2010

Numerical Simulation of Underground Solar Thermal Energy Storage

Marshall Sweet
Virginia Commonwealth University

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NUMERICAL SIMULATION OF UNDERGROUND SEASONAL SOLAR
THERMAL ENERGY STORAGE

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical and Nuclear Engineering at Virginia Commonwealth University.

by

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December 2010
Acknowledgement

First and foremost I express my sincerest and deepest appreciation to my committee chair, advisor, and mentor Dr. James McLeskey. His passion and dedication for teaching can not be expressed in words. His mentorship through my graduate studies will always inspire me to accomplish anything people think I am capable of and then some. I am grateful for him giving me the opportunity to work in his lab, and without his guidance this thesis would be non-existent.

I would also like to thank all of my professors here at Virginia Commonwealth University for all of the time, effort, knowledge, and help they have invested in my graduate education. A special thanks to Dr. Hooman Tafreshi and Dr. David Primeaux for serving on my committee. I would also like to give special thanks Dr. Karla Mossi for her mentorship and for always looking after me.

Thank you to all of my colleagues who I have worked with during the completion of my Masters. Thanks to Shinobu Nagata, Connie Wooldridge, Sonya Bhavsar, Corell Halsey-Moore, Ronald Clary, Luca Terziotti, Babak Seyed Aghazadeh, Josh Clarke, and the rest of Grad ME for your help in my studies, motivation, friendship, and keeping my days at school entertaining.

Lastly, I would like to thank my friends and family. Thanks to my mother and father for their endless love and support throughout my entire life. Thanks to my brother for an unconditional lifetime of friendship. Thanks to Laura for dealing with me through
thick and thin. Finally, thanks to Brian, DW, Travis, Bowling, Horst, and Ivan for always being good friends.
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Nomenclature

A  [m^2]  Area

C_i  [kJ/K]  Thermal capacitance

C_p  [kJ/kg-K]  Specific heat of fluid

C_pce  [kJ/kg-K]  Specific heat of collector fluid

F'  --  Fin efficiency factor

F_R,j  --  Overall collector heat removal efficiency factor

h  [W/m^2-K]  Average convection coefficient

I_T  [kJ/h-m^2]  Global radiation incident on the solar collector

j  --  Index variable

m_c  [kg/h]  Mass flow rate of fluid (constant)

m_cplg  [kg/hr]  Mass flow rate of air flow between two zones

m_inf  [kg/hr]  Mass flow rate of infiltration air

m_v  [kg/hr]  Mass flow rate of ventilation air

N_s  --  Number of identical collectors in series

Q  [W]  Internal heat gain

Q_cplg  [W/m^2]  Air coupling between two zones heat flux

Q_g,r  [W]  Radiative gains from internal gains

Q_L,conv  [W/m^2]  Total convective heat flux
Q_{inf} \ [W/m^2] \ \text{Infiltration heat flux}

Q_{long} \ [W] \ \text{Radiation exchange between a wall with all other walls}

Q_r \ [W] \ \text{Radiative gain for wall}

Q_{sol} \ [W] \ \text{Radiative solar gains through windows}

Q_{surf} \ [W/m^2] \ \text{Heat flux of a surface}

Q_u \ [kJ/hr] \ \text{Useful energy gain}

Q_{vent} \ [W/m^2] \ \text{Ventilation heat flux}

Q_{wallg} \ [W] \ \text{User specified heat flow to wall/window}

R_{ins} \ [K-m^2/W] \ \text{Thermal insulation R value between storage volume and ground}

R_{star} \ [m^2-K/W] \ \text{Resistance of artificial node}

T \ \left[{\degree}\right] \ \text{Temperature}

t \ \left[\text{hr}\right] \ \text{time}

T_a \ \left[{\degree}\right] \ \text{Ambient air temperature}

T_{av,j} \ \left[{\degree}\right] \ \text{Average fluid temperature in collector}

T_f \ \left[{\degree}\right] \ \text{Temperature of working fluid}

T_{i,j} \ \left[{\degree}\right] \ \text{Fluid inlet temperature to collector}

T_{i,i-\Delta t} \ \left[^{\circ}\mathrm{C}\right] \ \text{Zone temp at beginning of a time step } i

T_{o,j} \ \left[{\degree}\right] \ \text{Fluid outlet temperature from collector}

T_{star} \ \left[^{\circ}\mathrm{C}\right] \ \text{Temperature of artificial node}

U_{L,j} \ [kJ/h-m^2-K] \ \text{Overall thermal loss coefficient of the collector per unit area}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
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<tr>
<td>$V$</td>
<td>[m$^3$]</td>
<td>Volume</td>
</tr>
<tr>
<td>$x$</td>
<td>[m]</td>
<td>Spatial coordinate in x direction</td>
</tr>
<tr>
<td>$y$</td>
<td>[m]</td>
<td>Spatial coordinate in y direction</td>
</tr>
<tr>
<td>$z$</td>
<td>[m]</td>
<td>Spatial coordinate in z direction</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>[m$^2$/s]</td>
<td>Thermal diffusivity</td>
</tr>
<tr>
<td>$\beta$</td>
<td>[$^\circ$]</td>
<td>Collector slope above the horizontal plane</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>[s]</td>
<td>Simulation time step</td>
</tr>
<tr>
<td>$\Delta x_i$</td>
<td>[m]</td>
<td>Length of cell</td>
</tr>
<tr>
<td>$\lambda_i$</td>
<td>[W/m-K]</td>
<td>Thermal conductivity of cell $i$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>[kg/m$^3$]</td>
<td>Density</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>[C]</td>
<td>Temperature</td>
</tr>
<tr>
<td>$(\tau\alpha)$</td>
<td>--</td>
<td>Product of the cover transmittance and the absorber absorptance</td>
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Abstract

NUMERICAL SIMULATION OF UNDERGROUND SEASONAL SOLAR THERMAL ENERGY STORAGE

By Marshall L. Sweet, B.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

Virginia Commonwealth University, 2010

Director: Dr. James T. McLeskey, Jr.
Associate Professor, Department of Mechanical Engineering

The United States Department of Energy indicates that 97% of all homes in the US use fossil fuels either directly or indirectly for space heating. In 2005, space heating in residential homes was responsible for releasing approximately 502 million metric tons of carbon dioxide into the atmosphere. Meanwhile, the Sun provides the Earth with 1000 watts per square meter of power everyday. This document discusses the research of modeling a system that will capture and store solar energy during the summer for use during the following winter. Specifically, flat plate solar thermal collectors attached to the roof of a single family home will collect solar thermal energy. The thermal energy will then be stored in an underground fabricated Seasonal Solar Thermal Energy Storage
(SSTES) bed. The SSTES bed will allow for the collected energy to supplement or replace fossil fuel supplied space heat in typical single family homes in Richmond, Virginia.

TRNSYS is a thermal energy modeling software package that was used to model and simulate the winter thermal load of a typical Richmond home. The simulated heating load was found to be comparable to reported loads for various home designs. TRNSYS was then used to simulate the energy gain from solar thermal collectors and stored in an underground, insulated, vapor proof SSTES bed filled with sand. Combining the simulation of the winter heat demand of typical homes and the SSTES system showed reductions in fossil fuel supplied space heating in excess of 64%.
1. INTRODUCTION

1.1 Purpose

The purpose of the research described in this document is to simulate, optimize, and evaluate a method for storing the sun’s thermal energy during the warm season so it can be harvested later during the cold season. Specifically, the energy harvested during the cold season supplies a single story residential home with space heating via radiant floors. Figure 1 shows a basic schematic of the overall solar collection and Seasonal Solar Thermal Energy Storage (SSTES) scheme.

![Figure 1](image.png)

**Figure 1.** Basic schematic of how year round solar collection is coupled with a SSTES bed that provides heat to a single story residential home.
There are two different closed loop systems carrying a working fluid that are responsible for transferring thermal energy. The working fluid was modeled as water, but in practice is typically a water-glycol solution to prevent from freezing. By closed loop, the water never leaves the piping system except for when it’s in the solar collectors. The first loop is the heat addition loop in which solar collectors transfer heat from the sun to the working fluid. The working fluid is then pumped to the SSTES bed where the thermal energy is stored since the bed temperature is much lower than the solar collectors’ output temperature. The fluid is then returned to the solar collectors. The second loop is the heat extraction loop which uses the same working fluid to extract thermal energy from the SSTES bed and deliver it to the house. The heat is delivered to the house via radiant floor heat (tubes carrying hot water underneath the floor surface).

The SSTES bed is constructed underground to conserve available land space and to help insulate the bed since underground conditions are much more stable and less severe during the winter. The top of the bed is buried below the frost line in the ground where temperatures remain fairly constant year round. The outside of the bed is covered with a vapor barrier layer to keep all ground water flow out of the bed. Cold ground water flow through the bed would effectively remove all stored thermal energy. Inside of the vapor barrier, the SSTES bed is lined with insulation to minimize heat transfer to the surrounding ground. Sand is used as the bed medium because it is cheap and has a high thermal capacitance.

The purpose of the research in this document is to explore the effectiveness and the sizing parameters of the system. Data will be obtained through computer simulations
developed in TRNSYS, a software package that specializes in transient thermal energy system simulations. Different sized homes will be explored to see how the size of the SSTES bed and solar collector area should be varied based on different demands. The flow rate of the working fluid in the closed loop connecting the solar collectors to the SSTES bed will also be optimized.

1.2 Motivation

Data shows that space heating is a major consumer of energy which is primarily provided by the combustion of fossil fuels. Space heating accounts for 41% of all energy consumed in residential homes. In 2005, more than 97% of all homes in the United States used fossil fuels directly or electricity created from fossil fuels for space heating. Space heating in residential homes was responsible for releasing approximately 502 million metric tons of carbon dioxide into the atmosphere [1, 2].

The sun provides the Earth with an average of 1000 watts per square meter of power everyday during the daytime. This is a seemingly endless amount of renewable energy that can be used for space and domestic water heating in our homes. With an increasing demand and decreasing supply of fossil fuels, it is becoming more economically justifiable to research and develop new ways of storing the sun’s energy so it can be used for heating buildings. By decreasing the consumption of fossil fuels, we will also be decreasing the amount of carbon dioxide released into the atmosphere which is speculated to be a major contribution to global warming.
Storing thermal energy, or heat, from the sun for long periods of time is often referred to as Seasonal Solar Thermal Energy Storage (SSTES). Collecting thermal energy from the sun is not a new technology and has become fairly advanced and economical in recent years when the heat is used immediately. However, storing enough thermal energy to provide a home with space heating for an entire winter season is a fairly new concept. Figure 2 shows the amount of solar insolation available throughout the year which is asynchronous to the heating demand of buildings in the mid-Atlantic region [3]. By looking at the two y-axes shown in figure 2, the amount of energy provided by the sun is an order of magnitude greater than the space heating demand of a 2000 ft² home. The greatest demand for space heating occurs when the solar insolation intensity is at its lowest. SSTES schemes can be used to overcome this asynchronicity between when the energy is available and when it is needed.
The peak of the solar insolation is asynchronous with the space heating demand of buildings. The space heating demand shown is of a 2000 ft\(^2\) single story ranch style home located in Richmond, VA.

Utilizing SSTES to store solar thermal energy during the summer for use as space heating in the winter is now a developing technology, especially for individual residential homes. By coupling year round solar thermal collection with SSTES it is possible to provide over 50% of a building’s annual space heating load [4]. Serious reductions in fossil fuel consumption and carbon dioxide emissions are possible using this technology. Using stored thermal energy for space heating during peak electric demand can lower the demand on the electric grid and save money. This also results in freeing high quality electric energy for industrial value adding purpose to society.
1.3 History of SSTES in Single Residential Homes

The first attempt to store solar thermal energy from the summer to use in the winter was done in 1939 by the Massachusetts Institute of Technology (MIT). MIT constructed a house that later became known as the SOLAR I and tested it in Cambridge, Massachusetts. The house used 33 m² of pre-modern flat plate solar collectors and an insulated horizontal, cylindrical steel tank of about 63 m³. The tank was located underneath the house in the basement beneath a floor area of about 45 m². Temperature of the water in the storage tank ranged from 55 °C to 90 °C. The maximum temperature was reached in August. No solar energy could be stored in the late fall and early winter since the temperature leaving the collectors was below that of the storage [5]. This house ultimately failed after the first season due to condensation forming in the insulation of the tank. MIT did not build another solar house using seasonal solar thermal storage until 1959 which used a smaller above ground tank that supplied water for floor radiators. The design proved to be successful after 3 years of testing and was sold to a private owner.

More recently many other colleges and universities from around the world have been competing in the solar decathlon using seasonal solar thermal storage for space heating. They are mainly using a large above ground tanks for storage and running hot water through tubes embedded in the floor, known as radiant floor heating. These competitions have been the breeding ground for ideas of solar thermal heating. Beginning in the mid 1970’s, after the first major oil crisis, people began adapting solar thermal storage ideas into their homes. The most common being a large above ground tank. The size of the tank needed for adequate space heating is dependent upon the size of the house,
its geographic location, area of collectors, and the desired monetary investment. The optimal volume of the tank is 100 liters for every m² of collector area [6].

In 2006, a home was constructed in Amherst, Wisconsin that uses seasonal solar thermal storage to provide for most of home’s space heating requirements. The well insulated house was built on top of a 30 inch deep sand box that contains 800 tons of sand. The bottom and sides of the sand box are insulated with 2 inches of extruded polystyrene and a continuous vapor barrier. There is a 3.5 inch slab of concrete separating the first floor of the house from the top of the sand bed. There are seven 300 foot circuits of half-inch PEX tubing evenly spread out inside the sand box. The seven circuits are connected to 29.25 m² of flat plate solar collectors that constantly transfer heat from the sun into the sand box. During the heating season, the heat from the sandbox, shown in figure 3, conducts into the floor of the house sufficiently providing space heat for the entire three stories, 1,800 square foot home. The sandbox is serving as the seasonal thermal storage medium. The house is situated in a cold climate with almost 9,000 heating degree-days and only requires 1.5 cords of wood for backup heating annually [7].
Water tanks have been extensively researched as the SSTES medium while this is the first instance of sand being used. Sand is cheap and constructing an underground SSTES sand bed costs significantly less than constructing large insulated water tanks. Therefore, an underground sand bed was chosen as the SSTES medium to be studied in the research reported in this thesis.

1.4 History of Residential Communities

Research and development of large scale seasonal solar thermal energy storage began in northern and central Europe in the early 1980’s. Sweden, Denmark, Austria, and Germany have all built large seasonal thermal energy storage projects, which aim to serve multiple buildings, homes, apartments, etc. with space heat. The first major project built
was in Nykvarn, Sweden in 1985 which utilized 7500 m² of collector area and a 1500 m³ water tank for storage. Throughout the rest of the 1990’s and into the 21st century, several seasonal solar thermal storage projects have been built. Table 1 below lists the eleven largest European solar thermal storage projects as of 2006.

**Table 1. The eleven largest European seasonal solar thermal storage projects [4].**

<table>
<thead>
<tr>
<th>Name, Country</th>
<th>Year of initial operation</th>
<th>Collector area (m²)</th>
<th>Storage type and size</th>
<th>Load size (GWh per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marstal, Denmark</td>
<td>1996</td>
<td>18,300</td>
<td>2100 m³ water tank + 4000 m³ sand water store + 10,000 m³ water pit (to be built in 2003)</td>
<td>28</td>
</tr>
<tr>
<td>Kungalv, Sweden</td>
<td>2000</td>
<td>10,000</td>
<td>1000 m³ water tank</td>
<td>90</td>
</tr>
<tr>
<td>Nykvarn, Sweden</td>
<td>1985</td>
<td>7500</td>
<td>1500 m³ water tank</td>
<td>30</td>
</tr>
<tr>
<td>Crailsheim, Germany</td>
<td>2006</td>
<td>7300</td>
<td>37,500 m³ ground volume</td>
<td>N/A</td>
</tr>
<tr>
<td>Falkenberg, Sweden</td>
<td>1989</td>
<td>5500</td>
<td>1100 m³ water tank</td>
<td>30</td>
</tr>
<tr>
<td>Neckarsulm, Germany</td>
<td>1999</td>
<td>5044</td>
<td>63,400 m³ duct heat store</td>
<td>1.7</td>
</tr>
<tr>
<td>Aeroskoping, Denmark</td>
<td>1998</td>
<td>4900</td>
<td>1200 m³ water tank</td>
<td>13</td>
</tr>
<tr>
<td>Rise, Denmark</td>
<td>2001</td>
<td>3575</td>
<td>4000 m³ water tank</td>
<td>3.7</td>
</tr>
<tr>
<td>Friedrichshafen, Germany</td>
<td>1996</td>
<td>3500</td>
<td>12,000 m³ water filled concrete tank</td>
<td>2.4</td>
</tr>
<tr>
<td>Ry, Denmark</td>
<td>1990</td>
<td>3025</td>
<td>Directly connected to district heating</td>
<td>32</td>
</tr>
<tr>
<td>Hamburg, Germany</td>
<td>1996</td>
<td>3000</td>
<td>4500 m³ water filled concrete tank</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The government of the Federal Republic of Germany passed laws enacting federal funding for the country to reduce carbon dioxide emissions from 1990 by 25% by the end of 2005. Space heating in private homes accounted for 30% of the total German end-use energy sector at the time, which made space heating in residential homes a huge potential.
for savings. The first major long term thermal energy storage was built as a research installation in 1984. Germany has built eleven large scale seasonal thermal energy storage projects since 1996 [8]. This makes Germany the world wide leader in seasonal solar thermal energy storage in terms of GWh per year and number of realized projects.

The first, and to date only, large seasonal solar thermal energy storage built in North America was Drake Landing in the town of Okotoks, Alberta, Canada. Drake Landing utilizes borehole thermal energy storage and began operation as of sunrise on June 21, 2007. Drake Landing is a solar community consisting of 52 two story, energy efficient homes. Each home has a detached garage that is connected to the neighbors garage by a breeze way. The roof of each garage and breeze way has flat plate solar collectors installed. A total of eight hundred 2.45m x 1.18m flat-plate glazed collectors are currently in operation. The collectors heat a glycol solution that is circulated in a district heating system that is connected to the Energy Center. The Energy Center exchanges heat between the solar collector loop, the district heating loop, and the borehole thermal energy storage loop. Computer modeling has predicted that the Drake Landing system will be able to provide up to 90% of all space heating by the fifth year of operation when it is predicted to completely heat the 35,600 m$^3$ borehole thermal storage bank [9]. Figure 4 shows the basic schematic of how Drake Landing works.
Figure 4. Schematic of Drake Landing showing the detached garages with solar collectors, the energy center, borehole storage, and district heating loop[10].

