an hourly basis and was calculated as follows:

For exterior wall components: If $T_a > T_f$, then: $g = 1.43$

Otherwise: $g = 2.50$

For exterior the floor component: If $T_a > T_f$, then: $g = 1.11$

Otherwise: $g = 1.67$

In this instance, $T_f$ was the U-value threshold temperature and $g$ was the multiplier applied to the appropriate value of UA. Please refer back to Table A3.3 for a list of the monthly U-value threshold temperatures used for the RP-DG simulation model. The same values of $T_f$ were applied to both the RP and RP-DG models. Please be aware that the multiplier described here only pertained to the RP and RP-DG simulation models. If these simulation models were to be used for a different time or location, a more thorough understanding of what prompts this multiplier must be obtained.

The UA value multiplier did not pertain to the UA value for infiltration ($UA_{inf}$). This variable was calculated using the following equation from Balcomb et al. (1984):

$$UA_{inf} = 0.018 \times VOL_{air} \times ACH \times ADR$$
Sol-Air Temperature Calculations

As with the RP simulation model, the RP-DG model had to calculate hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the RP-DG cell’s exterior shell below the roofpond. In this instance, hourly sol-air temperatures had to be determined for the RP-DG cell’s vertical south-facing wall ($S_{\text{wall}}$) as well as the horizontal ground surface ($S_{\text{ground}}$) surrounding the RP-DG cell. As described previously, during the calibration of the simulation models, it became apparent that the sol-air temperature of the concrete patio also had a significant impact on the thermal performance of the RP-DG cell.

As with the previously described simulation models, the RP-DG model utilized the proceeding simplified equations for calculating the sol-air temperatures of both horizontal and vertical surfaces as detailed by ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces: $S_x = T_a + \left[ (\alpha_x \, H_x) / h_o \right] - 7^\circ F$

For vertical surfaces: $S_x = T_a + \left[ (\alpha_x \, H_x) / h_o \right]$

The value of $\alpha_x$ depended on the surface being considered (e.g. $\alpha_{\text{ex-walls}}$, $\alpha_{\text{roof}}$, or $\rho_g$). Similarly, the hourly value of $H_x$ depended on which surface was being considered (e.g. $H$, $H_a$, or $H_c$).
As mentioned earlier, according to ASHRAE (2001) and Stein et al. (2006) it is common practice to assume that $h_o$ is 3.0 Btu/h ft$^2$ °F. All of the simulation models made this assumption.

**CERES Patio Surface Temperature Calculation**

Please refer to the CC simulation model narrative for an explanation of how the effect of the CERES patio was compensated for within the RP-DG simulation model. The formula used to determine the surface temperature of the concrete patio upon which the MPSP test cells were constructed ($T_{\text{patio}}$) was as follows:

$$T_{\text{patio}} = S_{\text{ground}} + x(y - S_{\text{ground}})$$

As described within the CC simulation model's formulaic narrative, the variables $x$ and $y$ in this instance related to the conditioning of the spaces below the CERES patio. As information regarding the conditioning of the spaces below the patio was not recorded, the heat transfer through the patio and the subsequent effect on the thermal performance of the test cells was unpredictable. Nonetheless, monthly values for variables $x$ and $y$ were reverse engineered during the calibration studies. Please refer back to Table A3.1 for a list of the monthly values of $x$ and $y$. Please note that these values were unique to the specific year and month listed.

**Hourly Heat Exchange Calculations**

Once the above mentioned calculations had taken place for a considered hour, the RP-DG simulation model proceeded to calculate the composite heat exchange through the RP cell below the roofpond. Depending on the orientation and nature of a given surface, the
exchange was calculated somewhat differently. Therefore, it is necessary to delineate every equation used to calculate the composite hourly heat exchange below. These equations drew on the methodology for calculating design heat loss published by Stein et al. (2006). Please note that the following series of formulas was uniquely designed for the RP-DG simulation model:

\[
Q_{s\text{-}wall} = UA_{s\text{-}wall} \times (T_{prev} - S_{s\text{-}wall})
\]

\[
Q_{n\text{-}wall} = UA_{n\text{-}wall} \times (T_{prev} - T_a)
\]

\[
Q_{c\text{-}wall} = UA_{c\text{-}wall} \times (T_{prev} - T_a)
\]

\[
Q_{w\text{-}wall} = UA_{w\text{-}wall} \times (T_{prev} - T_a)
\]

\[
Q_{s\text{-}win} = UA_{s\text{-}win} \times (T_{prev} - T_a)
\]

\[
Q_{n\text{-}door} = UA_{n\text{-}door} \times (T_{prev} - T_a)
\]

\[
Q_{floor} = UA_{floor} \times (T_{prev} - T_{patio})
\]

Please note that depending on whether the direct gain system was “open” or “closed,” the value of \(UA_{s\text{-}win}\) differed. The RP-DG cell was programmed to apply the movable insulation in accordance with the schedule described by Fernandez-Gonzalez (2007).
$Q_{\text{inf}}$ was similarly calculated as listed below. However, during the calibration of the MPSP test cell simulation models, the simulation model required the ratio of the ambient outdoor air temperature to the wind chill temperature ($T_a/T_{wc}$) to serve as a multiplier in order to match the test cell’s measured values. Thus, the following equation:

$$Q_{\text{inf}} = UA_{\text{inf}} \times (T_{\text{prev}} - T_a) \times (T_a/T_{wc})$$

There were no internal gains. Therefore, $Q_{\text{int}}$ was continuously set to 0 Btu/h.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $T_{\text{int}}$ value for its $T_{\text{prev}}$ value. However, the initial hour’s heat exchange calculations required a manually input value for $T_{\text{int}}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the RP-DG simulation model received either an arbitrary $T_{\text{prev}}$ value influenced by the actual measured data from the previous hour or the most recently calculated value of $T_{\text{int}}$, even if the value was not calculated for the previous hour.

As the ceiling of the RP-DG cell’s occupiable volume was the metal decking supporting the roofpond system and its integral thermospace, $Q_{\text{roof}}$ did not need to be calculated. Rather, the heat exchange with the roofpond system, $Q_{\text{exchange}}$, was used in its place. The algorithm to determine $Q_{\text{exchange}}$ was rather complex, thus it was calculated using an entirely separate simulation model which ultimately interacted with the RP model. This separate model, the RP-T model, will be expanded upon in the proceeding section of this chapter.
As the RP-DG cell featured vertical, south-facing glazing as part of its direct gain strategy, the RP-DG simulation model had to calculate the transmitted radiation through the glazing. This was accomplished using the following formula from Fernández-González (2007):

\[ Q_{\text{sol}} = m A_{\text{s-win}} H_{\text{s-tran}} \]

As explained within the DG1 and DG2 formulaic narrative, the correction multiplier \( m \) has to be applied to \( Q_{\text{sol}} \) due to the gradual accumulation of particulate matter upon the surface of the south-facing glazing. Please refer back to Table A3.2 for the list of monthly values for \( m \) used within the simulation models featuring south-facing glazing.

Unlike any other simulation models featuring vertical, south-facing glazing, the RP-DG cell featured movable insulation. When the movable insulation was in place, \( Q_{\text{sol}} \) equaled 0 Btu/h.

Finally, the hourly value of \( Q_{\text{total}} \) for the RP-DG model was calculated via a summation of the previously explained hourly heat exchange values:

\[ Q_{\text{total}} = Q_{\text{s-wall}} + Q_{\text{n-wall}} + Q_{\text{d-wall}} + Q_{\text{w-wall}} + Q_{\text{s-win}} + Q_{\text{n-door}} + Q_{\text{floor}} + Q_{\text{exchange}} + Q_{\text{inf}} + Q_{\text{int}} + Q_{\text{sol}} \]

It is important to note that a positive value for \( Q_x \) equated to a loss of heat through the structure. Conversely, a negative value of \( Q_x \) equated to a gain of heat through the structure (i.e. a \( Q_{\text{total}} \) of -500 Btu/h indicated a collective gain of heat by the cell during
the hour of consideration and a $Q_{\text{total}}$ of 500 Btu/h indicated a collective loss of heat by the cell during the hour of consideration).

**Uncorrected Hourly Indoor Air Temperature Calculations**

The *uncorrected* internal air temperature of the RP-DG cell for the any given hour was calculated using the following formula from Professor Alfredo Fernández-González (2007):

$$T_{\text{int}} = \frac{Q_{\text{total}}}{\text{CAP}}$$

The reason that this value of $T_{\text{int}}$ was referred to as “uncorrected” within the RP-DG model was due to an unanticipated phenomenon of interior temperature spikes observed within the RP-DG cell. This phenomenon, to some extent, affected the DG1, DG2, and WW models as well. However, it was less pronounced within the RP-DG due to the high thermal capacity of the roofpond.

**Adjusted Hourly Indoor Air Temperature Calculations**

Similar to the DG1, DG2, and WW models, the RP-DG simulation model initially underestimated the daytime values for $T_{\text{int}}$ by a significant margin. According to measured data, unless the hourly values of $K_T$ were considerably low, the RP-DG cell exhibited a rapid increase in average indoor air temperature that peaked around midafternoon when incident solar radiation was most regular to the cells’ south-facing glass. This rapid increase was typically met with a similarly rapid decrease in cell’s average indoor air temperature, which would eventually align itself with the simulated $T_{\text{int}}$ values throughout the evening and nighttime hours.
As stated within previous formulaic narratives, a definitive explanation of this phenomenon was not determined. However, a thorough investigation into the discrepancies between the measured and simulated values of $T_{\text{int}}$ led to the following hypothesis: *While they adequately estimated the heat transfer through the building's exterior shell, the equations used within the simulation models were not complex enough to take into consideration the precise absorption rate exhibited by the interior surfaces directly exposed to transmitted incident solar radiation. Furthermore, as demonstrated in the DG1 and DG2 model's formulaic narrative, low-angle irradiation that struck the data loggers prompted an artificial spike in ambient temperature readings.*

Due to this phenomenon, a correlation between the transmitted hourly irradiation and the absolute difference between the hourly measured and simulated values of $T_{\text{int}}$ was observable within the RP-DG model which compensated for the model's formulaic shortcomings. Unlike the correlations relating to the DG1 and DG2 cells, which presented a similar relationship regardless of the time of year; the correlation relating to the RP-DG cell exhibited a seasonal variations. Below, a series of equations are presented which depict the aforementioned correlation per month in a given year. *Please note that the erroneous parametric input values regarding the RP-DG cell's south-facing window type and roofpond depth have likely rendered these equations invalid beyond this specific two-year simulation run. If the RP-DG model was to be applied elsewhere, one should take the time to reanalyze these monthly correlations after the parametric input values are corrected.* Unfortunately, these erroneous inputs were not discovered until after the completion of the study presented in this thesis. Nonetheless, the following equations compensated for the erroneous inputs. The ultimate accuracy of the simulation model will
be demonstrated later in this chapter. Additionally, one should note that the relatively limited amount of measured data from the RP-DG cell caused these equations to be especially experimental. Reliable measured data was not available for the months of September, October, November, or December. However, guided by an observable trend derived from the monthly formulas, as depicted in Figure A3.6, four of the monthly formulas were also utilized for the months devoid of useful measured data. All of the equations were derived from 2-order polynomial trendlines calculated from monthly correlation analyses. Refer to Appendix IV for figures derived from these monthly analyses. The equations were applied as follows:

For January and December: \[ y = (-0.0004 H_{s-tran}^2) + (0.0925 H_{s-tran}) + 2.5425 \]

For February and November: \[ y = (0.00003 H_{s-tran}^2) + (0.0506 H_{s-tran}) + 3.0013 \]

For March and October: \[ y = (0.00005 H_{s-tran}^2) + (0.0541 H_{s-tran}) + 3.121 \]

For April and September: \[ y = (-0.0005 H_{g-tran}^2) + (0.1044 H_{g-tran}) + 4.1394 \]

For May: \[ y = (0.0011 H_{g-tran}^2) + (0.0116 H_{g-tran}) + 4.1958 \]

Please note that these formulas were only useful when the RP-DG cell was operating in its heating mode. For the entire months of June, July, and August, the RP-DG cell was
operating in its cooling mode. Thus, no correlation data existed and corrective formulas were not necessary.

The values of \( y \) computed from the equations listed above were used to correct the corresponding hourly values of \( T_{\text{int}} \) via the following equation:

\[
T_{\text{int-a}} = [T_{\text{int}} - (Q_{\text{total}} / THC)] + y
\]

Figure A3.6  Illustration of the Seasonal Variation of the RP-DG Cell's Correlation between Transmitted Hourly Irradiation and the Absolute Difference between the Hourly Measured and Simulated Values of \( T_{\text{int}} \)
HVAC Simulation Calculations

Once the RP-DG simulation model was calibrated, an amended second version of the simulation model was designed to emulate the energy use and thermal performance influence of an auxiliary heat source within the test cell. Under the guidance of Professor Alfredo Fernández-González, the HVAC-enabled version of the RP-DG simulation model was designed to communicate the effect a thermostat-linked auxiliary heat source would have on $Q_{total}$ on an hourly basis. Please note that auxiliary cooling was never implemented into the models.

There were three basic calculation steps that separated the HVAC-enabled model from the free-running model. The first of which was the modified equation used to calculate $T_{int}$:

$$T_{int} = \left[ \frac{(Q_{total} + Q_{aux-ap})}{CAP} \right]$$

Next, the hour value of $Q_{aux}$ was calculated using the following formula from Fernández-González (2007):

If $T_{int} < T_{set}$, then: $Q_{aux} = -(T_{set} - T_{int}) \times CAP$

Otherwise: $Q_{aux} = T_{int}$

Finally, the value of $Q_{aux}$ had to be adjusted ($Q_{aux-a}$) as follows:
If $Q_{aux} > 0$, then: $Q_{aux-a} = 0$

Otherwise: $Q_{aux-a} = Q_{aux}$

This last step was necessary due to the fact that a mathematically positive value for $Q_{aux}$ simply indicated an absence of auxiliary heat during the current hour and a mathematically negative value of $Q_{aux}$ indicated the degree of utilized auxiliary heat during the current hour. Therefore, only negative values of $Q_{aux}$ were desired.

While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $Q_{aux-a}$ value for its $Q_{aux-ap}$ value. However, the initial hour’s HVAC-enabled calculations required a manually input value for $Q_{aux-ap}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the HVAC-enabled simulation model received either an arbitrary value for $Q_{aux-ap}$ influenced by the $T_{set}$ input value or the most recently calculated value of $Q_{aux-a}$, even if the value was not calculated for the previous hour.

**Formulaic Narrative of the Roofpond Thermospace (RP-T) Simulation Model**

The RP-T thermal simulation model implemented many of the formulas published by two previously developed roofpond thermal modeling software platforms: Dr. David Lord’s interactive, web-based computer program for thermal design of roofponds (1999) and Professor Alfredo Fernández-González’s $RP_{Performance}$ program (2004). Both of these programs were developed under grants from the Evelyn and Harold Hay Fund.
Please note that the RP-T model is coupled with both the RP simulation model as well as the RP-DG simulation model. However, in each case, specific parametric inputs were used based on the test cell in consideration.

_The RP-T model used I-P units_ in order to coincide and easily integrate with the RP and RP-DG simulation models. Some of the formulas derived from Lord (1999) were in SI units. However, using conversion factors, these formulas were integrated in way in which all of the input values from the user were still in I-P units.

**Corrected Programming Error**

Please be aware that the RP-T model featured one programming error. This error pertained to incorrect conversion factors within one of the employed formulas. This error was mathematically corrected during the calibration of the RP-T simulation model. Specific details regarding the programming error are disclosed within the relevant section of this formulaic narrative.

**Required Input Data**

The RP-T model required many of the same variable input values and hourly data as the other simulation models. In this case, however, the building parameters represented only that component for the test cell’s thermospace (i.e. the \(A_{\text{wall}}\) pertained _only_ to the east wall of the thermospace, and so on). With regard to parametric input values, the RP-T simulation model required several pieces of information, many of which related specifically to the roofpond itself. The required values were as follows: \(A_{\text{n-wall}}, A_{\text{s-wall}}, A_{\text{tilt-n}}, A_{\text{tilt-s}}, A_{\text{e-wall}}, A_{\text{wall}}, U_{\text{n-wall}}, U_{\text{s-wall}}, U_{\text{tilt-n}}, U_{\text{tilt-s}}, U_{\text{e-wall}}, U_{\text{wall}}, U_{\text{tilt-win-O}}, U_{\text{tilt-win-C}}, \text{VOL}_{\text{air}}, \text{ACH}, \text{OC}, Q_{\text{int}}, \text{SC}, \alpha_{\text{ex-walls}}, \alpha_{\text{roof}}, \text{CAP}, \text{ESL}, T_{\text{set}}, T_{\text{his}}, T_{\text{lo}}, A_{\text{rp}}, D_{\text{rp}}, E_{\text{rp}}, E_{\text{win}}, \text{and CT}._
As with the other simulation models, the various required area values from both the RP and RP-DG cell’s thermospaces were derived from cataloged field measurements and data, as well as construction drawings. This prior documentation was also relied upon for the values of VOL\textsubscript{air}, CAP, A\textsubscript{rp}, and D\textsubscript{rp}.

As with every simulation model, the required overall thermal conductance values relating to the RP thermospace’s exterior envelope were derived using the parallel path method as defined by ASHRAE (2001).

The ACH values used in the RP-T model for both the RP and RP-DG cell simulations were defined by Professor Alfredo Femández-González (2007), who oversaw the construction and operation of the MPSP.

Since the thermospaces were not intended to be occupied, the values of OC was set to zero.

The thermospaces did not feature any sources of internal heat gains. Thus, Q\textsubscript{int} was set to 0 Btu/h.

The exterior walls of the thermospace were painted with the same grey paint as the rest of the cell. Thus, the $\alpha_{\text{ex-walls}}$ value for the RP-T model was set to 0.73. The thermospace also exhibited the same EDPM liner as the rest of the cell. Therefore, the RP-T model’s value of $\alpha_{\text{roof}}$ was set to 0.93.

Consistent with the other simulation models, the ESL was set to 935-feet.

The $T_{\text{set}}$ for the RP-T simulation model was set to 65°F, $T_{\text{hi}}$ was set to 78°F, and $T_{\text{lo}}$ was set to 68°F.

Relating specifically to the roofpond itself, $E_{\text{rp}}$ was always assumed to be 0.80 for both the RP and RP-DG cell simulations.
The value of $E_{\text{win}}$ related only to the thermospace's tilted, south-facing glazing. The value was specific to the test cell of consideration and was determined from ASHRAE (2001).

The CT was specified by the user to indicate a location's prevailing cloud type. Four choices were listed, each with a numerical designation: cirrus (1), altocumulus (2), stratocumulus (3), and fog (4). The listed range of cloud types and their corresponding cloud value (CV) were based on Lord’s (1999) thermal modeling software for roofponds.

In addition to the parametric input values, the RP-T simulation model also required various forms of hourly data. From the on-site weather station, the following hourly data was required: $T_a$, $T_{wc}$, RH, DP, and $V_{\text{wind}}$. Since the MPSP test cells were set atop a concrete patio, hourly values of $\rho_g$ were assumed to be the 0.3 unless snow coverage was recorded by the National Climate Data Center’s (2007) Muncie weather station at Ball State University—in which case, an hourly $\rho_g$ value of 0.7 was assumed. The RP-T model also required the following hourly data, which was obtained using SOLRAD Model 6: $K_T$, $H$, $H_s$, $H_w$, $H_{e-50}$, and $H_{s-50-tran}$. Please note that all hourly input data were consistently applied to every simulation model.

The RP-T model also received hourly values of $T_{\text{prev}}$ from the simulation model to which it was linked (e.g. the RP or RP-DG simulation models).