Figure 5. Schematic of the Energy Centre heat exchanger at Drake Landing [10].
1.5 How the Technology Works

This section of the report will mostly focus on large scale seasonal solar thermal storage that is used to heat multiple buildings or dwellings. Individual homes with seasonal solar thermal storage have either already been discussed, or exercise very similar but simpler methods as those of large seasonal solar thermal energy storage. In the past, due to the large investment costs of this technology, it has typically been more economic to practice on a large scale.

The basic overview of how seasonal solar thermal energy storage works is quite simple. Solar collectors convert light energy from the sun into heat, and they store the heat in a working fluid. The working fluid is typically a glycol solution to prevent it from freezing in cold conditions. The working fluid is then pumped through a storage medium directly or through a heat exchanger to transfer the heat from the working fluid to the storage medium. The storage medium can range from the ground, rocks, water, sand, or a combination of them. It is essential that the storage medium is sealed and well insulated. The majority of the heat gained by the storage medium comes during the warm season of the year, though with improving collector technology it is possible to gain significant heat during the winter season. During the winter season heat is taken out of the storage medium and delivered back to the building for space heating. The most common way in Europe to deliver the heat to the homes is via radiant floor heating while Drake Landing utilizes a heat exchanger to blow warm air through the homes’ ductwork.
1.5.1 Water Tanks

The simplest storage medium is a large tank of water. Water is cheap, readily available, and has great thermodynamic properties such as high specific heat capacity and the high capacity rates for charging and discharging. The most common use of water tanks is above ground since they are cheaper and easier to build than underground water tanks. As mentioned earlier, the optimal amount of water for storage is about 100 liters per square meter of collector area. Generally water is not pumped directly from the solar collectors to the tank for two reasons. The first being that collectors generally run a glycol solution, the second being that most seasonal thermal water storage tanks are also used in combination with domestic hot water. Internal heat exchangers run the working fluid in a pipe through the inside of the tank while external heat exchangers run water out of the tank to the exchanger and then pumps warmer water back. Figure 6 shows a picture of a three different types of heat exchangers used with water tanks.

Figure 6. The tank to the far left shows a single internal heat exchanger that can retrieve about 40% of the input thermal energy. The middle tank has two internal heat exchangers and can retrieve about 70% of the input thermal energy. The tank on the right is an external heat exchanger and can retrieve up to 80% of the input thermal energy [11].
Large underground water tanks were the first means of storing large amounts of solar thermal energy in Europe. The largest water tank in use has a volume of 12,000 m³ and is in Friedrichshafen, Germany. These tanks are often only partially underground and then the tops are covered with insulation and then earth to make them underground tanks. This type of tank is synonymous with pit storage. These tanks are unique and built on site and can be quite expensive. They are made of thick reinforced concrete with a plastic liner so that no water can touch it since cold water would hamper the tanks efficiency.

The most recent and technologically advanced underground water tank built was in Munich, Germany in 2006 at a volume of 5,700 m³. Figure 7 shows a vertical section and the construction of the tank that was built on site. Steel liners were used as frame work during construction of the concrete walls. After the concrete walls were complete they were prestressed by steel cables, and stainless steel plates were welded together to ensure water and vapor tightness. Running vertically in the center of the tank is a stratification device to enhance temperature stratification and thereby the usability of the accumulated heat. During the springtime the solar collectors will only charge the upper part of the tank to reach usable temperatures as fast as possible. When an adequate buffer volume is created at higher temperatures, the flow from the collectors will then be switched to the bottom of the tank [8].
Figure 7. Underground water tank constructed in Munich, Germany. The upper image shows the construction layout while the bottom image shows the center stratification device[8].
1.5.2 Boreholes

Borehole technology, sometimes referred to as duct heat store, uses bedrock in the ground as the storage medium. The borehole is specifically the heat exchanger transferring the heat from the working fluid to the rock bed in the ground. Boreholes are deep holes drilled in the ground using mining technology typically ranging from 30 to 200 m deep. A u-tube (pipe that makes a 180 degree turn at the bottom) which carries the working fluid is placed in the hole and then the holes are filled with a highly conductive grout. The grout is usually made of sand, mortar, clay, and concrete. The heat from the working fluid is transferred to the grout and the grout conducts the heat directly into the surround rock bed.

Figure 8. A closed loop borehole used at Drake Landing [10].
In order to make a borehole seasonal thermal storage system work, several individual boreholes need to be drilled in a pattern throughout the ground volume to serve as the thermal storage bank. The holes can be connected in a serial configuration, in parallel, or in a combination of both. The warm working fluid from the collector enters the thermal storage bank at the center holes, as it leaves a center borehole it then travels outward to another borehole. This keeps the center of the storage bank the warmest and keeps the temperature gradient as the thermal storage bank expands outward low, minimizing conduction. Once the working fluid reaches the end of the thermal storage bank it is returned to the collectors. Often a heat exchanger exists between the working fluid of the collectors and the working fluid of the boreholes. This is so the working fluid from the boreholes can easily be reversed so that the cold working fluid from the outside of the storage bank can be brought back to the center to extract heat. Without a heat exchanger there have to be more boreholes drilled in a similar pattern so a separate network of u-tubes can extract the heat. Figure 9 shows three different patterns commonly used for a borehole thermal storage bank (square, circular, and expanding, respectively). Figure 10 shows movement of the warm working fluid and borehole pattern used at Drake Landing.
Figure 9. Examples of different borehole drilling patterns commonly used [11].

Figure 10. Schematic of the warm working fluid starting at the center and moving outward of Drake Landing. There are 24 parallel sets of 6 boreholes in series (144 boreholes) beginning and ending at the Energy Center heat exchanger [10].

The surface of the borehole thermal storage bank must be insulated for maximum efficiency. Peak temperatures throughout the year in borehole storage banks range between 80-90° C. Borehole technology will not work everywhere. The geologic conditions of the ground must be suitable for it to work. The two major factors in deciding if a borehole system will work is the specific heat of the ground, and the water flow. The
higher the specific heat, the better suited the ground. Water flow through the storage bank will remove most of the heat stored. Almost all previous large scale projects have used the software programming called TRNSYS to model the performance of a borehole system.

1.6 Advantages/Disadvantages of Technology

The greatest advantage of this technology is undeniably the use of a clean renewable energy source for space heating. The major disadvantage of this technology is the high initial installation costs. Currently, the only economically justifiable use of this technology is for large scale storage for multiple dwellings in climates that have both warm and cold seasons. District heating systems with seasonal thermal energy storage is, at maximum, twice as high as conventional heating costs [4]. However, due to the global political focus on reducing global warming, this technology may soon become a legislatively driven technology.

Borehole thermal storage and water tanks each have their advantages and disadvantages. Borehole storage only works well for large projects that need to store a lot of heat. The larger the borehole storage bank, typically the better efficiency it will have. However, it may take several of heating seasons for the storage bank to be filled. A major advantage for borehole storage is that during the summer months, the bank can be used as a heat sink for cooling a building which lowers air conditioning costs in the summer. The major disadvantage to borehole storage is geographic location. If the site of the project has poor soil conductivity and lots of water flow, then it will be impossible to install a successful borehole system. When the amount of desired thermal storage is large, then the
borehole storage system is much more economical than an on-site construction of a large water tank. For smaller thermal storage a water tank may be more economic especially for a single home. Another advantage for a water tank is that it can be placed anywhere around the project site, above or below the ground. The major disadvantage for both types of storage is that the entire process of solar thermal collection and storage needs to be incorporated during the initial construction of the building as the technology is not well fit for retrofitting.

1.7 Future Storage Expectations

1.7.1 Phase Change Materials

Phase change materials (PCM) exercise the use of latent heat storage. Latent heat is the heat acquired or lost during a phase change which is substantially more heat than in sensible storage. Energy densities for latent heat storage are greater than those for sensible heat storage (materials that don’t change phases). A phase change from a solid to a liquid is the most desired because a change to and from a gas requires a lot of additional volume. Commercially available PCM have melting temperature ranges from -21 °C (sodium chloride solution) to more than 200 °C (salts and eutectic salt mixtures). Paraffin wax is also a popular PCM and is an easy to use product that can be made with melting points between -20 °C and 120 °C. The most studied PCM include Glauber’s salt, calcium chloride hexahydrate, sodium thiosulfate pentahydrate sodium carbonate decahydrate, and disodium phosphate dodecahydrate [12]. Similar to a water tank, the PCM must be contained in a well insulated container. The working fluid must transfer its heat to the
PCM container via a heat exchanger with some sort of stratification device for optimal performance. Figure 11 compares the thermal energy storage of a PCM to other types of sensible heat storage.

**Figure 11. Performance comparison of a PCM to sensible heat storage [12].**

Notice that the temperature remains constant during the phase change which is when most of the heat is stored. This means that the PCM must be made to the temperature specifications of the application. The difficulty using PCM for seasonal storage is keeping the temperature within the PCM’s specified temperature range. PCMs are technically feasible as a storage medium but much more complicated. Another problem
with PCM is that they tend to corrode and lose their designed phase change properties over time.

1.7.2 Thermochemical Storage

Thermochemical storage refers to a reversible chemical process, involving two media, which has the ability to gain and release heat during a chemical reaction. One concept uses a salt, such as sodium sulphide and water. The salt can be dried using solar thermal heat, which will cause it to accumulate thermal energy. This energy can then be recovered by adding water vapor to the salt. The concept of chemical reactions like this work “on paper” and in the lab, but are not yet feasible on a large scale. The salt in the reaction must be stored in a vacuumed environment which is nearly impossible to do on a large scale. Despite a number of proposals regarding chemical storage systems in chemical engineering research, there is yet to be a breakthrough in the field.
2. TRNSYS

2.1 About

TRNSYS (pronounced ‘tran-sis’) is an acronym that stands for TRaNsient SYstem Simulation program. It is a software package designed to simulate the transient motion of thermal energy systems. It is written in the Fortran programming language. TRNSYS was first developed during a joint project between the Solar Energy Lab at the University of Wisconsin-Madison and the Solar Energy Applications Lab at the University of Colorado in the early 1970’s. Once the project was complete, the University of Wisconsin-Madison continued to rework the programming so that each component of the original project’s energy system had its own Fortran subroutine with unique inputs and outputs. This enabled anyone with a Fortran compiler to be able to use the basic component format to model new components of thermal energy systems and quickly incorporate them with existing components. A compilation of written components was put together to form the beginnings of the TRNSYS component library. This enabled users to be able to simulate complex energy systems in TRNSYS by selecting system components and linking their inputs and outputs together [13].

The driving force of TRNSYS’ success since its inception has been largely due to its open, modular structure. The source code for the kernel and existing components
simplifies extending existing models to make them fit the end user’s specific needs. The DLL based architecture enables users/developers to create new custom component models using all common programming languages including C, C++, Pascal, etc. TRNSYS is also able to communicate with many other software programs for pre and post processing such as Microsoft Excel, MatLab, COMIS, etc [14].

Since the 1970’s, the TRNSYS component library (individual components are referred to as Types in TRNSYS nomenclature) continued to grow as the aforementioned universities kept programming and simulating new thermal systems. Students who worked on TRNSYS graduated and formed their own private businesses that offered TRNSYS simulation services, further adding to the TRNSYS component library. Nearly 40 years since the inception of TRNSYS, it is continually under development by a joint team consisting of the Solar Energy Laboratory at the University of Wisconsin-Madison, The Centre Scientifique et Technique du Batiment in Sophia Antipolis, France, Transsolar Energietechnik GmBH in Stuttgart, Germany, and Thermal Energy Systems Specialists in Madison, Wisconsin. TRNSYS is currently sporting a graphical user interface (GUI) furthering its flexibility so that less experienced programmers can develop sophisticated models. The standard component library currently hosts 80 components, and private libraries offer over 300 components world wide. TRNSYS currently has a world wide user base with authorized distributors in France, Germany, Spain, Sweden, Luxembourg, Japan, and the United States [13].

The research detailed in this document utilized many components from the standard TRNSYS component library. The major components used were Type 56 (Building), Type
701 (Basement), and Type 76 (Theoretical Flat Plate Collector). In addition, the SSTES bed used was modeled using Type 342 (Multi-Flow Stratified Thermal Storage Model with Full-Mixed Layers) which was purchased from Transsolar Energietechnik. Type 56 (Building) was used to model single story ranch style homes that were built on top of a crawl space. The crawl space was modeled using Type 701 (Basement). Type 76 (Theoretical Flat Plate Collector) was used to model solar thermal collectors that provided thermal energy to the SSTES bed (Type 342). Other minor components used in the simulations functioned as variable manipulators, pump controllers, and data plotters. More information on the minor components can be found in section 2.6 Model Setup.

2.2 Type 56 (Building)

2.2.1 About Type 56

Type 56 is a component that models the movement of thermal energy of a building divided into individual thermal zones that have their own properties. In order for this component to work during a TRNSYS simulation, a pre-processing program (TRNBUILD) must first be executed. TRNBUILD generates two different files that Type 56 uses to model thermal energy during a simulation. The first is a building data file (.BUI) which contains all information about the building’s materials, architecture, orientation, and internal equipment. The second file is an information file (.nfo) that contains information regarding the required inputs to Type 56 and the expected outputs to be internally calculated.
Type 56 can model the humidification/dehumidification, heating, ventilation, and air conditioning equipment in two different ways. The two different methods are synonymous with the terms “energy rate” and “temperature level” control. The “energy rate” method is a simplified model where the user specifies set temperatures for heating and cooling, set points for humidity control, and maximum cooling and heating rates. The model then computes the necessary input energy to maintain user specifications to determine total thermal energy gains/losses. The “temperature level” method is a more accurate/detailed approach since separate external components are used to model heating/cooling equipment. The outputs from Type 56 are used as inputs from these external components, and the outputs of the external components are then passed back to Type 56 as inputs. The “energy rate” method is utilized in this research to account for traditional forced air heating in residential homes via outdoor heat pump which is the standard heating method in homes without SSTES and the auxiliary heating method for models with SSTES.

2.2.2 Mathematical Description

This section will describe the mathematical equations of major importance Type 56 computes during the simulations conducted for the data in this document. It will begin by discussing the general case where there is no heating or cooling present. Separate equipment modeled by external components can be coupled to individual thermal zones as either internal convective gains or ventilation gains. The optical and thermal properties of windows within a zone (the way in which solar and internal radiation are distributed within a zone) will then follow. Once those are accounted for, the “energy rate” method for
providing heat to the building within Type 56 (heating for models without SSTES and auxiliary heat for models with SSTES) will be described. Lastly, the integrated model for radiant floor heating will be described.

Each thermal zone created within a building has one air node that represents the thermal capacity of the zone air volume and capacities of internal equipment (lights, computers, people, etc) of the zone. Therefore, the node capacity is a user input as well as zone volume. Figure 12 shows the heat balance of the zone air node.

![Figure 12. Heat balance of a zone air node [15].](image)

Convective heat flux to the air node is represented by equation 2.2.1 which says the total convective heat flux is equal to the sum of the surface, infiltration, ventilation, internal convective gains, and connective air flow (air flow from adjacent zones) convective heat fluxes.

\[
Q_{\text{conv}} = Q_{\text{surf}} + Q_{\text{inf}} + Q_{\text{vent}} + Q_{gc} + Q_{\text{cplg}}
\]  

(2.2.1)

Where the infiltration (airflow from outside only), ventilation, and connective gaines are given by equations 2.2.2 to 2.2.4 respectively.

\[
Q_{\text{inf}} = V \rho c_p (T_{\text{outside}} - T_{\text{air}})
\]  

(2.2.2)
Similarly, radiative heat fluxes to walls and windows from other walls, as shown in figure 13, are also computed by equation 2.2.5.

\[
Q_{\text{vent}} = V \rho c_p (T_{\text{vent}} - T_{\text{air}}) \quad (2.2.3)
\]

\[
Q_{\text{cp}lg} = V \rho c_p (T_{\text{zone}} - T_{\text{air}}) \quad (2.2.4)
\]

Figure 13. Radiative energy flow for one wall showing its surface temperature node [15].

\[
Q_r = Q_{g,r} + Q_{\text{sol}} + Q_{\text{long}} + Q_{\text{wall}} \quad (2.2.5)
\]

The rate of change of internal energy for any zone is equal to the total heat gain of the zone as expressed by equation 2.2.6.

\[
C_i \frac{dT_i}{dt} = Q_i \quad (2.2.6)
\]

Where \( C_i \) is the thermal capacitance of zone \( i \) (minimum = \( \rho V_i C_p \)), and the net gain \( (Q_i) \) is a function of \( T_i \) and the temperatures of all other adjacent zones. To simplify the solution to the set of equations stemming from equation 2.2.6, \( Q_i \) is assumed to be constant during each time step and is evaluated with average values of the zone temperatures. The solution to the differential equation for the temperature at the end of the time step is given by:
\[ T_{i,\tau} = T_{i,\tau-\Delta t} + \frac{Q_{i,\Delta t}}{C_i} \quad (2.2.7) \]

The temperature variation is assumed to be linear, so that equation 2.2.8 is true.

\[ T_i = \frac{T_{i,\tau} + T_{i,\tau-\Delta t}}{2} \quad (2.2.8) \]

Once equation 2.2.8 is solved for \( T_{i,\tau} \) and is substituted into equation 2.2.7, along with the expressions above that represent the total heat gain, then equation 2.2.9 can be derived.

\[
\frac{2C_i(T_i - T_{i,\tau-\Delta t})}{\Delta t} = \sum \sum m_{cp,lg,i} C_p T_j + m_{inf,i} C_p T_a + \sum m_{cp,lg,i} C_p T_{b,s} \\
- \left( \frac{1}{R_{star}} + \sum \sum m_{cp,lg,i} + \sum m_{cp,lg,s} + m_{inf,i} + \sum m_{v,k,i} \right) C_p T_i \\
+ \left( \frac{1}{R_{star,i}} + \sum m_{v,k,i} C_p T_{v,k} + Q_{g,c,i} \right) \\ 
(2.2.9)
\]

Total gains from internal and external surfaces can be derived from equation 2.2.10 and 2.2.11:

\[
Q_{surf,i} = \sum A_s q_{comb,j} = \sum_{j=1} A_s B_s T_{star,i} + \sum A_s B_s T_a + \sum A_s B_s T_{star} \\
+ \sum A_s B_s T_{b,s} - \sum A_s (C_s T_{star,i} - D_s - S_{s,i}) \quad (2.2.10)
\]

\[
Q_{surf,i} = \frac{1}{R_{star}} (T_{star,i} - T_i) \quad (2.2.11)
\]

Where:
\[
B_s = \frac{b_s}{1 + c_s R_{\text{equiv},i} A_{s,i}} \quad (2.2.12)
\]
\[
C_s = \frac{c_s}{1 + c_s R_{\text{equiv},i} A_{s,i}} \quad (2.2.13)
\]
\[
D_s = \frac{K_{s,t} + c_s R_{\text{equiv},i} A_{s,i} S_{s,i}}{1 + c_s R_{\text{equiv},i} A_{s,i}} \quad (2.2.14)
\]

Equations 2.2.10 and 2.2.11 can be equated and regrouped to find equation 2.2.15:

\[
\left( \frac{1}{R_{\text{star},i}} - \sum_{\text{Int.Walls}} A_s B_s + \sum_{\text{surf.in}} A_s C_s \right) T_{\text{star},i} = \left( \sum_{\text{adj.zone walls}} \sum A_s B_s \right) T_{\text{star},j} - \frac{1}{R_{\text{star},i}} T_i
\]

\[
= \left( \sum_{\text{extsurf}} A_s B_s \right) T_a + \sum_{\text{known boundaries}} A_s B_s T_{b,s} + \sum_{\text{surf.zones}} A_s (D_s + S_{s,i}) \quad (2.2.15)
\]

Equation 2.2.9 and equation 2.2.15, written out for all zones, results in a set of linear equations expressed in average zone temperatures and average star temperatures.

\[
[Z] = [T_{\text{avg}}][X] \quad (2.2.16)
\]

These can be solved numerically in matrix form to find the final temperatures, \([Z]\), for each zone at the end of a time step.