The RP-T simulation model also received measured performance data (when available) from the RP and RP-DG cells themselves. However, as with all of the simulation models, the data were only used for comparative purposes. Measured data did not factor into any of the simulation model’s calculations.
Air Density Ratio Calculations

As with all of the simulation models, the RP-T model calculated the ADR by employing the following equation derived from the trendline depicting the ADR for different elevations as published on page 3-2 of Balcomb et al. (1984):

\[
ADR = -0.0321 \left( \frac{ESL}{1000} \right) + 1
\]

Capacitance Calculations

As mentioned above, the RP-T simulation model utilized a separate worksheet solely dedicated to calculating the cell’s CAP. The worksheet was identical to that described within the CC model’s formulaic narrative. This worksheet was utilized by all of the simulation models.

Within the worksheet, a material’s thermal heat capacity (Btu/ft^3 °F) is calculated as described by Stein et al. (2006). Using recorded measurements, each component’s capacitance (Btu/°F) was determined using the following formula:

\[
CAP_{(component)} = d \cdot c \cdot A_x \cdot L
\]

Next, this process was repeated for every thermally massive material within the thermospace. The total capacitance for the thermospace was determined via a summation of the CAP values from the thermospace’s individual thermally massive components:

\[
CAP_{(total)} = \left( \text{Sum of } CAP_{(components)} \right) (1 - \epsilon)
\]
Please notice that the final value of CAP took into consideration the percentage of its thermal mass that effectively performed as thermal mass for the immediately adjacent thermal zone. The value of $\epsilon$ was specific to the simulation model to which the RP-T model is linked. In the case of the RP model, the value of $\epsilon$ is 0.05. For the RP-DG model, the value of $\epsilon$ is 0.25. These values were determined during the calibration of the RP-T model using measured data from both the RP and RP-DG test cells.

**Total Load Coefficient Calculations**

Consistent with the other simulation models, the RP-T model used the following equation from Moore (1994) to calculate the TLC:

$$TLC = 24 \times UA_{total}$$

The RP-T model actually ran the UA calculations twice. The first time, the thermal conductance of the tilted, south-facing glass was calculated under the “open” circumstance in which the roofpond’s movable insulation was retracted and the roofpond was exposed to the sky through the glass (i.e. $U_{tint-win-O}$ was used as the U-value for the attic’s glazing). During the second run, the glass was calculated under the “closed” circumstance in which the roofpond’s movable insulation was detracted over the back face of the glass (i.e. $U_{tint-win-C}$ was used as the U-value for the attic’s glazing). These two sets of calculations (“open” and “closed”) were vital to the model’s operation as the situation of the movable insulation had a profound effect on the roofpond’s performance. Unlike the RP and RP-DG simulation models, the RP-T model’s UA calculations did not require a corrective multiplier.
Consistent with the other simulation models, the UA value for infiltration \( (UA_{\text{inf}}) \) was calculated using the following equation from Balcomb et al. (1984):

\[
UA_{\text{inf}} = 0.018 \times VOL_{\text{air}} \times ACH \times ADR
\]

**Sol-Air Temperature Calculations**

Next, the RP-T model calculated hourly sol-air temperatures for every major surface significantly exposed to direct beam radiation whose sol-air temperature had been determined to have considerable influence over the heat transfer throughout the thermospace. Since the thermospace was situated above the roof level of every non-roofpond test cell, the sol-air temperature had to be computed for four different surfaces: \( S_{s}\text{-wall}, S_{e}\text{-wall}, S_{w}\text{-wall}, \) and \( S_{s}\text{-tilt}. \) Please note that the specified tilt for \( S_{s}\text{-tilt} \) was \( ^{\circ}50 \) above the horizon.

As with the previously described simulation models, the RP-T model utilized the proceeding simplified equations for calculating the sol-air temperatures of both horizontal and vertical surfaces as detailed by ASHRAE (2001) and Stein et al. (2006):

For horizontal surfaces:

\[
S_x = T_a + \left[ \frac{(\alpha_x H_x)}{h_o} \right] - 7^\circ F
\]

For vertical surfaces:

\[
S_x = T_a + \left[ \frac{(\alpha_x H_x)}{h_o} \right]
\]

The equation for vertical surfaces was used to computer \( S_{s}\text{-tilt}. \) The value of \( \alpha_x \) depended on the surface being considered (e.g. \( \alpha_{\text{ex-walls}}, \alpha_{\text{roofs}}, \) or \( \rho_e \)).
Similarly, the hourly value of $H_x$ depended on which surface was being considered (e.g. $H$, $H_s$, or $H_e$).

As mentioned earlier, according to ASHRAE (2001) and Stein et al. (2006) it is common practice to assume that $h_0$ is 3.0 Btu/h ft$^2$ °F. All of the simulation models made this assumption.

**Hourly Non-Solar Conductive Heat Exchange Calculations**

Once the above mentioned calculations had taken place for a considered hour, the RP-T simulation model proceeded to calculate the composite heat exchange through the thermospaces’s non-solar exterior envelope. Depending on the orientation and nature of a given exterior surface, the non-solar conductive heat exchange was calculated somewhat differently. Therefore, it is necessary to delineate every equation used to calculate the composite hourly heat exchange through the non-solar exterior envelope. These equations drew on the methodology for calculating design heat loss published by Stein et al. (2006). Please note that the following series of formulas was uniquely designed for the RP-T simulation model:

$$Q_{s\text{-wall}} = U A_{s\text{-wall}} \times (T_{\text{prev}} - S_{s\text{-wall}})$$

$$Q_{\text{tilt\text{-}s}} = U A_{\text{tilt\text{-}s}} \times (T_{\text{prev}} - S_{\text{tilt\text{-}s}})$$

$$Q_{n\text{-wall}} = U A_{n\text{-wall}} \times (T_{\text{prev}} - T_a)$$

$$Q_{\text{tilt\text{-}n}} = U A_{\text{tilt\text{-}n}} \times (T_{\text{prev}} - T_a)$$
If adjacent cell to the east featured a thermospace, $Q_{e\text{-wall}} = UA_{e\text{-wall}} \times (T_{\text{prev}} - T_a)$

Otherwise, $Q_{e\text{-wall}} = UA_{e\text{-wall}} \times (T_{\text{prev}} - S_{e\text{-wall}})$

If adjacent cell to the west featured a thermospace, $Q_{w\text{-wall}} = UA_{w\text{-wall}} \times (T_{\text{prev}} - T_a)$

Otherwise, $Q_{w\text{-wall}} = UA_{w\text{-wall}} \times (T_{\text{prev}} - S_{w\text{-wall}})$

The summation of these values composed the total conductive heat exchange per hour through the non-solar exterior envelope of the thermospace. While conducting subsequent hourly calculations, the simulation model simply drew on the previous hour’s $T_{\text{int}}$ value for its $T_{\text{prev}}$ value. However, the initial hour’s heat exchange calculations required a manually input value for $T_{\text{int}}$. This was also the case where weather data was broken, thus prompting the model to restart its calculations at the next occurrence of hourly weather data. Under these conditions, the RP-T simulation model received either an arbitrary $T_{\text{prev}}$ value influenced by the actual measured data from the pertinent test cell or the most recently calculated value of $T_{\text{int}}$, even if the value was not calculated for the previous hour.

**Hourly Solar Conductive Heat Exchange Calculations**

From this point, the RP-T model had to calculate the conductive heat exchange through the tilted, south-facing glazing of the thermospace. The calculations had to be executed under the conditions in which the roofpond system was *closed* (and the movable insulation was oriented directly behind the glazing of the thermospace) as well as *open* (and the movable insulation was retracted from behind the glazing):
The value of $T_{prev}$ per hour was determined in accordance with the non-solar conductive heat exchange calculations.

**Total Hourly Conductive Heat Exchange Calculations**

After the program calculated the solar and non-solar conductive heat exchange per given hour, it calculated the total hourly conductive heat exchange through the exterior envelope of the thermospace for when roofpond system was either closed ($Q_{cond-C}$) or open ($Q_{cond-O}$):

$$Q_{cond-C} = Q_{s-wall} + Q_{tilt-s} + Q_{n-wall} + Q_{tilt-n} + Q_{e-wall} + Q_{w-wall} + Q_{tilt-win-C}$$

$$Q_{cond-O} = Q_{s-wall} + Q_{tilt-s} + Q_{n-wall} + Q_{tilt-n} + Q_{e-wall} + Q_{w-wall} + Q_{tilt-win-O}$$

**Hourly Heat Exchange Due to Infiltration**

$Q_{inf}$ was similarly calculated as listed below. However, during the calibration of the MPSP test cell simulation models, the simulation model required the ratio of the ambient outdoor air temperature to the wind chill temperature ($T_a/T_{wc}$) to serve as a multiplier in order to match the test cell's measured values. Thus, the following equation:

$$Q_{inf} = U A_{inf} \times (T_{prev} - T_a) \times \left(\frac{T_a}{T_{wc}}\right)$$
Hourly Heat Exchange Due to Infiltration

As the thermospace was not intended to be occupied, there were no internal gains. Therefore, $Q_{\text{int}}$ was continuously set to 0 Btu/h.

Hourly Transmitted Thermal Energy Due to Solar Strategy

The RP-AS simulation model also calculated the transmitted radiation through the tilted, south-facing glazing of the thermospace. This was accomplished using the following formula from Fernández-González (2007):

$$Q_{\text{sol}} = w A_{\text{tilt-win}} H_{0.50-\text{tran}}$$

Similar to the calculations regarding the south-facing glazing utilized by many of the simulation models, a correction multiplier ($w$) had to be applied to $Q_{\text{sol}}$ due to the gradual accumulation of particulate matter upon the surface of the tilted, south-facing glazing, which subsequently reduced its ability to absorb incident solar radiation. Further analyses indicated that the impact of the glazing's dirtiness was also affected by the Sun's altitude. Thus, the value of $w$ occasionally fluctuated in an unexpected fashion from one month to the next. Table A3.4 lists the monthly values of $w$ used to correct the value of $Q_{\text{sol}}$. Please note that the monthly values of the corrective multiplier used by the RP-T model (which compensated for the dirtiness of the tilted glass) were different from those implemented by the test cell simulation models that considered south-facing glass (which accumulated particulates at a different rate and was cleaned at different times than the tilted glass). The values listed in Table A3.4 values only pertained to the RP-T model and were determined during the calibration of the RP-T model.
### Table A3.4  Scheduled Values of Variable *w*

<table>
<thead>
<tr>
<th>Month</th>
<th>2003 Values</th>
<th>2004 Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.95</td>
<td>0.85&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>February</td>
<td>0.93</td>
<td>0.80</td>
</tr>
<tr>
<td>March</td>
<td>0.90</td>
<td>0.75</td>
</tr>
<tr>
<td>April</td>
<td>0.85</td>
<td>0.55</td>
</tr>
<tr>
<td>May</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>June</td>
<td>0.88</td>
<td>0.85</td>
</tr>
<tr>
<td>July</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>August</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>September</td>
<td>0.78</td>
<td>0.78&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>October</td>
<td>0.85</td>
<td>0.85&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>November</td>
<td>0.79</td>
<td>0.79&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>December</td>
<td>0.60</td>
<td>0.60&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> The tilted glazings of the thermospaces were cleaned in January 2004. The exact date of the cleaning was not officially recorded. However, during the calibration of the simulation models, a value of 0.85 best suited the entire month. This value indicated that the glass apparently was not thoroughly cleaned.

<sup>b</sup> Speculative values based on the previous year's data and/or observable trends.

### Cloud Value Specification

The CV was determined based on the specified CT value. The values were based on Lord's (1999) roofpond thermal modeling software: 0.16 (for 1 or cirrus), 0.66 (for 2 or altocumulus), 0.88 (for 3 or stratocumulus), and 1 (for 4 or fog).

### Clear Sky Emittance Calculation

The formula used to calculate the hourly value of $E_{\text{clear}}$ was also based on the software developed by Lord (1999). The equation is listed below:

$$E_{\text{clear}} = 0.634 + (0.00167 \, \text{DP}) + (0.0000226 \, \text{DP}^2)$$
Sky Emittance Calculation

The formula used to calculate the hourly value of $E_{\text{sky}}$ was also derived from Lord (1999):

$$E_{\text{sky}} = E_{\text{clear}} + (1 - E_{\text{clear}}) K_T CV$$

Minimum Sky Temperature Calculation

The formula used to calculate the hourly value of $T_{\text{sky}}$ was based on the software developed by Lord (1999). The equation is listed below:

$$T_{\text{sky}} = \left\{ \left[ \left( T_a - 32 \right) \frac{5}{9} + 273 \right] \left( E_{\text{sky}}^{0.25} - 273 \right) \right\} \frac{9}{5} + 32$$

Please note that the formula implemented by Lord (1999) used SI units. Therefore, $T_a$ had to be converted into °C for use within the formula. Subsequently, the value derived from the formula had to then be converted back into °F for use within the rest of the simulation model.

Stefan-Boltzman Coefficient

The Stefan-Boltzman coefficient is a physical constant denoted by the Greek letter $\sigma$, which mathematically conveys the constant of proportionality in the Stefan-Boltzman law. In simple terms, the law states that the total energy radiated per unit surface area of a black body in unit time is proportional to the fourth power of the thermodynamic temperature. While Lord (1999) listed the value of $\sigma$ at 5.70E-08 W/m² K⁴, Fernández-
González (2004) listed the value of $\sigma$ at 5.67E-08 W/m² K⁴. The latter value was used by the RP-T model.

**Roofpond Operation Mode Signifier**

The RP-T model used the $M_{\text{closed}}$ and $M_{\text{open}}$ signifiers in order to determine if the roofpond system's mode of operation for any given hour was *closed* (indicating that the movable insulation was oriented directly behind the glazing of the thermospace) or *open* (indicating that the movable insulation was retracted from behind the glazing). In each case, the signifier either possessed the value of 1 to indicate "yes" or the value of 0 to indicate "no." The following algorithm, which was used by the simulation model during the heating season, was designed to adhere to the schedule for moving the insulation panels as described by Fernández-González (2004):

If $H > 0$, then: $M_{\text{open}} = 1$

Otherwise: $M_{\text{open}} = 0$

If $M_{\text{open}} = 0$, then: $M_{\text{closed}} = 1$

Otherwise: $M_{\text{closed}} = 0$

The corresponding algorithm for the cooling season is listed below:

If $H > 0$, then: $M_{\text{open}} = 0$

Otherwise: $M_{\text{open}} = 1$
If \( M_{\text{open}} = 0 \), then: \( M_{\text{closed}} = 1 \)

Otherwise: \( M_{\text{closed}} = 0 \)

**Radiation Loss Expression Calculations**

The following equation used to compute the radiation loss expression was derived from Lord (1999):

If \( H_{s-50-\text{tran}} > 0 \), then:

\[
Q_{\text{rad-loss}} = E_{\text{rp}} \left\{ \left[ \sigma (T_{\text{prev}} + 273)^4 - E_{\text{sky}} \sigma (T_{\text{sky}} + 273)^4 \right] - w H_{s-50-\text{tran}} \right\}
\]

Otherwise:

\[
Q_{\text{rad-loss}} = E_{\text{rp}} \left[ \sigma (T_{\text{prev}} + 273)^4 - E_{\text{sky}} \sigma (T_{\text{sky}} + 273)^4 \right]
\]

The end result of the equation was in the SI units of W/m². The \( T_{\text{prev}} \) and \( T_{\text{sky}} \) inputs, which were in degrees Fahrenheit, should have been converted into degrees Celsius, as the formula is designed to convert Celsius temperatures into Kelvin temperatures. As well, values of \( H_{s-50-\text{tran}} \) should have been converted from the I-P units of Btu/h ft² to the SI units of W/m². During the development of the RP-T model, this error was not identified. However, during the calibration of the RP-T model, the discrepancy between the measured and simulated results stemming from this error was accounted for via a corrective multiplier. Had this error been identified, the multiplier would have been omitted and the following *corrected* formula would have been used in the RP-T model:

---

\(^5\) See the information below regarding the corrective multiplier of 0.55, which was deemed necessary during the calibration of the RP-T simulation model using the measured results from the RP and RP-DG cells.
If $H_{s-50-tran} > 0$, then:

$$Q_{\text{rad-loss}} = E_p \left\{ \sigma \left[ (T_{prev} - 32) \left( \frac{5}{9} \right) + 273 \right]^4 - E_{sky} \sigma \left[ (T_{sky} - 32) \left( \frac{5}{9} \right) + 273 \right]^4 \right\} - H_{s-50-tran} \times 3.1549$$

Otherwise:

$$Q_{\text{rad-loss}} = E_p \left\{ \sigma \left[ (T_{prev} - 32) \left( \frac{5}{9} \right) + 273 \right]^4 - E_{sky} \sigma \left[ (T_{sky} - 32) \left( \frac{5}{9} \right) + 273 \right]^4 \right\}$$

Despite the erroneous unit conversions, the initial value of $Q_{\text{rad-loss}}$ was recognized as possessing the SI units of $W/m^2$. Therefore, the values of $Q_{\text{rad-loss}}$ were subsequently converted into the I-P units (Btu/hr ft²) then multiplied with the area of the tilted, south-facing glazing (thus, producing units of Btu/h) via the following equation:

If $M_{open} = 1.$ then:

$$Q_{\text{rad-loss}} \text{ (Btu/h)} = (Q_{\text{rad-loss}} \text{ (W/m²) } 0.316967) A_{\text{tilt-win}} \times 0.55,$$

Otherwise:

$$Q_{\text{rad-loss}} \text{ (Btu/h)} = p (Q_{\text{rad-loss}} \text{ (W/m²) } 0.316967) A_{\text{tilt-win}} \times 0.55$$

The variable $p$ indicated the percent of hourly transmitted solar irradiation that was lost through the tilted, south-facing glazing of the thermospace while the movable insulation was positioned directly behind the glass. Even when the insulation was positioned behind the glass during the roofpond system’s closed condition, some degree of transmitted irradiation still managed to escape. Specifically in the case of the RP and RP-DG test cells, this phenomenon was exasperated by the movable insulation’s positioning approximately 1-inch away from the face of the window’s framing. The
variable $p$ compensated for the true heat loss of the thermospace when the roofpond system was closed. The monthly values listed in Table A3.5 were determined during the calibration of the RP-T model using measured data from the RP and RP-DG cells.

One should also observe that during the calibration of the RP-T simulation model, it was determined that the hourly values of $Q_{\text{rad-loss}}$ required a multiplier of 0.55 in order to produce acceptably accurate results. It has since been confirmed that this multiplier was compensating for the aforementioned error pertaining to the calculation of $Q_{\text{rad-loss}}$. Had the corrected formula for $Q_{\text{rad-loss}}$ been employed, then this multiplier would have been omitted.

<table>
<thead>
<tr>
<th>Month</th>
<th>2003 Values</th>
<th>2004 Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>February</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>March</td>
<td>0.05</td>
<td>0.20</td>
</tr>
<tr>
<td>April</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>May</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>June</td>
<td>0.05</td>
<td>0.05</td>
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<tr>
<td>July</td>
<td>0.05</td>
<td>0.05</td>
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<tr>
<td>August</td>
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<tr>
<td>September</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>October</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>November</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>December</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

It is unclear why the first three months of 2004 exhibited a larger degree of radiation heat loss during the roofpond system's closed mode of operation. However, it is suspected that this anomaly was linked to the severity of this 2003-2004 winter season coupled with the unusual degree of clearness of the night sky during this time period.