When the “energy rate” method for supplying heat is applied to a zone the final temperature matrix is held at a constant and a correction factor is added on the other side of equation 2.2.16. The correction factor accounts for maximum and minimum user specified rates. The simulation first calculates the final temperature solution for the case of no heating to estimate the power rate of heat needed to keep the control temperature. The estimated power rate needed is substituted into the correction factor and equation 2.2.16 is re-solved with the control temperature. If the required estimated power rate is greater than
the maximum allowed then the simulation moves on to the next time step. If it is less than
the maximum allowed, then equation 2.2.16 is repeatedly solved until the correction factor
is no longer changing.

Radiant floor heating with embedded pipes running through the center of the floor
results in a three dimensional conduction problem that is solved using a finite difference
method. Figure 14 shows a schematic of how the piping in the floor is diagrammed for the
equations used to solve the heat transfer from the fluid in the pipes to the surface of the
floor.

![Diagram of radiant floor heating showing variables used in equations](image)

**Figure 14.** Diagram of radiant floor heating showing variables used in equations [15].

Equation 2.2.17 and 2.2.18 describe the solution for the conductive heat flow for both
directions of the y axis:

\[
q_{\text{top}} = \phi U_1 (\vartheta_3 - \vartheta_1) + (1 - \phi) \frac{U_1 U_2}{U_1 + U_2} (\vartheta_2 - \vartheta_1) \tag{2.2.17}
\]

\[
q_{\text{bot}} = \phi U_2 (\vartheta_3 - \vartheta_2) + (1 - \phi) \frac{U_1 U_2}{U_1 + U_2} (\vartheta_1 - \vartheta_2) \tag{2.2.18}
\]
2.3 Type 701 (Basement)

Type 701 was developed by TESS, a product of their consulting projects, and they have allowed TRNSYS to include this component in their standard component library. This model simulates the heat transfer from a basement (four walls and a floor beneath ground surface) to the soil surrounding the five walls of the basement. Conduction is the only method of heat transfer from the building to the basement, and from the basement to the surrounding ground. Ground water and moisture effects are neglected. The conduction to the ground is based on a three dimensional finite difference model of the local soil. Conduction is programmed in the model using the partial differential heat equation as expressed in equation 2.3.1:

\[
\frac{\partial T}{\partial t} = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \tag{2.3.1}
\]

Where:

- \( T \) Temperature (C)
- \( t \) time (hr)
- \( \alpha \) Thermal diffusivity (determined internally from soil properties)
- \( x, y, \) and \( z \) Spatial coordinates (m)

The model computes the resulting inter-dependent differential equations using a simple forward marching iterative method. The temperature of the zone (basement) air and the temperature of the building floor are the inputs for the model. The user sets the U-value of the five walls based upon the building material. The user also sets the soil properties, grid geometry, and the conditions of the surrounding soil. The soil temperatures directly next
to the basement walls are mainly affected by the heat transfer from the basement. The soil temperatures far away from the home are mainly affected by the weather file’s ambient temperature. The model then computes the temperature of the outside surface temperature of the five basement walls and passes them back to the building model (Type 56) as an input[16].

2.4 Type 76 (Theoretical Flat Plate Collector)

Type 76 models the thermal performance of a solar thermal flat plate collector. The collector component was set up as an array of collectors connected in parallel. The total collector area’s thermal performance is determined by the number of collectors in parallel and their physical characteristics. The model utilizes the Hottel-Whillier steady-state technique to evaluate the thermal performance. The thermal energy gain of each module is modeled by the Hottel-Whillier steady-state equation (j is the module number):

\[
Q = \frac{A}{N} \sum_{j=1}^{N} F_{R,j} (I_T (\tau \alpha) - U_{L,j}(T_{i,j} - T_0)) \quad (2.4.1)
\]

Where the overall heat removal efficiency factor of the collector \( F_{R,j} \) is computed by:

\[
F_{R,j} = \frac{N_e m_c C_{pc}}{A U_{L,j}} \left( 1 - \exp \left( - \frac{F' U_{L,j} A}{N_e m_c C_{pc}} \right) \right) \quad (2.4.2)
\]

Where \( F' \) is the collector fin efficiency factor.

The following expression for the overall thermal loss coefficient, \( U_{L,j} \), can be approximated by[17]:

\[
U_{L,j} = \frac{1}{A} \left( \sum_{j=1}^{N} F_{R,j} \right)
\]
Where $h_w$ is the heat transfer coefficient which can be determined if the incident light power, $W$, is known by the following equation:

$$h_w = 5.7 + 3.8w \quad (2.4.4)$$

The following substitutions for variables from equation 2.4.3 also need to be solved:

$$f = (I - 0.04h_w + 0.0005h_w)(I + 0.091N_g) \quad (2.4.5)$$

$$C = 365.9(I - 0.00883\beta + 0.0001298\beta^2) \quad (2.4.5)$$

The overall transmittance-absorptance product, $(\tau\alpha)$, is determined from equation 2.4.6:

$$\tau\alpha = \left( \frac{I_{bT}(\tau\alpha)_b + I_d\left( \frac{1+\cos(\beta)}{2}\right)(\tau\alpha)_s + \rho I\left( \frac{1-\cos(\beta)}{2}\right)(\tau\alpha)_g}{I_T} \right) \quad (2.4.7)$$

The transmittance-absorptance products for beam $(\tau\alpha)_b$, sky diffuse radiation $(\tau\alpha)_s$, and ground diffuse reflected radiation $(\tau\alpha)_g$ are determined using an internal function. Since our modules are connected in parallel, the outlet temperatures of each module are the same and are given by equation 2.4.8:

$$T_{a,j} = \frac{AF_{R,j}(I_T(\tau\alpha) - U_{l,j}(T_{i,j} - T_a))}{N_jm_cC_{pc}} + T_i \quad (2.4.8)$$

When the mass flow rate of the fluid through the collector is zero, the stagnation temperature of the fluid is[18]:

$$34$$
Type 342 was used to simulate the SSTES bed in our models. It is capable of simulating heat storage in a cylindrical water-filled tank, pond, or rock-cavern buried in the ground. During the heat addition period (fluid outlet from solar collectors to SSTES) the working fluid is injected at the top of the storage volume. The water heats the volume, losing heat as it travels toward the bottom, and is then extracted from the bottom and sent back to the solar collectors. During the heat extraction period (when heating the house) water is injected from the bottom, gains heat, and is extracted from the top and returned to the house.
Storage with Two Flows

Initial Storage Temperature 50 °C

Figure 15. Type 342 models a vertically stratified cylindrical SSTES. The segments of the box represent different stratification layers. The heat addition enters from the top while the heat extraction process enters from the bottom [19].

The temperature in the storage volume is horizontally stratified. There is a vertical one-dimensional convective-diffusive thermal process in the storage volume. The model is capable of simulating an insulation layer between the SSTES bed and the surrounding ground. The surrounding ground implements a three-dimensional diffusive heat flow to simulate heat loss from the SSTES bed. Conduction is solely responsible for heat transfer in the ground. Thermal effects of local groundwater flow or natural convection in the surrounding ground are neglected. Surface temperature of the ground is a boundary condition accounted for by receiving information from the weather input file. Heat transfer
in the storage volume is computed from conduction between adjacent cells as well as conduction from the working fluid moving through the volume.

A finite difference method is applied to Fourier’s Law to solve the heat flow conduction equations where the time derivatives are approximated by the explicit forward difference approach. The ground and storage volume are programmed into a divided cell structure (mesh). The ground mesh structure has smaller cells of the same size near the storage walls and the cells increase in size as distance from the storage walls increase. The storage volume’s mesh has cells of equal heat capacity. Figure 16 shows two neighboring cells in the mesh.

Figure 16. Dimensions and thermal properties of two neighboring cells [19].

The thermal properties of two neighboring cells along the edge of the storage volume and the ground may differ, and an insulation layer may be placed in between the cells. The temperature of a cell is represented by the temperature value at the center of the cell. At time $t = t_0$ the temperatures of the cells are $T_1$ and $T_2$ respectively. The thermal energy flow $Q$ (watts) from cell 1 to cell 2 is computed from equation 2.5.1:

$$Q = (T_1 - T_2) \frac{A}{\Delta x_1 / 2\lambda_i + R_{ins} + \Delta x_2 / 2\lambda_2}$$

(2.5.1)

Where:

$\lambda_i$  Thermal conductivity of cell $I$ (W/(m K))
\( \Delta x_i \)  \hspace{1em} \text{Length of cell } I \text{ (m)}

\( R_{\text{ins}} \)  \hspace{1em} \text{Thermal insulation between storage volume and ground (K/(W/m}^2)\text{)}

\( A \)  \hspace{1em} \text{Boundary surface area between the cells (m}^2\text{)}

The thermal conductance, \( G \) (W/K), between the cells is computed from equation 2.5.2:

\[
G = \frac{Q}{T_1 - T_2} \tag{2.5.2}
\]

Heat flows through all boundaries of every cell for each time step. An approximation is made such that the temperature of each cell remains constant during a time step, \( \Delta t \), calculation. A heat balance is computed for each cell during each time step that computes the change in heat content for each cell. The new temperatures at the time \( t_0 + \Delta t \) are computed using the heat capacities, \( C \), of each cell. Heat capacities of each cell are dependent on the temperature, thermal property’s, and size of the cell. The explicit forward difference approach requires that the time step used in the computation does not exceed the stability time step, \( \Delta t_{\text{stab}} \). Thus, the following condition must be met to ensure a stable solution:

\[
\Delta t \leq \Delta t_{\text{stab}} = \frac{C}{\sum G_i} \tag{2.5.3}
\]

The value of \( \Delta t_{\text{stab}} \) depends solely on the size of the cell, and it decreases as the cell size decreases. The smallest value of \( \Delta t_{\text{stab}} \) in both the ground and the storage volume are calculated. The time step used during computation is then equal to \( 0.99*\Delta t_{\text{stab}} \). In most cases this means that the computation in the ground uses a different time step than in the storage volume.
A finite difference method of convection is also used during each time step in the storage volume to account for heat addition and extraction from the working fluid. Equation 2.5.4 is used to solve for the heat transfer due to convection using an explicit forward difference approach:

\[ Q = hA(T_i - T_f) \]  

(2.5.4)

Where:

- \( h \) Average Convection Coefficient (W/(m\(^2\) K))
- \( A \) Surface area of cell (m\(^2\))
- \( T_f \) Temperature of working fluid

The average convection coefficient is determined automatically based on the intrinsic properties of the storage medium and the working fluid and the flow rate of working fluid [19, 20].

### 2.6 Model Setup

There were two different types of models that were used to collect data for this thesis. The first type of model was a basic single story house model utilizing Type 56 (building) and Type 701 (basement). The second type of model was a basic single story house model with SSTES that provides heat to the home via radiant floor heating. The model with SSTES utilizes Type 76 (theoretical flat plate collectors) and Type 342 (seasonal thermal energy storage) in addition to the major components used in the first type. Each type of model was created for six different sized single story homes. Thus, the only variations between models of the same type were sizing parameters of the bed, house,
solar collectors, etc. (see Appendix B). Figure 17 shows the graphical user interface (GUI) of the first type of house model without SSTES.

Figure 17. The GUI of models without SSTES. This is also the kernel to models with SSTES.

The models without SSTES served as the building block for the models with a SSTES scheme. By comparing figures 17 and 18, it becomes obvious that the upper left portion of models with a SSTES scheme is identical to models without SSTES. All models with a SSTES scheme are basically extensions of the original house models without SSTES.
Figure 18. The GUI of models with SSTES. Notice the top left corner is identical to models without SSTES.

Lines with arrows entering an icon represent inputs, whereas lines with arrows exiting an icon represent outputs. Refer to Appendix C for specifics as to which variables are being passed between individual icons. A brief description of what each icon represents in the programming realm can be found in table 2.

Table 2. Brief description of what each icon in the GUI represents in the programming realm and their associated TRNSYS type number[21].

<table>
<thead>
<tr>
<th>Icon Name</th>
<th>TRYNSYS Type #</th>
<th>Brief Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Turn</td>
<td>Equation</td>
<td>Used to unify/pass cardinal directions to other components that weren't hard coded (not used).</td>
</tr>
<tr>
<td>2. Radiation</td>
<td>Equation</td>
<td>Renames radiation variables to match their input counterparts for 9. Building</td>
</tr>
<tr>
<td>Component</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>3. Weather Data</td>
<td>109</td>
<td></td>
</tr>
<tr>
<td></td>
<td>This component serves the main purpose of reading weather data at regular time intervals from a data file, converting it to a desired system of units and processing the solar radiation data to obtain tilted surface radiation and angle of incidence for an arbitrary number of surfaces. In this mode, Type 109 reads a weather data file in the standard TMY2 format. The TMY2 format is used by the National Solar Radiation Data Base (USA) but TMY2 files can be generated from many programs, such as Meteonorm.</td>
<td></td>
</tr>
<tr>
<td>4. Sky Temp</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td></td>
<td>This component determines an effective sky temperature, which is used to calculate the long-wave radiation exchange between an arbitrary external surface and the atmosphere. The effective sky temperature is always lower than the current ambient temperature. The black sky on a clear night for example, is assigned a low effective sky temperature to account for the additional radiative losses from a surface exposed to the sky. In this instance of Type 69, the cloudiness of the sky is calculated based on user provided dry bulb and dew point temperatures.</td>
<td></td>
</tr>
<tr>
<td>5. Psychrometrics</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>This component takes as input the dry bulb temperature and relative humidity of moist air and calls the TRNSYS Psychrometrics routine, returning the following corresponding moist air properties: dry bulb temperature, dew point temperature, wet bulb temperature, relative humidity, absolute humidity ratio, and enthalpy.</td>
<td></td>
</tr>
<tr>
<td>6. Lights</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Controls lights in the home being turned on and off.</td>
<td></td>
</tr>
<tr>
<td>7. Light thresholds</td>
<td>Equation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Used to give different power ratings for different types of lights used for 9. Building</td>
<td></td>
</tr>
<tr>
<td>8. Shading + Light</td>
<td>Equation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Used to give different power ratings for light when shading variables are present (not used).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>This component models the thermal behavior of a building having up to 25 thermal zones. The building description is read by this component from a set of external files having the extensions *.bui, *.bld, and *.trn. The files can be generated based on user supplied information by running the preprocessor program called TRNBuild (known as Prebid in TRNSYS versions prior to the release of v. 16.0). This instance of Type 56 generates its own set of monthly and hourly summary output files.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>9. Building</td>
<td>56</td>
<td>Computes the absolute value of negative variables so that data can be graphed as a more appealing visual manner.</td>
</tr>
<tr>
<td>10. Abs value</td>
<td>Equation</td>
<td>The online graphics component is used to display heating demand variables from 9. building while the simulation is progressing. The selected variables will be displayed in a separate plot window on the screen. In this instance of the Type 65 online plotter, data sent to the online plotter is automatically printed, once per time step to a user defined external file.</td>
</tr>
<tr>
<td>11. Aux heat</td>
<td>65</td>
<td>The online graphics component is used to display temperature variables while the simulation is progressing. The selected variables will be displayed in a separate plot window on the screen. In this instance of the Type 65 online plotter, data sent to the online plotter is automatically printed, once per time step to a user defined external file.</td>
</tr>
<tr>
<td>12. Temp</td>
<td>65</td>
<td>Models heat storage in a solid insulated cavern in the ground. During the heat injection period fluid is taken from the bottom of the volume, heated, and then returned through the top of the volume. During the heat extraction period the process is reversed.</td>
</tr>
<tr>
<td>13. SSTES</td>
<td>342</td>
<td>This routine models the heat transfer from a basement (typically four walls and a floor, all made of concrete) to the soil surrounding the five surfaces of the basement. The heat transfer is assumed to be conductive only and moisture effects are not accounted for in the model.</td>
</tr>
<tr>
<td>15. Controller for heat removal</td>
<td>2</td>
<td>Sets the mass flow rate for the heat extraction process.</td>
</tr>
<tr>
<td>17. Tbed&gt;Thouse</td>
<td>2</td>
<td>Controls the pump that moves fluid from the 9. building to 13. SSTES. Pump is on when 9. Building temperature is less than 13. SSTES average bed temperature.</td>
</tr>
<tr>
<td>-----------------</td>
<td>----</td>
<td>-----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>18. Controllers</td>
<td>65</td>
<td>The online graphics component is used to display controller variables from 15. Controller for heat removal, 17. Tbed&gt;Thouse, and 19. Controller for heat add while the simulation is progressing. The selected variables will be displayed in a separate plot window on the screen. In this instance of the Type65 online plotter, data sent to the online plotter is automatically printed, once per time step to a user defined external file.</td>
</tr>
<tr>
<td>19. Controller for heat add</td>
<td>2</td>
<td>Controls the pump that moves fluid from the 21. Solar Collectors to 13. SSTES. Pump is on when outlet temperature of collectors is greater than average bed temperature.</td>
</tr>
<tr>
<td>20. Mass flow-2</td>
<td>Equation</td>
<td>Sets the mass flow rate for the heat addition process</td>
</tr>
<tr>
<td>22. Total Gain</td>
<td>Equation</td>
<td>Multiplies the total gain of 21. Solar Collector by the number of collectors</td>
</tr>
</tbody>
</table>
3. METHODOLOGY

The ultimate goal of this project was to model the yearly space heating demands of typical ranch style homes, with and without a Seasonal Solar Thermal Energy Storage (SSTES) scheme. Six different sized homes were modeled: 800 ft$^2$, 1000 ft$^2$, 1400 ft$^2$, 1600 ft$^2$, 2000 ft$^2$, and 2400 ft$^2$. After each sized home was modeled without a SSTES scheme, they were then modeled with a SSTES scheme where the volume of the storage bed was varied. The 2000 ft$^2$ model was then used to optimize the solar thermal collector area and the flow rate through collectors. This house size was selected for optimization since the average house size for newly built houses in the US was 2100 ft$^2$ in 2009, which has been gradually declining over the past 5 years[22]. The efficiency of the models with SSTES was calculated using two different standards for comparison. The first was comparing the space heat demand provided by the SSTES scheme to the total amount of solar energy available to the solar collectors. The second was comparing the space heat demand provided by the SSTES scheme to the total energy gain of the solar collectors. The pump to the solar collectors was not always “turned on” because is it only possible to add heat to the system when the output temperature of the solar collectors exceeds the temperature of the storage medium. This prevents the solar collectors from being capable of capturing all of the available solar energy.
Preliminary data has shown that there can be a significant amount of time required for an SSTES scheme to “charge up” or reach steady state. After several simulations of the models with SSTES, it was obvious that the charge up time of our models was approximately one to two years. Thus, all models utilizing a SSTES were simulated for 5 years and the values corresponding to the final year were used during analysis.