Speculative values based on the previous year's data and/or observable trends.
Sub-Total Hourly Heat Exchange Calculations

After the program had executed the previously described calculations, the sub-total hourly heat exchange was calculated. One should keep in mind that the sub-total had to be computed for both the closed \( Q_{\text{subt-c}} \) and open \( Q_{\text{subt-o}} \) modes of operation. Moreover, these sub-totals did not take into consideration the heat exchange between the thermospaces and the adjacent occupiable volume below the roofpond’s water bags and metal decking. The equations were programmed as follows:

\[
Q_{\text{subt-c}} = (Q_{\text{sol}} + Q_{\text{cond-c}} + Q_{\text{inf}} + Q_{\text{int}} + Q_{\text{rad-loss}}
\]

\[
Q_{\text{subt-o}} = Q_{\text{sol}} + Q_{\text{cond-o}} + Q_{\text{inf}} + Q_{\text{int}} + Q_{\text{rad-loss}}
\]

As stated above, when the movable insulation panels were positioned directly behind the tilted, south-facing windows, there was still a small 1-inch air gap between the panels and the inward-facing frame of the window. While most of the transmitted irradiation was reflected back outward through the window due to the insulation panel’s high reflective white paint, the air gap permitted a considerable fraction of transmitted irradiation to circulate throughout the thermospaces relatively freely. The variable \( k \) was used to compensate for the percentage of transmitted irradiation that was converted into thermal energy and contributed to the heat gains within the thermospaces during the closed mode of operation. Table A3.6 lists the monthly values used for \( k \). These values were determined during the calibration of the RP-T simulation model using measured data.
Table A3.6  Scheduled Value of Variable $k$

<table>
<thead>
<tr>
<th>Month</th>
<th>2003 Values</th>
<th>2004 Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>February</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>March</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>April</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>May</td>
<td>0.30</td>
<td>0.05</td>
</tr>
<tr>
<td>June</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>July</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>August</td>
<td>0.15</td>
<td>0.30</td>
</tr>
<tr>
<td>September</td>
<td>0.30</td>
<td>0.30$^a$</td>
</tr>
<tr>
<td>October</td>
<td>0.30</td>
<td>0.30$^a$</td>
</tr>
<tr>
<td>November</td>
<td>0.30</td>
<td>0.30$^a$</td>
</tr>
<tr>
<td>December</td>
<td>0.30</td>
<td>0.30$^a$</td>
</tr>
</tbody>
</table>

$^a$ Speculative values based on the previous year's data and/or observable trends.

Hourly Indoor Air Temperature Calculations

Using the sub-totaled values of $Q_{subt-C}$ and $Q_{subt-O}$, the simulated internal air temperature of the thermospace was then calculated for the considered hour. The hourly value of $T_{int}$ was calculated using the following formula from Professor Alfredo Fernández-González (2007):

$$T_{int} = \frac{Q_{total}}{CAP}$$

Hourly Heat Exchange With Occupiable Volume

At this juncture, the RP-T model compared the simulated mean interior air temperatures of both the thermospace and the occupiable volume of the simulated model to which the RP-T model was linked. The adjacent thermal zones constantly sought
equilibrium. Thus, the exchange of thermal energy between the zones was estimated in hourly intervals. The following algorithm used to determine $Q_{\text{exchange}}$ was adapted from RP Performance (Fernández-González 2004) under the guidance of its author, Professor Alfredo Fernández-González. Please observe that in order for these calculations to be conducted, $T_{\text{prev}}$ values were needed from both the RP-T model and the simulation model to which the RP-T model was linked (e.g. the RP or RP-DG simulation model).

$$U_{\text{pi}} = \frac{4}{1.6664 + (0.348 D_{\text{RP}}/12)}$$

$$U_{\text{ip}} = \frac{7}{1.3564 + (0.348 D_{\text{RP}}/12)}$$

If $(T_{\text{prev from RP-T model}} > T_{\text{prev from linked sim. Model}})$, then:

$$Q_{\text{exchange}} = U_{\text{pi}} A_{\text{RP}} (T_{\text{prev from RP-T model}} - T_{\text{prev from linked sim. Model}})$$

Otherwise:

$$Q_{\text{exchange}} = U_{\text{ip}} A_{\text{RP}} (T_{\text{prev from RP-T model}} - T_{\text{prev from linked sim. Model}})$$

If the value of $Q_{\text{exchange}}$ was positive, then it's a heat loss for the RP-T model. Conversely, a negative value of $Q_{\text{exchange}}$ indicated a heat gain for the RP-T model from the linked simulation model. Finally, these values of $Q_{\text{exchange}}$ were exported to the linked simulation model as corresponding heat gains or losses (i.e. an hourly $Q_{\text{exchange}}$ value of 500 Btu/h would have been exported to the linked simulation model as -500 Btu/h for the same hour).
HVAC Simulation Calculations

As with the other models, an HVAC-enabled version of the RP-T model was also developed. However, the HVAC-enabled version did not feature any amendments. It only needed to be dedicated to the HVAC-enabled version of the simulation model linked to the free-running version of the RP-T model. As the auxiliary heat source supplied heat to the occupiable volume of the linked simulation model, heat was transferred to the coupled RP-T model as the two thermal zones approach equilibrium.

Validation of the MPSP Simulation Models

For organizational purposes, the simulation models were executed for individual months. Also, each of the simulation models was calibrated against measured data.

In order to demonstrate the accuracy of the simulation models and their final $T_{int}$ output, a series of figures are presented below which compare the simulations models to the test cells’ measured data for the months of February 2003 and February 2004. Please note that the RP-T model was integrated into both the RP and RP-DG models. Also, the DG2 test cell was the DG1 cell after it was renovated. Therefore, measured data from the DG1 and DG2 cells can not overlap. Be mindful that the MPSP was in its first phase in February 2003 and in its second phase in February 2004. However, in order to create a valid comparison between the test cells, the simulation models were used to eliminate the parametric discrepancies and/or systemic irregularities exhibited by a the test cells at various points in time. For clarification purposes, major system malfunctions are clearly identified in the figures below. A complete graphic account of the individual monthly simulation runs used for the purposes of this thesis is exhibited in Appendix V.
Figure A3.7  Control Cell (CC) Performance Summary – February 2003

Figure A3.8  Control Cell (CC) Performance Summary – February 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A3.9  Direct Gain, Model 1 (DG1) Performance Summary – February 2003

Figure A3.10  Direct Gain, Model 1 (DG1) Performance Summary – February 2004

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Figure A3.11 Trombé-Wall (TW) Performance Summary – February 2003

Figure A3.12 Trombé-Wall (TW) Performance Summary – February 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A3.13  Water-Wall (WW) Performance Summary – February 2003

Figure A3.14  Water-Wall (WW) Performance Summary – February 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A3.15  Roofpond (RP) Performance Summary – February 2003

Figure A3.16  Roofpond (RP) Performance Summary – February 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A3.17  Direct Gain, Model 2 (DG2) Performance Summary – February 2003

Figure A3.18  Direct Gain, Model 2 (DG2) Performance Summary – February 2004
Figure A3.19  Roofpond-Direct Gain (RP-DG) Performance Summary –
February 2003

Figure A3.20  Roofpond-Direct Gain (RP-DG) Performance Summary –
February 2004

(Please note systemic irregularities exhibited by the measured test cell data.)

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The following charts depict two series of correlation data. The first series, Figures A3-1 through A3-12, illustrates the correlation between hourly global horizontal irradiation and the absolute difference between the corresponding hourly measured and simulated values of $T_{int}$ of the water-wall (WW) test cell. The second series, Figures A3-13 through A3-17, illustrates the correlation between hourly transmitted irradiation and the absolute difference between the corresponding hourly measured and simulated values of $T_{int}$ of the roofpond-direct gain (RP-DG) test cell.

Unlike the correlations relating to the direct gain, model 1 (DG1) or model 2 (DG2) test cells, which presented a strong relationship regardless of the time of year, the correlations relating to the WW and RP-DG cells exhibited very strong seasonal variations. Since the WW and RP-DG simulation models were applied in monthly increments, the seasonal correlations were analyzed in monthly increments. From the monthly correlation data, equations were derived from 2-order polynomial trendlines as illustrated in the figures below.
Figure A4.1  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for January

\[ y = 0.0004x^2 + 0.0742x + 2.2004 \]
\[ R^2 = 0.7466 \]

Figure A4.2  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for February

\[ y = 2E-05x^2 + 0.079x + 15561 \]
\[ R^2 = 0.7504 \]
Figure A4.3  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for March

Figure A4.4  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for April
Figure A4.5  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for May

Figure A4.6  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for June
Figure A4.7  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for July

Figure A4.8  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for August

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Figure A4.9  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for September

Figure A4.10  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for October
Figure A4.11  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for November

Figure A4.12  XY Scatter Chart Illustrating the Correlation between Global Horizontal Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the WW Cell for December
Figure A4.13  XY Scatter Chart Illustrating the Correlation between Transmitted Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the RP-DG Cell for January (and December)

Figure A4.14  XY Scatter Chart Illustrating the Correlation between Transmitted Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the RP-DG Cell for February (and November)
Figure A4.15  XY Scatter Chart Illustrating the Correlation between Transmitted Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the RP-DG Cell for March (and October)

Figure A4.16  XY Scatter Chart Illustrating the Correlation between Transmitted Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the RP-DG Cell for April (and September)
Figure A4.17  XY Scatter Chart Illustrating the Correlation between Transmitted Irradiation and the Absolute Value of the Temperature Difference between the Measured and Simulated Temperature within the RP-DG Cell for May
APPENDIX V

TEST CELL MONTHLY PERFORMANCE SUMMARIES

Presented below is a series of charts, each graphically depicting key variables used to evaluate the thermal performance of the MPSP test cells. Each chart illustrates data for a single month, as indicated within the figure. Data for the individual test cells considered for this thesis are presented in succession. Thus, only one test cell is exhibited per figure. For each test cell, the complete 24-month simulation period is disclosed. Within every figure, simulated data are plotted. When available, measured data are also plotted. Where indicated, please note the discrepancies between measured and simulated data due to systemic irregularities, operational changes, and major experimental modifications.