3.1 House Details

The ranch style homes were modeled from a typical rectangle floor plan single story home commonly built in Richmond, Va. Figure 19 shows the blueprint drawing for the front of the home used to model in TRNSYS. See Appendix A for the complete house blueprints provided by a local contractor that was used to derive the dimensions of the six different sized homes.

![Figure 19](image)

*Figure 19. Drawing of the front (north facing) of house modeled in simulations.*

The dimensions of the house were then proportionally scaled to meet the desired square footage of the six models described in table 3. Dimensions proportionally scaled were the base length and width of house, and the window and door area of each exterior wall.
<table>
<thead>
<tr>
<th>sq ft</th>
<th>sq m</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>74.32</td>
</tr>
<tr>
<td>1000</td>
<td>92.90</td>
</tr>
<tr>
<td>1400</td>
<td>130.06</td>
</tr>
<tr>
<td>1600</td>
<td>148.64</td>
</tr>
<tr>
<td>2000</td>
<td>185.81</td>
</tr>
<tr>
<td>2400</td>
<td>222.97</td>
</tr>
</tbody>
</table>

There were three thermal zones modeled for each house: attic, crawl space, and living zone. The interior of each home was modeled as a single zone without any internal walls or heat gains and was the only zone with a heating source. The back side of the house models faced due south since the back wall had the largest window area which allows for the most passive solar thermal heating of the home in the winter. Refer to Appendix B for exact dimensions of each individual home model.

Each home has a 3.5 ft (0.91 m) tall crawl space below the main floor and a pitched roof with a center attic height of 8 ft (2.48 m). The crawl space was to be modeled so that 0.5 ft (0.1524 m) was above the soil surface and 3 ft (0.9144 m) was below the soil surface. To model this in TRNSYS, two separate zones needed to be created for the crawl space. The zone above the soil line was called the sub crawl space while the zone below the soil line was called the crawl space (modeled with Type 701). Each home had the same center attic height resulting in the following discrepancies from keeping each house proportionally identical (as the square footage increased):

- The slope of the roof decreased
- The side walls’ area of the attic decreased
- The pitched roof area increased.
The discrepancies in the dimensions of the roof were deemed to have minimal impact on the homes’ total space heating demand since slight changes affected the total space heating demand by less than 5,000 kJ.

Heat demands for homes modeled without SSTES were computed by using the built in heating function in Type 56 which models an idealized heating system to maintain a minimum temperature of 68°F (20°C) inside the house. The same system was used as the auxiliary heating system in models with SSTES except the minimum temperature was set to 66.2°F (19°C). This is because in the models with SSTES the main heating system (radiant floor system) was set to turn ‘on’ when the house temperature dropped below 68°F (20°C), and was to remain on until the temperature reached 69°F (20.5°C). The reason why the radiant floor was set to turn off at 69°F was because if it were set to turn on and off at 68°F then the system would oscillate on and off every hour which is unrealistic. This also caused the auxiliary heat to operate nearly the entire cold season, which was not the purpose of this study. The auxiliary heating system was only to keep the house from getting too cold (dropping below 19°C). If the temperature of the SSTES bed was less than the temperature of the home then the radiant floor was never activated.

All simulations began with the initial temperature of the house at 68°F (20°C). The radiant floor system kept all the same parameters in all six models except for the length of pipe embedded in the floor. Tables 4 and 5 detail the dimensions of the radiant floor heating system. The thermal conductivity of the radiant floor piping was 1.476 $\frac{kJ}{h \cdot m \cdot K}$. All radiant floor specs have been modeled after REHAU pex tubing for radiant floors[23].
Outdoor air infiltration was also accounted for in every house model. The infiltration rates were based on values obtained from the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) handbook. The crawl space and attic both had infiltration rates of two (2) Air Changes per Hour (ACH), while the heated zone had an infiltration rate of one (1) ACH [24].

### 3.1.1 Building Materials

Materials used in the house models are standard materials used in typical new home construction. For simplicity, the front door of the homes was omitted and the exterior wall was used instead. All window areas and the back door area were modeled as a standard non-glazed double pane glass window. The only difference in the materials between models with SSTES was in the floor. The floor used for non SSTES models was a traditional hardwood floor, where the floor in SSTES models used a radiant hardwood floor. TRNSYS models the radiant floor essentially by having the tubes embedded within the hardwood, causing the hardwood to be much thicker than a traditional hardwood floor.
Since the hardwood had to be much thicker the plywood sub floor was omitted. Properties of all materials used were from the standard American library supplied by TRNSYS.

Table 6 summarizes all of the materials and their thickness used to model each wall of the house.

- Attic outwall – vertical exterior wall of attic facing east and west
- Ceiling – horizontal wall adjoining attic to living zone
- Crawl wall – the exterior wall of the crawl space
- Interior floor – horizontal wall adjoining living zone to crawl space in non SSTES models
- Out wall – exterior wall of living zone
- Rad floor – horizontal wall adjoining living zone to crawl space in SSTES models
- Roof – tilted roof wall facing north and south
Table 6. Summary of all materials and their thickness used to model each wall of the house. Layers listed from inside of the home towards the exterior. English units are approximate.

<table>
<thead>
<tr>
<th>Location</th>
<th>Material</th>
<th>m</th>
<th>in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attic Outwall</td>
<td>Plywood</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Poly Vinyl Siding</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Dry Wall</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>R-13 insul</td>
<td>0.318</td>
<td>12.52</td>
</tr>
<tr>
<td>Crawl Wall</td>
<td>Hollow Mason Block</td>
<td>0.203</td>
<td>7.99</td>
</tr>
<tr>
<td>Interior Floor</td>
<td>Hardwood floor</td>
<td>0.019</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Plywood</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>R-13 insul</td>
<td>0.191</td>
<td>7.52</td>
</tr>
<tr>
<td>Out wall</td>
<td>Dry Wall</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>R-13 insul</td>
<td>0.089</td>
<td>3.50</td>
</tr>
<tr>
<td></td>
<td>Plywood</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Poly Vinyl Siding</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td>Rad floor</td>
<td>Hardwood w/ pipe embeded</td>
<td>0.090</td>
<td>3.54</td>
</tr>
<tr>
<td></td>
<td>R-13 insul</td>
<td>0.192</td>
<td>7.56</td>
</tr>
<tr>
<td>Roof</td>
<td>Plywood</td>
<td>0.013</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Asphalt Shingles</td>
<td>0.006</td>
<td>0.24</td>
</tr>
</tbody>
</table>

3.2 SSTES Details

The SSTES is modeled in TRNSYS using Type 342 (Multi-Flow Stratified Thermal Storage Model with Fully Mixed Layers). This type was set up to simulate heat storage in an insulated cylindrical sand bed buried in the ground. Water was used as the working fluid to transfer thermal energy to and from the SSTES. Likewise, water was also used as the working fluid to collect thermal energy from the solar collectors, and to deliver thermal energy to the home via the radiant floor. The heat capacity and density of water used in the models was $4.2 \frac{kJ}{kgK}$ and 1000 kg/m³, respectively. The standard flow rate used from the collectors to the SSTES sand bed was 340.65 kg/hr (1.5 gpm), and the flow
rate for heat removal from the SSTES sand bed to the radiant floor was 1135.5 kg/hr (5 gpm). The flow rate values were determined from reviewing recommended flow rates for existing solar thermal collectors and radiant floor heating installation guides.

The properties of the storage medium (sand) used in the models were derived from several sources and an actual measurement. The density of dry sand ranges from 1200 kg/m$^3$ to 2000 kg/m$^3$ depending on the granular size and compaction[25]. An actual calculation was conducted from a SSTES sand bed currently being built in Richmond, VA from locally provided sand showed the density to be 1201 kg/m$^3$, thus this was the value used for the density of sand. A low density value was also used because the greater the density of the sand, the greater its ability to transfer heat within the SSTES sand bed. Therefore, the results will reflect a lower performance capability of the SSTES scheme.

The specific heat capacity of sand in the models was 830 J/h g C[26]. Using these values the SSTES capacity and conductivity were computed to be 996.83 $\frac{kJ}{m^3 K}$ and 3.24 $\frac{kJ}{hr m K}$, respectively.

Parameters regarding the geometry of the underground SSTES were limited by the TYPE 342 used to simulate the SSTES. The SSTES sand bed was always cylindrical where the total depth (from top to bottom) was always kept constant at 3 meters (9.8425 ft). Thus by varying the total volume of the SSTES sand bed, TYPE 342 automatically determined the corresponding radius. All models were designed such that the top of the SSTES was 1 meter below the ground surface. The basis of this parameter was to keep the SSTES bed below the frost line, which would decrease the thermal losses. The frost line
for the Richmond, VA area is taken to be 0.4572 m (1.5 ft)[27]. The SSTES sand bed is surrounded on all six sides by 0.1 m (3.94 in) rigid board insulation with a conductivity value of 0.2 \( \frac{kJ}{h\cdot m\cdot K} \) (approximately equal to an R value of 6.8 per inch). The insulation conductivity used is a value for thermal conductivity which assumes that the heat transfer of the material is linearly related to its thickness and can not be directly related to an R-value.

The initial temperature conditions for the SSTES bed and the surrounding ground was 55.4°F (13°C). This was chosen because the underground temperature of soil temperature is relatively constant and is roughly the same as the water temperature measured in groundwater wells. In Virginia, the average soil temperature ranges from 52°F in the northern Shenandoah Valley and Winchester area to 62°F in the coastal Tidewater region[28].

### 3.3 Solar Collector Details

The solar collectors used in the model simulated the performance of a theoretical flat plate collector. Optimum incident solar radiation upon the collectors is achieved when they face south and their tilt angle is approximately the same as the angle of latitude in which they are located. Since Richmond, VA is located at 37°32’27.5” latitude, the best location for the collectors in a real life situation would be on top of the south facing pitched roof. The idea was to cover the entire south facing portion of the pitched roof with solar collectors to achieve maximum insolation. However, it is unfeasible to cover the
entire south facing half of the roof with useful collector area so 80% of the south facing roof area was modeled to be covered in useful solar collector area. Typically the largest solar collectors manufactured have an area of 2.972 m² (32 ft²). Thus, our models simulate that sized solar collectors connected in parallel until the total area reaches 80% of the total south facing roof area. Table 7 below shows the angles of the pitched roofs (solar collectors) of the six house models used and the total useful collector area used.

**Table 7.** The six different house models and their corresponding collector angle, collector area, and number of collectors connected in parallel.

<table>
<thead>
<tr>
<th>House Floor Area (sq ft)</th>
<th>Angle (degrees)</th>
<th>Collector Area</th>
<th># of Collectors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>sq ft</td>
<td>sq m</td>
</tr>
<tr>
<td>800</td>
<td>40.1098</td>
<td>127.53</td>
<td>38.871</td>
</tr>
<tr>
<td>1000</td>
<td>36.9958</td>
<td>152.652</td>
<td>46.5283</td>
</tr>
<tr>
<td>1400</td>
<td>32.4879</td>
<td>202.356</td>
<td>61.678</td>
</tr>
<tr>
<td>1600</td>
<td>30.78</td>
<td>227.055</td>
<td>69.2065</td>
</tr>
<tr>
<td>2000</td>
<td>28.047</td>
<td>276.287</td>
<td>84.2122</td>
</tr>
<tr>
<td>2400</td>
<td>25.9357</td>
<td>325.378</td>
<td>99.1753</td>
</tr>
</tbody>
</table>
4. RESULTS/DISCUSSION

4.1 Preliminary Data

Before simulating any of the house models with SSTES using TYPE 342, a 10 year simulation was run using TYPE 10, Rock Bed Storage, from the standard TRNSYS component library. TYPE 10 models a thermal rock bed storage described by the relations governing heat transfer for fluid flow in packed beds. The model neglects temperature gradients within the bed and neglects axial conduction, and assumes a uniform flow distribution of the fluid through the bed. Two partial differential equations are solved by finite difference methods to describe the fluid and bed temperatures as a function of position and time. This model only works for one flow, thus the model does not include any heat removal by a load. It only accounts for solar heat gain from the solar collectors, and conductive losses from the underground insulation [21].
Table 8. Parameters used for Type 10 model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector Area</td>
<td>77 m²</td>
</tr>
<tr>
<td>Specific heat of water</td>
<td>4.2 kJ/(kg-K)</td>
</tr>
<tr>
<td>Fluid flow rate</td>
<td>100 kg/hr</td>
</tr>
<tr>
<td>Length of sand bed</td>
<td>16.31 m</td>
</tr>
<tr>
<td>Cross-sectional area of bed</td>
<td>40.775 m²</td>
</tr>
<tr>
<td>Perimeter of sand bed</td>
<td>65.24 m</td>
</tr>
<tr>
<td>Volume of bed</td>
<td>665.04 m³</td>
</tr>
<tr>
<td>Specific heat of sand</td>
<td>0.83 kJ/(kg-K)</td>
</tr>
<tr>
<td>Density of sand</td>
<td>1602 kg/m³</td>
</tr>
<tr>
<td>Loss coefficient of bed to surroundings</td>
<td>varied --</td>
</tr>
<tr>
<td>Effective thermal conductivity of sand</td>
<td>0.9 kJ/(hr m K)</td>
</tr>
<tr>
<td>Initial temperature of sand and surrounding</td>
<td>13 °C</td>
</tr>
</tbody>
</table>
Figure 20. Ten year simulation of SSTES using TYPE 10 – Rock Bed Storage. The loss coefficient of the bed is varied.

By looking at figure 20, we see that there was a time delay before the bed reached a steady state. For all cases except for the one with the lowest loss coefficient, $0.01 \frac{kJ}{hr m^2 K}$, the bed reached a steady state by the end of the third year. The case with the lowest loss coefficient reached a steady state by the end of the fifth year. This data shows that we must simulate our models with SSTES for at least five years to ensure the bed reaches steady state.
4.2 No Storage Models

The six different sized house models were simulated for one year because the results repeat themselves every year since the incoming data from the weather file is repeated each simulation year. The annual temperature profile of the living zone where a heating schedule was applied resulted in graphs similar to figure 21. During the colder months we see the temperature bottoms out at the heating set point of 20 °C (68 °F). Heat is supplied consistently to the home from January through March and tapers off during April and May. During April and May we see spikes in the temperature that are primarily during daylight hours when passive solar energy is able to keep the home’s temperature above 20 °C, however heat was still supplied to the house during the cooler nights. Little to no heat was supplied during the summer months between late May and August where we see the highest inside temperature of the house. Temperatures reach as high as 34 °C (93.2 °F) inside the home because the models do not account for air conditioning or extra forced air ventilation. The beginning of September marks the beginning of the cold season where heat began to be supplied to the home again. Heat was steadily supplied to the home during October, November, and December.
Figure 21. Annual temperature profile for 2000 $ft^2$ home without SSTES.

The heat demand per unit time also followed the same pattern as the temperature profile. The demand per unit time reaches its peak demand during the first two months of the year and tapers down to none by June. Figure 22 shows the heat demand per unit time for the 2000 $ft^2$ model. Regional HVAC companies typically size heat pumps for residential homes by the general rule of 1 ton per 650 $ft^2$ of conditioned space [29]. This general rule means a 2000 $ft^2$ house would need a heat pump capable of producing 37,982 kJ/hr. The peak demand from our model reaches a maximum of approximately 34,000 kJ/hr in February. This indicates our model’s heat demand per unit time is valid.
The demand steadily increases from January through March, and tapers down during April through May. The total demand does not begin to increase again until late September. It then steadily increases through the end of December. Figure 23 displays the trend of the annual heat demand.
The total annual heat demand of our models increased linearly as the floor area of the homes increased as shown in figure 24. We were able to validate this data because our models’ total annual heat demand coincides with space heating data of local homes in Richmond.
Figure 24. Annual heat demand of singly story homes in Richmond, VA based upon the floor area of the home.