Please note that the RP and RP-DG cells required manual operation of their movable insulation panels. Occasionally, their systems were not properly operated. Many of these operational irregularities were not recorded within the MPSP activity log (Appendix I) but are identified within the figures below. For analytical purposes, these irregularities were not programmed into the final simulation runs.
Figure A5.1  Control Cell (CC) Performance Summary – January 2003

Figure A5.2  Control Cell (CC) Performance Summary – February 2003
Figure A5.3  Control Cell (CC) Performance Summary – March 2003

Figure A5.4  Control Cell (CC) Performance Summary – April 2003
Figure A5.5  Control Cell (CC) Performance Summary – May 2003

Figure A5.6  Control Cell (CC) Performance Summary – June 2003
Figure A5.7  Control Cell (CC) Performance Summary – July 2003

Figure A5.8  Control Cell (CC) Performance Summary – August 2003

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Figure A5.9  Control Cell (CC) Performance Summary – September 2003

Figure A5.10  Control Cell (CC) Performance Summary – October 2003

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.11  Control Cell (CC) Performance Summary – November 2003
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.12  Control Cell (CC) Performance Summary – December 2003
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.13  Control Cell (CC) Performance Summary – January 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.14  Control Cell (CC) Performance Summary – February 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.15  Control Cell (CC) Performance Summary – March 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.16  Control Cell (CC) Performance Summary – April 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.17  Control Cell (CC) Performance Summary – May 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.18  Control Cell (CC) Performance Summary – June 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.19  Control Cell (CC) Performance Summary – July 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.20  Control Cell (CC) Performance Summary – August 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.21  Control Cell (CC) Performance Summary – September 2004

Figure A5.22  Control Cell (CC) Performance Summary – October 2004
Figure A5.23  Control Cell (CC) Performance Summary – November 2004

Figure A5.24  Control Cell (CC) Performance Summary – December 2004
Figure A5.25  Direct Gain, Model 1 (DG1) Performance Summary – January 2003

Figure A5.26  Direct Gain, Model 1 (DG1) Performance Summary – February 2003
Figure A5.27  Direct Gain, Model 1 (DG1) Performance Summary – March 2003

Figure A5.28  Direct Gain, Model 1 (DG1) Performance Summary – April 2003
Figure A5.29  Direct Gain, Model 1 (DG1) Performance Summary – May 2003

Figure A5.30  Direct Gain, Model 1 (DG1) Performance Summary – June 2003
Figure A5.31  Direct Gain, Model 1 (DG1) Performance Summary – July 2003

Figure A5.32  Direct Gain, Model 1 (DG1) Performance Summary – August 2003
Figure A5.33  Direct Gain, Model 1 (DG1) Performance Summary – September 2003

Figure A5.34  Direct Gain, Model 1 (DG1) Performance Summary – October 2003

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.35  Direct Gain, Model 1 (DG1) Performance Summary – November 2003
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.36  Direct Gain, Model 1 (DG1) Performance Summary – December 2003
Figure A5.37  Direct Gain, Model 1 (DG1) Performance Summary – January 2004

Figure A5.38  Direct Gain, Model 1 (DG1) Performance Summary – February 2004

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Figure A5.39  Direct Gain, Model 1 (DG1) Performance Summary – March 2004

Figure A5.40  Direct Gain, Model 1 (DG1) Performance Summary – April 2004
Figure A5.41  Direct Gain, Model 1 (DG1) Performance Summary – May 2004

Figure A5.42  Direct Gain, Model 1 (DG1) Performance Summary – June 2004
Figure A5.43  Direct Gain, Model 1 (DG1) Performance Summary – July 2004

Figure A5.44  Direct Gain, Model 1 (DG1) Performance Summary – August 2004

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Figure A5.45  Direct Gain, Model 1 (DG1) Performance Summary – September 2004

Figure A5.46  Direct Gain, Model 1 (DG1) Performance Summary – October 2004
Figure A5.47  Direct Gain, Model 1 (DG1) Performance Summary – November 2004

Figure A5.48  Direct Gain, Model 1 (DG1) Performance Summary – December 2004
Figure A5.49  Trombé-Wall (TW) Performance Summary – January 2003

Figure A5.50  Trombé-Wall (TW) Performance Summary – February 2003
Figure A5.51  Trombé-Wall (TW) Performance Summary – March 2003

Figure A5.52  Trombé-Wall (TW) Performance Summary – April 2003
Figure A5.53  Trombé-Wall (TW) Performance Summary – May 2003

Figure A5.54  Trombé-Wall (TW) Performance Summary – June 2003
Figure A5.55  Trombé-Wall (TW) Performance Summary – July 2003

Figure A5.56  Trombé-Wall (TW) Performance Summary – August 2003

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Figure A5.57  Trombé-Wall (TW) Performance Summary – September 2003

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.58  Trombé-Wall (TW) Performance Summary – October 2003
Figure A5.59  Trombé-Wall (TW) Performance Summary – November 2003

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.60  Trombé-Wall (TW) Performance Summary – December 2003

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.61 Trombé-Wall (TW) Performance Summary – January 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.62 Trombé-Wall (TW) Performance Summary – February 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.63 Trombé-Wall (TW) Performance Summary – March 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.64 Trombé-Wall (TW) Performance Summary – April 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

328
Figure A5.65  Trombé-Wall (TW) Performance Summary – May 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.66  Trombé-Wall (TW) Performance Summary – June 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.67 Trombé-Wall (TW) Performance Summary – July 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.68 Trombé-Wall (TW) Performance Summary – August 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.69  Trombé-Wall (TW) Performance Summary – September 2004

Figure A5.70  Trombé-Wall (TW) Performance Summary – October 2004

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure A5.71 Trombé-Wall (TW) Performance Summary – November 2004

Figure A5.72 Trombé-Wall (TW) Performance Summary – December 2004
Figure A5.73  Water-Wall (WW) Performance Summary – January 2003

Figure A5.74  Water-Wall (WW) Performance Summary – February 2003
Figure A5.75  Water-Wall (WW) Performance Summary – March 2003

Figure A5.76  Water-Wall (WW) Performance Summary – April 2003
Figure A5.77  Water-Wall (WW) Performance Summary – May 2003

Figure A5.78  Water-Wall (WW) Performance Summary – June 2003
Figure A5.79 Water-Wall (WW) Performance Summary – July 2003

Figure A5.80 Water-Wall (WW) Performance Summary – August 2003
Figure A5.81  Water-Wall (WW) Performance Summary – September 2003

Figure A5.82  Water-Wall (WW) Performance Summary – October 2003

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.83  Water-Wall (WW) Performance Summary – November 2003

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.84  Water-Wall (WW) Performance Summary – December 2003

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.85  Water-Wall (WW) Performance Summary – January 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.86  Water-Wall (WW) Performance Summary – February 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.87 Water-Wall (WW) Performance Summary – March 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.88 Water-Wall (WW) Performance Summary – April 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.89  Water-Wall (WW) Performance Summary – May 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.90  Water-Wall (WW) Performance Summary – June 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.91  Water-Wall (WW) Performance Summary – July 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.92  Water-Wall (WW) Performance Summary – August 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.93  Water-Wall (WW) Performance Summary – September 2004

Figure A5.94  Water-Wall (WW) Performance Summary – October 2004
Figure A5.95  Water-Wall (WW) Performance Summary – November 2004

Figure A5.96  Water-Wall (WW) Performance Summary – December 2004
Figure A5.97  Roofpond (RP) Performance Summary – January 2003

Figure A5.98  Roofpond (RP) Performance Summary – February 2003
Figure A5.99  Roofpond (RP) Performance Summary – March 2003

(Please note that the major discrepancies between simulated and measured data signify systemic irregularities encountered by the RP cell during experimental monitorization.)

Figure A5.100  Roofpond (RP) Performance Summary – April 2003
Figure A5.101 Roofpond (RP) Performance Summary – May 2003

Figure A5.102 Roofpond (RP) Performance Summary – June 2003
Figure A5.103  Roofpond (RP) Performance Summary – July 2003

Figure A5.104  Roofpond (RP) Performance Summary – August 2003
Figure A5.105  Roofpond (RP) Performance Summary – September 2003

Figure A5.106  Roofpond (RP) Performance Summary – October 2003

(Please note that the major inconsistencies between simulated and measured data signify either parametric discrepancies and/or systemic irregularities encountered by the RP cell during experimental monitorization.)
Figure A5.107 Roofpond (RP) Performance Summary – November 2003

(Please note the parametric discrepancies between simulated and measured test cell data.)

Figure A5.108 Roofpond (RP) Performance Summary – December 2003

(Please note parametric discrepancies between simulated and measured test cell data.)

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Figure A5.109  Roofpond (RP) Performance Summary – January 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.110  Roofpond (RP) Performance Summary – February 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.111  Roofpond (RP) Performance Summary – March 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.112  Roofpond (RP) Performance Summary – April 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.113  Roofpond (RP) Performance Summary – May 2004
(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.114  Roofpond (RP) Performance Summary – June 2004
(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.115 Roofpond (RP) Performance Summary – July 2004

(Please note parametric discrepancies between simulated and measured test cell data.)