4.3 SSTES Models

4.3.1 Annual Temperature Profiles of House

Models utilizing a SSTES scheme were modeled for five years to ensure the system reached a steady state. The only changes between each simulated year were the initial temperature conditions of the bed and variables directly related to the bed temperature. All models showed the exact same trends for all variables, they just had different magnitudes. Our data showed that the system reached a fairly steady state by the end of the first year. Comparing the first year’s annual temperature profile to the fifth year’s (figures 25 and
26), we can see that there was barely a difference for a 2000 ft² home with a 15 m³ SSTES bed.

**Figure 25.** First year annual temperature profile for a 2000 sq ft home with SSTES. The SSTES was 15 m³.

Heat supplied by the radiant floor was set to turn on when the temperature dropped below 68°F (20°C), and did not turn off until the temperature reached 69°F (20.5°C). This effect can be seen in the graphs where the house temperature oscillated between 19°C and 20°C. A point in the graph where there is a flat line at 19°C is when the auxiliary heat turned on. Comparing the annual temperature profiles between models with SSTES to models without, we saw that the auxiliary heat was used much less. The auxiliary heat was primarily used during January, February, November, and December.
Figure 26. Fifth year annual temperature profile for a 2000 ft² home with SSTES. The SSTES was 15 m³.

4.3.2 Annual Auxiliary Heat Demands

The auxiliary heat demand per unit time for models with SSTES also stayed fairly identical between the first and fifth year (figures 27 and 28), further proving the system reached a steady state by the second year. The peak demands per unit time are slightly lower during the fifth year. This was because the temperature of the SSTES bed was slightly warmer by the fifth year and was able to provide slightly more heat to the home, decreasing the demand placed on the auxiliary heater.
The radiant floor was actively providing heat to the home for two more hours during the fifth year compared to the first. These two hours occurred during October. The fifth year provided 113368.5 kJ more than what it supplied during the first year of operation. The auxiliary heat demand per unit time in models with SSTES was also much lower than the heat demand in models without SSTES. The maximum peak for models with SSTES was approximately 25,000 kJ/hr, nearly 10,000 kJ/hr lower than models without SSTES. Auxiliary heating systems for homes with SSTES do not require the same size heat capacity as heating systems in traditional homes without SSTES.
Figure 28. Fifth year’s annual heat demand profile for 2000 ft² home with a 15 m³ SSTES.

4.3.3 Annual Temperature Profiles of SSTES Bed

Figures 29 and 30 show the annual temperature profiles of the SSTES bed for a 2000 ft² home with a 15 m³ SSTES bed for the first and fifth year. We see the same pattern in both years. The major difference occurred during the beginning of the first year where the initial temperature of the storage bed as set at 13°C (55.4°F).
Figure 29. First year’s annual SSTES bed temperature profile for a 2000 ft\(^2\). The SSTES was 15 m\(^3\).

The average annual bed temp increased from 53.5\(^\circ\)C to 53.7\(^\circ\)C from the first year to the fifth year. The maximum temperature obtained throughout the five year simulation was 96.1\(^\circ\)C which occurred during September of the fifth year. During the first year the bed was colder than the house for 40 hours while it was only colder than the house for 30 hours during each subsequent year.
4.3.4 Auxiliary Heat Demand with Varied Storage Volumes

The total auxiliary heat demand also increased as the floor area of the homes increased. Figure 31 shows the total amount of auxiliary heat supplied to the homes during the fifth year of operation. The amount of auxiliary heat supplied sharply decreased as the volume of the SSTES bed went from 10 m$^3$ to 15 m$^3$. For bed sizes from 15 m$^3$ to 50 m$^3$, the amount of auxiliary heat supplied continued to decrease, but at a much lower rate. This was because the total solar collector area remained the same while the SSTES volume increased. The 10 m$^3$ SSTES bed did not have enough thermal mass to store as much useful energy as the larger beds. SSTES beds 15 m$^3$ and larger were able to store more useful energy that was transferred to the home via the radiant floor.

Figure 30. Fifth year’s annual SSTES bed temperature profile for a 2000 ft$^2$. The SSTES was 15 m$^3$. 
Figure 31. Auxiliary heat demand of each sized house model with SSTES compared to the size of the SSTES bed.

House models with 15 m$^3$ SSTES storage beds were able to provide more heat to the home via radiant floor heat which lowered the amount of heat supplied by the auxiliary heater. However, as the volume of the SSTES increased, the amount of heat supplied by the radiant floor increased only slightly. Figure 32 shows the useful energy gain of the collectors and the amount of heat provided by the radiant floor compared to the volume of the SSTES bed. The heat supplied by the floor increased as the volume of the SSTES bed increased from 10 m$^3$ to 15 m$^3$. The heat supplied by the floor slightly increased as the volume of the SSTES bed increased from 15 m$^3$ to 50 m$^3$. This was expected since the heat provided by the auxiliary heater slightly decreased through the same SSTES bed volumes.
Figure 32. Useful solar energy gain from collectors and the heat supplied by the radiant floor compared to the volume of the SSTES bed. Data for this graph was obtained from the 2000 ft² house model with 80% of the south side facing roof covered with solar collectors.

The sum of the heat provided by the auxiliary heater and the radiant floor was just slightly higher than the totally amount of heat provided to the homes in the models without a SSTES scheme. The reason why models with an SSTES scheme provided slightly more total heat to the home was because the radiant floor thermostat was set to turn of at 69°F whereas models without SSTES turned the heat off at 68°F. The reason why the useful energy gain from the collectors continues to increase while the heat supplied to the radiant floor remains constant is because of the extra volume, or sand mass, in the SSTES bed. The greater the storage mass, the more energy required to raise the temperature. The average temperature of the 15 m³ bed was 58.6°C while it was 51.4°C for the 60 m³ SSTES
bed. Thus, the extra gain from the solar collectors was still unable to heat the 60 m³ bed to the same temperature as the smaller bed. Since heat transfer is directly proportional to the temperature difference, the 15 m³ SSTES bed was able to transfer heat to the radiant floor more efficiently than the 60 m³ bed even though the larger bed stored more total energy.

The amount of auxiliary heat required in the homes with a SSTES scheme was between 64% and 77% less than the total amount of heat provided to homes without SSTES. In other words, this means that the solar energy stored in the SSTES bed provided the home with 64%-77% of the total heat demand of the home via radiant floor. Figures 33 and 34 shows the auxiliary heat reductions of each model.

![% Aux. Heat Demand Reduction vs Storage Volume](image)

**Figure 33.** Auxiliary heat reductions of SSTES models compared to the total heat provided to models without SSTES.
The greatest reduction in auxiliary heat occurs when the volume of the SSTES bed was between 15 m³ and 16 m³. As the volume of the SSTES increased beyond 20 m³ the percentage of heat reduction of all sized models began to converge toward 75%.

![Graph showing % Aux. Heat Demand Reduction vs Storage Volume](image)

**Figure 34.** A zoomed in view of figure 33 showing the auxiliary heat demand reduction of SSTES models compared to models without SSTES.

### 4.4 Optimizing SSTES Models

The 2000 ft² model was used to optimize the solar thermal collector area and the flow rate through collectors. This house size was selected for optimization since the average house size for newly built houses in the US was 2100 ft² in 2009, which has been gradually declining over the past 5 years[22].
The first variable that was optimized was the area of solar collectors used. Figures 35 and 36 show the percent reduction of auxiliary heat compared to the 200 ft² model without SSTES as the area of the solar collectors is increased. The reduction in the auxiliary heat reduction increased at the collector area increased. This is because the greater area of solar collectors, the greater amount of energy can be captured, stored, and distributed into the home.

![% Aux. Heat Reduction vs Collector Area](image)

**Figure 35.** Percent heat reduction of the 2000 ft² model with a 15 m³ SSTES compared to the one without SSTES as the area of the solar collectors is increased.

Earlier simulations were run with 80% of the south facing roof (84.2 m²) covered in solar collectors. This data shows that by increasing the collector area to 90%, the percent reduction in auxiliary heat can be increased from 72% to 75%. This would be optimal since this is where the slope of the graph distinctively decreases the first time. If the entire
roof were to face the south and it was completely covered (200% of initial south facing roof area) with solar collectors then just over 81% of the home’s total heat demand would be provided by the SSTES scheme.

**Figure 36.** Percent heat reduction of the 2000 ft² model with a 15 m³ SSTES compared to the one without SSTES as the area of the solar collectors is increased. The collector area is measured as a percentage of the south side facing roof area.

Figure 37 compares the heat supplied to the home by the floor to the total useful energy gain from the solar collectors as the area of the collectors increased.
As the collector area increased so did the useful energy gain from the collectors. The useful gain from the collectors increased at a slightly greater rate than the amount of heat provided by the radiant floor. The difference between the two at 50% of the south facing roof (52 m²) was 18,307,413 kJ and the difference at 200% (210 m²) was 22,940,266 kJ. The difference between the useful gain and the heat provided by the floor was energy: A) used to heat the SSTES bed from its initial temperature of 55.4°F (13°C) to 68°F (20°C) which is the lowest temperature in which the radiant floor could operate or B) energy lost from the warm SSTES bed into the cold ground.

The second parameter that was optimized was the flow rate of the water through the solar collectors. Figure 38 compares the percent auxiliary heat reduction of a 2000 ft²
home with a 15 m$^3$ SSTES bed to the solar collector flow rate. Manufacturers of solar thermal collectors typically advise flow rates between 1 to 3 gallons per minute. Our data shows that the faster the flow rate the greater the reduction in auxiliary heat. Our initial simulations used 1.5 gpm and showed a percent reduction in auxiliary heat of 72% for a 200 ft$^2$ with a 15 m$^3$ SSTES bed. The optimum appears to be 3 gpm through the solar collector which increases the percent reduction to 79%. A flow rate of 6 gpm further increases the percent reduction to 82.5%.

![% Aux. Heat Reduction vs Solar Collector Flow Rate](image)

**Figure 38.** Percent auxiliary heat reduction for 2000 ft$^2$ with a 15 m$^3$ SSTES bed as the flow rate through the solar collectors is varied.
4.5 Efficiency

The efficiency of the system was calculated in two different manners. The first was comparing the total useful energy gain of the solar collectors to the amount of heat provided to the home via radiant floor heat from the SSTES bed. With 80% of the south side facing roof covered with solar collectors our models experienced efficiencies from 50% to 70%. The efficiencies of all the models with a SSTES scheme are shown in figure 39. Each models’ highest efficiency was achieved with a SSTES bed size of 15 m³. This was expected since the highest percent reduction in auxiliary heat occurred at this size as shown previously in figure 33.

![Efficiencies Compared to Total Useful Gain of Collectors](image)

**Figure 39.** Efficiency curves of all models with 80% of the south side facing roof covered in solar collectors. The efficiency compares the amount of energy provided to the home via radiant floor heat from the SSTES to the total useful energy gain of the solar collectors.
All the models experience the same shape efficiency curve. Greater efficiencies were achieved as the floor area of the house models increased. This is because as the floor area increases, the volume of the conditioned zone increases faster than the total surface area. Having a smaller surface area to volume ratio means there are fewer losses through the walls of the home with a greater area. The highest efficiency achieved was 70.6% for a 2400 ft² house model with a 15 m³ SSTES bed. The efficiency of the 2000 ft² house model with a 15 m³ SSTES bed was 67.7%.

The second way the efficiency was calculated was by comparing the amount heat provided to the home via the radiant floor to the total amount of energy incident on the solar collectors. The average annual solar radiation for Richmond, Va for a flat plat collector facing south tilted at 37° is 4-5 \( \frac{kWh}{m^2 \text{day}} \) [3]. For a 2000 ft² home with a 15 m³ SSTES bed the efficiency is between 6.1% and 7.6%.

4.6 Economic Analysis
The following economic analysis was done for the same 2000 ft² home with 80% of it’s south side facing roof covered in panels and, a 15 m³ SSTES bed as described previously in this section. The most expensive part of the entire scheme is the cost of the solar thermal collectors and their installation. The costs of solar collectors and their installation decreases per unit as the total number of collectors bought and installed increases (buying in bulk). These estimates are based on needing to buy 23 solar collectors to cover 80% of the south facing roof. The cost of a solar collector was estimated to be $828 for one 4 ft x
10 ft (2.972 m²) collector. Each collector must be installed onto a roof rack which was estimated to cost $1,380 for all 23 collectors [30]. The cost of the collectors and their installation accounts for $20,425 which is over 70% of the total cost. The cost of digging the hole, hauling sand to site, filling with sand, and hauling dirt away varied depending on if the installment was to a new home being built or a retrofitted home. The retrofitted home costs more due to the fact that the dirt from the hole must be hauled away, whereas in a new construction the dirt can be spread around the landscape. The estimated costs were $78.48 and $130.80 per cubic meter, respectively [31]. Pipe fittings are used to connect the copper piping of the collectors to the PEX tubing which is buried in the sand and floor. Two pumps contained in outdoor weather boxes are needed to move the fluid through both the radiant floor and solar collectors. The radiant floor used in this estimate is from REHAU where the cost is $2 per ft² ($21.52 per m²)[32]. The vapor liner comes in a standard size of 2,000 ft² (185.8 m²) for $95 which is more than enough since a 15 m³ cylindrical bed has a total surface area of 33.78 m². Copper piping is used to connect the storage bed to the collectors since the PEX tubing will not safely connect to the collectors. Traditional outdoor heat pumps, which run off of electricity, were assumed to supply heat to homes without SSTES. The cost of electricity for this analysis was assumed to be 10.77 cents per kilowatt hour.
Table 9. Cost analysis of constructing a SSTES scheme for a 2000 ft² home with a 15 m³ SSTES bed. Values do not include cost to operate pumps, maintenance, or the time value of money.

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5. CONCLUSIONS

Preliminary modeling showed that a SSTES bed in the ground without any attached load required between one and a half to five years to reach a steady state condition. The higher end of the range belonged to beds with a high loss coefficient of 0.2 kJ/(hr m² K), where the lower end of the range had a loss coefficient of 0.01 kJ/(hr m² K). This indicated that we needed to run our simulations that utilized SSTES for a minimum of 5 years. Our data showed that our house models with SSTES reached steady state between the second and third years even though the differences between the first and fifth years were minimal.

Six different sized one story house models (sizing based on floor area) were built in TRNSYS: 800 ft², 1000 ft², 1400 ft², 1600 ft², 2000 ft², and 2400 ft². Each home was first modeled using the “energy rate” method for supplying heat to the home. This method mimics the behavior of a traditional outdoor heat pump that would normally be the sole heating supply to the home. The temperature inside the home was maintained at 20°C. The annual temperature profile of these models repeated themselves each year since the incoming data from the weather file was repeated each year. Heat was supplied consistently to the home from January through March and tapered off during April and May. During April and May the temperature spiked during the day time but heat was still
added during the night to maintain 20°C. Little to no heat was supplied during the summer months between late May and August. The beginning of September marked the beginning of the cold season where heat was steadily supplied to the home from October through December.

The heat demand per unit time also followed the same pattern as the temperature profile. This is because in order for the temperature to be maintained during the cold season, heat must be added to the home. The maximum heat demand during the simulations stayed within the range of traditional demands that are anticipated by HVAC companies which verified our models were accurate. The 2000 ft² model’s annual heating demand was compared to the actual local heating demand of a similar sized home which coincided with our simulation’s demand, thus validating our results. The total annual heating demand of our house models increased linearly as the size of the home was increased. The results show that our models required 24,344 kJ/ft² of heat each year.

The six different sized homes were then modeled to have a SSTES scheme to supply the majority of the heat to the home. Heat was harvested from the SSTES bed and returned to the homes via radiant floor heating. Since the radiant floor heating coupled with the SSTES bed could not provide the home with enough heat to maintain a minimum temperature of 20°C, an auxiliary heater was also modeled. The auxiliary heater was modeled in the same way as for simulations without a SSTES scheme. Each of the different sized homes was modeled for 5 years, with 80% of the south facing roof covered in solar collectors to add heat to the SSTES bed. The bed size was varied for each sized home and the optimal bed size for each home was determined to be 15 m³. The annual
temperature profile was very similar to homes with out a SSTES scheme. The auxiliary heat was primarily used during January, February, November, and December. During the spring and fall seasons the radiant floor heating was able to accommodate the heat demand.

Simulations also showed that a 15 m$^3$ bed SSTES bed reached steady state by the end of the second year of operation. The average annual bed temperature increased from 53.5$^\circ$C to 53.7$^\circ$C from the first year to the fifth year. The maximum temperature obtained throughout the five year simulation was 96.1$^\circ$C which occurred during September of the fifth year. During the first year the bed was colder than the house for 40 hours while it was only colder than the house for 30 hours during each subsequent year.

The bed sizes for each home was varied from 10 m$^3$ to 50 m$^3$ to determine that 15 m$^3$ was the optimal bed size. The amount of auxiliary heat supplied sharply decreased as the volume of the SSTES bed went from 10 m$^3$ to 15 m$^3$. The amount of auxiliary heat supplied remained fairly constant for all models when the SSTES bed ranged from 15 m$^3$ to 50 m$^3$. This is because beds larger than 15 m$^3$ could store more thermal energy but at a lower average temperature, while beds smaller than 15 m$^3$ weren’t able to store enough thermal energy. Beds sized at 15 m$^3$ were able to store enough thermal energy for the homes at a high enough temperature to be useful in combination with the radiant floor heating. The only changes to the SSTES scheme between the different sized homes were the demand of the home and the area of solar collectors feeding the SSTES bed. Since both of those variables both increased linearly as the size of the home increased, 15 m$^3$ remained optimal for all sized homes. Models with a SSTES scheme were able to reduce their auxiliary heat demand compared to models without SSTES by 64% to 77%. Vice
versa, the SSTES bed coupled with the radiant floor heating was able to provide homes with 64% to 77% of the annual heating demand.