Figure A5.116 Roofpond (RP) Performance Summary – August 2004

(Please note parametric discrepancies between simulated and measured test cell data.)
Figure A5.117  Roofpond (RP) Performance Summary – September 2004

Figure A5.118  Roofpond (RP) Performance Summary – October 2004
Figure A5.119  Roofpond (RP) Performance Summary – November 2004

Figure A5.120  Roofpond (RP) Performance Summary – December 2004
Figure A5.121  Direct Gain, Model 2 (DG2) Performance Summary – January 2003

Figure A5.122  Direct Gain, Model 2 (DG2) Performance Summary – February 2003
Figure A5.123  Direct Gain, Model 2 (DG2) Performance Summary – March 2003

Figure A5.124  Direct Gain, Model 2 (DG2) Performance Summary – April 2003
Figure A5.125  Direct Gain, Model 2 (DG2) Performance Summary – May 2003

Figure A5.126  Direct Gain, Model 2 (DG2) Performance Summary – June 2003

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Figure A5.127  Direct Gain, Model 2 (DG2) Performance Summary – July 2003

Figure A5.128  Direct Gain, Model 2 (DG2) Performance Summary – August 2003
Figure A5.129  Direct Gain, Model 2 (DG2) Performance Summary – September 2003

Figure A5.130  Direct Gain, Model 2 (DG2) Performance Summary – October 2003
Figure A5.131  Direct Gain, Model 2 (DG2) Performance Summary – November 2003

Figure A5.132  Direct Gain, Model 2 (DG2) Performance Summary – December 2003
Figure A5.133  Direct Gain, Model 2 (DG2) Performance Summary – January 2004

Figure A5.134  Direct Gain, Model 2 (DG2) Performance Summary – February 2004
Figure A5.135  Direct Gain, Model 2 (DG2) Performance Summary – March 2004

Figure A5.136  Direct Gain, Model 2 (DG2) Performance Summary – April 2004
Figure A5.137  Direct Gain, Model 2 (DG2) Performance Summary – May 2004

Figure A5.138  Direct Gain, Model 2 (DG2) Performance Summary – June 2004
Figure A5.139  Direct Gain, Model 2 (DG2) Performance Summary – July 2004

Figure A5.140  Direct Gain, Model 2 (DG2) Performance Summary – August 2004
Figure A5.141  Direct Gain, Model 2 (DG2) Performance Summary – September 2004

Figure A5.142  Direct Gain, Model 2 (DG2) Performance Summary – October 2004
Figure A5.143  Direct Gain, Model 2 (DG2) Performance Summary – November 2004

Figure A5.144  Direct Gain, Model 2 (DG2) Performance Summary – December 2004
Figure A5.145  Roofpond-Direct Gain (RP-DG) Performance Summary –
January 2003

Figure A5.146  Roofpond-Direct Gain (RP-DG) Performance Summary –
February 2003

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Figure A5.147  Roofpond-Direct Gain (RP-DG) Performance Summary –
March 2003

Figure A5.148  Roofpond-Direct Gain (RP-DG) Performance Summary –
April 2003

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Figure A5.149  Roofpond-Direct Gain (RP-DG) Performance Summary –  
May 2003

Figure A5.150  Roofpond-Direct Gain (RP-DG) Performance Summary –  
June 2003

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Figure A5.151  Roofpond-Direct Gain (RP-DG) Performance Summary –
July 2003

Figure A5.152  Roofpond-Direct Gain (RP-DG) Performance Summary –
August 2003
Figure A5.153  Roofpond-Direct Gain (RP-DG) Performance Summary –
September 2003

Figure A5.154  Roofpond-Direct Gain (RP-DG) Performance Summary –
October 2003
Figure A5.155  Roofpond-Direct Gain (RP-DG) Performance Summary – November 2003

Figure A5.156  Roofpond-Direct Gain (RP-DG) Performance Summary – December 2003
Figure A5.157  Roofpond-Direct Gain (RP-DG) Performance Summary – January 2004

(Please note systemic irregularities exhibited by the measured test cell data.)

Figure A5.158  Roofpond-Direct Gain (RP-DG) Performance Summary – February 2004

(Please note systemic irregularities exhibited by the measured test cell data.)
Figure A5.159  Roofpond-Direct Gain (RP-DG) Performance Summary –
March 2004

(Please note systemic irregularities exhibited by the measured test cell data.)

Figure A5.160  Roofpond-Direct Gain (RP-DG) Performance Summary –
April 2004

(Please note systemic irregularities exhibited by the measured test cell data.)

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Figure A5.161  Roofpond-Direct Gain (RP-DG) Performance Summary –
May 2004

(Please note systemic irregularities exhibited by the measured test cell data.)

Figure A5.162  Roofpond-Direct Gain (RP-DG) Performance Summary –
June 2004
Figure A5.163  Roofpond-Direct Gain (RP-DG) Performance Summary –
July 2004

(Please note systemic irregularities exhibited by the measured test cell data.)

Figure A5.164  Roofpond-Direct Gain (RP-DG) Performance Summary –
August 2004
Figure A5.165  Roofpond-Direct Gain (RP-DG) Performance Summary –
September 2004

Figure A5.166  Roofpond-Direct Gain (RP-DG) Performance Summary –
October 2004
Figure A5.167  Roofpond-Direct Gain (RP-DG) Performance Summary –

November 2004

Figure A5.168  Roofpond-Direct Gain (RP-DG) Performance Summary –

December 2004

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APPENDIX VI

COMPARATIVE THERMAL PERFORMANCE SUMMARY TABLES

The following tables present the monthly and annual breakdown of each considered test cell's SSF and $Q_{aux}$. Both simulated performance data and predicted data derived from the LCR and SLR methods are presented. While observing the simulated data from each passive solar test cell, please keep in mind that the primary goal of the MPSP dictated that the passive solar test cells feature less-than-optimal design configurations.

As a result, their thermal performance paled in comparison to what would have been achieved though optimized passive solar heating systems.

Table A6.1  Control Cell – 2003 & 2004 Simulated Thermal Performance

<table>
<thead>
<tr>
<th>Month</th>
<th>2003 Simulated $Q_{aux}$ (Mega Btu)</th>
<th>2004 Simulated $Q_{aux}$ (Mega Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.09</td>
<td>0.91</td>
</tr>
<tr>
<td>Feb</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>Mar</td>
<td>0.52</td>
<td>0.44</td>
</tr>
<tr>
<td>Apr</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>May</td>
<td>0.73</td>
<td>0.06</td>
</tr>
<tr>
<td>Jun</td>
<td>0.03</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Jul</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Aug</td>
<td>0.00</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Sep</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Oct</td>
<td>0.19</td>
<td>0.17</td>
</tr>
<tr>
<td>Nov</td>
<td>0.41</td>
<td>0.45</td>
</tr>
<tr>
<td>Dec</td>
<td>0.72</td>
<td>0.76</td>
</tr>
<tr>
<td>Ann</td>
<td>4.22</td>
<td>3.69</td>
</tr>
</tbody>
</table>
Table A6.2  DG1 Cell – 2003 Simulated Thermal Performance vs. Results from Annual LCR and Monthly SLR Method

<table>
<thead>
<tr>
<th>Year: 2003</th>
<th>SSF (%)</th>
<th>Q_{aux} (Mega Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Simulated</td>
<td>SLR Method</td>
</tr>
<tr>
<td>Jan</td>
<td>-12.9</td>
<td>-15.2</td>
</tr>
<tr>
<td>Feb</td>
<td>-9.0</td>
<td>-14.5</td>
</tr>
<tr>
<td>Mar</td>
<td>21.2</td>
<td>15.8</td>
</tr>
<tr>
<td>Apr</td>
<td>13.0</td>
<td>48.8</td>
</tr>
<tr>
<td>May</td>
<td>98.9</td>
<td>94.6</td>
</tr>
<tr>
<td>Jun</td>
<td>68.2</td>
<td>100.0</td>
</tr>
<tr>
<td>Jul</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Aug</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Sep</td>
<td>78.3</td>
<td>97.6</td>
</tr>
<tr>
<td>Oct</td>
<td>68.0</td>
<td>74.3</td>
</tr>
<tr>
<td>Nov</td>
<td>10.1</td>
<td>20.4</td>
</tr>
<tr>
<td>Dec</td>
<td>-14.6</td>
<td>-12.9</td>
</tr>
<tr>
<td>Ann</td>
<td>2.5</td>
<td>5.5</td>
</tr>
</tbody>
</table>

LCR Method -4.5 4.49

Table A6.3  DG1 Cell – 2004 Simulated Thermal Performance vs. Results from Annual LCR and Monthly SLR Method

<table>
<thead>
<tr>
<th>Year: 2004</th>
<th>SSF (%)</th>
<th>Q_{aux} (Mega Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>Simulated</td>
<td>SLR Method</td>
</tr>
<tr>
<td>Jan</td>
<td>-29.6</td>
<td>-23.4</td>
</tr>
<tr>
<td>Feb</td>
<td>8.4</td>
<td>-3.3</td>
</tr>
<tr>
<td>Mar</td>
<td>12.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Apr</td>
<td>53.0</td>
<td>40.3</td>
</tr>
<tr>
<td>May</td>
<td>66.8</td>
<td>96.8</td>
</tr>
<tr>
<td>Jun</td>
<td>100.0</td>
<td>94.5</td>
</tr>
<tr>
<td>Jul</td>
<td>100.0</td>
<td>73.4</td>
</tr>
<tr>
<td>Aug</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Sep</td>
<td>100.0</td>
<td>100.0</td>
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<tr>
<td>Oct</td>
<td>37.3</td>
<td>69.1</td>
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<td>Nov</td>
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<td>Ann</td>
<td>0.9</td>
<td>5.4</td>
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</table>

LCR Method -4.5 4.63

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**Table A6.4**  
*DG2 Cell – 2003 Simulated Thermal Performance vs. Results from Annual LCR and Monthly SLR Method*

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<tr>
<th>Year: 2003</th>
<th>SSF (%)</th>
<th>Q\textsubscript{aux} (Mega Btu)</th>
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<tr>
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<td>Simulated SLR Method</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Month</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>-3.6</td>
<td>-17.7</td>
</tr>
<tr>
<td>Feb</td>
<td>-0.2</td>
<td>-16.9</td>
</tr>
<tr>
<td>Mar</td>
<td>32.0</td>
<td>16.5</td>
</tr>
<tr>
<td>Apr</td>
<td>26.1</td>
<td>51.6</td>
</tr>
<tr>
<td>May</td>
<td>100.0</td>
<td>95.9</td>
</tr>
<tr>
<td>Jun</td>
<td>85.4</td>
<td>100.0</td>
</tr>
<tr>
<td>Jul</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Aug</td>
<td>100.0</td>
<td>100.0</td>
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<tr>
<td>Sep</td>
<td>96.9</td>
<td>98.3</td>
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<tr>
<td>Oct</td>
<td>77.8</td>
<td>77.2</td>
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<tr>
<td>Nov</td>
<td>23.1</td>
<td>21.5</td>
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<tr>
<td>Dec</td>
<td>-3.6</td>
<td>-15.2</td>
</tr>
<tr>
<td>Ann</td>
<td>12.8</td>
<td>4.5</td>
</tr>
<tr>
<td>LCR Method</td>
<td></td>
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</tr>
</tbody>
</table>