The area of the solar thermal collectors used was optimized for the 2000 ft² model with a 15 m³ SSTES bed. The optimal area for solar thermal collectors was found to be 90% of the total south facing roof area. This increased the amount of heat supplied by the radiant floor from 72% (with 80% of south facing roof covered) to 75%. The reason 80% was used is due to the fact that the useful collector area of a solar collector is less than the total area, and there needs to be some extra room on the roof for workers operate. If there were enough solar collectors to cover 200% of the south facing roof area then the total amount of heat supplied by the radiant floor would increase to 81%.

The flow rate of water through the solar collectors was also optimized for the 2000 ft² model with a 15 m³ SSTES bed. All previous simulations used a manufacturer’s recommended flow rate of 1.5 gpm. The optimum flow rate was 3 gpm through the solar collector which increased the amount of heat supplied from the radiant floor to 79% from 72%.

The efficiency of the SSTES scheme on our models was calculated in two different methods. The first method compared the total useful energy gain of the solar collectors to the heat provided to the home via radiant floor heat form the SSTES bed. With 80% of the south side facing roof covered with solar collectors our models experienced efficiencies from 50% to 70%. Higher efficiencies were achieved with larger sized homes. The 2400 ft² house model achieved an efficiency of 70.6% while the 800 ft² house model achieved an efficiency of 51.2%. This is because as the floor area increases, the volume of the
conditioned zone in the house increases faster than the total surface area of the surround walls. A smaller exterior wall surface area to internal volume ratio means there are fewer losses through the walls of the home. A 2000 ft\(^2\) house with a 15 m\(^3\) SSTES bed had an efficiency of 67.7%. The second method the efficiency was calculated was by comparing the amount of heat provided to the home via radiant floor heating to the total amount of energy incident on the solar collectors. For a 2000 ft\(^2\) house with a 15 m\(^3\) SSTES bed the efficiency was between 6.1% and 7.6%.

The economic analysis of the entire system was calculated for both the installation of a SSTES scheme on a new house and retrofitting an existing home. The major difference was that for an existing home dirt from the SSTES bed needed to be hauled away which costs an extra fee. The expected number of years to pay off a SSTES system is approximately 28 years for both new and retrofit installations. The cost of the solar thermal collectors and their installation was the most expensive part accounting for $20,425 which is over 70% of the total cost. The cost of solar thermal collectors needs to decrease for this technology to become attractive.
Literature Cited
Literature Cited

APPENDIX A

Blueprints from “The Randolph” in which the six house models’ parameters were derived from. The dimensions of “The Randolph” were proportionally scaled to meet the desired square footage of each model.
APPENDIX B

House dimensions of the six different sized homes modeled with a base unit of meters.

The volume of the sub crawl space for 2000 ft² was incorrectly entered into TRNSYS. The
value should have been 28.3169 m.

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<td>2.165624</td>
<td>2.503261</td>
<td>2.676099</td>
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Roof

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<td>58.16041</td>
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<tr>
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<tr>
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Crawl

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<td>6.01113</td>
<td>12.92249</td>
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<tr>
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<tr>
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Sub Crawl

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<tr>
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</table>
APPENDIX C

Both files, TRNSYS Input File and TRNBuild building description, in this Appendix are from the 2000 ft² model with a 15 m³ SSTES created with TRNSYS version 16.1. Nomenclature of variables and icons correspond to section 2.6 Model Setup. The TRNSYS Input File shows all the components used and their inputs/outputs. The TRNBuild building description file describes how the house was modeled. All six different sized house models with SSTES scheme differ only by parameter dimensions as described in Appendix B. All six different sized house models without SSTES can be derived from the following files by referring to figure # in section 2.6 Model Setup.

**TRNSYS Input File (TRNSED)**

*******************************************************************************
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Wednesday, October 13, 2010 at 10:19
*** from TrnsysStudio project:
C:\TRNSYS\Trnsys16_1\MyProjects\V2_2000singlezonetype342\2000singlezone342.tpf
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:software@cstb.fr
***
*******************************************************************************

*******************************************************************************
*** Units
*******************************************************************************

*******************************************************************************
*** Control cards
*******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=43800
STEP=1
* User defined CONSTANTS

SIMULATION START STOP STEP ! Start time End time Time step
TOLERANCES 0.001 0.001 ! Integration Convergence
LIMITS 30 50 30 ! Max iterations Max warnings Trace limit
DFQ 1 ! TRNSYS numerical integration solver method
WIDTH 72 ! TRNSYS output file width, number of characters
LIST ! NOLIST statement
SOLVER 0 1 1 ! Solver statement Minimum relaxation factor
          ! Maximum relaxation factor
          ! Nan DEBUG statement
          ! Overwrite DEBUG statement
          ! disable time report
EQSOLVER 0 ! EQUATION SOLVER statement

* EQUATIONS "1. Turn"
*
EQUATIONS 5
TURN = 0
AA_N = 180 + TURN
AA_S = TURN
AA_E = -90 + TURN
AA_W = 90 + TURN
*$UNIT_NAME 1. Turn
*$LAYER Main
*$POSITION 46 61

* EQUATIONS "2. Radiation"
*
EQUATIONS 18
AISZ = [109,10]
AISA = [109,11]
IT_H = Max([109,12],0)
IB_H = Max([109,13],0)
ID_H = [109,14]
AI_H = [109,16]
IT_N = [109,18]
AI_N = [109,19] * LT(AI_N,90)
IB_N = [109,22]
IT_S = [109,24]
IB_S = [109,25]
AI_S = [109,28]
IT_E = [109,30]
IB_E = [109,31]
AI_E = [109,34]
IT_W = [109,36]
IB_W = [109,37]
AI_W = [109,40]

*UNIT_NAME 2. Radiation
*SLAYER Main
*SPOSITION 164 82

* EQUATIONS "8. Shading+Light"
*
EQUATIONS 1
BRIGHT = [200,1]  ! 27

*UNIT_NAME 8. Shading+Light
*SLAYER Controls
*SPOSITION 423 306

* Model "3. Weather data" (Type 109)
*
UNIT 109 TYPE 109  3. Weather data
*UNIT_NAME 3. Weather data
*$MODEL .\Weather Data Reading and Processing\Standard Format\TMY2\Type109-TMY2.tmf
*SPOSITION 67 146
*SLAYER Main #
PARAMETERS 4
2  ! 1 Data Reader Mode
30  ! 2 Logical unit
4  ! 3 Sky model for diffuse radiation
1  ! 4 Tracking mode
INPUTS 15
0,0  ! [unconnected] Ground reflectance
0,0  ! [unconnected] Slope of surface-1
0,0  ! [unconnected] Azimuth of surface-1
0,0  ! [unconnected] Slope of surface-2
0,0  ! [unconnected] Azimuth of surface-2
0,0  ! [unconnected] Slope of surface-3
0,0  ! [unconnected] Azimuth of surface-3
0,0  ! [unconnected] Slope of surface-4
0,0  ! [unconnected] Azimuth of surface-4
0,0  ! [unconnected] Slope of surface-5
0,0  ! [unconnected] Azimuth of surface-5
0,0  ! [unconnected] Slope of surface-6
0,0  ! [unconnected] Azimuth of surface-6
0,0 ! [unconnected] Slope of surface-7
0,0 ! [unconnected] Azimuth of surface-7

*** INITIAL INPUT VALUES
0.2 90 AA_N 90 AA_S 90 AA_E 90 AA_W 28.047 180 28.047 0 37 0

*** External files
ASSIGN "C:\TRNSYS\Trnsys16_1\Weather\Weather\US-TMY2\US-VA-Richmond-13740.tm2" 30
*

* Model "5. Psychrometrics" (Type 33)
*

UNIT 331 TYPE 33 5. Psychrometrics
*SUNIT_NAME 5. Psychrometrics
*SMODEL \Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Relative
Humidity Known\Type33e.tmf
*SPOSITION 190 218
*S LAYER Main #
PARAMETERS 3
2 ! 1 Psychrometrics mode
1 ! 2 Wet bulb mode
1 ! 3 Error mode
INPUTS 3
109,1 ! 3. Weather data:Ambient temperature ->Dry bulb temp.
109,2 ! 3. Weather data:relative humidity ->Percent relative humidity
0,0 ! [unconnected] Pressure

*** INITIAL INPUT VALUES
20 50 1

* Model "4. Sky temp" (Type 69)
*

UNIT 69 TYPE 69 4. Sky temp
*SUNIT_NAME 4. Sky temp
*SMODEL \Physical Phenomena\Sky Temperature\calculate cloudiness factor\Type69b.tmf
*SPOSITION 248 135
*S LAYER Main # #
PARAMETERS 2
0 ! 1 mode for cloudiness factor
0 ! 2 height over sea level
INPUTS 4
331,7 ! 5. Psychrometrics:Dry bulb temperature ->Ambient temperature
331,8 ! 5. Psychrometrics:Dew point temperature. ->Dew point temperature at ambient
conditions
109,13 ! 3. Weather data:beam radiation on horizontal ->Beam radiation on the horizontal
109,14 ! 3. Weather data:sky diffuse radiation on horizontal ->Diffuse radiation on the horizontal

*** INITIAL INPUT VALUES
0 0 0 0

* EQUATIONS "7. Light Thresholds"

98
EQUATIONS 2
Toth_L_on = -3.6*120
Eoth_L_off = -3.6*200
*SUNIT_NAME 7. Light Thresholds
*SLAYER Controls
*SPOSITION 291 285

* Model "6. Lights" (Type 2)
*
UNIT 200 TYPE 2  6. Lights
*SUNIT_NAME 6. Lights
*$MODEL .\Controllers\Differential Controller w_ Hysteresis\generic\Solver 0 (Successive Substitution)
Control Strategy\Type2d.tmf
*SPOSITION 358 200
*SLAYER Controls #
*$# NOTE: This controller can only be used with Solver 0 (Successive substitution)
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*PARAMETERS 2
5  ! 1 No. of oscillations
40000  ! 2 High limit cut-out
INPUTS 6
0,0  ! [unconnected] Upper input value
IT_H  ! 2. Radiation:IT_H ->Lower input value
0,0  ! [unconnected] Monitoring value
200,1  ! 6. Lights:Output control function ->Input control function
Toth_L_on  ! 7. Light Thresholds:Toth_L_on ->Upper dead band
Eoth_L_off  ! 7. Light Thresholds:Eoth_L_off ->Lower dead band
*** INITIAL INPUT VALUES
0 0 0 0 0
*----------------------------------------------------------------------

* Model "9. Building" (Type 56)
*
UNIT 56 TYPE 56  9. Building
*SUNIT_NAME 9. Building
*$MODEL .\Loads and Structures\Multi-Zone Building\With Standard Output Files\Type56a.tmf
*SPOSITION 513 253
*SLAYER Main ##
$\star\$#

PARAMETERS 6
31 ! 1 Logical unit for building description file (.bui)
1 ! 2 Star network calculation switch
0.5 ! 3 Weighting factor for operative temperature
32 ! 4 Logical unit for monthly summary
33 ! 5 Logical unit for hourly temperatures
34 ! 6 Logical unit for hourly loads

INPUTS 40
331,7 ! 5. Psychrometrics:Dry bulb temperature -> 1- TAMB
331,6 ! 5. Psychrometrics:Percent relative humidity -> 2- RELHUMAMB
69,1 ! 4. Sky temp:Fictive sky temperature -> 3- TSKY
IT_N ! 2. Radiation:IT_N -> 4- IT_NORTH
IT_S ! 2. Radiation:IT_S -> 5- IT_SOUTH
IT_E ! 2. Radiation:IT_E -> 6- IT_EAST
IT_W ! 2. Radiation:IT_W -> 7- IT_WEST
IT_H ! 2. Radiation:IT_H -> 8- IT_HORIZONTAL
109,42 ! 3. Weather data:total radiation on tilted surface-5 -> 9- IT_NSLOPE
109,48 ! 3. Weather data:total radiation on tilted surface-6 -> 10- IT_SSLOPE
IB_N ! 2. Radiation:IB_N -> 11- IB_NORTH
IB_S ! 2. Radiation:IB_S -> 12- IB_SOUTH
IB_E ! 2. Radiation:IB_E -> 13- IB_EAST
IB_W ! 2. Radiation:IB_W -> 14- IB_WEST
109,43 ! 3. Weather data:beam radiation on tilted surface-5 -> 16- IB_NSLOPE
109,49 ! 3. Weather data:beam radiation on tilted surface-6 -> 17- IB_SSLOPE
AI_N ! 2. Radiation:AI_N -> 18- AI_NORTH
AI_S ! 2. Radiation:AI_S -> 19- AI_SOUTH
AI_E ! 2. Radiation:AI_E -> 20- AI_EAST
AI_W ! 2. Radiation:AI_W -> 21- AI_WEST
AI_H ! 2. Radiation:AI_H -> 22- AI_HORIZONTAL
109,52 ! 3. Weather data:angle of incidence for tilted surface -5 -> 23- AI_NSLOPE
109,52 ! 3. Weather data:angle of incidence for tilted surface -6 -> 24- AI_SSLOPE
0,0 ! [unconnected] 25- CNAT_1
0,0 ! [unconnected] 26- CNAT_2
0,0 ! [unconnected] 27- CNAT_3
0,0 ! [unconnected] 28- T_COOL_ON
0,0 ! [unconnected] 29- S_NORTH
0,0 ! [unconnected] 30- S_SOUTH
0,0 ! [unconnected] 31- S_EAST
0,0 ! [unconnected] 32- S_WEST
BRIGHT ! 8. Shading+Light:BRIGHT -> 33- BRIGHT
12,1 ! 14. Basement:Front wall outer surface temperature -> 34- FRONTSOIL
12,2 ! 14. Basement:Left wall outer surface temperature -> 36- LEFT
12,4 ! 14. Basement:Right wall outer surface temperature -> 37- RIGHT
12,5 ! 14. Basement:Floor outer surface temperature -> 38- FLOORSOIL
20,6 ! 13. SSTES:Fluid Temp 1-2 -> 39- TEMPIN
20,7 ! 13. SSTES:Mass Flowrate 1-2 -> 40- MASSIN

*** INITIAL INPUT VALUES
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

*** External files
ASSIGN "2000singlezone.bui" 31
*|? Building description file (*.bui) |1000
ASSIGN "T56_std-Output.sum" 32
*|? Monthly Summary File |1000
ASSIGN "T56_std-temp.prn" 33
*|? Hourly Temperatures |1000
ASSIGN "T56_std-q.prn" 34
*|? Hourly Loads |1000
*----------------------------------------------------------------------------------------------------------------------

* Model "14. Basement" (Type 701)
*

UNIT 12 TYPE 701  14. Basement
*$UNIT_NAME 14. Basement
*$MODEL .\Ground Coupling Library (TESS)\Basement Heat Losses\Interfaces with Type56\No Output
File No Input File\Type701d.tmf
*$POSITION 592 82
*$LAYER Main #
PARAMETERS 60
3   ! 1 Nodes along length (Nx_adj)
6   ! 2 Nodes beyond length (Nx_ext)
5   ! 3 Nodes along width (Ny_adj)
4   ! 4 Nodes beyond width (Ny_ext)
4   ! 5 Nodes along depth (Nz_adj)
4   ! 6 Depth nodes (Nz_ext)
10  ! 7 Mean surface temperature
5   ! 8 Amplitude of surface temperature
36  ! 9 Day of minimum surface temperature
8.722 ! 10 Soil conductivity
3200 ! 11 Soil density
0.84 ! 12 Soil specific heat
0.9  ! 13 Surface emissivity
0.6  ! 14 Surface absorptance
1   ! 15 Side boundary heat transfer
1   ! 16 Bottom boundary heat transfer mode
5.0  ! 17 U-value for the front wall
5.0  ! 18 U-value for the left wall
5.0  ! 19 U-value for the back wall
5.0  ! 20 U-value for the right wall
5.0  ! 21 U-value for the floor
-1  ! 22 Logical unit for output file
-1  ! 23 Logical unit of input file
1   ! 24 Surface mode
0.1  ! 25 Length of soil node-1
0.1  ! 26 Length of soil node-2
0.1  ! 27 Length of soil node-3
0.1  ! 28 Length of soil node-4
0.1  ! 29 Length of soil node-5
0.1  ! 30 Length of soil node-6
0.1  ! 31 Length of soil node-7
0.1  ! 32 Length of soil node-8
0.1 ! 33 Length of soil node-9
0.1 ! 34 Length of soil node-10
0.1 ! 35 Length of soil node-11
0.1 ! 36 Length of soil node-12
0.1 ! 37 Length of soil node-13
0.1 ! 38 Length of soil node-14
0.1 ! 39 Length of soil node-15
0.1 ! 40 Width of soil node-1
0.1 ! 41 Width of soil node-2
0.1 ! 42 Width of soil node-3
0.1 ! 43 Width of soil node-4
0.1 ! 44 Width of soil node-5
0.1 ! 45 Width of soil node-6
0.1 ! 46 Width of soil node-7
0.1 ! 47 Width of soil node-8
0.1 ! 48 Width of soil node-9
0.1 ! 49 Width of soil node-10
0.1 ! 50 Width of soil node-11
0.1 ! 51 Width of soil node-12
0.1 ! 52 Width of soil node-13
0.1 ! 53 Depth of soil node-1
0.1 ! 54 Depth of soil node-2
0.1 ! 55 Depth of soil node-3
0.1 ! 56 Depth of soil node-4
0.1 ! 57 Depth of soil node-5
0.1 ! 58 Depth of soil node-6
0.1 ! 59 Depth of soil node-7
0.1 ! 60 Depth of soil node-8

INPUTS 11
109,1 ! 3. Weather data: Ambient temperature -> Ambient temperature
69,1 ! 4. Sky temp: Fictive sky temperature -> Sky temperature
109,12 ! 3. Weather data: total radiation on horizontal -> Incident solar radiation
0,0 ! [unconnected] Convection coefficient
56,10 ! 9. Building: 10- TSI_S13 -> Inside surface temperature - front wall
56,7 ! 9. Building: 7- TSI_S27 -> Inside surface temperature - left wall
56,8 ! 9. Building: 8- TSI_S28 -> Inside surface temperature - right wall
0,0 ! [unconnected] Near-field surface temperature
0,0 ! [unconnected] Far-field surface temperature

*** INITIAL INPUT VALUES
20 10 0 15 10.0 10.0 10.0 10.0 10.0 10 10

* Model "15. controller for heat removal" (Type 2)
*

UNIT 15 TYPE 2 15. controller for heat removal
*SUNIT_NAME 15. controller for heat removal
*$MODEL \Controllers\Differential Controller w_Hysteresis\for Temperatures\Solver 0 (Successive Substitution) Control Strategy\Type2b.tmf
*$POSITION 724 82
PARAMETERS 2
5 ! 1 No. of oscillations
130 ! 2 High limit cut-out

INPUTS 6
0,0 ! [unconnected] Upper input temperature Th
56.4 ! 9. Building: 4- TAIR_2000 ->Lower input temperature Tl
0,0 ! [unconnected] Monitoring temperature Tin
15.1 ! 15. controller for heat removal:Output control function ->Input control function
0,0 ! [unconnected] Upper dead band dT
0,0 ! [unconnected] Lower dead band dT

*** INITIAL INPUT VALUES
20 18 120 0.5 0

* EQUATIONS "16. mass flow"

EQUATIONS 1
massflowheatremove = [15,1]*1135.5*[24,1]

* Model "21. Solar Collectors" (Type 73)

UNIT 19 TYPE 73 21. Solar Collectors
*SUNIT_NAME 21. Solar Collectors
*SMODEL \Solar Thermal Collectors\Theoretical Flat-Plate Collector\Type73.tmf
*SPOSITION 382 477
*SAYER Main #
PARAMETERS 10
1 ! 1 Number in series
2.972 ! 2 Collector area
4.190 ! 3 Fluid specific heat
0.7 ! 4 Collector fin efficiency factor
3.0 ! 5 Bottom, edge loss coefficient
0.7 ! 6 Absorber plate emittance
0.8 ! 7 Absorptance of absorber plate
1 ! 8 Number of covers
1.526 ! 9 Index of refraction of cover
0.0026 ! 10 Extinction coeff. thickness product

INPUTS 10
20.1 ! 13. SSTES:Fluid Temp 1-1 ->Inlet temperature
Collectormassflow ! 20. mass flow-2:Collectormassflow ->Inlet flowrate
109,1 ! 3. Weather data:Ambient temperature ->Ambient temperature
109.54 ! 3. Weather data:total radiation on tilted surface-7 ->Incident radiation
109,3  ! 3. Weather data: wind velocity -> Windspeed
109,12  ! 3. Weather data: total radiation on horizontal -> Horizontal radiation
109,14  ! 3. Weather data: sky diffuse radiation on horizontal -> Horizontal diffuse
109,15  ! 3. Weather data: ground reflected diffuse radiation on horizontal -> Ground reflectance
109,16  ! 3. Weather data: angle of incidence on horizontal surface -> Incidence angle
0,0  ! [unconnected] Collector slope

*** INITIAL INPUT VALUES
20.0 100.0 10.0 0.0 0.0 0.0 0.2 20.0 37

* EQUATIONS "20. mass flow-2"
*
EQUATIONS 2
Collectormassflow = [22,1]*bedheataddflow/28.337
bedheataddflow = [22,1]*340.65
*$UNIT_NAME 20. mass flow-2
*$LAYER Main
*$POSITION 213 424

* MODEL "19. controller for heat add" (Type 2)
*
UNIT 22 TYPE 2 19. controller for heat add
*$UNIT_NAME 19. controller for heat add
*$MODEL \\Controllers\\Differential Controller w_ Hysteresis\\for Temperatures\\Solver 0 (Successive Substitution) Control Strategy\\Type2b.tmf
*$POSITION 314 392
*$LAYER Controls#
*$# NOTE: This control strategy can only be used with solver 0 (Successive substitution)
*$# PARAMETERS 2
5  ! 1 No. of oscillations
130  ! 2 High limit cut-out
INPUTS 6
19,1  ! 21. Solar Collectors: Outlet temperature -> Upper input temperature Th
20,12  ! 13. SSTES: Ave Storage Temp -> Lower input temperature Tl
0,0  ! [unconnected] Monitoring temperature Tin
0,0  ! [unconnected] Input control function
0,0  ! [unconnected] Upper dead band dT
0,0  ! [unconnected] Lower dead band dT

*** INITIAL INPUT VALUES
20.0 10.0 120 0.5 0

* MODEL "13. SSTES" (Type 342)
*
UNIT 20 TYPE 342 13. SSTES
*$UNIT_NAME 13. SSTES

104
*MODEL \type342_studio_proforma\TYPE342.tmf
*POSITION 740 194
*SLAYER Main #
PARAMETERS 78
0  ! 1 imode
2  ! 2 segments
2  ! 3 iconv
2  ! 4 Nflow
1  ! 5 NPin-1
1  ! 6 Jinj-1
1  ! 7 NPout-1
1  ! 8 Joutj-1
1  ! 9 NPin-2
1  ! 10 Jinj-2
1  ! 11 NPout-2
1  ! 12 Joutj-2
15  ! 13 Volumne
3  ! 14 Height
1  ! 15 Top Depth
3.24  ! 16 Storage Conductivity
996  ! 17 Storage Heat Capacity
0  ! 18 Minimum Velocity
3000  ! 19 Max Flowrate
4.2  ! 20 Fluid Heat Capacity
1000  ! 21 Fluid Density
0  ! 22 Dispersion Length
0  ! 23 Darcy Exponent
.1  ! 24 Insulation Thickness
1  ! 25 Top Fraction
1  ! 26 Side Fraction
1  ! 27 Bottom Fraction
.2  ! 28 Insulation Conductivity
10  ! 29 Number of Years
100  ! 30 Max Temperature
13  ! 31 Initial Storage Temp
13  ! 32 Initial Ground Temp
0  ! 33 Init. Thermal Gradient
0  ! 34 No of Preheat Cycles
0  ! 35 Max Preheat Temp
0  ! 36 Min Preheat Temp
0  ! 37 Preheat Phase Time
13  ! 38 Average Annual Air Temp
5  ! 39 Temp Amplitude
0  ! 40 Air Temp Phase Time
9  ! 41 Layers
3.24  ! 42 Layer Conductivity-1
996  ! 43 Layer Heat Capacity-1
.33  ! 44 Layer Thickness-1
3.24  ! 45 Layer Conductivity-2
996  ! 46 Layer Heat Capacity-2
.33  ! 47 Layer Thickness-2
3.24  ! 48 Layer Conductivity-3
**UNIT 24 TYPE 2 17. Tbed>Thouse**

*UNIT_NAME 17. Tbed>Thouse*

*$MODEL \Controllers\Differential Controller w_ Hysteresis\generic\Solver 0 (Successive Substitution)*

Control Strategy:Type2d.tmf

*$SPOSITION 859 168*

*$SLAYER Controls #*
*$# NOTE: This controller can only be used with Solver 0 (Successive substitution)
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#

PARAMETERS 2
5  ! 1 No. of oscillations
130  ! 2 High limit cut-out

INPUTS 6
20.6  ! 13. SSTES:Fluid Temp 1-2 ->Upper input value
56.4  ! 9. Building: 4- TAIR_2000 ->Lower input value
0.0  ! [unconnected] Monitoring value
24.1  ! 17. Tbed>Thouse:Output control function ->Input control function
0.0  ! [unconnected] Upper dead band
0.0  ! [unconnected] Lower dead band

*** INITIAL INPUT VALUES
20.0 10.0 50 0 .5 0

*---------------------------------------------------------------

* Model "18. Controllers" (Type 65)
*

UNIT 23 TYPE 65  18. Controllers
*$UNIT_NAME 18. Controllers
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 886 285
*$LAYER Main #

PARAMETERS 12
2  ! 1 Nb. of left-axis variables
2  ! 2 Nb. of right-axis variables
0.0  ! 3 Left axis minimum
2  ! 4 Left axis maximum
0.0  ! 5 Right axis minimum
1000.0  ! 6 Right axis maximum
1  ! 7 Number of plots per simulation
5  ! 8 X-axis gridpoints
0  ! 9 Shut off Online w/o removing
35  ! 10 Logical Unit for output file
0  ! 11 Output file units
0  ! 12 Output file delimiter

INPUTS 4
22.1  ! 19. controller for heat add:Output control function ->Left axis variable-1
24.1  ! 17. Tbed>Thouse:Output control function ->Left axis variable-2
massflowheatremove  ! 16. mass flow:massflowheatremove ->Right axis variable-1
15.1  ! 15. controller for heat removal:Output control function ->Right axis variable-2

*** INITIAL INPUT VALUES
Solarcontroller bedcontroller massflowheatremove housebedsignal
LABELS 3
"Temperatures"
"Heat transfer rates"
"control"
*** External files
ASSIGN "***.plt" 35
*? What file should the online print to? |1000
*-------------------------------------------------------------

* Model "11. Aux Heat" (Type 65)
*

UNIT 26 TYPE 65  11. Aux Heat
*$UNIT_NAME 11. Aux Heat
*$MODEL .\Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*$POSITION 597 317
*$SLAYER Main #
PARAMETERS 12
  3    ! 1 Nb. of left-axis variables
  3    ! 2 Nb. of right-axis variables
  0.0  ! 3 Left axis minimum
40000.0 ! 4 Left axis maximum
  0.0  ! 5 Right axis minimum
1000.0 ! 6 Right axis maximum
  1    ! 7 Number of plots per simulation
  5    ! 8 X-axis gridpoints
   0    ! 9 Shut off Online w/o removing
  36    ! 10 Logical Unit for output file
   0    ! 11 Output file units
   0    ! 12 Output file delimiter
INPUTS 6
 fluidenergyinput    ! 10. Abs Value:fluidenergyinput ->Left axis variable-2
 TotalGain            ! 22. Total Gain:TotalGain ->Left axis variable-3
 15,1    ! 15. controller for heat removal:Output control function ->Right axis variable-1
 22,1    ! 19. controller for heat add:Output control function ->Right axis variable-2
 24,1    ! 17. Tbed>Thouse:Output control function ->Right axis variable-3
*** INITIAL INPUT VALUES
QHEAT fluidEnergyInput CollectorGain floorThermo solarcontrol bed>house

LABELS 3
"heat transfer rates"
"Heat transfer rates"
"Aux heating"
*** External files
ASSIGN "qheat.xls" 36
*? What file should the online print to? |1000
*-------------------------------------------------------------

* EQUATIONS "10. Abs Value"
*

108
EQUATIONS 1
fluidenergyinput = [56,12]*-1
*SUNIT_NAME 10. Abs Value
*SLAYER Main
*SPOSITION 506 328

* Model "12. Temp" (Type 65)
*
UNIT 28 TYPE 65 12. Temp
*SUNIT_NAME 12. Temp
*SMODEL \Output\Online Plotter\Online Plotter With File\No Units\Type65c.tmf
*SPOSITION 642 253
*SLAYER Main #
PARAMETERS 12
8 ! 1 Nb. of left-axis variables
0 ! 2 Nb. of right-axis variables
-10 ! 3 Left axis minimum
110 ! 4 Left axis maximum
0.0 ! 5 Right axis minimum
1000.0 ! 6 Right axis maximum
1 ! 7 Number of plots per simulation
5 ! 8 X-axis gridpoints
0 ! 9 Shut off Online w/o removing
37 ! 10 Logical Unit for output file
0 ! 11 Output file units
0 ! 12 Output file delimiter
INPUTS 8
56,3 ! 9. Building: 3- TAIR_SUBCRAWL ->Left axis variable-3
20,6 ! 13. SSTES: Fluid Temp 1-2 ->Left axis variable-5
20,12 ! 13. SSTES: Ave Storage Temp ->Left axis variable-7
19,1 ! 21. Solar Collectors: Outlet temperature ->Left axis variable-8
*** INITIAL INPUT VALUES
TAIR_CRAWL TAIR_ATTIC TAIR_SUBCRAWL TAIR_1400 Tfluidinho Tfluidoutho
tbed Toutcollector
LABELS 3
"Temperatures"
"Heat transfer rates"
"temp"
*** External files
ASSIGN "temp.xls" 37
*? What file should the online print to? |1000
*----------------------------------------------------------------------

* EQUATIONS "22. Total Gain"
* EQUATIONS 1
TotalGain = [19,3]*28.337
*UNIT_NAME 22. Total Gain
*SLAYER Main
*SPOSITION 547 562

*-------------------

END
TRNSYS Building Description File (.bui)

******************************************************
*  TRNBuild  1.0.94
******************************************************
******************************************************
***************************
*   BUILDING DESCRIPTIONS FILE TRNSYS
*   FOR BUILDING: C:\TRNSYS\Trnsys16_1\MyProjects\V2_2000singlezonetype342\2000singlezone.bui
*   GET BY WORKING WITH TRNBuild 1.0 for Windows
**************************************************************
**************************************************************
***************************
* C o m m e n t s
**************************************************************

*#C  ------------------------------------------ TYPES ------------------------------- *
*#C  ------------------------------------------LAYERS ----------------------------- *
*#C  ------------------------------------------ INPUTS ----------------------------- *
*#C  ------------------------------------------ SCHEDULES ------------------------ *
*#C  ------------------------------------------ WALLS ----------------------------- *
*#C  ------------------------------------------ WINDOWS --------------------------- *
*#C  ------------------------------------------ GAINS ----------------------------- *
*#C  ------------------------------------------ COMFORT -------------------------- *
*#C  ------------------------------------------ INFILTRATION --------------------- *
*#C  ------------------------------------------ VENTILATION ---------------------- *
*#C  ------------------------------------------ HEATING -------------------------- *
*#C  ------------------------------------------ ORIENTATIONS --------------------- *
*#C  ------------------------------------------ ZONES ---------------------------- *
*#C  ------------------------------------------ BUILDING ------------------------- *
*#C  ------------------------------------------ GEOSURF -------------------------- *
*#C  ------------------------------------------ OUTPUTS -------------------------- *

111
*#C

---

# Project

---

+++ PROJECT
+++ TITLE=2000 SINGLE ZONE
+++ DESCRIPTION=UNDEFINED
+++ CREATED=SWIZZLE
+++ ADDRESS=UNDEFINED
+++ CITY=RICHMOND
+++ SWITCH=UNDEFINED

---

# Properties

---

PROPERTIES

--- alpha calculation
---

KFLOORUP=7.2 : EFLOORUP=0.31 : KFLOORDOWN=3.888 : EFLOORDOWN=0.31
KCEILUP=7.2 : ECEILUP=0.31 : KCEILDOWN=3.888 : ECEILDOWN=0.31
KVERTICAL=5.76 : EVERTICAL=0.3

---

# Layers

---

LAYER BRICK
CONDUCTIVITY= 3.2 : CAPACITY= 1 : DENSITY= 1800
LAYER CONCRETE
CONDUCTIVITY= 7.56 : CAPACITY= 0.8 : DENSITY= 2400
LAYER STONE
CONDUCTIVITY= 5 : CAPACITY= 1 : DENSITY= 2000
LAYER PLASTER
CONDUCTIVITY= 5 : CAPACITY= 1 : DENSITY= 2000
LAYER FLOOR
CONDUCTIVITY= 0.252 : CAPACITY= 1 : DENSITY= 800
LAYER SILENCE
CONDUCTIVITY= 0.18 : CAPACITY= 1.44 : DENSITY= 80
LAYER GYPSUM
CONDUCTIVITY= 0.756 : CAPACITY= 1 : DENSITY= 1200
LAYER INSUL  
CONDUCTIVITY= 0.144 : CAPACITY= 0.8 : DENSITY= 40
LAYER WALL_BOARD  
CONDUCTIVITY= 1.04 : CAPACITY= 1 : DENSITY= 600
LAYER BATINSUL_R13  
CONDUCTIVITY= 0.14 : CAPACITY= 0.9 : DENSITY= 80
LAYER PLYWOOD  
CONDUCTIVITY= 0.54 : CAPACITY= 1.2 : DENSITY= 800
LAYER POLY_VINYL  
CONDUCTIVITY= 0.83 : CAPACITY= 1 : DENSITY= 1500
LAYER TIMBERFLOO  
CONDUCTIVITY= 0.504 : CAPACITY= 1.2 : DENSITY= 650
LAYER CLINKER_HO  
CONDUCTIVITY= 1.8 : CAPACITY= 1 : DENSITY= 1200
LAYER COPPER  
CONDUCTIVITY= 1340 : CAPACITY= 0.419 : DENSITY= 8300
LAYER BITUMENROO  
CONDUCTIVITY= 0.61 : CAPACITY= 1 : DENSITY= 1200
LAYER SAND_GRAVE  
CONDUCTIVITY= 2.52 : CAPACITY= 1 : DENSITY= 1800
LAYER RADLAY3QUART  
PSPACING= 0.15 : PDIAMETER= 0.022 : PWALLTHICKNESS= 0.0025 : PCONDUCTIVITY= 1.476  
: CPFLUID= 4.18
LAYER RESIST  
RESISTANCE= 6

*----------------------------------------------------------------------------------------------------------------------------------

LAYER RESIST  
RESISTANCE= 6

*----------------------------------------------------------------------------------------------------------------------------------

INPUTS CNAT_1 CNAT_2 CNAT_3 T_COOL ON_S_NORTH S_SOUTH S_EAST S_WEST BRIGHT  
FRONTSOIL BACKSOIL LEFT RIGHT FLOORSOIL TEMPIN MASSIN

*----------------------------------------------------------------------------------------------------------------------------------

SCHEDULE WORKDAY  
HOURS =0.000 8.000 18.000 24.0  
VALUES=0 1 0 0
SCHEDULE WEEKEND  
HOURS =0.000 1.000 24.0  
VALUES=0 0 0
SCHEDULE WORKLIGHT  
HOURS =0.000 8.000 18.000 24.0  
VALUES=0 1 0 0
SCHEDULE DAYNIGHT  
HOURS =0.000 6.000 18.000 24.0  
VALUES=0 1 0 0
SCHEDULE USE  
DAYS=1 2 3 4 5 6 7  
HOURLY=WORKDAY WORKDAY WORKDAY WORKDAY WORKDAY WEEKEND WEEKEND
SCHEDULE LIGHT
DAYS=1 2 3 4 5 6 7
HOURLY=WORKLIGHT WORKLIGHT WORKLIGHT WORKLIGHT WORKLIGHT WORKLIGHT WEEKEND
SCHEDULE SETOFF
DAYS=1 2 3 4 5 6 7
HOURLY=DAYNIGHT DAYNIGHT DAYNIGHT DAYNIGHT DAYNIGHT WEEKEND WEEKEND