**Table A6.5**  
*DG2 Cell – 2004 Simulated Thermal Performance vs. Results from Annual LCR and Monthly SLR Method*

<table>
<thead>
<tr>
<th>Year: 2004</th>
<th>SSF (%)</th>
<th>Q\textsubscript{aux} (Mega Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulated SLR Method</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Month</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>-20.7</td>
<td>-26.9</td>
</tr>
<tr>
<td>Feb</td>
<td>8.4</td>
<td>-4.5</td>
</tr>
<tr>
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Table A6.6  TW Cell – 2003 Simulated Thermal Performance vs. Results from Annual LCR and Monthly SLR Method

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### Table A6.8  WW Cell – 2003 Simulated Thermal Performance vs. Results from Annual LCR and Monthly SLR Method

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### Table A6.11  
**RP & RP-DG Cells – 2004 Simulated Thermal Performance Comparison**

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APPENDIX VII

PSHA WORKSHEETS

The following worksheets are reproduced from *Passive Solar Heating Analysis: A Design Manual* (Balcomb et al. 1984).

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# NET LOAD COEFFICIENT and ANNUAL LCR METHOD WORKSHEET

**NET LOAD COEFFICIENT, NLC**

<table>
<thead>
<tr>
<th>BUILDING ELEMENT</th>
<th>FORMULA</th>
<th>Fill in the Blanks and Perform Arithmetic</th>
<th>LOAD, UA</th>
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<tbody>
<tr>
<td>WALLS</td>
<td>$(UA)_{w} = A_w/R_w$</td>
<td>________ / ________</td>
<td>________</td>
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<tr>
<td>ROOF</td>
<td>$(UA)_r = A_r/R_r$</td>
<td>________ / ________</td>
<td>________</td>
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<tr>
<td>E, W, N WINDOWS</td>
<td>$(UA)_q = 1.1 A_q/N$</td>
<td>________ x ________</td>
<td>________</td>
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<tr>
<td>FLOOR</td>
<td>$(UA)_f = A_f/R_f$</td>
<td>________ / ________</td>
<td>________</td>
</tr>
<tr>
<td>PERIMETER</td>
<td>$(UA)_p = 4.17 P_p/(R_p + 5)$</td>
<td>4.17 x ________ / (_______ + 5)</td>
<td>________</td>
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<tr>
<td>BASEMENT</td>
<td>$(UA)_b = 10.7 P_b/(R_b + 8)$</td>
<td>10.7 x ________ / (_______ + 8)</td>
<td>________</td>
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<tr>
<td>INFILTRATION</td>
<td>$(UA)_i = 0.018 V x ACH x ADR$</td>
<td>0.018 x ________ x ________ x ________</td>
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**LOAD COLLECTOR RATIO, LCR**

$$LCR = \frac{NLC}{A_p}$$

$$= \frac{_______}{_______} = \frac{_______}{_______}$$

**WEIGHTED AVERAGE, SSF**

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<th>REFERENCE DESIGN</th>
<th>PROJECTED AREA</th>
<th>FRACTION OF $A_p$</th>
<th>SSF FOR EACH REFERENCE DESIGN</th>
<th>PRODUCT OF SSF x FRACTION</th>
<th>$U_c$</th>
<th>$U_c A_p$</th>
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<tr>
<td></td>
<td></td>
<td>x ________</td>
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<td>x ________</td>
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<td>x ________</td>
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$$\text{TOTAL } A_p = \frac{_______}{\text{TOTAL } (U_c A_p) =}$$

**BASE TEMPERATURE, $T_b$**

$$T_b = T_{set} - Q_{int/ TLC} = \frac{_______}{_______} = _______ \text{°F}$$

**AUXILIARY HEAT, $Q_{aux}$**

$$Q_{aux} = NLC \times DD(1 - SSF) = \frac{_______ x _______ x (1 - _______)}{10^{-6}} = _______ \text{ Mega Btu/year}$$
SOLAR GAIN WORKSHEET

<table>
<thead>
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<th>ITEM</th>
<th>SOLAR NOON ZENITH ANGLE Weather Table</th>
<th>CLEARNESS FACTOR Weather Table</th>
<th>NUMBER OF DAYS IN MONTH</th>
<th>HORIZONTAL TOTAL INSULATION Weather Table</th>
<th>GLAZED AREA TO PROJECTED AREA RATIO</th>
<th>INCIDENT FRACTION</th>
<th>TRANSMITTED FRACTION</th>
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<td>HS</td>
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Source: Balcomb et al. 1984
**SLR METHOD WORKSHEET**

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<td>SLR (=) (S/DD + LCR \cdot \frac{G}{LCR}), SSF (=) (1 - C \cdot \text{exp}(-\text{D} \cdot \text{SLR}))</td>
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</table>

**KEY FORMULAS**
- SLR \(=\) \(S/DD + LCR \cdot G\) \(\text{SSF} = 1 - (1 + G/LCR) \cdot (1 - F(SLR))\)
- Compute SLR then use graphs to find \(F(SLR)\)
- \(\text{SSF} = 1 - (1 + G/LCR) \cdot (1 - F(SLR))\)
- If \(SLR < R\), \(F(SLR) = A \cdot SLR\)
- If \(SLR \geq R\), \(F(SLR) = B - C \cdot \text{exp}(-\text{D} \cdot \text{SLR})\)

**FORMULAS**
- \(TW\cdot WW, SS = \frac{\text{ANNUAL}}{\text{ABSORBED SOLAR ENERGY}}\)
- \(\text{SLR} = \frac{\text{SLR}}{\text{DO} \cdot \text{SAV}}\)
- \(\text{DG}\)

**ALL SYSTEMS**
- Annual SSF = \(\frac{\text{Annual} \ Q_{sav}}{\text{Annual} \ Q_{net}}\)

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<th>LCR</th>
<th>LCRg</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>G</th>
<th>H</th>
<th>R</th>
<th>LCRg (\cdot H)</th>
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<th>DEGREE-DAYS (T_b = \text{____}^\circ\text{F})</th>
<th>SOLAR LOAD RATIO</th>
<th>SOLAR SAVINGS FRACTION</th>
<th>NET REFERENCE LOAD</th>
<th>SOLAR SAVINGS</th>
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<td>UNITS</td>
<td>(Btu/h ft²)</td>
<td>(°F \cdot day)</td>
<td>Dimensionless</td>
<td>Dimensionless</td>
<td>(Mega Btu)</td>
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<td>ORIGIN</td>
<td>SOLAR GAIN WORKSHEET</td>
<td>Weather Data</td>
<td>* *</td>
<td>* *</td>
<td>NLC (\cdot DD) (\cdot 10^{-6})</td>
<td>(Q_{net} \cdot SSF)</td>
<td>(Q_{net} (1-SSF))</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>S</td>
<td>DD</td>
<td>SLR</td>
<td>SSF</td>
<td>(Q_{net})</td>
<td>(Q_{sav})</td>
<td>(Q_{aux})</td>
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- JAN
- FEB
- MAR
- APR
- MAY
- JUN
- JUL
- AUG
- SEP
- OCT
- NOV
- DEC

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GLOSSARY OF SELECTED TERMS

*Altitude* (degrees) – The angular distance between the horizon and the sun’s position above the horizon.

*Azimuth* (degrees) – The angular distance along the horizon between the projected position of the sun and solar (true) south.

*Density, $\rho$ (lb/ft$^3$)* – Mass per unit volume.

*Extinction coefficient* (dimensionless) – The measure of the rate of reduction of transmitted light by means of scattering and absorption for a specified medium.

*Heat capacity* (Btu/°F ft$^3$) – The amount of thermal energy (heat) that can be stored in a material per unit of volume. The heat capacity is the product of a material’s density and specific heat.

*Index of refraction* (dimensionless) – The ratio of the speed of light in a vacuum to the speed of light in a specified medium.
Insolation (Btu/ft²) – The total amount of incident solar radiation (direct, diffuse, and reflected) reaching a unit area of a surface.

Irradiance (Btu/ft²) – The amount of radiant flux incident upon a unit area of a surface.

Load collector ratio, LCR (Btu/°F day ft²) – As defined by Balcomb et al. (1984), the load collector ratio is the quotient of the net load coefficient and the projected area.

Net load coefficient, NLC (Btu/°F day) – As defined by Balcomb et al. (1984), the net load coefficient refers to the total load coefficient minus the load coefficient for the solar wall.

Projected area (of glazing), A_p (ft²) – The projection of a passive system’s solar openings on a vertical plane facing the same direction as the system’s principal opening.

Solar load ratio, SLR (dimensionless) – As defined by Balcomb et al. (1984), the SLR is the quotient of the monthly solar gain and the monthly heat load.

Solar savings fraction, SSF (percentage) – The extent to which a building’s passive solar feature(s) reduce a building’s auxiliary heat requirement relative to a comparable building devoid of any passive solar feature(s).
Specific heat, \( c \) (Btu/lb °F) – The quantity of thermal energy (heat) needed to increase the temperature of one unit of mass one degree.

Thermal conductance, \( C \) (Btu/h ft\(^2\) °F) – The rate of heat transfer through a specified nonhomogenous material or a specified thickness of a homogenous material.

Thermal conductivity, \( k \) (Btu in./h ft\(^2\) °F) – The rate of heat transfer through a unit thickness of a homogenous material.

Total load coefficient, TLC (Btu/°F day) – As defined by Balcomb et al. (1984), the total load coefficient refers to the steady-state heat loss of a building per degree of inside-outside difference per day.
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