*----------------------------------------------------------------------------------------------------------------------------------
* W a l l s
*----------------------------------------------------------------------------------------------------------------------------------

WALL OUTWALL
LAYERS = WALL_BOARD BATINSUL_R13 PLYWOOD POLY_VINYL
THICKNESS= 0.013 0.089 0.013 0.013
ABS-FRONT= 0.8 : ABS-BACK= 0.3
HFRONT = 11 : HBACK= 64

WALL INTFLOOR
LAYERS = TIMBERFLOOR PLYWOOD BATINSUL_R13
THICKNESS= 0.019 0.013 0.191
ABS-FRONT= 0.8 : ABS-BACK= 0.4
HFRONT = 11 : HBACK= 999

WALL CRAWLWALL
LAYERS = CLINKER_HO
THICKNESS= 0.203
ABS-FRONT= 0.6 : ABS-BACK= 0.6
HFRONT = 11 : HBACK= 11

WALL CEILING
LAYERS = WALL_BOARD BATINSUL_R13
THICKNESS= 0.013 0.318
ABS-FRONT= 0.6 : ABS-BACK= 0.6
HFRONT = 11 : HBACK= 11

WALL PLYWOOD
LAYERS = PLYWOOD
THICKNESS= 0.013
ABS-FRONT= 0.6 : ABS-BACK= 0.6
HFRONT = 11 : HBACK= 11

WALL ROOF
LAYERS = PLYWOOD BITUMENROO
THICKNESS= 0.013 0.006
ABS-FRONT= 0.6 : ABS-BACK= 0.6
HFRONT = 11 : HBACK= 11

WALL ATTIC_OUTWALL
LAYERS = PLYWOOD POLY_VINYL
THICKNESS= 0.013 0.013
ABS-FRONT= 0.6 : ABS-BACK= 0.6
HFRONT = 11 : HBACK= 11

WALL EARTH
LAYERS = SAND_GRAVE
THICKNESS= 0.015
ABS-FRONT= 0.6 : ABS-BACK= 0.6
HFRONT = 11 : HBACK= 0
WALL RADFLOOR
LAYERS = TIMBERFLOO RADLAY3QUART TIMBERFLOO RESIST
THICKNESS = 0.045 0 0.05 0
ABS-FRONT = 0.6 : ABS-BACK = 0.6
HFRONT = 50 : HBACK = 0.5

*----------------------------------------------------------------------------------------------------------------------------------

* Windows
*----------------------------------------------------------------------------------------------------------------------------------

WINDOW DOUBLE
WINID = 2001 : HINSIDE = 11 : HOUTSIDE = 64 : SLOPE = 90 : SPACID = 0 : WWID = 0 : WHEIG = 0 :
FFRAME = 0.2 : UFRAME = 8.17 : ABSFRAME = 0.6 : RISHADE = 0 : RESHADE = 0 : REFISHADE = 0.5 :
REFLOSHADE = 0.5 : CCISHADE = 0.5
WINDOW OPEN
WINID = 10001 : HINSIDE = 11 : HOUTSIDE = 64 : SLOPE = 90 : SPACID = 1 : WWID = 0.77 : WHEIG = 1.08 :
FFRAME = 0 : UFRAME = 8.17 : ABSFRAME = 0 : RISHADE = 0 : RESHADE = 0 : REFISHADE = 0.5 :
REFLOSHADE = 0.5 : CCISHADE = 0.5

*----------------------------------------------------------------------------------------------------------------------------------

* Default Gains
*----------------------------------------------------------------------------------------------------------------------------------

*----------------------------------------------------------------------------------------------------------------------------------

* Other Gains
*----------------------------------------------------------------------------------------------------------------------------------

GAIN PER_SP
CONVECTIVE = 15 : RADIATIVE = 10 : HUMIDITY = 0.058
GAIN LIGHT_SP
CONVECTIVE = INPUT 12*BRIGHT : RADIATIVE = INPUT 24*BRIGHT : HUMIDITY = 0
GAIN GAIN_SP
CONVECTIVE = 42 : RADIATIVE = 8.4 : HUMIDITY = 0

*----------------------------------------------------------------------------------------------------------------------------------

* Comfort
*----------------------------------------------------------------------------------------------------------------------------------

*----------------------------------------------------------------------------------------------------------------------------------

* Infiltration
*----------------------------------------------------------------------------------------------------------------------------------

INФILTRATION 2ACH
AIRCHANGE = 2
INФILTRATION 1ACH
AIRCHANGE = 1

*----------------------------------------------------------------------------------------------------------------------------------

* Ventilation
VENTILATION VENTZONE1
TEMPERATURE=OUTSIDE
AIRCHANGE=INPUT 3*CNAT_1
HUMIDITY=OUTSIDE
VENTILATION VENTZONE2
TEMPERATURE=OUTSIDE
AIRCHANGE=INPUT 3*CNAT_2
HUMIDITY=OUTSIDE
VENTILATION VENTZONE3
TEMPERATURE=OUTSIDE
AIRCHANGE=INPUT 3*CNAT_3
HUMIDITY=OUTSIDE
VENTILATION VENTMECH
TEMPERATURE=20
AIRCHANGE=SCHEDULE 0*USE
HUMIDITY=50

*----------------------------------------------------------------------------------------------------------------------------------

*  C o o l i n g
*----------------------------------------------------------------------------------------------------------------------------------

*----------------------------------------------------------------------------------------------------------------------------------

*  H e a t i n g
*----------------------------------------------------------------------------------------------------------------------------------

HEATING HEAT20
ON=19
POWER=999999999
HUMIDITY=0
RRAD=0

*----------------------------------------------------------------------------------------------------------------------------------

*  Z o n e s
*----------------------------------------------------------------------------------------------------------------------------------

ZONES CRAWL ATTIC SUBCRAWL 2000

*----------------------------------------------------------------------------------------------------------------------------------

*  O r i e n t a t i o n s
*----------------------------------------------------------------------------------------------------------------------------------

ORIENTATIONS NORTH SOUTH EAST WEST HORIZONTAL NSLOPE SSLOPE

BUILDING
ZONE CRAWL
AIRNODE CRAWL

WALL =CRAWLWALL : SURF=  6 : AREA=  18.275 : EXTERNAL : ORI=NORTH : FSKY=0.5 : GEOSURF=0.1
WALL =CRAWLWALL : SURF=  7 : AREA=  18.275 : EXTERNAL : ORI=SOUTH : FSKY=0.5 : GEOSURF=0.1
WALL =CRAWLWALL : SURF=  8 : AREA=  8.501 : EXTERNAL : ORI=EAST : FSKY=0.5 : GEOSURF=0.1
WALL =CRAWLWALL : SURF=  9 : AREA=  8.501 : EXTERNAL : ORI=WEST : FSKY=0.5 : GEOSURF=0.1
WALL =PLYWOOD    : SURF= 14 : AREA=  0.106 : ADJACENT=SUBCRAWL : FRONT
WINDOW=OPEN       : SURF= 22 : AREA=  185.7 : ADJACENT=SUBCRAWL : FRONT : COUPL=16
  : ORI=HORIZONTAL
REGIME
GAIN        = PER_SP     : SCALE= SCHEDULE 111.48*USE
GAIN        = LIGHT_SP   : SCALE= SCHEDULE 111.48*LIGHT
GAIN        = GAIN_SP    : SCALE= SCHEDULE 111.48*USE
INFILTRATION= 2ACH
CAPACITANCE = 203.88  : VOLUME= 169.901 : TINITIAL= 20  : PHINITIAL= 50  : WCAPR= 1

ZONE ATTIC
AIRNODE ATTIC

WALL =ROOF       : SURF=  11 : AREA= 105.265 : EXTERNAL : ORI=NSLOPE : FSKY=0.5
WALL =ROOF       : SURF=  24 : AREA= 105.265 : EXTERNAL : ORI=SSLOPE : FSKY=0.5
WALL =ATTIC_OUTWALL : SURF=  25 : AREA= 11.512 : EXTERNAL : ORI=EAST : FSKY=0.5
WALL =ATTIC_OUTWALL : SURF=  26 : AREA= 11.512 : EXTERNAL : ORI=WEST : FSKY=0.5
WALL =CEILING    : SURF=  16 : AREA= 185.806 : ADJACENT=2000 : BACK
REGIME
GAIN        = PER_SP     : SCALE= SCHEDULE 111.48*USE
GAIN        = LIGHT_SP   : SCALE= SCHEDULE 111.48*LIGHT
GAIN        = GAIN_SP    : SCALE= SCHEDULE 111.48*USE
INFILTRATION= 2ACH
CAPACITANCE = 276.09  : VOLUME= 230.074 : TINITIAL= 20  : PHINITIAL= 50  : WCAPR= 1

ZONE SUBCRAWL
AIRNODE SUBCRAWL

* Z o n e S U B C R A W L / A i r n o d e S U B C R A W L
ZONE SUBCRAWL
AIRNODE SUBCRAWL
WALL = PLYWOOD : SURF= 21 : AREA= 0.106 : ADJACENT=CRAWL : BACK
WALL = CRAWLWALL : SURF= 13 : AREA= 3.0458 : BOUNDARY=INPUT 1*FRONTSOIL
WALL = CRAWLWALL : SURF= 12 : AREA= 3.0458 : BOUNDARY=INPUT 1*BACKSOIL
WALL = CRAWLWALL : SURF= 27 : AREA= 1.4168 : BOUNDARY=INPUT 1*LEFT
WALL = CRAWLWALL : SURF= 28 : AREA= 1.4168 : BOUNDARY=INPUT 1*RIGHT
WALL = EARTH : SURF= 29 : AREA= 185.806 : BOUNDARY=INPUT 1*FLOORSOIL
REGIME
INFILTRATION= 2ACH
CAPACITANCE = 27.18 : VOLUME= 22.6535 : TINITIAL = 20 : PHINITIAL = 50 : WCAPR = 1

ZONE 2000 / AIRNODE 2000

WALL = OUTWALL : SURF= 1 : AREA= 42.99 : EXTERNAL : ORI=NORTH : FSKY=0.5
WINDOW=DOUBLE : SURF= 17 : AREA= 6.505 : EXTERNAL : ORI=NORTH : FSKY=0.5
WALL = OUTWALL : SURF= 2 : AREA= 39.941 : EXTERNAL : ORI=SOUTH : FSKY=0.5
WINDOW=DOUBLE : SURF= 18 : AREA= 9.554 : EXTERNAL : ORI=SOUTH : FSKY=0.5
WALL = OUTWALL : SURF= 3 : AREA= 21.528 : EXTERNAL : ORI=EAST : FSKY=0.5
WINDOW=DOUBLE : SURF= 19 : AREA= 1.496 : EXTERNAL : ORI=EAST : FSKY=0.5
WALL = OUTWALL : SURF= 4 : AREA= 20.032 : EXTERNAL : ORI=WEST : FSKY=0.5
WINDOW=DOUBLE : SURF= 20 : AREA= 2.992 : EXTERNAL : ORI=WEST : FSKY=0.5
WALL = CEILING : SURF= 5 : AREA= 185.806 : ADJACENT=ATTIC : FRONT
REGIME
INFILTRATION= 1ACH
HEATING = HEAT20
CAPACITANCE = 552.18 : VOLUME= 460.149 : TINITIAL = 20 : PHINITIAL = 50 : WCAPR = 1

OUTPUTS
TRANSFER : TIMEBASE=1.000
AIRNODES = CRAWL ATTIC SUBCRAWL 2000
NTYPES = 1 : TAIR - air temperature of zone
AIRNODES = 2000
NTYPES = 30 : QHEAT - sensible heating demand of zone (positive values)
AIRNODES = SUBCRAWL
NTYPES = 17 : SURF = 12, 27, 28, 29, 13, : TSI - inside surface temperature
AIRNODES = 2000
NTYPES = 58 : SURF = 10, : TOFL - fluid outlet temperature of active layer
= 61 : SURF = 10, : QALTL - total energy input by fluid+gains of active layers

*----------------------------------------------------------------------------------------------------------------------------------
** End
*----------------------------------------------------------------------------------------------------------------------------------

END

_EXTENSION_WINPOOL_START_

WINDOW 4.1 DOE-2 Data File : Multi Band Calculation
Unit System : SI
Name : TRNSYS 15 WINDOW LIB
Desc : Single, 5.8
Window ID : 1001
Tilt : 90.0
Glazings : 1
Frame : 11 2.270
Spacer : 5 Class5 0.000 1.000 0.000
Total Height: 1219.2 mm
Total Width : 914.4 mm
Glass Height: 1079.5 mm
Glass Width : 774.7 mm
Mullion : None
Gap | Thick | Cond | dCond | Vis | dVis | Dens | dDens | Pr | dPr
---|-------|------|-------|-----|------|------|-------|---|----
1  | 0     | 0    | 0     | 0   | 0    | 0    | 0     | 0 | 0
2  | 0     | 0    | 0     | 0   | 0    | 0    | 0     | 0 | 0
3  | 0     | 0    | 0     | 0   | 0    | 0    | 0     | 0 | 0
4  | 0     | 0    | 0     | 0   | 0    | 0    | 0     | 0 | 0
5  | 0     | 0    | 0     | 0   | 0    | 0    | 0     | 0 | 0
Angle | 0 10 20 30 40 50 60 70 80 90 Hemis
Tsol : 0.830 0.829 0.827 0.823 0.813 0.792 0.744 0.632 0.384 0.000 0.749
Abs1 : 0.095 0.096 0.098 0.101 0.105 0.109 0.114 0.117 0.114 0.000 0.106
Abs2 : 0 0 0 0 0 0 0 0 0 0 0
Abs3 : 0 0 0 0 0 0 0 0 0 0 0
Abs4 : 0 0 0 0 0 0 0 0 0 0 0
Abs5 : 0 0 0 0 0 0 0 0 0 0 0
Abs6 : 0 0 0 0 0 0 0 0 0 0 0
Rfsol : 0.075 0.074 0.075 0.076 0.082 0.099 0.142 0.251 0.502 1.000 0.135
Rbsol : 0.075 0.074 0.075 0.076 0.082 0.099 0.142 0.251 0.502 1.000 0.135
Tvis : 0.901 0.901 0.900 0.897 0.890 0.871 0.824 0.706 0.441 0.000 0.823
Rfvis : 0.081 0.081 0.082 0.083 0.090 0.108 0.155 0.271 0.536 1.000 0.146
Rbvis : 0.081 0.081 0.082 0.083 0.090 0.108 0.155 0.271 0.536 1.000 0.146
SHGC : 0.855 0.855 0.853 0.849 0.841 0.821 0.774 0.663 0.414 0.000 0.777
SC: 0.78
Layer ID# : 9052 0 0 0 0 0 0 0
Tir : 0.000 0 0 0 0 0 0
Emis F : 0.840 0 0 0 0 0 0
Emis B : 0.840 0 0 0 0 0 0
Thickness(mm) : 4.0 0 0 0 0 0 0 0
Cond(W/m2-C) : 225.0 0 0 0 0 0 0
Spectral File : None None None None None None
Overall and Center of Glass Igs U-values (W/m2-C)
<table>
<thead>
<tr>
<th>Outdoor Temperature</th>
<th>-17.8 C</th>
<th>15.6 C</th>
<th>26.7 C</th>
<th>37.8 C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar WdSpd</td>
<td>hcout hrout</td>
<td>hin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(W/m²)</td>
<td>(m/s)</td>
<td>(W/m²-C)</td>
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<td></td>
</tr>
<tr>
<td>0</td>
<td>12.25</td>
<td>3.42</td>
<td>8.23</td>
<td>5.27</td>
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<td>3.33</td>
<td>8.29</td>
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<tr>
<td>783</td>
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<td>8.17</td>
</tr>
<tr>
<td>783</td>
<td>6.71</td>
<td>25.47</td>
<td>3.37</td>
<td>8.27</td>
</tr>
</tbody>
</table>

WINDOW 4.1 DOE-2 Data File: Multi Band Calculation
Unit System: SI
Name: TRNSYS 15 WINDOW LIB
Desc: Waermeschutzglas, Ar, 1.4 71/59
Window ID: 2001
Tilt: 90.0
Glazings: 2
Frame: 11 2.270
Spacer: Class1 2.330 -0.010 0.138
Total Height: 1219.2 mm
Total Width: 914.4 mm
Glass Height: 1079.5 mm
Glass Width: 774.7 mm
Mullion: None

<table>
<thead>
<tr>
<th>Angle</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90 Hemis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsol</td>
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<td>0.428</td>
<td>0.422</td>
<td>0.413</td>
<td>0.402</td>
<td>0.380</td>
<td>0.333</td>
<td>0.244</td>
<td>0.113</td>
<td>0.000</td>
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<td>0.120</td>
<td>0.123</td>
<td>0.129</td>
<td>0.135</td>
<td>0.142</td>
<td>0.149</td>
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<tr>
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<td>0.198</td>
<td>0.201</td>
<td>0.200</td>
<td>0.199</td>
<td>0.199</td>
<td>0.185</td>
<td>0.117</td>
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<tr>
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<td>0.266</td>
<td>0.262</td>
<td>0.266</td>
<td>0.262</td>
<td>0.269</td>
<td>0.286</td>
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*WinID  Description                  Design | U-Value | g-value | T-sol | Rf-sol | T-vis |
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VITA

Marshall Louis Sweet was born September 8, 1985 in Winchester, Virginia, USA. He graduated from James Wood High School in June of 2003. He entered George Mason University in the fall of 2004 majoring in Physics before transferring to James Madison University in the fall of 2005. He graduated from James Madison University in May of 2008 with a Bachelor’s of Science degree in Integrated Science and Technology with a concentration in Energy.

During his undergraduate studies he completed two different internships in the field of alternative energy. During the summer of 2007 he worked for EMO Energy Solutions in Falls Church, Virginia constructing DOE-2 energy models for new and existing commercial buildings. The following summer of 2008 he worked for the government of Frederick County, Virginia conducting an energy audit of all government entities, including buildings and transportation.

In the fall of 2008, Marshall entered the Masters program in Mechanical and Nuclear Engineering at Virginia Commonwealth University. He worked as a teaching/research assistant in the Energy Conversion Systems Laboratory under the supervision of Dr. James T. McLeskey Jr. As of the spring of 2009 he has began working towards his PhD in Mechanical Engineering in the same laboratory.